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MATHEMATICAL MODEL OF SPEECH INTELLIGIBILITY IN MOSQUE WITH COLUMN PILLARS

(MODEL MATEMATIK KEJELASAN PERCAKAPAN DI DALAM MASJID YANG BERTIANG)

FAREHA ABDUL RAHMAN

MOHAMAD NGASRI BIN DIMON

MOKHTAR BIN HARUN

SITI ZALEHA BADUL HAMID

AHMAD HAFIZ BIN HUSSIN

Jabatan Kejuruteraan Perhubungan Radio

Fakulti Kejuruteraan Elektrik

Universiti Teknologi Malaysia

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ABSTRACT

(Keywords: Speech intelligibility, mosque with column pillars, sound pressure level, reverberation time)

The mosques in Malaysia are normally built in large scale with at least 280 m^3 in volume. These large mosques usually have domes as partial of the ceiling and column pillars to support the large areas of the ceiling. The existence of domes and column pillars in large rooms can introduce a problem in speech intelligibility. Column pillars in the main prayer hall are usually covered with decorated tiles which are very reflective surfaces. The reflected sounds from such surfaces can create sound shadow zone between those pillars. This research explores effects of the column pillars in mosque towards speech intelligibility. This fundamental knowledge is required for optimum audio quality and predicting speech intelligibility for mosque. The research objectives are to conduct topology study of column pillars in mosques, to perform parameters selection in mosques with column pillars to evaluate its speech intelligibility, and to quantify the speech intelligibility in mosques with column pillars.

From analysis of the result it can be concluded that the number of room samples chosen, and the number of measured speech intelligibility scores are sufficient to predict speech intelligibility in room with column pillars. By using only two room dimension parameters, the D_{SL} and D_{FL} in this case, the developed mathematical expressions have already achieved credible minimum coverage of statistical data of credible prediction accuracy of 71%. The mathematical expression development improved to a significant minimum coverage of statistical data of credible prediction accuracy of 93% when four room dimension parameters have been used.

Key researchers:

Mrs Fareha Abdul Rahman (Project Leader)
Dr. Mokhtar Harun
Assc. Prof. Dr. Mohamad Ngasri Dimon
Mrs Siti Zaleha Abdul Hamid
Mr Ahmad Hafiz Hussin

E-mail : fareha@fke.utm.my
Tel. No. : 075535219

Vote No. : 78370

ABSTRAK

(Kata kunci:Kecekapan percakapan, masjid bertiang, aras tekanan bunyi, masa gemaan)

Masjid di Malaysia kebiasaannya dibina dalam skala besar sekurang-kurangnya 280m^3 isipadu. Masjid yang besar ini selalunya mempunyai kubah sebagai sebahagian bumbungnya, dan tiang-tiang utama untuk mengukuhkannya. Kewujudan kubah dan tiang-tiang ini boleh menimbulkan masalah dalam kejelasan percakapan. Tiang-tiang utama ini biasanya dibaluti dengan jubin yang bersifat memantul. Pantulan bunyi dari permukaan tersebut boleh menghasilkan zon terlindung bunyi di kawasan antara tiang. Penyelidikan ini mengkaji kesan tiang utama di dalam masjid terhadap kejelasan percakapan. Pengetahuan asas ini perlu untuk menghasilkan kualiti bunyi yang optimum dan seterusnya meramalkan kejelasan percakapan untuk masjid. Objektif penyelidikan ini adalah untuk memulakan kajian topologi tiang utama masjid, untuk mendapatkan parameter-parameter yang bersesuaian dalam masjid bertiang bagi menilai kejelasan percakapan, dan untuk menyatakan kuantiti kejelasan percakapan di dalam masjid bertiang utama.

Penyelidikan ini merumuskan jumlah sampel ruang yang dipilih, dan jumlah skor kejelasan percakapan adalah cukup untuk meramalkan kejelasan percakapan di dalam masjid yang bertiang. Menggunakan hanya dua parameter, D_{SL} dan D_{FL} , rumusan matematik yang dihasilkan telah mencapai liputan minima data statistik ketepatan ramalan yang boleh dipercayai sebanyak 71%. Rumusan matematik yang dihasilkan diperbaiki dengan liputan minima data statistik ketepatan ramalan yang boleh dipercayai bertambah sehingga 93% apabila empat parameter ruang digunapakai.

Kunci penyelidik:

Mrs Fareha Abdul Rahman (Project Leader)
Dr. Mokhtar Harun
Assc. Prof. Dr. Mohamad Ngasri Dimon
Mrs Siti Zaleha Abdul Hamid
Mr Ahmad Hafiz Hussin

E-mail **:** fareha@fke.utm.my
Tel. No. : 075535219
Vote No. : 78370

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LIST OF SYMBOLS

α	-	Absorption coefficient
E_i	-	Incident sound energy
E_r	-	Reflected energy
E_a	-	Absorbed energy
E_t	-	Transmitted energy
δ	-	Dissipation coefficient
τ	-	Transmission coefficient
S	-	Surface area of material
V	-	Volume of the reverberation room
r_1	-	Distance of direct sound
r_2	-	Distance of reflected sound
d_1	-	Distance of direct path from listener-to-receiver
c	-	Speed of sound in air
f_m	-	One-octave modulating frequency from 0.63 Hz to 12.5 Hz
m	-	Resultant reduction factor
S/N	-	Sound pressure level difference between signal and background noise
D_{SL}	-	Distance between sound source and listener (m)
D_{FL}	-	Distance between front wall and listener (m)
D_{S1R}	-	Distance between sound source and first reflection (m)
D_{BWL}	-	Distance between center of back wall and listener (m)
dB	-	Decibel

LIST OF ABBREVIATIONS

RT60	-	Reverberation Time
STI	-	Speech Intelligibility Index
ITDG	-	Initial Time Delay Gap

CHAPTER 1

INTRODUCTION

1.1 Background of the Research

This research explores the effects of the column pillars in mosque towards speech intelligibility. This fundamental knowledge is required for optimum audio quality and predicting speech intelligibility for mosque.

Many mosques in Malaysia are large. Except the for main prayer floor that is normally fully carpeted, the wall and ceiling are made of hard and reflective materials. With huge volume and hard reflective surfaces, sound reflection in mosques is massive and thus contribute to poor speech intelligibilty. In addition, the column pillars create shadow that may degrates speech intelligibility.

For other fellow researchers, the outcomes of this research will strengthen current and available knowledge in terms of good result of speech intelligibility in mosque during any events. The addition of reflective dome and column pillars is expected to affect the speech intelligibility inside a large mosque.

The electro acoustics room designers will have more options of what frequency to work on in their filter design so that better noise filtration and bigger attenuation can be achieved. It would be more practical to design noise filter, canceller, and attenuator for this specific environment rather than to have current design of all-in-one on the shelf to fit in audio system in a room.

Finally, the community which is the congregation will benefit intelligible, noise free and comfortable loudness sermon or any speech related activity in large mosques.

1.2 Research Objective

The following discussions illustrate the undertaken research objectives.

i To conduct topology study of column pillars in mosques to get the effect compare to the mosque without the column pillars.

ii. To perform parameters selection in mosques with column pillars so as to evaluate speech intelligibility in it.

iii. To quantify the speech intelligibility in mosques with column pillars.

1.3 Research Scope

The researchers had used 01dB Symphonie frequency analyzer to perform the measurement of STI. STAT VIEW was used to analyze the data. The effects of speech intelligibility for the mosque with column pillars were conducted as to how speech intelligibility was affected in the whole mosque.

1.4 Report Outline

This report is divided into five chapters, which describe the entire process of the research work. The outlines of the report are as follow:

Chapter 1 highlights the background of the research problem and the objectives of the research. It is followed by research scope and report outline.

Chapter 2 reviews the theory of sound absorption, reverberation time, and sound reflections that affect speech intelligibility

Chapter 3 describes the research methodology and the measurement processes that have been made to the selected mosques with column pillars.

Chapter 4 discusses the results from the measurements that had been conducted, and the results from the STAT VIEW modeling works.

Chapter 5 concludes the findings of the research work. It also provides the suggestion for future development of the related research project.

CHAPTER 2

LITERATURE REVIEWS

2.1 Introduction

The theories of sound absorption, reverberation time, and sound reflections that affect speech intelligibility are elaborated in this chapter.

2.2 Sound Absorption in Enclosed Rooms

When the sound wave impinges on an acoustic material, some energy will be absorbed while some energy will be reflected depend on the material's sound absorption performance. For instance, the sound absorption coefficient (α) is 0.4 if 60% of the incidence energy is reflected but the other 40% of remaining energy is absorbed. When all the incidence energy transferred to the other side of the window or open window phenomena or perfect absorbed will occur, which results in α = 1.0. Sound absorption of an acoustic material varies with frequency and angle of incidence of the sound waves impinge upon the material (Everest, 1994). When the sound energy is reflected from the wall, phenomena of sound refection is occurred which is opposite to sound absorption. Specular reflections will occur if the reflecting surface is large enough compared to the wavelength of the incidence energy.

When a sound impinges a wall, its incident sound energy E_i will be divided into three parts which are reflected energy E_r, absorbed energy E_a, and transmitted energy E_t as illustrated in Figure 2.1. This phenomena can be written as follows. (Maekawa and Lord, 1994).

$$E_i = E_r + E_a + E_t \tag{2.1}$$

The absorption coefficient, α is defined as follows

$$\alpha = \frac{E_i - E_r}{E_i} = \frac{E_a + E_t}{E_i} \tag{2.2}$$

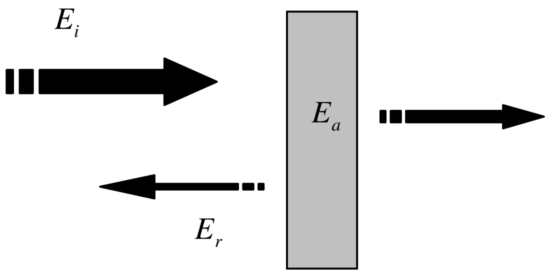

Figure 2.1 Reflection, absorption and transmission.

The Equation 2.2 above shows that all portions of the sound energy which are not reflected are considered to be absorbed. According to Sabine, sound absorption coefficient, α is defined by the ratio between the non-reflected sound intensity and the incident sound intensity. Sabine (α) is comprised of dissipation coefficient (δ) and transmission coefficient (τ).

$$\alpha = \delta + \tau \tag{2.3}$$

2.3 Reverberation Time (RT60)

Reverberation time is the time required for the sound level in the room to decay 60 dB or the time when sound energy left is only one-millionth of its initial energy. RT60 is the time needed for a loud sound to be inaudible after the sound source is turned off. This concept is shown in the following diagram.

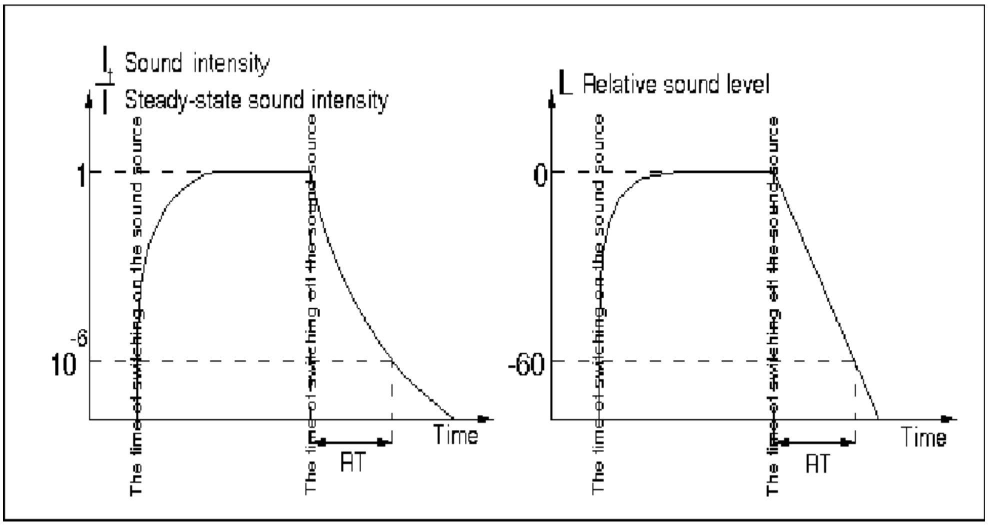

Figure 2.2 Relationships between Sound Intensity and Relative Sound Level with Time (Azman Jaafar, 1981).

RT60 is good enough to describe characteristics of sound build up and attenuation in the room. In case the sound in the room is not diffused enough, such as rooms with good absorption surfaces in some areas, or with an unusual shape (long and narrow, very low ceiling, or many different focusing surfaces), the RT calculation will not be accurate. The optimum reverberation time for different rooms depend on the volume of the space, finishes of the room, and the frequency of the sound concerned. In general, the optimum RT60 for rooms for speech is less than the optimum RT60 for rooms used for music.

Reverberation time (RT60) formula is given as the followings:

$$RT60 = \frac{0.1\,6V}{S\alpha} \quad (2.4)$$

Where:

V = Volume of the room, m^3

S = Total surface area of the room, m^2

α = absorption coefficient of the surface, material or finishes of the room

2.4 Room Acoustic

The propagation of sound is bounded by walls, ceiling and floor of the room. These room boundaries usually reflect a certain fraction of the sound impinging on them. If the energy of sound is not absorbed or extracted from the sound field inside the room, the sound will be reflected. The reflected sound component is responsible for what is known as ‘the acoustics of a room’. These reflected sound components will cause the reverberant field in the room to increase. This is the complexity of the sound field in a room (Cremer and Muller, 1982). From Eqs. 2.2, it is found that absorption of sound will be smaller if reflected energy E_r is bigger.

2.4.1 Initial Time Delay Gap (ITDG)

Initial time delay gap (ITDG) is defined as the difference between time taken for a complete first sound reflections and the time taken for the direct sound path to reach the listener (Burroughs, 2001). Alternatively, as shown Figure 2.3,

$$ITDG = \left(\frac{(r_1 + r_2) - d_1}{c} \right) \tag{2.5}$$

Where;

r_1 is the distance of direct sound, in meter

r_2 is the distance of reflected sound, in meter

d_1 is the distance of direct path from listener-to-receiver, in meter

c is the speed of sound in air, m/s

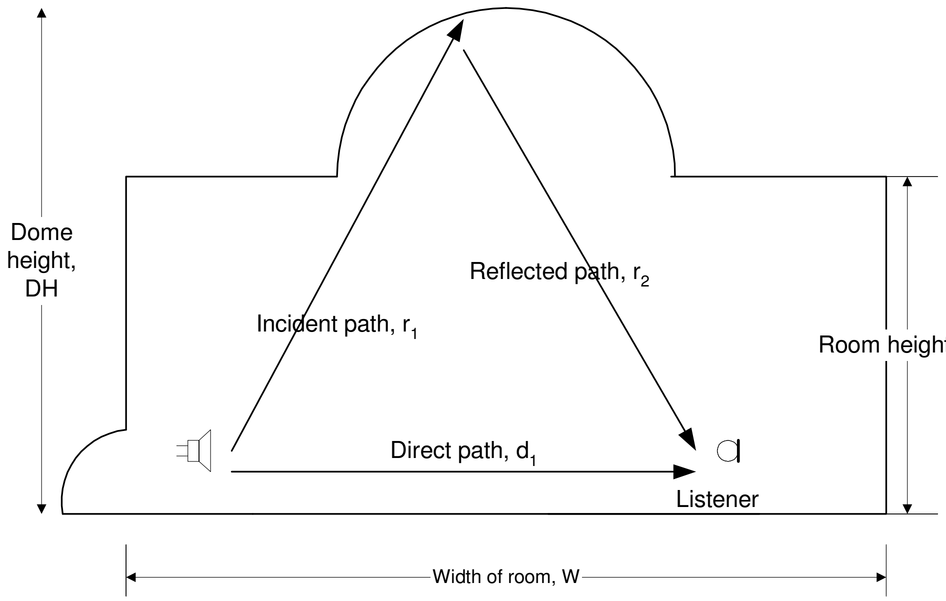

Figure 2.3

Section view of room sample showing calculation of initial-time-delay gap (ITDG) via Ray Tracing (Burroughs, 2002)

2.5 Speech Intelligibility

Speech intelligibility is the ability to understand spoken message, necessary for communication, announcement and instruction for safety. Longman Dictionary of Contemporary English (1978) defines speech intelligibility as "speech that can be understood". According to Mapp (1999) speech intelligibility describes the ability to distinguish the structure of the speech sound, and to be able to hear the consonants or vowels of a word without masking. Templeton *et al.* (1993) asserts that the ability to hear a speech is not as same as to be intelligible upon hearing a speech. Speech intelligibility is established when the listener hears the word that is uttered by a speaker and the word is not mistaken with other word.

2.5.1 Speech Transmission Index (STI)

STI is a speech intelligibility assessor that quantifies the effect of sound transmission system upon speech intelligibility. It is based upon an analysis of the reduction in intensity modulation of a signal, which occurs along the transmission path from the sound source to the listener. STI equals 1 is for perfect sound transmission and STI equals 0 is for no signal recognition (Templeton *et al*., 1993a)

STI had been established by Houtgast and Steeneken in 1980 (Houtgast and Steeneken, 2002). Speech disturbances in room such as background noise and reverberation result in reduced speech intelligibility. Modulation Transfer Function (MTF) is employed in STI to evaluate speech intelligibility in room with such disturbances (Houtgast and Steeneken, 1985). Mathematically, STI is defined by the following formula.

$$\text{STI} = \frac{(\overline{S/N}) + 15}{30} \tag{2.6}$$

Where;

$$(\overline{S/N}) = \sum_{k=1}^{7} (W_k)(S/N)_{app,k} \tag{2.7}$$

$$(S/N)_{app,k} = 10\log\left(\frac{m}{1-m}\right) \tag{2.8}$$

$(S/N)_{app,k}$ is calculated over each octave band of noise from 125 Hz to 8000 Hz.

And

$$m(f_m) = \frac{1}{\left[\left[1+\left(\frac{2\pi f_m T}{13.8}\right)^2\right]^{1/2}\left[1+10^{-\left(\frac{S/N}{10}\right)}\right]\right]}$$

f_m the one-octave modulating frequency from 0.63 Hz to 12.5 Hz

m is the resultant reduction factor of each $m(f_m)$

S/N is the sound pressure level difference between signal and background noise

STI = 0, when $(S/N)_{app.k} << -15$ dB

STI = 1, when $(S/N)_{app.k} >> 15$ dB

T is the reverberation time or RT60 (in second)

Table 2.1 Speech intelligibility rating of STI (Templeton *et al*., 1993c)

RATING	STI Score
Bad	STI < 0.3
Poor	0.3 to 0.45
Fair	0.45 - 0.6
Good	0.6 to 0.75
Excellent	STI > 0.75

CHAPTER 3

METHODOLOGY

3.1 Introduction

Research flow chart, selection of room samples and parameters used for the research, and data acquisition process are described in this chapter.

3.2 Research Flow Chart

It is shown in Figure 3.1.

Table 3.1 Selected room samples for the research

Room samples	**Length (m)**	**Width (m)**	**Height (m)**	**Surface area (m^2)**	**Volume (m^3)**
Masjid Tangkak (TNK)	46	35	25	4390	11460
Masjid Kpg. Jawa (SEG)	29	25	21	2350	6400
Masjid IKBN Pagoh (IKBN)	30	25	20	2380	6560
Masjid Sedili (SED)	29	25	20	2300	6750
Masjid Tandop Alor Setar (TAN)	27	24	14	1850	3750

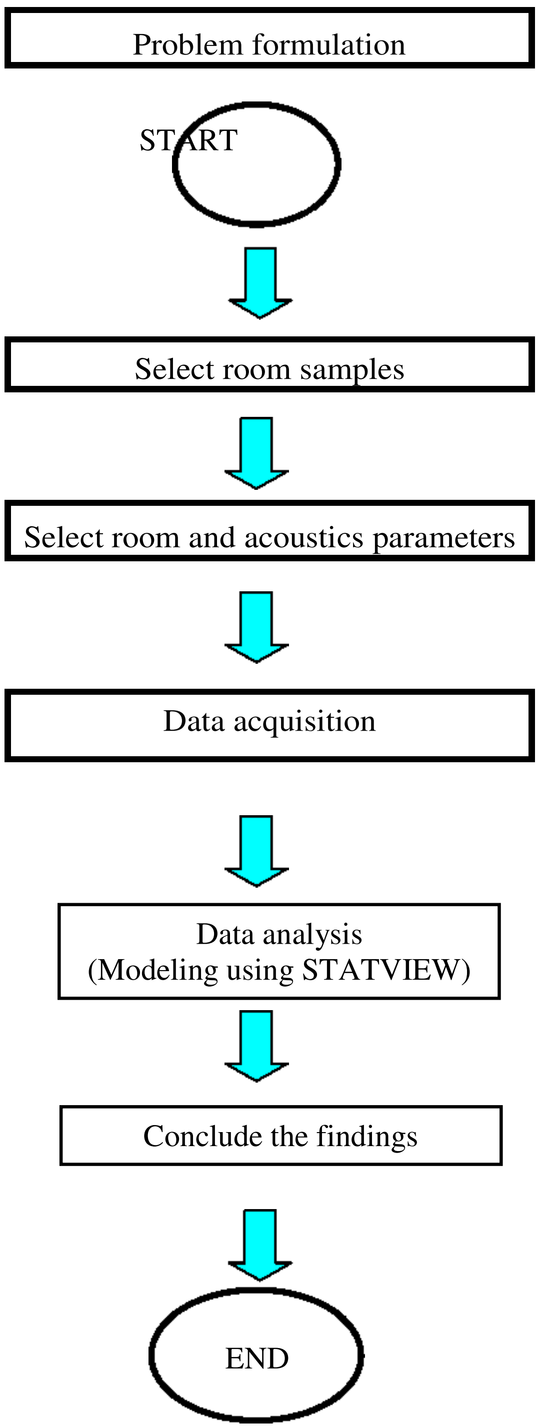

Figure 3.1 Research Flow Chart

3.3 Selection of Room Samples

It is tabulated in Table 3.1. Plan layout and side view of room samples are shown in Figure 3.2 and Figure 3.3 respectively.

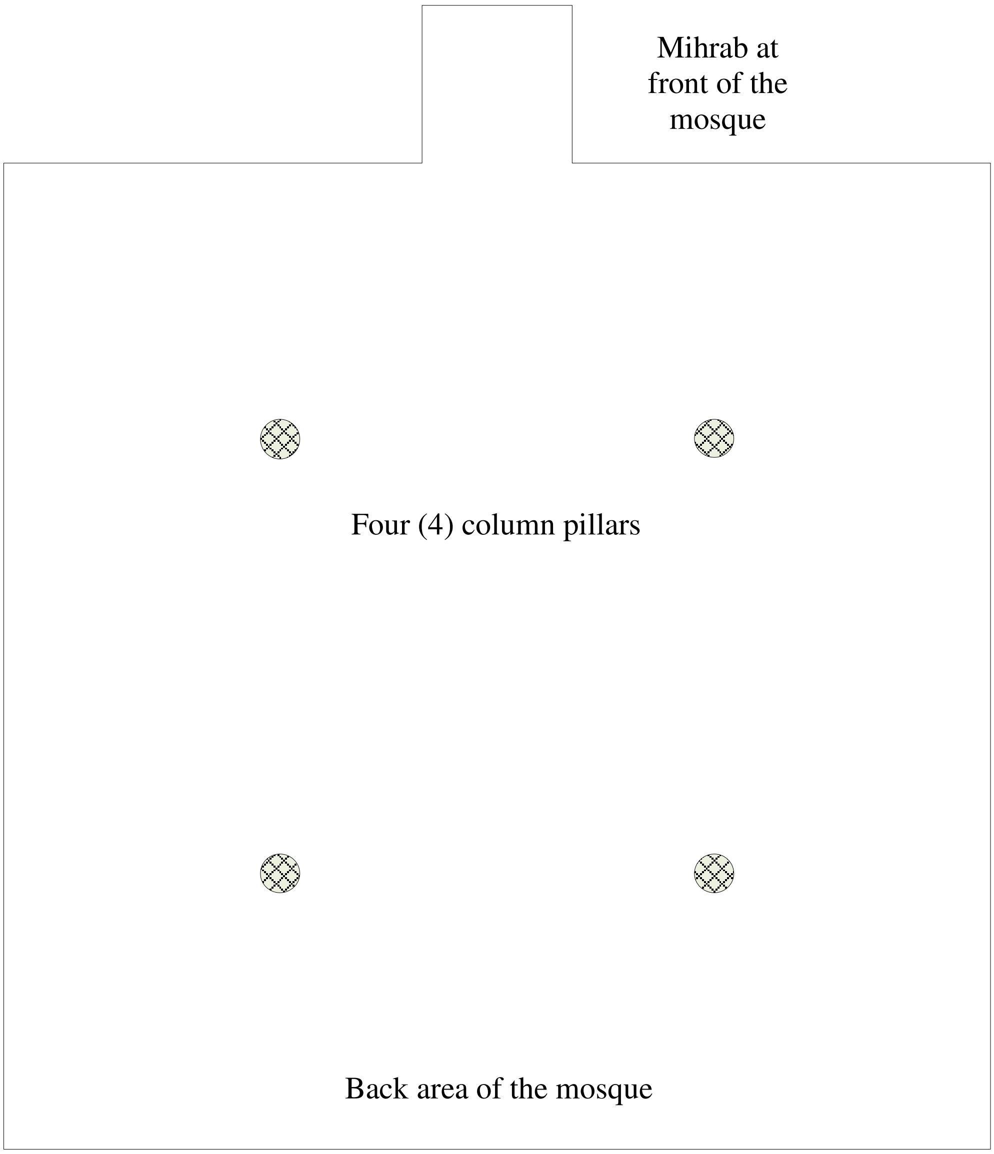

Figure 3.2 Plan layout of a room sample

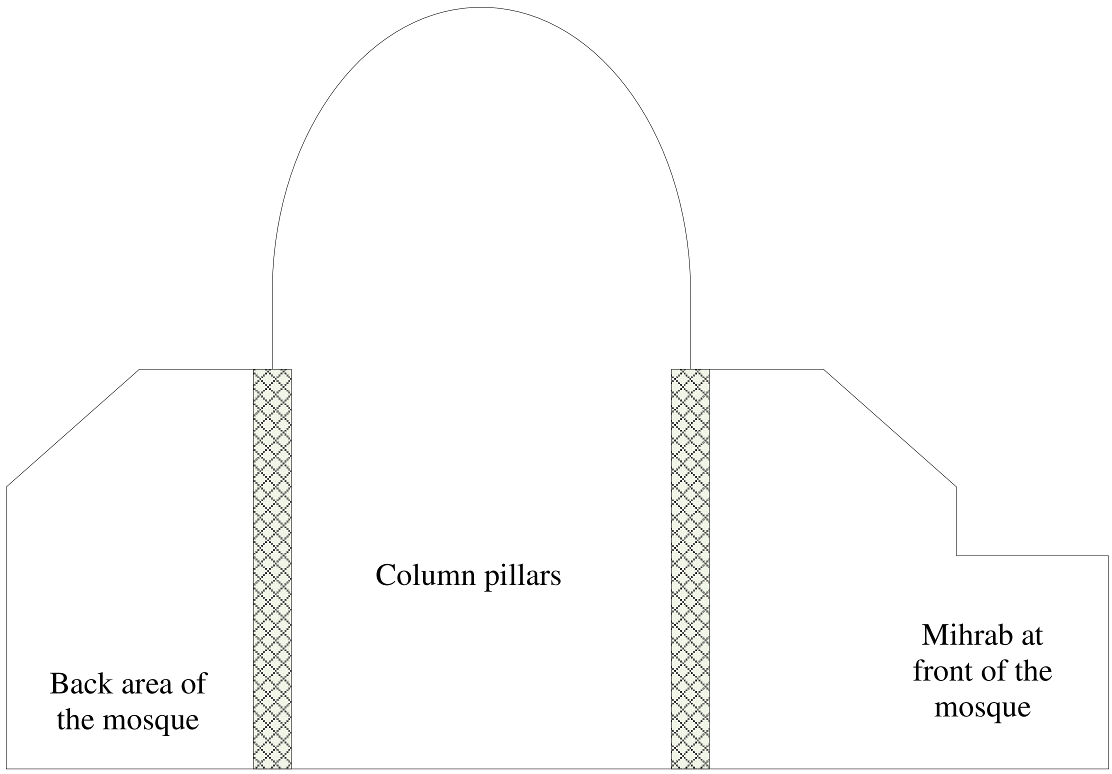

Figure 3.3 Side view of a room sample

3.4 Selection of Acoustics and Room Parameters

It is tabulated in Table 3.2. Room parameters are depicted in Figure 3.4.

Table 3.2 Selected acoustics and room parameters for the research

Parameters	Length (m)	Unit	Description
Acoustics	STI	-	Speech intelligibility assessor that returns speech intelligibility score by evaluating sound response over octave frequency range of 125 Hz to 8 kHz
Room	D_{SL}	meter (m)	Sound source to listener distance
	D_{FL}	meter (m)	Front wall to listener distance
	D_{S1R}	meter (m)	Sound source to the center at tip of the dome
	D_{BWL}	meter (m)	Mid section of back wall to listener distance

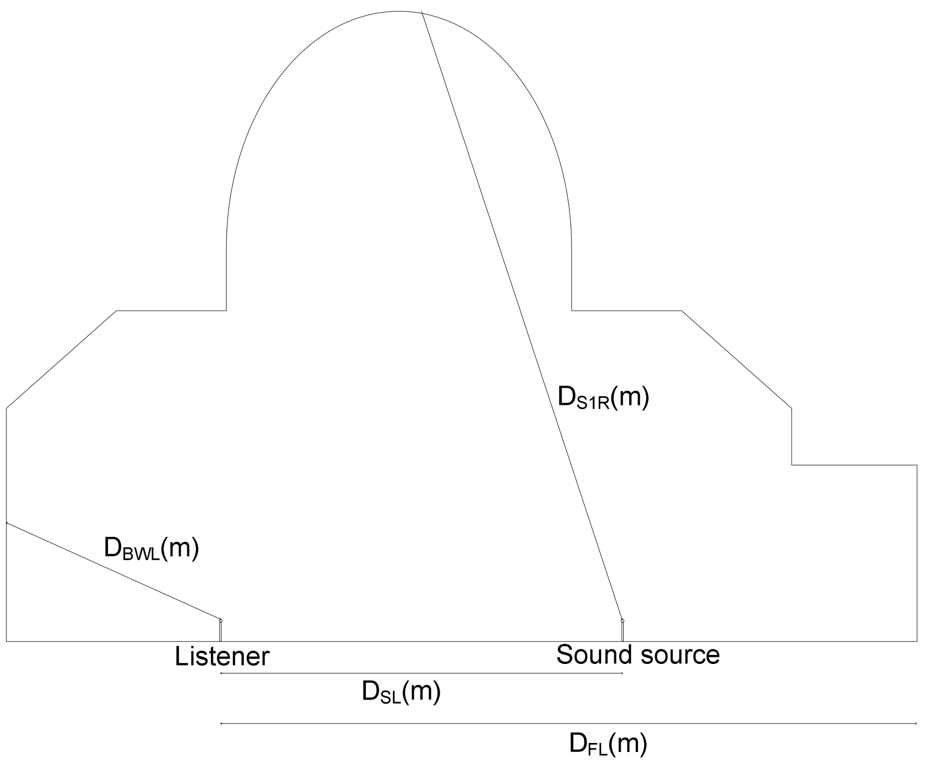

Figure 3.4 Room parameters

3.5 Measurement Positions and Points

Figure 3.5 shows location and points of measurement of acoustics parameter. For this research, the measurement of STI was the concern.

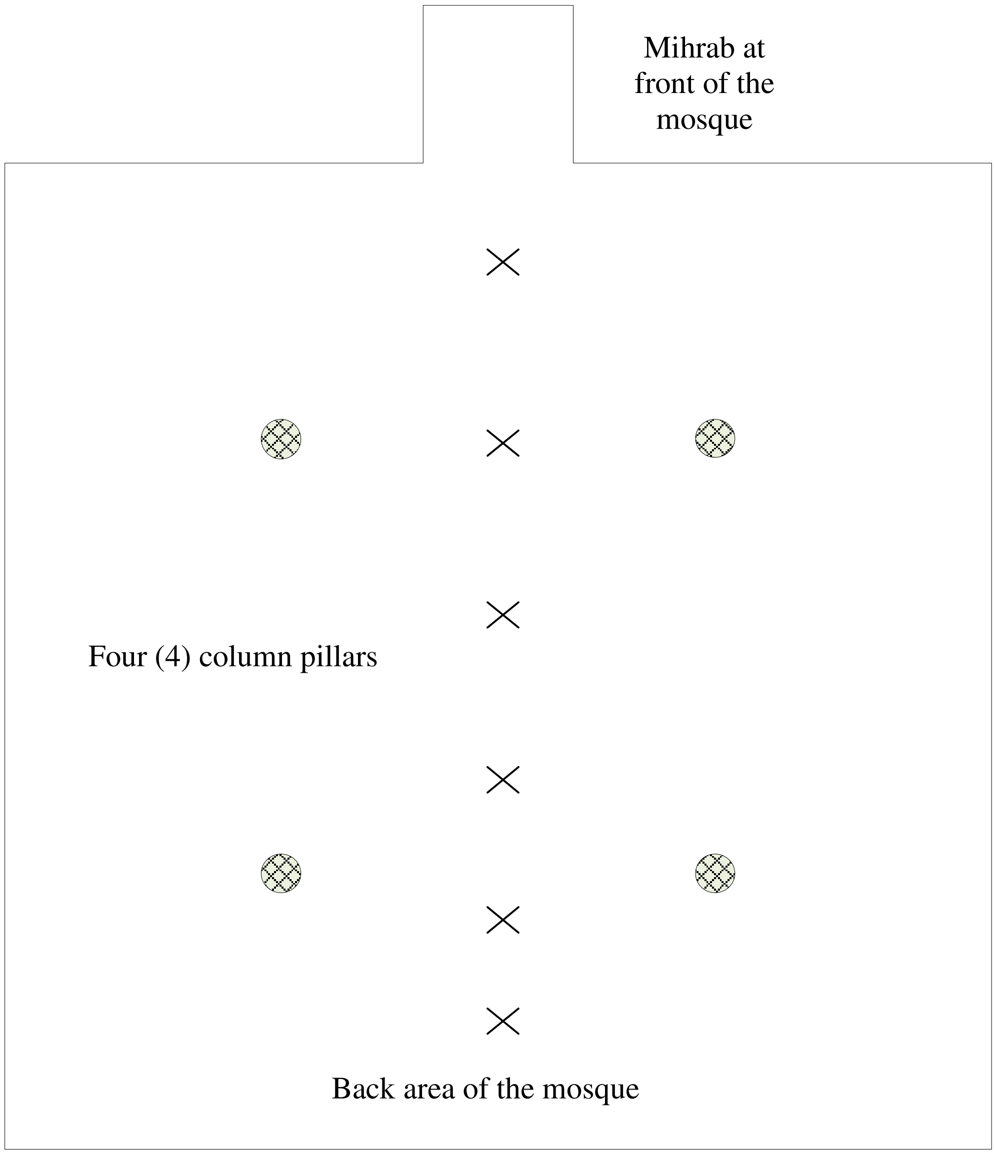

Figure 3.5 Measurement location and points of measurement of acoustic parameter

CHAPTER 4

RESULTS AND DATA ANALYSIS

4.1 Introduction

In this chapter the mathematical expressions developed are discussed.

4.2 Development of Mathematical Expression

The developed modeling expressions are tabulated in Table 4.1.

The mathematical expression development begins by using two room dimension parameters, in all five samples. The parameters used were D_{SL} and D_{FL}. They were tested against speech intelligibility assessor, STI. It has been found out that through correlation coefficients R^2, the developed two-parameters mathematical expressions have accuracy ranging from 0.71 to 0.92.

Table 4.1 Developed mathematical expressions of STI with respect to room dimensions.

MOSQUES	STI vs D_{SL} (m), D_{FL} (m)	STI vs D_{SL} (m), D_{FL} (m), D_{S1R} (m)	STI vs D_{SL} (m), D_{FL} (m), D_{S1R} (m), D_{BWL} (m)
IKBN	$STI = 0.608-0.051D_{SL}+0.034D_{FL}$; P-Value = 0.0146 $R^2 = 0.879$	$STI = 0.656-0.045D_{SL}+0.035D_{FL}-0.008D_{S1R}$; P-Value = 0.0494 $R^2 = 0.903$	$STI = -11.129-0.004D_{SL}+0.364D_{FL}+0.011D_{S1R}+0.410D_{BWL}$; P-Value = 0.0060 $R^2 = 0.997$
SEGAMAT	$STI = 0.779-0.008D_{SL}-0.005D_{FL}$; P-Value =0.0212 $R^2 = 0.723$	$STI = 0.795-0.004D_{SL}-0.006D_{FL}-0.004D_{S1R}$; P-Value = 0.0717 $R^2 = 0.726$	$STI = -5.439-0.016D_{SL}+0.198D_{FL}+0.010D_{S1R}+0.217D_{BWL}$; P-Value = 0.0129 $R^2 = 0.933$
TANGKAK	$STI = 1.112+0.027D_{SL}-0.036D_{FL}$; P-Value = 0.0033 $R^2 = 0.852$	$STI = 1.085+0.022D_{SL}-0.034D_{FL}+0.005D_{S1R}$; P-Value = 0.0152 $R^2 = 0.856$	$STI = -831.876+0.068D_{SL}+17.887D_{FL}-0.122D_{S1R}+17.921D_{BWL}$; P-Value = 0.0027 $R^2 = 0.970$
TANDOP	$STI = 0.729-0.030D_{SL}+0.016D_{FL}$; P-Value = 0.0465 $R^2 = 0.707$	$STI = 0.868+0.031D_{SL}-0.061D_{FL}+0.033D_{S1R}$; P-Value = 0.0141 $R^2 = 0.912$	$STI = -56.431+0.061D_{SL}+2.023D_{FL}-0.084D_{S1R}+2.146D_{BWL}$; P-Value = 0.0006 $R^2 = 0.996$
SEDILI	$STI = 0.601-0.065D_{SL}+0.046D_{FL}$; P-Value = 0.0208 $R^2 = 0.924$	$STI = 0.669-0.063D_{SL}+0.058D_{FL}-0.019D_{S1R}$; P-Value = 0.0877 $R^2 = 0.941$	$STI = -0.526-0.007D_{SL}+0.055D_{FL}-0.017D_{S1R}+0.053D_{BWL}$; P-Value = 0.1316 $R^2 =0.992$

The mathematical expressions later on were developed by using three room dimension parameters. The parameters used were D_{SL}, D_{FL} , and D_{S1R} . They were tested against speech intelligibility assessor, STI. It has been found out that the R^2 of the developed three-parameters mathematical expressions have accuracy ranging from 0.73 to 0.94.

Finally, the mathematical expressions were developed by using four room dimension parameters. The parameters used were D_{SL}, D_{FL} , D_{S1R}, and D_{BWL} that were tested against STI. It has been found out that the R^2 of the developed four-parameters mathematical expressions have accuracy ranging from 0.93 to 0.99.

CHAPTER 5

CONCLUSIONS

5.1 Conclusion

From analysis of the result it can be concluded that:

i. The number of room samples chosen, and the number of measured speech intelligibility scores are sufficient to predict speech intelligibility in room with column pillars.

ii. By using only two room dimension parameters, the D_{SL} and D_{FL} in this case, the developed mathematical expressions have already achieved credible minimum coverage of statistical data of credible prediction accuracy of 71%.

iii. The chosen room dimension parameters for this research, for mathematical expression development have achieved significant minimum coverage of statistical data of credible prediction accuracy of 93%.

5.2 Recommendations for future works

The recommendations for future work are as follows.

i. The per room sample mathematical expressions developed shall be normalized as per all room samples.

ii. The room samples with lower p-value shall be checked for variance and data discrepancies so as to increase the coverage of statistical data and thus increase prediction accuracy.

iii. Mathematical expressions shall be developed from plan layout point of view of the chosen room samples.

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