

SPEECH INTELLIGIBILITY PREDICTION MODEL
IN ROOM WITH REFLECTIVE DOME

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To my dearest parents for their love, kindness and blessings

To my beloved wife for her understanding, support and encouragement

To my children Muhammad Haziq, Muhammad Hafiz, Muhammad Haikal and Nureen

Farhanah whose presences are precious and enlighten my life

To my sisters and brothers, and their family

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ABSTRACT

This thesis presents research works on developing the objective speech intelligibility prediction models in room with dome in terms of acoustics, and room and dome geometry. The purpose of the research was to enable one to predict speech intelligibility (SI) in room with dome as early as at the conceptual design stage. The developed SI prediction models have made possible the estimation of the acceptable room and dome dimension ratios for speech, the determination of the significant acoustics parameters that affect SI, and the determination of achievable SI scores at any audience area in room with dome. The research was begun with pilot study and room investigations in large mosques with dome in Johor. Similar works were later extended in Negeri Sembilan, Selangor and Kedah. Basic dimensions of room and dome, types of dome, types of ceiling, and types of material and finishes in room and on dome surfaces were obtained. Having completed room investigation activity, acoustics measurements were conducted in thirty-two mosques with dome, with dome volume ranging from 100 m³ to 10000 m³ to determine Speech Interference Level (SIL), reverberation time (RT60) and speech intelligibility assessor, Speech Transmission Index (STI); the parameters that are required for the development of SI prediction models. It was found that RT60 is able to predict minimum SI scores in area 6° outside sound source coverage area, which is $STI_{OUT6(min)}$. Average SI under dome area, $STI_{DA(mean)}$ is found to be efficiently predicted by average sound absorption coefficients of the room. Both $STI_{DS(min)}$ and $STI_{DS(mean)}$ are well predicted by room and dome geometry. From the simulation works, it has been found that the developed SI prediction models have achieved acceptable prediction accuracy for the practical purposes, with multiplication of 0.2 to 2.6. Therefore, the development of SI prediction models has been successful, accurate and time effective to obtain optimum achievable SI in room with dome.

ABSTRAK

Tesis ini menerangkan hasil kerja penyelidikan membina model objektif untuk meramal kejelasan percakapan (KP) dalam ruang berkubah menggunakan parameter akustik, dan geometri ruang dan kubah. Tujuan kajian ini ialah untuk membolehkan peramalan KP dalam ruang berkubah, sebelum ianya dibina lagi. Model peramalan KP yang berjaya dibina dapat menentukan dimensi ruang dan kubah yang betul, dapat menentukan parameter akustik signifikan yang mempengaruhi KP, dan dapat membuat peramalan tahap KP pada mana-mana kedudukan pendengar dalam ruang berkubah. Penyelidikan dimulakan dengan kajian pandu dan penyiasatan ruang di masjid-masjid besar di Johor. Kajian yang sama kemudiannya diteruskan di Negeri Sembilan, Selangor dan Kedah. Dimensi asas ruang dan kubah, jenis kubah, jenis siling, dan jenis bahan yang menyelaput permukaan ruang dan kubah telah diperolehi. Selepas itu, pengukuran akustik telah dijalankan di tiga puluh dua buah masjid berkubah, berisipadu 600 hingga 10000 meter-padu, bagi mendapatkan Tahap Gangguan Percakapan (SIL), masa gemaan (RT60) dan penilai KP Index Penghantaran Percakapan (STI). Hasil kajian mendapati bahawa RT60 dapat meramalkan KP terendah di luar kawasan 6° liputan sumber bunyi, iaitu $STI_{OUT6(min)}$. Purata KP di ruang bawah kubah $STI_{DA(mean)}$ boleh diramal oleh purata angkali penyerapan bunyi. Kedua-dua $STI_{DS(min)}$ dan $STI_{DS(mean)}$ dapat diramalkan oleh geometri ruang dan kubah. Hasil kerja simulasi menunjukkan bahawa model peramalan KP yang dibina berjaya mencapai tahap kejituan yang boleh diterima, dengan faktor pekali 0.2 hingga 2.6. Oleh itu, kerja pembangunan model peramalan KP telah berjaya, tepat serta menjimatkan masa untuk digunakan bagi meramal tahap optima KP sesebuah ruang berkubah.

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LIST OF SYMBOLS

| | | |
|--|---|---|
| A | - | Cross-sectional area of the hole |
| A_c | - | Total absorption area of the calibration room |
| a | - | Zero correction constant |
| $\alpha, \bar{\alpha}$ | - | Average sound absorption coefficient |
| $\bar{\alpha}_{n-e}$ | - | Average sound absorption coefficient from Norris-Eyring method |
| $\bar{\alpha}_x, \bar{\alpha}_y, \bar{\alpha}_z$ | - | Average sound absorption coefficient in x, y, and z-axis respectively |
| C_{te} | - | Early-to-late-arriving sound energy ratio |
| C_{50} | - | Clarity |
| c | - | Speed of sound in air |
| D, D_{SL} | - | Source-to-listener distance |
| D_{cr} | - | Critical distance |
| D/R | - | Direct-to-reverberant ratio |
| Df | - | Average frequency range per mode |
| D_{jrc} | - | Just-reliable communication distance |
| d_1 | - | Distance of direct path from listener-to-receiver |
| $\frac{dN}{Df}$ | - | Average number of modes per frequency or mode density |
| δ | - | Dissipation coefficient |
| F | - | Frequency of the eigentone |
| f | - | Frequency |
| f_0 | - | Frequency of the first mode |
| f_m | - | Octave modulating frequency from 0.63 Hz to 12.5 Hz |

| | | |
|-------------------------------------|---|--|
| f_N | - | Number of eigentone |
| f_c | - | Critical frequency |
| K | - | Listener correction factor |
| k | - | A constant equals $13.82/RT60$ |
| L | - | Loudness |
| l | - | Thickness of the perforated panel |
| $L1 \dots L5$ or $L_{1,2,3,4,5}$ | - | Lengths of a room |
| L_D | - | Direct sound level |
| L_N | - | Background noise level |
| L_K | - | Sensitivity of microphone |
| L_{eq} | - | Sound pressure level at listener's position |
| L_{fc} | - | Sound pressure level at the center of calibration room |
| L_{nc} | - | Sound pressure level at the sound source, with microphone touching perpendicular to the source |
| L_n | - | Average stationary mean background noise level in the room (dB) |
| L_r | - | Mean square value of the reflected sound pressure (dB) |
| L_R | - | Reverberant level |
| L_w | - | Sound power level |
| L_x, L_y, L_z | - | Room dimensions in x, y and z-axis |
| λ | - | Wavelength |
| M_o | - | Resulting modulation index at listener's position |
| M_i | - | Initial modulation index of the test signal |

| | | |
|-----------------|---|--|
| $M(F)$ | - | Modulation Transfer Function |
| m | - | Modulation factor |
| m_a | - | Mass of air |
| $m(f_m)$ | - | Resultant reduction factor as function of modulating frequency |
| N_x, N_y, N_z | - | Integers 0, 1, 2, 3 ∞ |
| N | - | Total number of sound source |
| P, p | - | Pressure |
| P_{el} | - | Maximum electrical power |
| P_{ref} | - | Reference pressure |
| p_n | - | Stationary uniform noise pressure inside the room |
| p_r | - | Mean value of the reflected sound pressure in the room |
| π | - | Constant equals 3.1412 |
| ρ_o | - | Air density |
| q, Q | - | Directivity factor |
| σ | - | Perforation ratio |
| R^2 | - | Multiple correlation coefficient |
| $RT60_e$ | - | Reverberation time of an empty reverberant chamber |
| $RT60_{ws}$ | - | Reverberation time of a reverberant chamber with sample |
| R_T | - | Room constant |
| r_l | - | Distance of direct sound |

| | | |
|---------------------|---|---|
| r_2 | - | Distance of reflected sound |
| r_{LH} | - | Source-to-listener distance |
| r_h | - | Reverberation distance |
| σ | - | Perforation ratio |
| τ | - | Transmission coefficient |
| S | - | Total surface area of the room |
| S_1 | - | The surface area of the hole |
| S_2 | - | The surface area of solid of the perforated panel |
| S_x, S_y, S_z | - | Total surface area of the parallel surfaces on the x, y and z-axis |
| $\overline{S/N}$ | - | Normalized signal to noise |
| T | - | Reverberation time |
| t_x | - | The time taken when the sound source is stopped until that sound is 10 dB decayed |
| θ | - | <i>Angle between direct and reflection sound path</i> |
| U | - | Total volume flow density |
| V | - | Volume of room |
| $W_{1,2,3,\dots,N}$ | - | Widths of a room |
| W_k | - | Weighting factor |
| ω | - | Angular frequency |
| Z_a | - | Acoustics impedance of material |
| z_c | - | Characteristics impedance of material |

LIST OF ABBREVIATIONS

| | |
|---------------------|---|
| ACV | Area of curvature |
| ACY | Area of dome cylinder |
| AI | Articulation Index |
| AL_{cons} | Articulation Loss of Consonants |
| AMP | Area of main prayer area |
| ANOVA | Analysis of variance |
| ANSI | American National Standards Institute |
| AveSTI | Average value of simulated STI and measured STI |
| AWA | Area of wall |
| CSA | Ceiling surface area |
| CVO | Ceiling volume |
| DC | Dome diameter of curvature |
| DD | Dome diameter |
| DH | Dome height |
| DSA | Dome surface area |
| DVO | Dome volume |
| EDT | Early Decay Time |
| EVO | Volume of dome cylinder |
| HB | Height to mouth of dome |
| HC | Height of dome cylinder |
| ITDG | Initial Time Delay Gap |
| $L_{1,2,3,\dots,N}$ | Lengths in room |
| MEH | Mean height of the room |
| MEL | Mean length of room |

| | |
|------------|---|
| MEW | Mean width of the room |
| MFP | Mean Free Path |
| MNH | Minimum height in the room |
| MNL | Minimum length in the room |
| MNW | Minimum width in the room |
| MPA | Main prayer area |
| MRT | Modified Rhyme Test |
| MsmdSTI | Measured STI |
| MXH | Maximum height in the room |
| MXL | Maximum length in the Room |
| MXW | Maximum width in the Room |
| NCB | Balanced Noise Criteria |
| NH | Minimum dimension in room |
| NomdFactor | Normalized factor |
| NomdSTI | Normalized STI |
| NSR | Noise-to-Signal Ratio |
| PredSTI | Predicted STI |
| RASTI | Rapid Speech Transmission Index |
| RC | Radius of curvature |
| RCB | Balanced Room Criteria |
| RDDL | Ratio dome diameter to length of room |
| RDHFA | Ratio DH to floor area of the room |
| RDMEH | Ratio dome diameter to MEH |
| RDMEL | Ratio dome diameter to MEL |
| RDMEW | Ratio dome diameter to MEW |
| RDMNL | Ratio dome diameter to MNL |
| RDMXH | Ratio dome diameter to MXH |
| RDSPH | Ratio of dome surface area to product of floor and ceiling surface area |

| | |
|-------|--|
| RFSCW | Ratio of floor surface area to product of wall and ceiling surface area |
| RH | Room height not including the dome |
| RHEPT | Ratio of mean height to product of mean length, width and height of room sample |
| RHSAH | Ratio of surface area of cylinder of dome to surface area of floor of room samples |
| RMNVH | Ratio of minimum height to minimum length in room sample |
| RMWLH | Ratio MEW to MEL to MEH |
| RMXH | Ratio maximum height to mean height of the room |
| RMXL | Ratio maximum length to mean length of the room |
| RMXW | Ratio maximum width to mean width of the room |
| RRCDD | Ratio RC to DD |
| RRHDD | Ratio of RH to DD |
| RRMEW | Ratio radius of curvature to MEW |
| RRMNL | Ratio radius of curvature to MNL |
| RRSTS | Ratio of room surface area to total surface area of sample |
| RRVTV | Ratio of room volume to total volume of room samples |
| RSA | Room surface area |
| RT60 | Reverberation time |
| RVO | Room volume |
| RVEHP | Ratio of mean height to product of mean length and mean width of room sample |
| RWSFC | Ratio of wall surface area to floor and ceiling surface area |
| RXWLH | Ratio MXW to MXL to MXH |
| SE | Standard error |

| | |
|---------------------|---|
| SIL | Speech Interference Level |
| SimSTI | Simulated STI |
| SNR | Signal-to-Noise Ratio |
| STI | Speech Transmission Index |
| STI _{ALL} | Group STI values measured throughout the room |
| STI _{DA} | Group of all STI data measured under the dome area in a room |
| STI _{DS} | Group of all STI data measured in line and in front of sound source |
| STI _{max} | Maximum value of STI _{ALL} |
| STI _{mean} | Average value of STI _{ALL} |
| STI _{min} | Minimum value of STI _{ALL} |
| STI _{OUT6} | Group of all STI data measured in area off 6° off-axis in front of sound source |
| TSA | Total surface Area of Sample |
| TVO | Total volume of sample |
| V | Room volume |
| VCY | Volume of dome cylinder |
| VSA | Surface area of voids on wall |
| XH | Maximum dimension in room |

LIST OF APPENDICES

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The chapter begins with an explanation of the background of research problem. It then proceeds with listing the objectives of the undertaken research. Next, it lays out research questions, scope of work and limitations in the study. Finally it list down the contributions of the research, and structure of chapters in the thesis.

1.2 Background of Research Problem

An ability to hear a speech is not the same as intelligible upon hearing a speech. Speech intelligibility means how clearly what is said can be heard. Although a speech is heard, the speech may not be clear or understood at all (Templeton *et al.*, 1993).

The objective of hearing a speech is speech intelligibility. Speech intelligibility is the net result of the conditions under which communications takes place. It includes the behavior of talker and listener, the shape and finishes of the room, and the communication system under which the speech sound is propagated (French and Steinberg, 1947).

Dome, the shape that generates unequal distribution of sound waves, may cause a serious speech intelligibility problem (Cremer *et al.*, 1982). The existence of dome in a room causes the arrival of groups of reflection within a short period of time, which degrades speech intelligibility (Mapp, 2002).

Attempts were made to study spatial distribution of speech intelligibility in relation to the location of dome. Using the score of Speech Transmission Index (STI) as the criteria, Ahmad Khan Said (2001) has found out that the STI scores are relatively low under the dome area (Figure 1.1). This is due to high reverberation time $RT60$ of this mosque. In a different study using $RT60$ as the criteria, Mokhtar Harun *et al.* (2000) found that the $RT60$ under the dome area was relatively high. This is due to reflective surface of the dome.

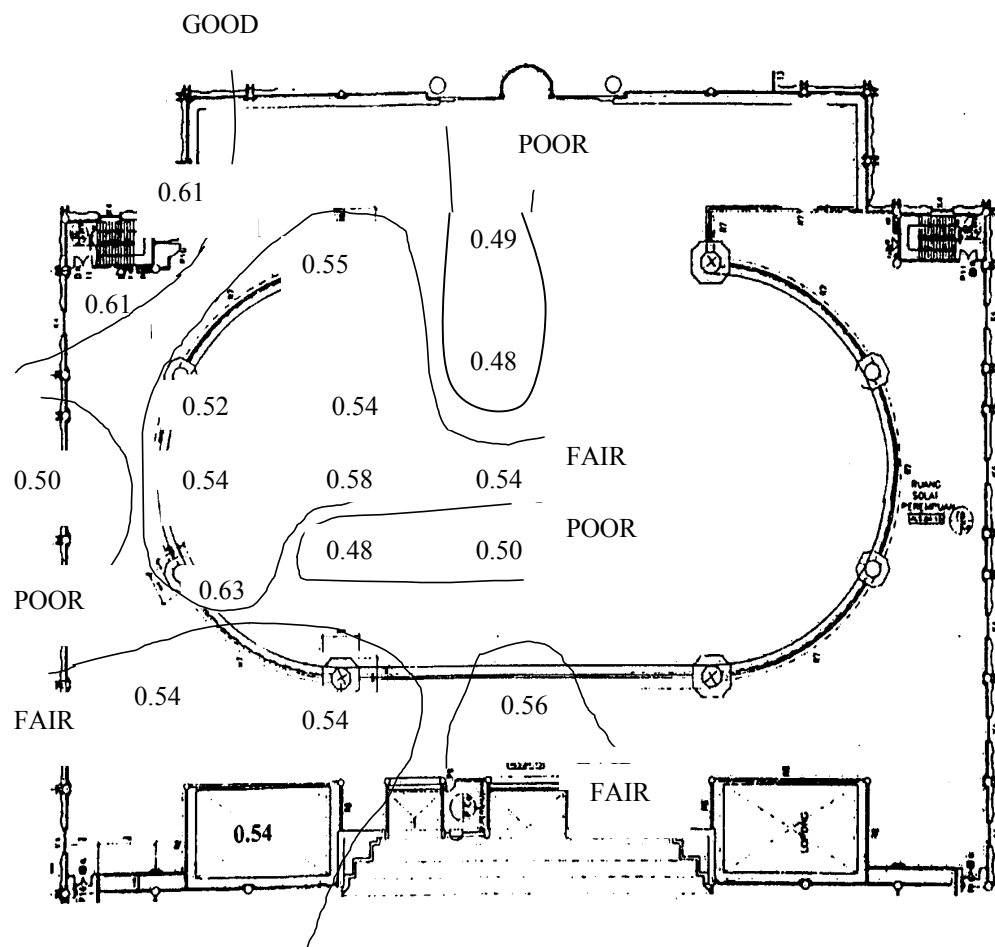


Figure 1.1 Floor plan showing STI in room with dome (Ahmad Khan Said, 2001)

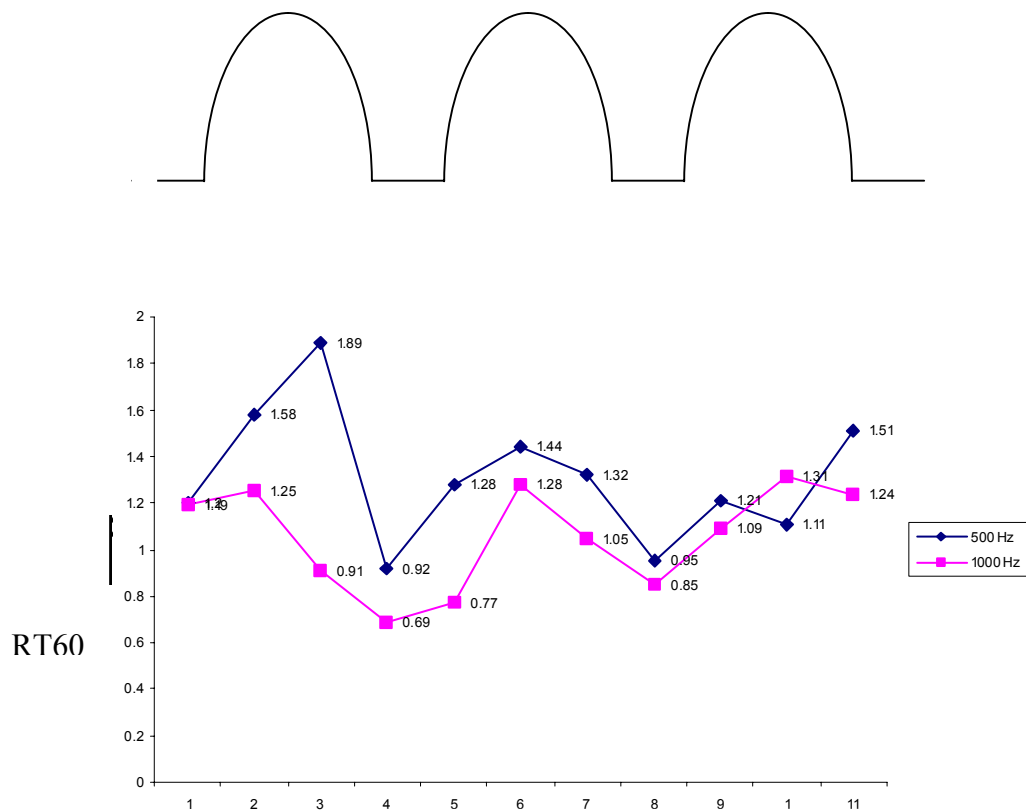


Figure 1.2 Patterns of RT60 in a room with domes (Mokhtar Harun et al., 2000)

Note: Domes are displayed to show location at which the measurement of RT60 were made.

Reports show room with dome poses speech intelligibility problems, which requires extensive and expensive treatment. Inoue *et al.* (1998) reported that a 20 m dome in an underground working area was treated with 12 pieces of 1.7 m width hanged cotton canvases, 310 m² absorptive rubber tiles on the floor, and 30 pieces of 32 kg/ m³ glass fibre boards (Figure 1.3). Clark (1999) reported that a 17187 m² exhibition space was treated with 9300 m² banners (Figure 1.4). Abdelazeez *et al.* (1991) reported that the King Abdullah Mosque in Jordan was treated with sandwiched panels that consist of 50 mm thick mineral wool and 8 mm thick plywood with 24% perforated of 50 mm air gap (Figure 1.5).

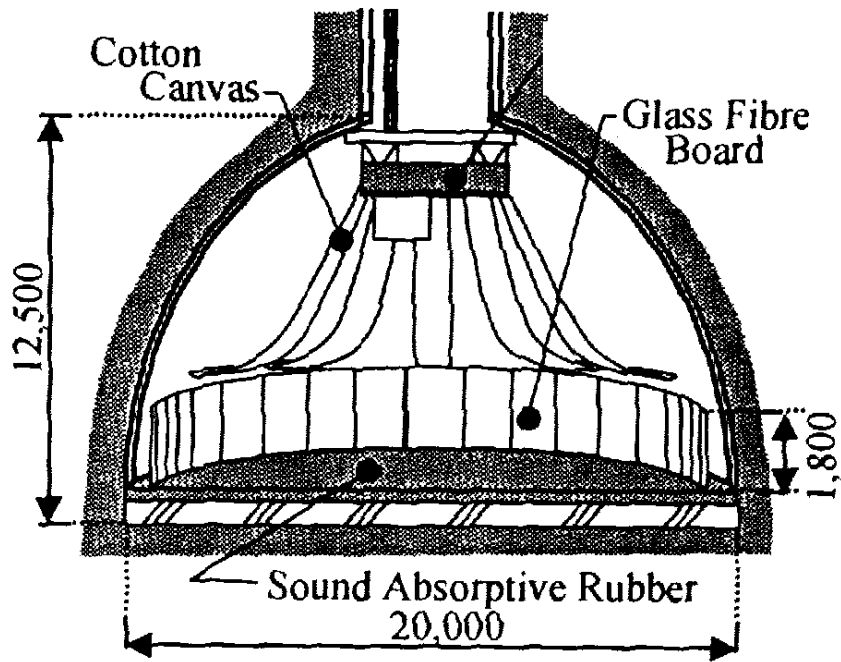


Figure 1.3 : Solutions to speech intelligibility problem in underground working area enclosed by the dome (Inoue *et al.*, 1998)

The 1100 pieces of banners cover 9300 squared-meter area attached to the ceiling support beams.

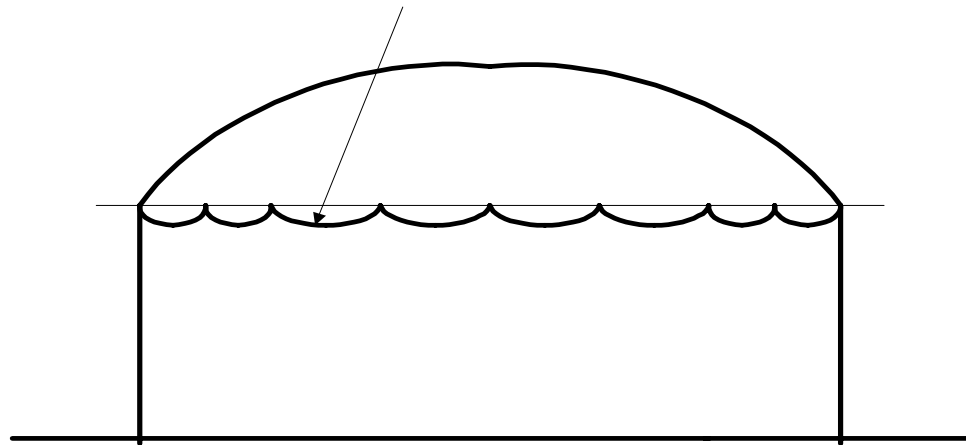


Figure 1.4 Illustration of the acoustics treatment for dome in Trans World Dome exhibition center (Clark, 1999)

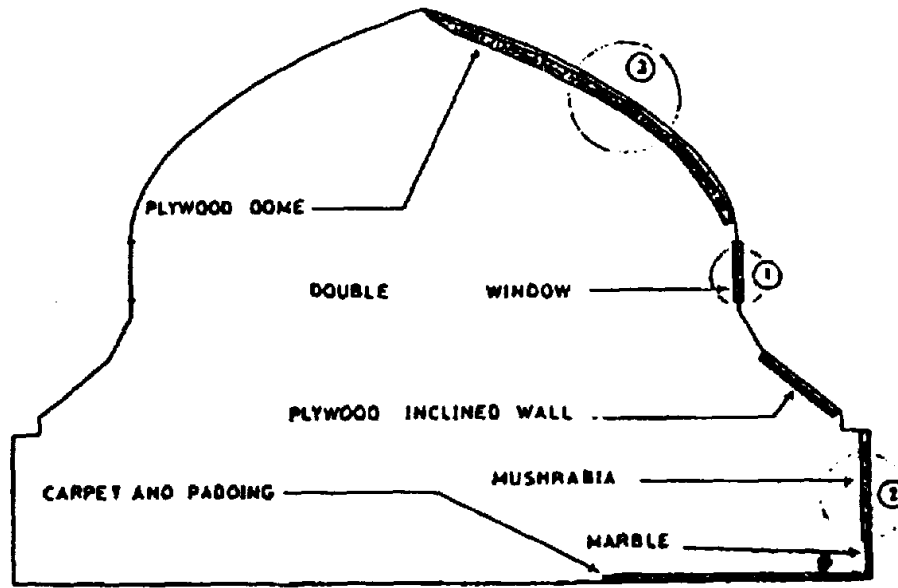


Figure 1.5 Solutions to speech intelligibility problem in King Abdullah Mosque Amman Jordan (Abdelazeez *et al.*, 1991)

Extensive treatment does not guarantee satisfactory speech intelligibility. Md. Najib Ibrahim *et al.* (2003) has found out that sound reflections in room with dome cannot be reduced solely by room treatment. For instance, the National Stadium in Kuala Lumpur had once undergone a major treatment to improve its speech intelligibility (Ahmad Khan Said, 1990). Even after the remedies, the existing sound system installation has to be operated below the optimum level.

If the treatment were not possible in order to preserve the originality and aesthetics of the room, the sound system arrangement of the room would be extensive, obtrusive and costly. Mapp (2003) has cautioned that by mounting small, high-density, and low directivity loudspeakers in room with speech intelligibility problem, the number of loudspeakers could easily exceed 100 to 200 loudspeakers.

In extreme case, the mosque with reflective dome may have to be demolished. The Sultan Ahmad Shah I Mosque, in Kuantan Pahang, had been demolished in 1989 due to serious speech intelligibility problems. The cost for

acoustics treatment was unbearable and it was more economical to rebuild the mosque with treated dome (Ahmad Khan Said, 1990).

The above problems arise because speech intelligibility in those rooms cannot be predicted prior to construction. Such an extensive and costly mistake would have been avoided should speech intelligibility could be predicted during the design stage. Therefore, this research attempts to develop speech intelligibility prediction model in room with reflective dome.

1.3 Purpose and Objectives of Research

The purpose of this research is to develop the speech prediction models in room with dome that is accurate and acceptable for practical purposes.

The objectives of this study are as follows.

1. To identify factors that affect speech intelligibility.
2. To identify and select the most reliable and comprehensive speech intelligibility assessor.
3. To develop speech intelligibility prediction model for room with dome.
4. To verify the developed prediction models with the Ray Tracing based simulation.

1.4 Scope of Work and Limitations of the Research

Mosques are selected as samples due to the fact that mosque acoustical function is mainly for speech. Unlike churches and multipurpose rooms, such as National Stadium and National Science Centre in Kuala Lumpur, mosque adopts no musical performance or musical instruments to be played in it.

The geometry of room samples selected for the study is restricted to combination of rectangular room and dome. Follows are scope set for this research.

- a. The room sample selected has not undergone any acoustics treatment.
- b. The plan and form of samples are symmetrical.
- c. The dome, material and room finishes of dome in room samples are made of hard material, and are sounds reflective.
- d. Volume of room sample is 10000 ft³ (or 280 m³) and above.
- e. Ratio of dome to room volume of room samples is at least 1:10.
- f. Ray Tracing Simulation of EASE 3.0 is used to verify the developed speech intelligibility (SI) prediction models
- g. Real room with dome are to be used to analyse and compare the developed SI prediction models

1.5 Research Contributions

The undertaken research work has contributed to the expansion of knowledge in the field of acoustics and speech intelligibility in room with reflective dome.

The developed speech intelligibility prediction models are capable of predicting the speech intelligibility at the room's architectural design stage. The prediction model at such an early stage enables the changes in form, shapes, and material and finishes of room

before the design is finalized. The use of prediction models save time, cost, and maintains the aesthetics of the room.

1.6 Structure and Thesis Layout

The next five chapters cover all research activities in evaluating and developing speech intelligibility prediction models in room with dome.

The second chapter provides a summary of literature on factors affecting speech intelligibility in room. Three speech intelligibility assessors currently available and used are also discussed.

The third chapter describes methodology of the research. Pilot study, sampling of room samples, and room investigation are described. The calibration of equipment, equipment set up, and procedures for measurement of objective measures and acoustics measures are presented in this chapter.

Acoustics quality of room samples in terms of objective measures are described in Chapter IV. This chapter presents analysis of objective measures and their relation to STI. The developed speech intelligibility prediction models in terms of RT60, sound absorption coefficient, and ITDG is also tabulated.

The process of developing speech intelligibility prediction model in terms of room and dome dimensions is described in Chapter V. The simulation of the prediction model to Ray Tracing based simulation is presented at the final section of this chapter.

Lastly, the final chapter provides conclusions of the research. The undertaken research also has brought about future suggestions and strategy to improve the developed models. Those ideas are presented in section on suggestions for future work.

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