THE ACOUSTICAL CHARACTERISTICS OF
THE SAYYIDINA ABU BAKAR MOSQUE, UTeM

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Abstract

In the Muslim world, mosques are built with grandeur architectural design to
depict an important house of worship in Islam. Unfortunately the acoustical
performance in mosque is rarely considered at the design stage which
eventually deteriorates the speech intelligibility. This includes the Sayyidina
Abu Bakar Mosque in UTeM where poor subjective speech clarity is
experienced during congregation. The objective of this paper is to discuss the
acoustical characteristics of the mosque. The CATT indoor acoustic software
was used to calculate important room acoustic parameters such as reverberation
time (RT) and clarity (C50). The measurement was conducted to validate the
RT from the simulation where good agreement is obtained. This study finds that
the Sayyidina Abu Bakar Mosque UTeM has poor acoustical performance at
low frequencies below 1 kHz, i.e., the frequency range which is significantly
responsible for the speech intelligibility.

Keywords: Acoustics, Mosque, Speech intelligibility, Reverberation time.

1. Introduction

Mosque can be described as a multifunction public space where the Muslims perform
various activities including praying, preaching and Quran recitation. In contrast to
churches which require the harmonic of music, activities in mosque are mostly
focused for those relating to speech. However, design of mosque often neglects the
effect on its acoustical performance especially on the speech intelligibility.
Consideration of its acoustical quality usually comes after the completion of the
mosque and it is mainly focused on enforcing the sound system equipment.
Several works have been published which studied the acoustical performance of mosque. Hammad performed acoustic measurement in different mosques in Amman, Jordan including the King Abdullah mosque where rapid sound transmission index (RASTI), early decay time (EDT) and reverberation time (RT) were assessed [1]. The acoustical performance was found to be poor for most of the mosques, including the grand central King Abdullah mosque. The later was then treated by changing the wall materials and carpets to improve the articulation index [2].

Similar study was also conducted by Abdou [3] for mosques in Saudi Arabia employing the impulse response measurement. Out of 21 mosques under the study, 20 mosques show poor RT below 1 kHz. Abdou [4] then continued with computer simulation to investigate the effect of mosque’s wall geometry on the acoustical performance.

In conjunction with Abdou [4], recent study is conducted by Eldien and Qahtani [5] on concrete mosque with two different floor plans. It consists of square and rectangular shape with ratio of length to width is 1:2. The RT, EDT and sound transmission index (STI) were measured to evaluate and to predict the acoustical quality of the main prayer hall. For the square floor, results show good acoustical performance at the front rows around the mihrab and acceptable performance at the mimbar. For the rectangular floor, poor performance is obtained both at the mihrab and at the mimbar.

The effect of geometry was also studied by Setiowati [6] in three different mosques in Indonesia to investigate the acoustical performance of mosque without sound reinforcement system. The three mosques have different volume, materials, floor shape, ceiling and opening area, but have similar height. It is found that the ceiling materials and shape as well as the opening area of the mosque are the factors contributing to poor reverberation time.

Sü and Yılmaz [7] studied the interior acoustic of Kocatepe Mosque in Ankara, Turkey. They found that the mosque is a good place for reciting the musical version of the Holy Quran, as it creates a ritual and tranquil acoustical atmosphere. However, for the prayer mode, the mosque still has inadequate intelligibility of speech.
In another study in Turkey, Karabiber and Erdogan [8] compared the acoustical properties of an ancient Sokullu Mehmet Pasa and a new Sisli Merkez Mosque. It is concluded that although the sound absorption properties in the mosques are almost similar, the acoustical performance in the ancient mosque was better. This is most related to the Sinan architecture which includes the insertion of cavity resonators mainly in the construction of the dome to absorb the low frequency of sound energy giving low reverberation time and better speech clarity.

The architectural design of roof or ceiling also contributes to the acoustical performance as it affects sound distribution inside a mosque. The ceiling with dome shape in particular, has been recognised to form a focusing sound. Soegijanto [9] studied the acoustics in mosque with five different types of ceiling shape. Percentage numbers of reflected rays are counted through simulation to determine the ceiling reflection characteristic. Satisfying results of acoustical performance are led by a flat ceiling followed by the pyramidal and dome shapes. The focusing and scattering effects from the ceilings are also observed.

Prodi and Marsilo [10] used a scale model of mosque with dome shape ceiling to investigate its effect on the acoustical characteristic. The coupling of the dome volume to the remaining volume of the mosque is discussed. It is found the domed ceiling can lower the RT at low frequency if the floor is reflective. Absorptive floor and balconies, however, give an insignificant increase of RT except at high frequency. It is also concluded that reduction of RT can also be achieved by increasing the absorption coefficient of the dome surface material.

This paper presents the study of acoustical performance of the Sayyidina Abu Bakar Mosque in UTeM which is initiated due to poor clarity of speech experienced during congregation. A simulation model was developed using CATT indoor acoustic software and RT measurement was also conducted to validate the model. This study is expected to contribute among other studies concerning the acoustical performance of mosques around the world.

2. Modelling and Validation

2.1. Architectural design of Sayyidina Abu Bakar mosque

Most of the mosques around the world can be observed to have rectangular walls usually parallel to each other and with the ceiling roof having large dome-like geometry. The architectural design of a mosque may also be influenced by the traditional local architecture. This includes the Sayyidina Abu Bakar Mosque, where the general form of its design follows the Malay traditional house marked by the roof geometry of a pyramidal shape as seen in Fig. 1.

The Sayyidina Abu Bakar Mosque has parallel walls and consists of two pyramidal tier inclined roofs. The mosque was first built in 2007 and finished in 2010 with the full capacity of 4,000 congregation at one time distributed to two prayer halls. The approximate volume is 19,500 m$^3$. The main prayer hall is located at the second floor with the total area of 1,200 m$^2$. The women prayer hall is located at the third floor having a smaller area of 560 m$^2$. Figure 2 shows the interior of the main hall in Sayyidina Abu Bakar Mosque, UTeM.
2.2. CATT model

Computer model of an acoustical space has now become an important tool to acoustic engineer to simulate the effectiveness of room acoustical performance based on a simulation based technique. For this purpose, the 3D model of the Sayyidina Abu Bakar Mosque was developed using CATT v.9 indoor acoustic software according to its actual dimensions.

The Sayyidina Abu Bakar Mosque has a square plan with wall dimensions of $33.6 \times 33.6$ meters and a height of 11.2 meters. The tier roof is comprised of two inclined angles of 27 degree and 30 degree equipped with a small spherical dome at the top tier seen from the inside. Supporting the roofs are four rectangular pillars embedded to the main prayer hall. The concrete walls for most of its surfaces are installed with glass windows except on the front wall.

The material properties, namely the sound absorption coefficients are selected from the software data library and to be as closely matched properties as possible with the actual condition. The scattering coefficient is assumed 10% for each frequency for every material. Note that a thick carpet covers the whole surface area of the floor. Table 1 lists the absorption coefficient of materials used in the simulation.

<table>
<thead>
<tr>
<th>Material</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>125</td>
</tr>
<tr>
<td>Concrete (Wall)</td>
<td>0.20</td>
</tr>
<tr>
<td>Plaster (Ceiling)</td>
<td>0.15</td>
</tr>
<tr>
<td>Carpet on concrete</td>
<td>0.02</td>
</tr>
<tr>
<td>Glass (Window)</td>
<td>0.20</td>
</tr>
<tr>
<td>Solid wooden door</td>
<td>0.14</td>
</tr>
</tbody>
</table>
Figure 3 shows the 3D CATT model of the mosque and Fig. 4 shows the CATT model of the mosque interior. The model includes the sound sources with the sound directivity of omni-directional. The different colors are used to identify the different materials (with different properties). Note that the woman’s praying area is not included in the calculation of the acoustical parameters. The assessment is focused only for the man’s prayer hall which is mainly used for all functions in the mosque.
2.3. Measurement of reverberation time

To ensure that the developed CATT model is sufficiently accurate to simulate the real acoustical condition of the mosque, measurement of the reverberation time (RT) was conducted in the Sayyidina Abu Bakar Mosque for an unoccupied condition. The 01-dB Choralis Solo analyzer with dBBati software was used with a GDB-S 01dB Metravibi as the sound generator. The analyzer is equipped with an acoustic microphone to measure the sound pressure. The recorded signal was then transferred to the computer for the signal processing. The measurement setup is shown in Fig. 5.

The measurement was taken at night to reduce the background noise particularly generated by the passing vehicles beside the mosque. Sixteen locations in the main hall were chosen as the measurement points, the same as in the simulation model (see Fig. 3). The analyzer was positioned at 0.5 m above the floor to represent the height of a person’s ear from floor in sitting condition. Figure 6 shows the comparison of the measured RT and those from the CATT simulation.
It can be seen that in average, the simulation results have reasonably good agreement with the measured values, although at some measurement points, for example at point 6 and 10 at 500 Hz, the results from the simulation overestimates the measured values by nearly 1 second. However, this can still be acceptable providing all the assumptions and simplification made in the model compared to the real condition of the mosque.

2.4. Occupied reverberation time

The simulated and measured RT from the previous section was done for empty congregation. As people also provide sound absorption, it is necessary to simulate the RT based on the volume of congregation in order to present the RT when the mosque is in function. The audience area represents the most important absorption surface for a functional room. For a room equipped with seats, absorption from the audience is included together with the absorption of the seat. In the case of mosque, sound absorption depends on the person’s clothes and also the density of the congregation. Here the simulation is conducted for one-third and full occupation volume of the main hall.

The absorption coefficient of person assumed in the simulation is listed in Table 2. The absorption coefficient is according to the assumption of 2 person/m² for praying mode, i.e., standing position and 1.52 person/m² for preaching mode, i.e., sitting position. Standing person can occupy more per meter square as they are less in width but more on height. However, people in sitting condition during the sermon occupy wider area.

Fig. 6. Comparison of the reverberation time (RT) from measurement and simulation at 16 receivers.
Table 2. Absorption coefficient for the audiences used in the simulation [11].

<table>
<thead>
<tr>
<th>Material</th>
<th>Frequency (Hz)</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1 k</th>
<th>2 k</th>
<th>4 k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Praying mode</td>
<td></td>
<td>0.26</td>
<td>0.46</td>
<td>0.87</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Preaching mode</td>
<td></td>
<td>0.22</td>
<td>0.38</td>
<td>0.71</td>
<td>0.95</td>
<td>0.99</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Figure 7 shows the averaged RT plotted against the recommended RT as suggested by Egan [12] for the room with volume of more than 10,000 m$^3$ where an optimum RT can be achieved between the speech and liturgical music lines. Speech line represents the optimum reverberation that should be achieved by a room with main purpose of speech, whereas liturgical line describes the optimum RT for room with orchestra, chorus or organ functions. As can be seen in Fig. 7, the results for sitting (preaching mode) and standing positions (praying mode) do not have significant difference. The remaining analysis throughout this paper is therefore made for the congregation using the absorption coefficient for the sitting position only.

It can be seen that the Sayyidina Abu Bakar Mosque has poor RT at low frequencies particularly at 500 Hz which is sensitive for the speech clarity [13]. High RT result is expected in the mosque not only based on the subjective experience, but also for the fact that the mosque has large volume and only the carpet covering the floor acts as the absorptive material. As the male voice is dominant for most of the functions in the mosque, this worsens the problem as the male voice has more low frequency contents compared to the female voice. Acoustic absorbers having good sound absorption at low frequencies are therefore required to lower down the RT as close as possible to the speech line.

![Fig. 7. Averaged RT in the Sayyidina Abu Bakar Mosque](image_url)
3. Mapping of Acoustical Parameters

This section discusses other important acoustical parameters to describe the acoustical performance of the Sayyidina Abu Bakar Mosque. These are presented as the distribution of the parameter values across the main hall of the mosque. The hall area was grid into 1 × 1 m$^2$ elementary area where the calculation was made at a plane 0.5 m above the floor representing the height of the ears from the floor in sitting condition. The simulation was performed for 1/3 volume of congregation as this is the typical volume of people in the Sayyidina Abu Bakar Mosque; mostly occupied the front area of the hall. The histogram of the parameters is also presented here to provide the statistical distribution of the acoustical parameters.

3.1. Reverberation Time (RT)

The reverberation time (RT) is a basic parameter used in every evaluation of acoustical performance of a room. It is defined as the time required for sound energy to decay 60 dB after the sound source is switched off. The recommended of RT can be determined according to the volume of the room and its function. For the Sayyidina Abu Bakar Mosque having volume of 19,500 m$^3$ and based on the category of ‘house of worship emphasizing speech’, the recommended RT is around 1.8 to 2 seconds [14, 15]. According to Baron [13], in practice RT should be flat at least 2 seconds for frequency below 1 kHz for speech intelligibility. As in the previous section, Egan [12] also suggests the RT to be close to 2 seconds for clarity of speech. However recitation of the Quran also compromised as similar to liturgical music, thus a bit higher RT between 2 to 3 second can still be considered acceptable [7].

Figure 8 shows the mapping and histogram for the RT. This is represented here with $T_{30}$, i.e., the sound decay calculation is made up to 30 dB reduction and the remaining of the decaying trend is interpolated to 60 dB to avoid the effect of the background noise. It can be seen that the RT is mostly around 3.5 s in average. The front area of the hall and that in front of the mihrab can have the RT up to 4 second. This is the area exposed with late reflection of sound possibly due to reflection from the sidewalks and from the roof. The area with RT less than 3 second can be seen at the side walls and at the back pillars. This is due to the domination of the direct field from the loudspeaker just above the corresponding area and where they have less late reflections compared to the area at the front hall.

![Fig. 8. (a) Area mapping and (b) histogram results for reverberation time ($T_{30}$).](image-url)
3.2. Early decay time

The defined reverberation time as above corresponds to the ‘terminal’ reverberation time where we have to ‘wait’ for sometimes for the sound energy to decay (in a silence environment) by 60 dB. However, in real situation where the speech is continuous; it is a ‘running reverberation time’. As we feel only the early portion of the energy, i.e., the first 10 dB decay, a more appropriate parameter is proposed called the early decay time (EDT) which is a better indicator for the subjective feeling of the reverberation time [13, 14].

In a highly diffuse room, the ratio of EDT/RT is almost equal to 1.0 which indicates diffuseness and directness of sound energy. For the Sayyidina Abu Bakar Mosque as seen in Fig. 9, the EDT at 500 Hz from simulation shows the average value of 3.85 s throughout the hall. The EDT/RT is therefore around 0.9 implying good sound distribution throughout the mosque. This could be due to the pyramidal ceiling which is discussed in a different section.

Templeton [16] suggested that to satisfy both functions of speech and music, the EDT value should be between 2.7 second and 3.85 second. However, for the mosque, the lower end value is preferred to emphasize the speech function. In order for the ratio EDT/RT to be close to unity, it has to be compensated by also lowering the RT.

Fig. 9. (a) Area mapping and (b) histogram results for early decay time (EDT).

3.3. Clarity (C50)

Clarity (also called early-to-late sound index) is the ratio of direct sound energy arriving before 50 ms over reverberant energy arriving after 50 ms. C50 is applied for speech clarity while C80 is more suitable for music [13]. According to Cavanaugh et al. [17] good C50 should have clarity above -1 dB. However, it is not about ‘the higher C50 the better’, but this should also be balanced with the reverberation time. For 1 kHz, good C50 is considered to be +5 dB with RT = 0.5 s. Poor C50 is -3 dB with RT = 2 s [17]. This is not much different for 500 Hz.

In Fig. 10, good clarity of -1 to 3 dB can be seen at the area behind the back pillars and at the side walls; all of these are area close to the sound sources therefore the receivers will have dominant direct sound. However, at the area in front of the mimbar and the mihrab up to the middle of the hall below the dome,
poor clarity of -8 to -5 dB can be observed which is due to the dominant late reflections from the ceiling and the walls. Although at the front walls there are two main loudspeakers, the dominant late reflection energy is masking the direct sound energy. The loudspeakers at the ceiling are also suspected to create late reflections rather than contributing direct field of sound energy.

![Fig. 10. (a) Area mapping and (b) histogram results for clarity (C50).](image)

### 3.4. Definition (D50)

The subjective speech intelligibility is often described by Definition or Deutlichkeit or early-to-total sound energy ratio defined as the ratio of the early received sound energy up to 50 ms after the arrival of the direct sound to the total received energy. This parameter should be greater than 20% to satisfy both music and speech performances [8].

Again from Fig. 11, at the front wall area in front of the mihrab and mimbar to the middle of the hall, D50 can be seen to only reach 15% in average, while only small area at the back pillars and at the side walls has D50 above 40%. The correlation of D50 and speech intelligibility can be explained as the D50 increase, speech intelligibility also increase proportionally.

![Fig. 11. (a) Area mapping and (b) histogram results for definition (D50).](image)

### 3.5. Lateral fraction (LF)

One indicator of good acoustic quality is where the audience will feel enveloped or surrounded by the sound. In a mosque, this is important to add the sacred sense
and devotion when listening the recitation of the Holy Quran and the sermon delivered by the Imam. This requires strong lateral reflections with a significant fraction of the energy arriving from the side of the listeners. The magnitude of this effect is found to be related to the proportion of sound which arrives from the lateral direction within the first 80 ms after the direct sound [14]. Therefore the reflections from the ceiling will have different subjective feeling to the listeners than those from the vertical walls. For music, the parameter should be between 0.1–0.35 and greater than 0.35 for all other purposes including speech.

From Fig. 12, in contrary from the previous results, good LF can be seen around the area in front of the mihrab straight up to the back wall with LF is between 0.4–0.5 due to the strong reflections from the side walls. The rest of the area has LF below 0.3.

![Fig. 12. (a) Area mapping and (b) histogram results for lateral fraction (LF).](image)

### 3.6. Speech transmission index (STI)

Speech transmission index (STI) is an objective measure for speech intelligibility. It is highly related to reverberation time and also to the signal-to-noise level. The scale for STI is shown in Table 3 [18].

<table>
<thead>
<tr>
<th>Quality Score</th>
<th>STI value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bad</td>
<td>&lt;0.32</td>
</tr>
<tr>
<td>Poor</td>
<td>0.32 – 0.45</td>
</tr>
<tr>
<td>Fair</td>
<td>0.45 – 0.60</td>
</tr>
<tr>
<td>Good</td>
<td>0.60 – 0.75</td>
</tr>
<tr>
<td>Excellent</td>
<td>&gt;0.75</td>
</tr>
</tbody>
</table>

As can be seen in Fig. 13, The Sayyidina Abu Bakar Mosque experiences very poor speech transmission index. Most of the front area until the center has 0.25-0.3 STI values. This change slightly to the back area of the mosque as the STI value increases. The result is also consistent with those from EDT, C50 and D50 where the back area is found to have better acoustical performance. Here the
effect of late reflections might be reduced due to large opening area at the third
floor, i.e., the woman prayer area.

4. Conclusion

Assessment of acoustical performance for the Sayyidina Abu Bakar Mosque has
been addressed. Simulation results of several important acoustical parameters
show that the mosque has poor acoustical performance at low frequencies below
1 kHz particularly at 500 Hz which degrades the speech intelligibility in the
mosque. The reverberation time at this frequency reaches more than 5 s in an
unoccupied condition and 3.5 s in 1/3 volume of congregation. The acoustic
clarity is also poor mainly at the middle area of the hall. Sound distribution
(diffuseness and directness) is however acceptable which could be due to the help
of the leaning ceiling of the mosque. With the large volume of the mosque,
acoustical performance can be improved by introducing acoustic materials and
resonators to reduce the reflected sound energy especially for the late reflections.

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