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# MODELLING OF SOUND FIELDS IN PERFORMANCE SPACES WITH ABSORBENT ROOM SURFACES.

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## 1. INTRODUCTION

To fully describe the sound field in an enclosed space both the spatial and temporal acoustic characteristics should be predicted simultaneously using a consistent description of the space. The spatial characteristics of a room are best described using sound propagation curves, as this is well understood and can be easily compared to previous works; similarly reverberation time (RT) can be used as a descriptor of the temporal characteristics. Previously, it has been found difficult to accurately predict the complete sound field in an enclosed space using a consistent room description [1].

There are many types of enclosed space including factories, theatres, atria and offices, which can be broadly categorised as either work or performance spaces. This reports is concerned with the prediction of sound field characteristics in performance spaces using classical theory and computer models. The classical theory includes that of Sabine [2], Eyring [3] and Millington [4] from the early part of last century, and the computer models FAME [5], CISM [6] and RAMSETE [7], which are all currently available. The rooms chosen to evaluate the prediction accuracy of the models included a hypothetical room, a recording studio and a concert hall across a range of frequencies. The authors would like to thank INRS, France for providing the original RAYCUB model; Dr Lam of Salford University for allowing the use of the measurement data; and John Mills for providing access to the recording studio. This research was funded by the Engineering and Physical Sciences Research Council.

## 2. CLASSICAL THEORY

The background to the Sabine and Eyring reverberation time formula is well known and hence the Millington formula has been highlighted. The Millington formula for the prediction of reverberation time has not been extensively used in computer models in the past, as previous predictions have been poor [8]. The reason for the consistently under-predicted reverberation time when the Millington formula is used is that standard based absorption coefficients were used. To enable the Millington formula to be used correctly it is necessary to use Millington based absorption coefficients and hence a conversion graph has been created, as described below, so that Millington absorption coefficients can be simply found from the standard absorption coefficients. The Millington reverberation time, RT, is given below

$$RT = \frac{0.161V}{-\sum_i S_i \ln(1-\alpha_i)}$$

where V is the volume of the space ($m^3$) and $S_i$ is each surface area and a is the absorption coefficient of the room surface.

As can be seen from above the Millington formula is similar to the Sabine and Eyring formula and hence the information required is identical. However, precise details concerning the size of the room are lacking and hence certain assumptions are necessary in order to create the conversion graph. The assumptions were based on those of Miles [9] for a hypothetical reverberation chamber. The absorbent sample size was assumed to be 10.8 $m^2$ and the room size dimensions were given as 6.0 m by 5.0 m by 4.0 m with a uniform distribution of absorbent material, the absorption coefficient was assumed to be 0.04.

The conversion graph, shown in Figure 1, was created by calculating the Sabine reverberation time as the sample became more absorptive, the absorption coefficient ranged from 0.04 to 1.0. The same procedure was followed in reverse, that is taking the Sabine reverberation time for a specific sample and calculating the absorption necessary to give the same value using the Millington formula.

It can be seen that the difference between a standard and a Millington absorption coefficient is small when the coefficient is below 0.2, but grows steadily as the standard coefficient approaches unity. Hence a suitable test for the formulae would be predictions in rooms where highly absorbent surfaces are prevalent, such as recording studios and concert halls.

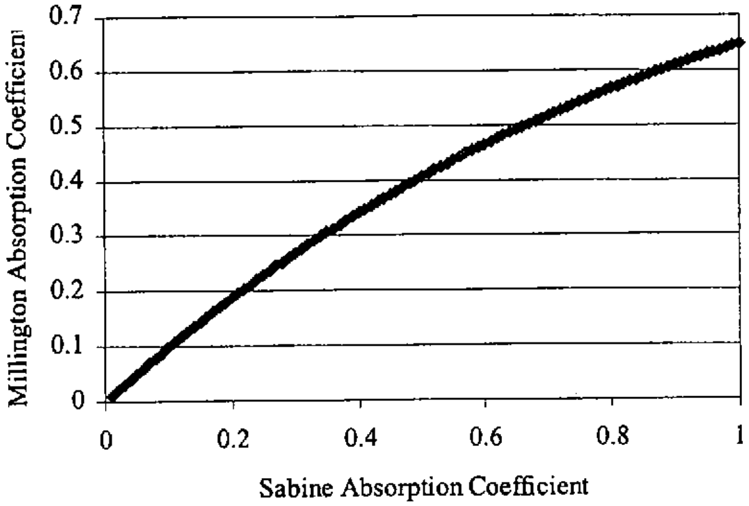



Figure 1. The Sabine to Millington absorption coefficient conversion graph.

## 3. MATHEMATICAL MODELS

Three computer models were used to predict the sound propagation and reverberation time during the investigation. Each room was predicted using both standard absorption coefficients and Millington absorption coefficients.

**FAME** is a ray-tracing model in which the sound is treated as energy. FAME was based on the Ondet and Barbry model RAYCUB [9], but has been significantly optimised and extended to include arbitrary shaped rooms with arbitrary located absorbent material, multiple directional sound sources, multiple receivers, arbitrarily located fittings using a statistical representation [10], barrier diffraction [11], specular and diffuse reflections [12] and internal to external environments using multiple diffraction [13]. FAME can simultaneously predict sound propagation, reverberation time, early decay time and the clarity index using a single set of data for each octave band. FAME models each octave band individually.

**CISM** is based on the image-source method in which the sound is treated as energy, which is traced along a sound path. A sound path travels from the mirror image of the source to the real receiver, which is the same journey through imaginary space as the reflected journey in real space. CISM can represent rooms which are parallelepiped in shape, with multiple directional sound source, multiple receivers, fittings located parallel to one room surface using a statistical representation [14], specular reflections, arbitrarily located absorbent material and totally sound absorbing acoustic barriers. CISM can simultaneously predict sound propagation, reverberation time, early decay time and the clarity index using a single set of data for each octave band. CISM models each octave band individually. A web version of CISM can be used at http://www.sbu.ac.uk/~acogrp/cism.html

**RAMSETE** is a software package developed by Farina [5]. The mathematics of the model are based on the beam tracing technique, specifically pyramid tracing. Pyramid tracing treats the source as a point, which can emanate pyramids in 8 octets, each of which can be further subdivided. RAMSETE can represent rooms which are arbitrarily shaped, with multiple directional sound sources, multiple receivers, fittings represented by individual surfaces, specular reflections, arbitrarily located absorbent material, barrier diffraction and internal to external environments using double diffraction. RAMSETE can simultaneously predict sound propagation, reverberation time, early decay time, centre time, speech transmission index, RASTI, lateral efficiency, initial time delay gap and the clarity index using a single set of data for each octave band. RAMSETE models all ten octave band simultaneously.

## 4. RECORDING STUDIO

A recording studio was used as a test case to demonstrate the accuracy of the Millington reverberation time formula when Millington absorption coefficients were applied. The predictions were compared to those of the Sabine and Eyring formulae.

### 4.1 The Recording Studio

The recording studio was still under construction when the measurements were taken. The shell was completed, but the room was empty except for the acoustic treatment of the walls with framed mineral wool. The studio was 4.88 m long, 4.15 m wide and 2.4 m high. The floor was a screed concrete construction, with a suspended tile ceiling 0.27 m beneath a wood wool decking. The brick walls were covered with painted plaster with a 1.43 m tall rockwool frame positioned at a height of 0.71 m, see Figure 2.

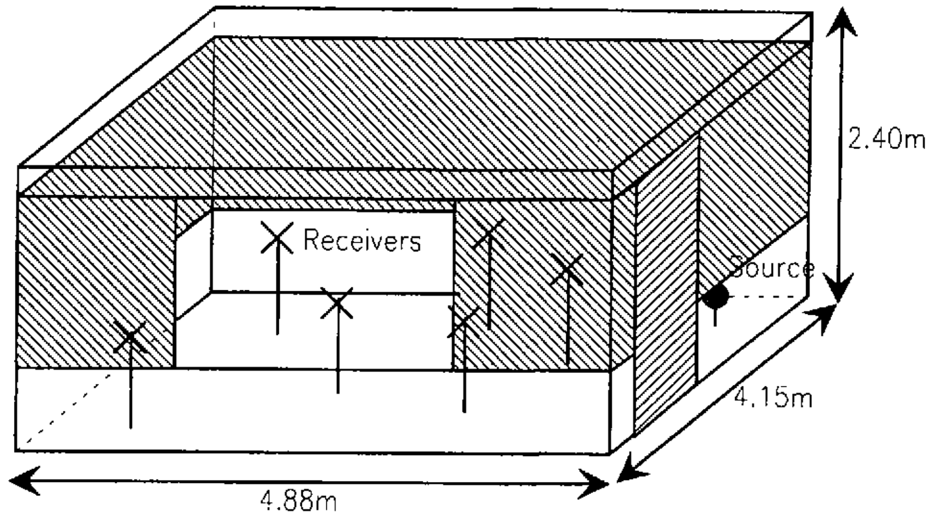



Figure 2. The recording studio showing the source and receiver positions.

In one wall was a triple glazed window 2.0 m by 1.2 m. A loudspeaker was positioned in one corner of the room, facing the corner, while measurements were taken at six positions at a height of 1.6 m, see Figure 2.

### 4.2 Reverberation Time Predictions

The standard absorption coefficients chosen to represent the absorptive material, the suspended ceiling and the wall panels, in the recording studio are given in Table 1. The predictions using various classical theory are given in Table 2.

**TABLE 1**

*Sabine absorption coefficients for the absorptive material in the recording studio, 125Hz-4kHz*

| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| Ceiling | 0.30 | 0.40 | 0.50 | 0.65 | 0.75 | 0.70 |
| Wall Panels | 0.15 | 0.65 | 0.95 | 0.92 | 0.80 | 0.85 |

Table 1 shows the measured and predicted reverberation times averaged over all six receiver positions. The Sabine and Eyring reverberation time formulae used the standard absorption coefficients in Table 1 and the Millington formula used absorption coefficients converted using the graph in Figure 1.

**TABLE 2**

*Measured and predicted reverberation times (sec) in the recording studio, 125 Hz- 4kHz*

| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| Measured | 0.60 | 0.40 | 0.28 | 0.38 | 0.24 | 0.25 |
| Sabine | 0.76 | 0.39 | 0.29 | 0.26 | 0.26 | 0.26 |
| Eyring | 0.71 | 0.34 | 0.24 | 0.21 | 0.21 | 0.21 |
| Millington | 0.72 | 0.37 | 0.27 | 0.25 | 0.24 | 0.25 |

From Table 2 it is clear that the Millington formula is at least as accurate as the Eyring or Sabine formulae when the 'corrected' absorption coefficients were used. Over all the receiver positions and frequencies the Millington formula gave a 10.9% prediction error, as compared to 12.8% and 20.1% for the Sabine and Eyring formulae, respectively. This demonstrates the accuracy of the Millington formula and raises the question: What are the correct absorption coefficients for use in a computer model based on geometric acoustics?

## 5. COMPUTER PREDICTIONS

Computer predictions for performance spaces are complex and hence it was considered prudent to initially validate the computer models in the simplest space possible, a hypothetical reverberation chamber. In this space with uniform absorption distribution the Millington formula gives identical results to those given by the Eyring formula.

### 5.1 Hypothetical reverberation chamber predictions

The chamber was assumed to be 7 m long, 6 m wide and 5 m high with evenly distributed absorption coefficients; air absorption was assumed to be 0.001 dB/m for both the models. Predictions were made for three values of absorption coefficient: α=0.05, α=0.10, α=0.2. The number of reflections traced for the three absorption coefficients were 83, 42 and 20 respectively. The sound source was treated as omni-directional and was positioned in one corner, with the receiver in the farthest corner from the source. An accurate prediction in terms of computer modelling of RT may be taken to be when the error is equal to or less than the difference between the Sabine and Eyring predictions with an average absorption coefficient of 0.2, a difference of 14%. Table 3 shows the reverberation time predicted by the various models.

**TABLE 3**

*The models predicted reverberation time (sec), in a hypothetical reverberation chamber.*

| | α=0.05 | α=0.10 | α=0.20 |
|---|---|---|---|
| Eyring/Millington | 2.86 | 1.45 | 0.70 |
| FAME | 2.86 | 1.37 | 0.66 |
| CISM | 3.10 | 1.56 | 0.79 |
| RAMSETE | 2.43 | 1.18 | 0.63 |

The Eyring formula and the Millington formula gave identical results, as the room surfaces are defined as having uniform surface absorption in the hypothetical reverberation chamber. It can be seen that for an average absorption coefficient of 0.05, as in a typical reverberation chamber, there was no difference between the value predicted by the FAME model and the Eyring formula. CISM predicted reverberation times 8.4% longer than the Eyring prediction, well within the prescribed limits of accurate prediction; RAMSETE produced a 15.0% under-prediction. For α=0.1 the difference compared with the Eyring formula for REDIR RT was 0.08 seconds, for CISM 0.11 seconds and RAMSETE 0.27 seconds, thus the first two computer models can be considered to give accurate predictions, where as the latter gave a 18.6% error. Increasing the absorption to α=0.2 produced predictions by all models within 14% of the Eyring prediction, the differences were 5.7% for FAME, 12.9% for CISM and 10.0% for RAMSETE. These results demonstrate that the models are accurate in the simplest possible space, giving an overall average error of 3.5%, 9.6% and 14.4% for FAME, CISM and RAMSETE, respectively. This is similar to those recorded by Hodgson [15], and thus that they may be of practical use in more realistic spaces.

**5.2 The Concert Hall**

The concert hall, shown in Figure 4, was 34.9 m long, 17.7 m wide and 11.8 m high and empty. The walls were constructed from plastered and painted brickwork, the floor from timber boards and the barrel vaulted ceiling was plastered; the wall height was 7.3 m. Located along the length of the room were glazed windows with closely folded curtains on each side. At one end of the room there was a full width wooden stage 1.0 m high with a full height velvet curtain across the back stage wall. On the opposite wall was a partial height curtain, see Figure 3.

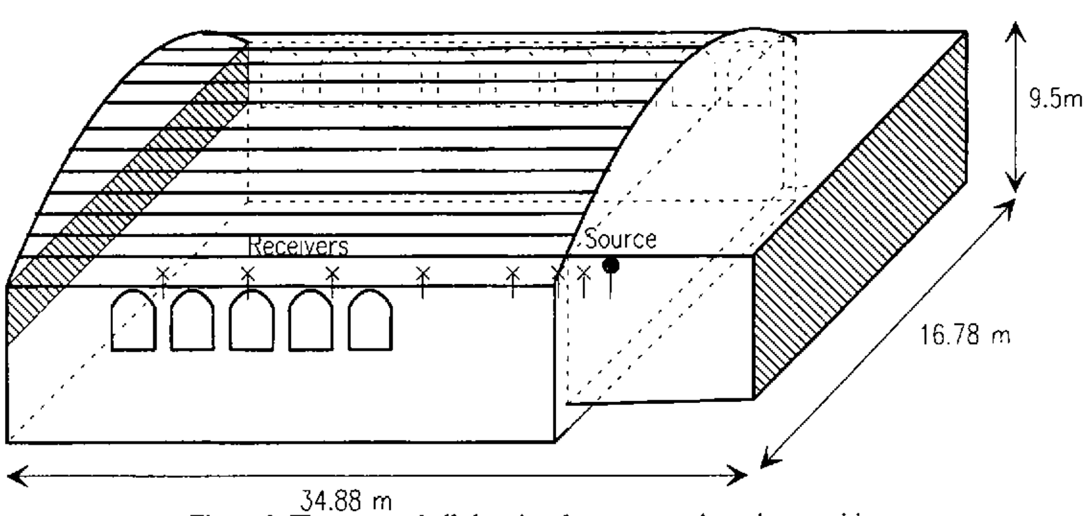



Figure 3. The concert hall showing the source and receiver positions

The sound source was omni-directional and a computer measurement system (MLSSA) was used to take a set of measurements. The measurements were taken along the length of the room, with the source positioned 23 m from the end wall and 8.39 m from the side wall. The sound source was mounted on a tripod at a height of 1.7 m. Measurements of reverberation time and sound levels were made for the 125 Hz to 4 kHz octave bands at a height of 1.25 m, see Figure 3.

Each of the computer models represented the room as a parallelepiped shaped space with absorptive patches corresponding to the curtains at each end of the room. The curtains hanging against the windows contributed to the average absorption coefficient for each of the long walls. The room was given a geometry equal in volume to that of the actual space, the stage being represented as being at the same level as the floor. The standard absorption coefficients used to represent the curtains were as follows: 0.14, 0.35, 0.55, 0.72, 0.70 and 0.65 for the six octave bands 125 Hz to 4 kHz. The number of reflections was determined as 28, 35, 36, 39, 36 and 30 for the CISM using the Millington absorption coefficients, slightly less than those using the standard coefficients. The FAME and RAMSETE reflection orders were exactly half those for the CISM model.

### 6.3 Reverberation Time Results

Table 4 shows the average measured reverberation time for each octave band and the classical predictions using their corresponding absorption coefficients.

**TABLE 4**

*Measured and predicted reverberation time (sec) in the Concert Hall, 125Hz-4kHz*

| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| Measured | 2.28 | 2.23 | 2.24 | 2.22 | 2.17 | 1.93 |
| Sabine | 2.61 | 3.22 | 3.23 | 3.21 | 2.95 | 2.51 |
| Eyring | 2.40 | 3.02 | 3.03 | 3.03 | 2.82 | 2.41 |
| Millington | 2.49 | 3.16 | 3.26 | 3.24 | 3.15 | 2.63 |

Table 4 shows that the average prediction accuracy was less than for the recording studio at approximately 35.6%, 27.9% and 36.6% for Sabine, Eyring and Millington, respectively. All methods over-predicted the reverberation time by between 0.2 and 1.0 seconds. This clearly demonstrates that as a room becomes less diffuse the classical formulae begin to give inaccurate results.

The computer models simultaneously predicted the sound propagation and the reverberation time using both standard and Millington absorption coefficients for the curtains. Tables 5 and 6 show the average predicted reverberation time for each of the models using the standard and Millington absorption coefficients, respectively.

**TABLE 5**

*Measured and predicted reverberation time (sec) in the concert hall-Standard absorption coefficients,125Hz-4kHz*

| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| Measured | 2.28 | 2.23 | 2.24 | 2.22 | 2.17 | 1.93 |
| FAME | 2.13 | 2.31 | 2.04 | 1.78 | 1.65 | 1.49 |
| CISM | 2.59 | 2.43 | 2.05 | 1.72 | 1.54 | 1.42 |
| RAMSETE | 3.15 | 2.48 | 2.17 | 1.88 | 1.88 | 1.88 |

**TABLE 6**

*Measured and predicted reverberation time (sec) in the concert hall-Millington absorption coefficients, 125Hz-4kHz*

| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| Measured | 2.28 | 2.23 | 2.24 | 2.22 | 2.17 | 1.93 |
| FAME | 2.39 | 2.51 | 2.26 | 2.19 | 1.96 | 1.66 |
| CISM | 2.68 | 2.56 | 2.30 | 2.10 | 1.86 | 1.63 |
| RAMSETE | 2.82 | 2.32 | 2.10 | 1.89 | 1.87 | 1.87 |

Comparison of Table 5 and Table 6 shows that all three mathematical models were more accurate than the classical formulae, with on average prediction errors of 14.3%, 18.2% and 14.0% for FAME, CISM and RAMSETE, respectively. Table 6 shows that using Millington absorption coefficients increased the average prediction accuracy of FAME and CISM by approximately 7%, and increased that of RAMSETE by 3%. It should be remember that only one short wall was covered with absorptive material and hence any improvement would be small. The predicted reverberation time errors were on average 7.2% for FAME, 11.7% for CISM and 11.0% for RAMSETE.

### 6.4 Sound Propagation Results

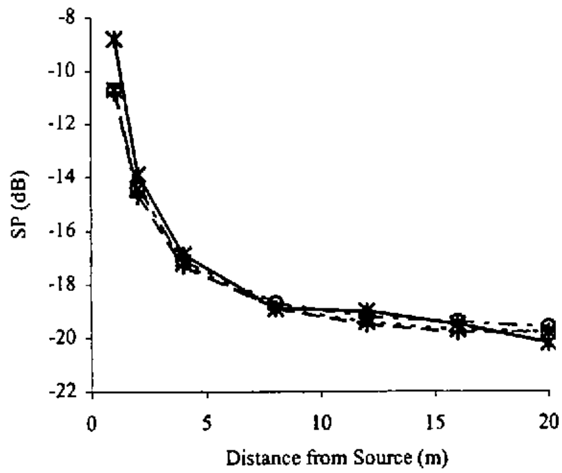
The computer models additionally predicted the sound levels along the length of the concert hall allowing the sound propagation curves (SP) to be derived for each of the six octave bands. Only the sound propagation curve for the 1 kHz octave band is presented, along with the summary of the predictions for all six octave bands, Table 7. Table 7 gives the average absolute prediction errors (the predicted minus the measured sound level) for each of the three mathematical methods using both standard and Millington absorption coefficients.

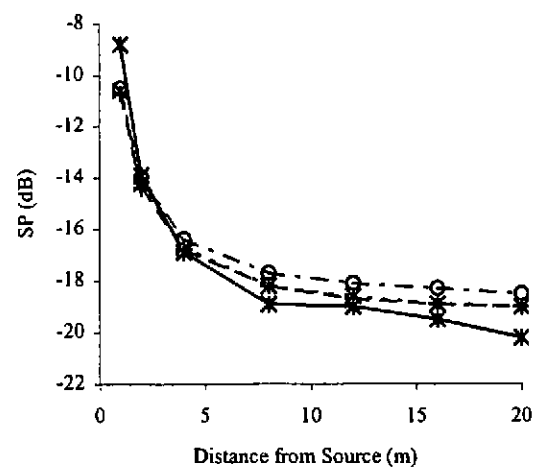
**TABLE 7**

*Average predicted sound levels errors (dB) in the Concert Hall, 125Hz- 4kHz*

| Absorption | Model | 125Hz | 250Hz | 500Hz | 1 kHz | 2 kHz | 4 kHz | Average |
|---|---|---|---|---|---|---|---|---|
| Standard | FAME | 2.8 | 2.1 | 1.8 | 0.5 | 1.7 | 2.6 | 1.9 |
| | CISM | 2.5 | 1.9 | 1.5 | 0.5 | 1.8 | 2.8 | 1.8 |
| | RAMSETE | 2.6 | 2.3 | 1.8 | 0.6 | 2.4 | 3.5 | 2.2 |
| Millington | FAME | 2.5 | 1.9 | 1.5 | 0.5 | 1.8 | 2.8 | 1.8 |
| | CISM | 2.2 | 1.7 | 1.4 | 0.6 | 2.2 | 2.9 | 1.8 |
| | RAMSETE | 2.5 | 2.1 | 1.6 | 0.8 | 2.8 | 3.8 | 2.3 |

In terms of sound level prediction accuracy the difference between each model using either the standard or the Millington absorption coefficient for the curtains was marginal, on average 0.1 dB in all cases. The FAME and CISM models produced similar predictions, giving a 1.8 dB average prediction error overall. RAMSETE was approximately 0.4 dB worse giving results on average 2.2 dB in error.




Figures 4 and 5 show the measured (*) and CISM (x), RAMSETE (o) and FAME (+) predicted sound propagation curve in the concert hall, 1 kHz Octave Band, for the standard and Millington absorption coefficients.

It can be clearly seen that in the reverberant sound field, beyond 8m from the sound source, the sound levels reach a near constant level and hence the room could be said to be diffuse. All the models accurately predicted the sound levels using standard based absorption coefficients. In Figure 5 the predictions were made using Millington based absorption coefficients. The sound levels, as expected, are approximately 0.8 dB higher in the reverberant sound field than those using the standard absorption coefficients. Thus this approach also provides accurate prediction.

## 7. THE TEST ROOM

This section presents the work of Mehta and Mulholland [16] as applied by Arau-Puchades [7] for a test room configured with absorbent material covering entire room surfaces.

### 7.1 The Test Room

The experimental room used by Mehta and Mulholland was 4.54 m long, 2.73 m wide and 2.40 m high with an absorption coefficient for the room surfaces of 0.036 for the 1 kHz third octave band, calculations based on the standard reverberation time formula. The absorptive material was Rocksil, in 1.25 m long by 0.90 m wide panels, which was used to add non-uniform absorption to the room. In the investigation described here the Millington absorption coefficient of 0.59 was used as well as the standard absorption coefficient, 0.86. Early decay time rather than RT was predicted due to the size of the room.

Five of the eleven Mehta and Mulholland cases were investigated by Arau-Puchades. In the investigation discussed here these five configurations were simulated. As a verification of the accuracy of the models the simplest possible space, that is the room with no absorptive panels, was also simulated. This is referred to as Case 0. No detailed measurement information was presented by Mehta and Mulholland, except that three receiver positions were used and the reverberation time averaged. The computer models each averaged the reverberation time over eight receiver positions, located 1.0 m from the nearest wall and separated by 0.5 m, at a height of 1.5 m. The sound source was treated as omni-directional and was located in two positions: in the corner of the room, and 1.0 m from the centre of the nearest wall, both at a height of 0.5 m from the floor.

### 7.2 The Classical Predictions

Table 1 shows the reverberation times at 1000 Hz predicted by the classical reverberation time formulae in the six configurations of the Mehta and Mulholland space listed above.

**TABLE 8**

The measured and predicted reverberation times (s) 1 kHz

| Case | Measured | Eyring | Sabine | Millington |
|---|---|---|---|---|
| 0 | 2.20 | 2.18 | 2.23 | 2.18 |
| 1 | 0.52 | 0.20 | 0.24 | 0.23 |
| 2 | 0.71 | 0.39 | 0.43 | 0.41 |
| 3 | 0.29 | 0.16 | 0.21 | 0.20 |
| 4 | 0.40 | 0.23 | 0.27 | 0.26 |
| 5 | 0.17 | 0.14 | 0.18 | 0.17 |

**Case 0: Empty Configuration.** All three reverberation time formulae predicted similar reverberation times, all within 6% of the measured value. Hence the formulae were considered to be accurate in the case with no absorptive panels.

**Case 1: Absorption on 2 Long Walls.** With absorption panels on the two longest walls the classical formulae all predicted a reverberation time of approximately half that of the measured RT. This clearly demonstrates the limitation of the classical methods, in that they cannot predict reverberation time in rooms with a non-uniform distribution of room surface absorption.

**Case 2: Absorption on a Long Wall.** With absorption on just one long wall the reverberation time was 0.19 seconds longer than in Case 1, when both long walls were absorptive. This difference was accurately predicted by the three classical formulae. However, in terms of absolute accuracy the results were poor

**Case 3: Absorption on the Floor and 2 Short Walls.** With absorption covering the floor and the two shorter walls the reverberation time was reduced to 0.29 seconds, which was under predicted by the classical formulae by approximately 0.1 seconds. This again demonstrates the limitations of the classical approach to reverberation time prediction when the sound field is less diffuse.

**Case 4: Absorption on the Floor and a Short Wall.** This is as Case 3, but with the absorptive panels removed from one of the short walls. All the classical models under predicted the reverberation time. The predicted differences between the reverberation times in Cases 4 and 3 were consistent for all the classical formulae at 0.06 seconds, compared to the measured difference of 0.11 seconds. The prediction error was approximately 35% for all the classical formulae.

**Case 5: Absorption on 3 Adjacent Room Surfaces.** When three adjacent surfaces were covered in absorptive material the reverberation time difference between the formulae were so small, the error became marginal. The Millington formula was the most accurate, predicting the reverberation time exactly.

Overall, ignoring the empty configuration of the room the classical methods produced 42.3%, 31.8% and 32.9% average errors for the Eyring, Sabine and Millington formulae, respectively. Finally, it should be noted that the results presented by Arau-Puchades for the Millington formula were based on standard absorption coefficients and hence produced very poor predictions, producing his dismissal of the formula.

### 7.3 Computer Model Predictions

Table 2 shows the reverberation times at 1kHz predicted by the three computer models in all six cases, using both standard and Millington based absorption coefficients for the absorptive panels.

**Case 0: Empty Configuration.** Predictions by all three computer models were consistent with those for the hypothetical space in section 5.1. FAME and CISM predicted the reverberation time accurately, with 3.2% and 1.8% error, respectively. RAMSETE under-predicted the reverberation time by 37.3%, as compared to 15.0% in the hypothetical space used in the earlier investigation. The predicted reverberation time was the same for both sets of absorption coefficients for each model.

**Case 1: Absorption on 2 Long Walls.** For all of the models Millington based predictions were significantly more accurate than the predictions with standard absorption coefficients, the increase in accuracy being approximately 30%. The most accurate prediction was that of CISM, which produced a 3.8% error using Millington absorption coefficients; FAME had a 9.6% error; and RAMSETE a 15.6% error. By comparison using the standard absorption coefficients the errors ranged from 34.6% to 44.2%, due to under-prediction of the reverberation time.

**Case 2: Absorption on a Long Wall.** When the absorptive panels were removed from one of the longest walls, the measured reverberation time was increased by 0.19 seconds. Only RAMSETE predicted this increase accurately, 0.20 seconds, using both the standard and Millington based absorption coefficients. FAME and CISM both predicted a greater difference ranging between from 0.24 seconds to 0.29 seconds. The overall computer models prediction error using standard based absorption coefficients was 21.1%, as compared to 7.1% for the Millington based predictions. This is as expected, there being only half the amount of absorbent material in the room, as compared to Case 1. The most accurate model was FAME using the Millington based absorption coefficients, with an average error of 2.8%.

**Case 3: Absorption on 2 Short Walls.** For all three models the standard predictions gave too short a reverberation time, by on average 26.7%, whereas the Millington formula gave too long a reverberation time, by on average 12%. All the mathematical models were more accurate using the Millington absorption coefficient than the standard absorption coefficients. The most accurate prediction was given by the Millington based RAMSETE model, an 8% error.

**Case 4: Absorption on a Short Wall.** All three models gave significantly more accurate predictions using Millington rather than the standard absorption coefficients, 7.5% compared to 38.3% average error. The most accurate model was FAME using the Millington absorption coefficients, which gave an error of 2.5%.

**Case 5: Absorption on 3 Adjacent Room Surfaces.** As in the previous case the computer models using standard absorption coefficients predicted too short a reverberation time, and hence gave an average error of 41.2%. When Millington absorption coefficients were used to represent the absorptive panels the average error was reduced to 13.7%. The most accurate model was RAMSETE using Millington absorption coefficients.

Overall, in the cases where absorptive panels are fitted over entire room surfaces, using a Millington based absorption coefficient improves the accuracy of the computer models by on average 23.3%, compared with using the standard absorption coefficients. When using each type of absorption coefficient all three computer models predicted very similar values for reverberation time. The errors for RAMSETE, CISM and FAME were 36.1%, 32.4% and 31.4% using standard absorption coefficients, and 10.3%, 9.9% and 9.7% errors using Millington absorption coefficients, respectively.

## 8. SUMMARY

The prediction accuracy of both classical formulae and computer models for the prediction of reverberation time has been investigated in three spaces, a recording studio, a concert hall and a test room. From the results it was clear that the Millington formula was as accurate as the Sabine and Eyring formulae when appropriate absorption coefficients were used to represent highly absorbent room surfaces. Based on the predictions of three computer models there was found to be a significant improvement in sound level and reverberation time accuracy when Millington rather than standard absorption coefficients were used.

## 9. REFERENCES

1. M HODGSON, Evaluation of the performance of suspended arrays in typical industrial sound fields. JASA, 97 (1), 349-, 1995.
2. W. SABINE, Collected papers on acoustics. Harvard University Press, 1922.
3. C. EYRING, Reverberation time in 'dead' rooms, JASA, 1,217-226. 1930.
4. G. MILLINGTON, A modified formula for reverberation. JASA, 4, 69-81, 1932.
5. S. DANCE, J. ROBERTS and B. SHIELD, Computer prediction of insertion loss due to a single barrier in a non diffuse empty enclosed space, JBA, 1(2), 125-136, 1994.
6. S. DANCE and B. SHIELD. The complete image-source method for the prediction of sound distribution in non-diffuse enclosed space. JSV, 201(4), 473-489, 1997.
7. A. FARINA, RAMSETE- A new pyramid tracer for medium and large scale acoustic problems, Euro-Noise 95, 55-60, 1995.
8. H. ARAU-PUCHADES, An improved reverberation formula, Acustica, 65(4), pp.163-179, 1988.
9. A. ONDET and J. BARBRY, Modelling of sound propagation in fitted workshops using ray tracing, JASA, 85(2), 787-, 1989.
10. S. DANCE, The representation of fittings in the computer prediction of sound propagation in enclosed spaces, Applied Acoustics, 52(1), 71-83, 1997.
11. S. DANCE and B. SHIELD, A refined diffraction approximation for free standing barriers in enclosed spaces, Inter-Noise 98.
12. S. DANCE, N. PINDER and B. SHIELD, The prediction of reverberation time in fitted rooms, Euro-Noise 98, Munich.
13. S. DANCE and B. SHIELD, Simultaneous prediction of internal and external sound fields, Inter-Noise 2000, Nice, 2000.
14. S. DANCE, The development of computer models for the prediction of sound distribution in fitted non-diffuse spaces, Ph.D. Thesis, South Bank University, 1993.
15. M. HODGSON, On the Prediction of sound fields in empty room, JASA, 84(1), 253-261. 1988.
16. M. MEHTA and K. MULHOLLAND, Effect of non-uniform distribution of absorption on reverberation time, JSV, 46(2), 209-224, 1976