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Modelling of sound fields in enclosed spaces with absorbent room surfaces. Part I: performance spaces

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Abstract

This paper introduces a three-part report describing research into the use of Millington absorption coefficients in the computer modelling of sound fields in enclosed spaces with absorbent room surfaces. The historical background to the prediction of reverberation time is presented together with three types of computer models used in the investigation. In part one, the computer models are described, the Millington reverberation time formula is validated, Millington absorption coefficients are derived and the sound field in a concert hall is predicted. This enables the accuracy of the three types of computer models to be compared and the effect of applying different absorption coefficients to be studied. Part two of the report consists of an extensive investigation into the prediction of reverberation time in multiple configurations of an experimental room with absorbent material partially covering the room surfaces. This determined the accuracy of reverberation time formulae and the computer models using both standard and Millington absorption coefficients under controlled conditions. The final part contributes a verification of the accuracy of the predictions using Millington absorption coefficients in a factory space with a barrier installed, and a refined diffraction model based on a ray-tracing model.

Keywords: Mathematical modelling; Sound fields; Enclosed spaces; Sound propagation; Reverberation time; Millington formula

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

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description of the space. The spatial characteristics are best described using sound level distribution 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. The three parts of this paper deal with both performance and work spaces, using three computer models based on three different mathematical approaches. Many computer models have been developed to predict sound propagation (SP) in work spaces [2–4], but little has been published concerning the prediction of reverberation time. The computer model RAYCUB-DIR REDIR [5] was designed to predict SP in workspaces and was extended for this investigation to predict RT, creating REDIR RT. This paper gives a brief historical review of how the prediction of reverberation time in enclosed spaces has progressed. An explanation as to why the Millington formula was shown to produce poor predictions is presented. A reverberation time validation of a recording studio using this information is included, together with a comparison with results using the Sabine and Eyring formulae. An outline of the basis of the three different computer models used in the investigation is presented together with a hypothetical investigation to demonstrate the accuracy of the reverberation time prediction of the models in the simplest possible room. Finally, the sound field in a performance room is simulated using the computer models and the classical formulae, with both reverberation time and sound propagation being predicted across a range of frequencies.

2. Historical review of reverberation time prediction

The prediction of reverberation time in enclosed spaces consists of four different approaches: classical theory; numerical solutions; empirical expressions; physical scale models and mathematical models.

2.1. Classical theory

The prediction of RT in enclosed spaces was first accomplished by Sabine [6] and a theoretical basis for this work was developed by Eyring [7] for diffuse spaces. For practical purposes it is generally assumed that the Eyring expression for RT is applicable if the average absorption coefficient is greater than 0.2. In diffuse rooms with less absorption, the Sabine RT formula is generally used. However, recent work by Hodgson [8,9], has shown that the application of the Sabine theory in certain types of room can lead to error, and that the Eyring formula gives a more accurate result. Millington [10] provided an immediate refinement to the Eyring formula whereby the proportionate size of the absorptive material is averaged geometrically rather than arithmetically, although Gomperts [11] in an extensive analysis of diffuse theory stated that either approach could be correct.

Arau-Puchades [12] developed the idea of Fitzroy [13] based on a theoretical approach to account for non-uniform distribution of absorption by determining the inhomogeneity of the sound field in three directions. The formula was validated in six configurations of the Mehta and Mulholland [14] experimental space, predicting to within 10% of the measured values.

2.2. Numerical solutions

Miles [15] derived a numerical solution for the steady state and transient sound field in empty enclosed rooms. It was shown that, given the same set of assumptions, the integral equation could be simplified to the classical formula. The integral equation also allowed for diffuse or Lambertian reflections without any assumptions concerning the diffuseness of the predicted sound field, thus the classical assumption of a diffuse reverberant sound field could be removed. In addition, it was possible to represent non-uniform distribution of absorption on the room surfaces. Three integral solutions were found: the steady state solution; the early decay numerical solution; and a solution for time-varying sources. A hypothetical investigation into the accuracy of the standard absorption coefficient in typical reverberation chambers with test samples of absorbent material was undertaken. When the test samples were positioned centrally on one of the room surfaces, covering 7.3% of the total room surface area, it was found that as the absorption coefficient increased the Sabine result diverged from the exact integral solution. For an acoustically hard test sample with an absorption coefficient of 0.01, the difference was only 1.0%; increasing the absorption coefficient to 0.2 resulted in a difference of 5.5%; the deviation rising linearly to 16.0% when the standard absorption coefficient was 1.0.

The prediction of the decay exponent, the denominator in the classical formula, which is constant for a diffuse sound field was first attempted by Gerlach and Mellert [16]. This would give an exact solution to the reverberation time in any room. Gilbert [17] proposed a refinement to the Gerlach and Mellert integration based on an iterative process to establish the path length of each reflection rather than using the average length. Kuttruff [18] simplified the iteration and hypothetically validated this method, and compared the results with those of Sabine and Eyring for empty rooms with different absorption distribution and aspect.

2.3. Empirical expressions

To try and predict reverberation time in rooms with a non-uniform distribution of absorbent material on room Fitzroy [13] combined three Eyring formulae, one for each pair of parallel surfaces, to account for the non-constant decay rate. The basis of this research was an intuitive idea and primarily results suggested the method was accurate.

In work spaces the sound field is usually non-diffuse, that is the sound level decreases with increasing distance from a sound source. For these types of space, which may be disproportionate, fitted, or have unevenly distributed room surface absorption, Friberg [19] developed an empirical expression for RT based on measurements in

139 factories. The empirical expression derived was capable of predicting RT at 1 kHz only, based on tabulated constants which varied with the height of the fittings and the shape of the factory. Hodgson [20] and Orlowski [21] independently validated the Friberg formulae: Hodgson used two spaces, a 1:50 scale model and a warehouse, both configured as empty and fitted; Orlowski used 15 fitted factories. Both concluded that there was a poor correlation between the measured and the predicted RT results.

Hirata [22] produced an image-source method based on calculating the density of the room nodes over a frequency band to predict the sound field in an enclosed space. However, for irregularly shaped spaces an approximate formula was introduced to predict the reverberation time in a tunnel section with and without acoustic treatment.

2.4. Physical scale models

Physical scale model measurements have been extensively used as research tools in the prediction of RT. Hodgson and Orlowski showed that RT in a 1:16 scale model of a real factory could be predicted with an accuracy of 10% across the third octave bands [23]. They further demonstrated that increasing the number of fittings reduced the RT, independent of frequency. Additionally, it was shown through measurements that varying the size and position of the fittings, which were either isotropically distributed or located on the floor, while maintaining the same overall surface area had no effect on the RT.

Hodgson showed, using a scale model, that in a non-diffuse sound field the Sabine formula still produced reasonably accurate predictions and hence that diffuse absorption coefficients were relevant to non-diffuse spaces [24]. Orlowski [25] continued 1:16 scale modelling by predicting RT in more complex spaces with barriers and suspended absorbers present; the measurements were within 10% of the full scale measured values.

2.5. Mathematical models

Four types of computer model have been developed to predict RT in work spaces: the image-source method [2]; the ray-tracing technique [4]; beam-tracing [26] and sound particle tracing [27] models.

All the methods have been used primarily in work spaces to predict SP but there is significantly less published work on RT prediction. The Schroeder reverse integration of the impulse response is used in all types of model to generate the energy decay curve, which can be used to approximate RT and other room acoustic parameters [28].

Mehta and Mulholland [14] produced the first computer model to be able to predict reverberation time based on only geometrical considerations using a ray- tracing approach. Significant disagreements were found when the model was validated using fifteen configurations of an experimental room for the 1 kHz one-third octave band. These disagreements were reduced when the model was modified to approximate the scattering of sound from the edges and corners of the room, the sound being scattered according to the Eyring formula if it strikes a surface within half a wavelength of an edge. This modification worked in all cases when at least one entire surface was covered with absorptive material, but not when a surface was only partially covered with absorbent.

Hodgson produced an image–source model, which could represent a parallelepiped space with isotropically distributed fittings [29]. In an empty cubic scale model the image–source model produced a similar RT to that predicted by the Eyring formula. In a disproportionate empty scale model both the Eyring formula and the image–source model produced inaccurate predictions, except for the early sound decay.

Hammad developed an image–source model, which could represent empty parallelepiped spaces with sloping floor or ceiling [30]. In a preliminary analysis of RT predictions in a flat square room, 14×14×5 m, with an average absorption coefficient of 0.2, the image-source model produced results which varied with the prediction position. It was found that in the middle of the room the predicted RT was 1.65 s compared to 1.95 s in the corners. The Sabine formula gave the RT as 1.2 s and the Eyring formula 1.05 s. This would indicate that the room was non-diffuse due to a disproportionate geometry.

Hodgson used an extended version of the ray-tracing model of Ondet and Barbry [4] to represent two empty scale models and two empty spaces [31]. The model generally predicted too high a RT, the error becoming greater the more disproportionate the room, assuming standard absorption coefficients and specular reflecting surfaces. Diffusion was then introduced into the model, assuming a diffusion coefficient for each surface of 25%; this produced good agreement between the measured and predicted RT, with an error of 5%.

Vermeir developed a ray-tracing model for the prediction of RT, so that on-site analysis could be used for cost benefit calculations of various acoustic treatments [32]. The predictions were optimised by varying the modelling parameters until a minimum error was produced. The space used for the measurements and predictions was a large complex factory approximately 30000 m^3 in volume, configured both with and without machines. The 1 kHz predictions were reasonably accurate, with an error of 3% in the empty case and 21% with the machines installed; overall, for the third octave bands the errors were 37 and 44% for the empty and fitted cases, respectively. This indicates that modelling RT across a range of frequencies is very difficult and modelling a fitted room is more difficult than an empty room, as would be expected.

3. The Millington formula

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 [12]. 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 a conversion graph has been created, as described below, so that Millington absorption coefficients can be simply found from the standard absorption coefficients.

As the information required by both the Sabine and Millington formulae is identical, but precise details are lacking and hence certain assumptions were necessary in order to create the conversion graph. The assumptions were based on those of Miles [15] 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 $6.0 \times 5.0 \times 4.0$ m with a uniform distribution of absorbent material, the absorption coefficient was assumed to be 0.04.

The conversion graph, shown in Fig. 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. A recording studio has therefore been used, as described below. Subsequently, three computer models were investigated, using both standard and Millington absorption coefficients for the absorbent material, for a concert hall, as described in Section 6.2.

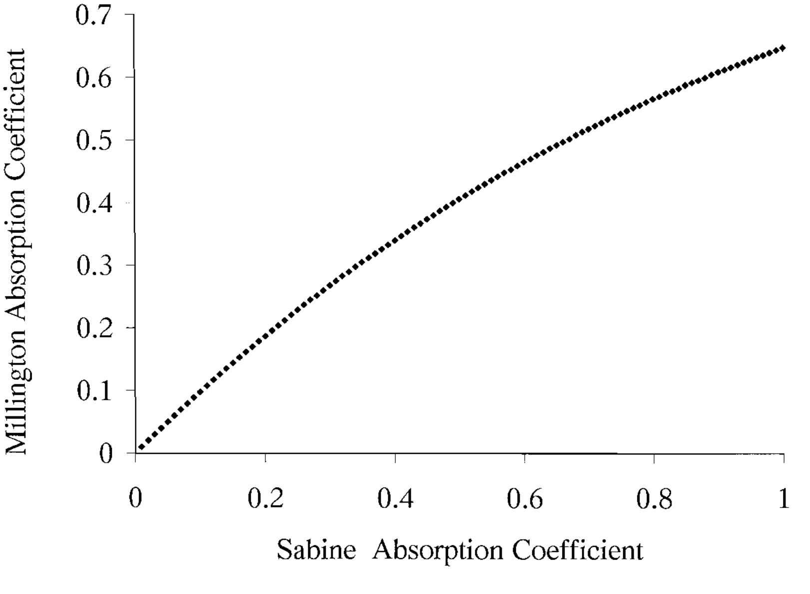

Fig. 1. The standard to Millington absorption coefficient conversion graph.

4. Recording studio predictions

A recording studio was used to test case for the accuracy of the Millington RT formula using Millington absorption coefficients. 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 Fig. 2). In one wall was a triple glazed window 2.0 m×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 Fig. 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.

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 Fig. 1.

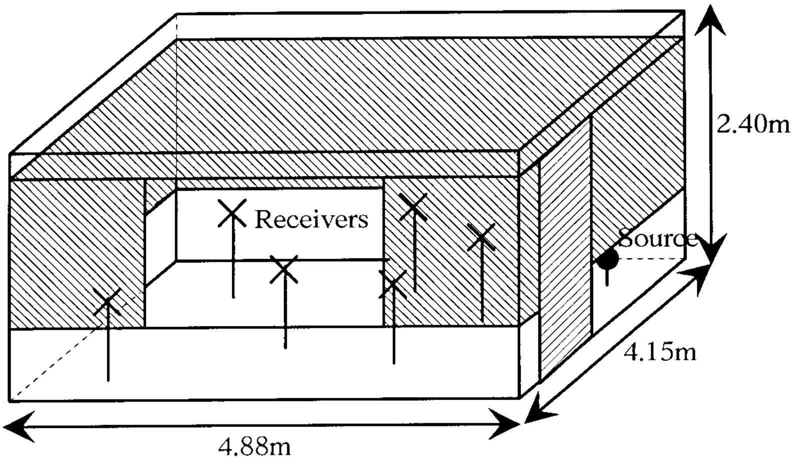

Fig. 2. The recording studio showing the source and receiver positions and the different room surfaces (hatching).

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 are 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. The computer models

The computer models were used to predict the reverberation time in a hypothetical reverberation chamber; sound propagation and reverberation time in a concert hall; six configurations of an experimental room; a factory space containing a barrier. The latter two spaces are discussed in parts II and III of this report. Each room was predicted using both standard absorption coefficients and Millington absorption coefficients. The prediction models use three different mathematical approaches, all of which are based on geometric acoustic assumptions [11]. The models used were REDIR RT, CISM and RAMSETE.

5.1. The REDIR RT model

REDIR RT is a ray-tracing model, which has extended the representational ability of the Ondet and Barbry model RAYCUB [4] to include sound source directivity and barrier diffraction [5]. REDIR RT was further developed to predict the sound field more completely by simultaneously predicting the sound propagation, reverberation time, early decay time and the clarity index using a single set of data for each octave band. To achieve this the entire energy decay curve was predicted by

Table 1
Standard absorption coefficients for the absorptive material in the recording studio, 125 Hz to 4 kHz

	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 2
Measured and predicted reverberation times (sec) in the recording studio, 125 Hz to 4 kHz

	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

geometric acoustics using a 90% energy discontinuity [33]. The energy decay curve was predicted from a discretised energy response, using intervals of 0.0029 s, and reverse integrated according to Schroeder [28]. An analysis was performed using a least squares regression based on a T_{20} decay. The reflection order, n, was calculated from the energy discontinuity percentage as given below

$$n = \frac{\ln\left(1 - \frac{P}{100}\right)}{\ln(1 - \alpha_{av}) - hl} \tag{1}$$

where P is the energy discontinuity percentage, α_{av} is the average absorption coefficient of the surfaces and fittings, h is the air attenuation coefficient (dB/m) and l is the mean free path length.

Each individual ray is traced until the number of reflections, from the room surfaces, barriers or statistically scattering fittings, is equal to the reflection order. REDIR RT calculates the acoustic parameters SPL, RT, EDT and C80 each octave band separately. The execution time of the model is short at approximately 10 s for the concert hall on a Pentium Pro personal computer for each frequency investigated.

5.2. The CISM model

CISM [34] is based on the image–source method [35] 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. The sound path is attenuated by air and room surface absorption. The geometry of the space must be parallelepiped with absorptive patches being modelled as rectangles on any of the six room surfaces. Barriers are modelled as rectangular planes, which must be parallel to a room surface and totally sound absorbing. Sound sources are points as are receivers. An energy discontinuity of 99% provides accurate reverberation time predictions as the entire decay curve is directly predicted without the need for a linear regression analysis. CISM models each octave band individually. The run-time for the concert hall was of the order of a few seconds using a personal computer for each frequency of interest.

5.3. The RAMSETE model

RAMSETE is a commercial software package developed by Farina [36]. 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 eight octets, each of which can be further subdivided. The receiver is also a point either inside or outside the room, which is encompassed by the pyramid. Planes are used to define a room, each plane has an associated absorption coefficient for the ten octave bands 31 Hz to 16 kHz and hence the model is only run once for all frequencies. The contribution to the receivers from individual sound sources can be established using the energy response, which is stored for each source–receiver combination. Diffraction can be modelled based on Fresnal theory using the Kurze–Anderson formula for either single or double diffracted beams for any type of edge.

The precision of the representation is user-defined, the recommended setting have been found to predict poorly [37] and hence the same settings as were used for REDIR RT were used for RAMSETE. The model was also capable of modelling three-dimensional directivity using directivity factors at 10° intervals, although this was not used, as it was thought to be impractical due to the 1296 directivity factors involved. The run-times of RAMSETE were of the order of 1 h on a personal computer for the concert hall, including all frequencies of interest.

6. 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. Once the models had been shown to give similar results to those of the Eyring formula the temporal and spatial acoustic characteristics of a concert hall were predicted using all three models using both sets of absorption coefficients.

6.1. Hypothetical reverberation chamber predictions

If a model is to be developed for any type of enclosed space it should first be tested in the simplest possible space, hence REDIR RT, CISM and RAMSETE were used to predict the RT in a hypothetical reverberation chamber, for comparison with the predictions of the Eyring formula. 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%.

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: $\alpha = 0.05$, $\alpha = 0.10$, $\alpha = 0.2$. An energy discontinuity of 99% was necessary due to the size of the room and the hardness of the room surfaces. 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 (see Fig. 3), with the receiver in the farthest corner from the source. As the space is hypothetical, and the model is based on geometric acoustics the frequency at which the prediction were made is irrelevant.

Table 3 shows the RT values predicted by the REDIR RT, CISM and RAMSETE models together with those given by the Eyring formula, the Millington formula gave identical results as the room surfaces are defined as having uniform surface

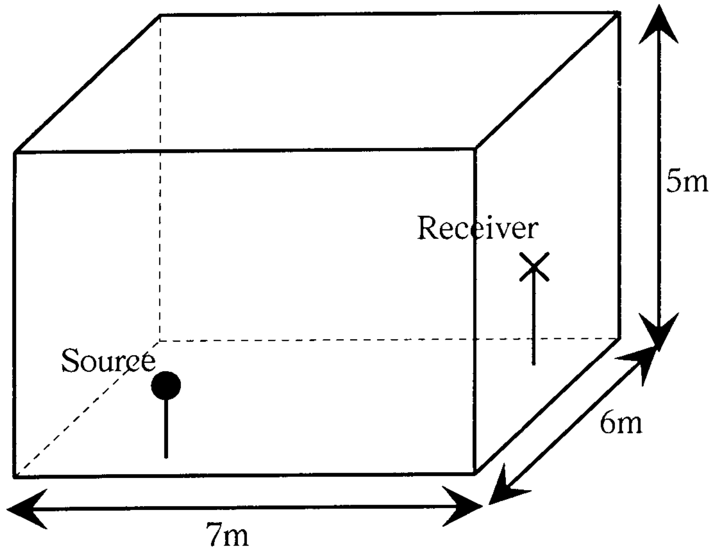

Fig. 3. The hypothetical reverberation chamber showing the source and receiver positions.

Table 3
REDIR RT, CISM, RAMSETE and Eyring RT predictions (s), in a hypothetical reverberation chamber with increasing absorption

	$\alpha=0.05$	$\alpha=0.1$	$\alpha=0.2$
Eyring	2.86	1.45	0.70
REDIR RT	2.86	1.37	0.66
CISM	3.10	1.56	0.79
RAMSETE	2.43	1.18	0.63

absorption. 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 REDIR RT and Eyring. CISM predicted reverberation times 8.4% longer than the Eyring prediction, well within the prescribed limits of accurate prediction; RAMSETE produced a 15% under-prediction. For $\alpha = 0.1$ the difference compared with the Eyring formula for REDIR RT was 0.08 s, for CISM 0.11 s and RAMSETE 0.27 s, 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 $\alpha = 0.2$ produced predictions by all models within 14% of the Eyring prediction, the difference was 5.7% for REDIR, 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 REDIR RT, CISM and RAMSETE, respectively. This is similar to those recorded by Hodgson [24], and thus that they may be of practical use in more realistic spaces.

6.2. The concert hall

The concert hall, shown in Fig. 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 Fig. 4).

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 RT and SPL were made for the 125 Hz to 4 kHz octave bands at a height of 1.25 m (see Fig. 4).

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 using energy discontinuities of 99 and 90% for CISM and REDIR RT, respectively. These gave reflection orders of 28, 35, 36, 39, 36 and 30 for CISM using the Millington absorption coefficients, slightly less than those using the standard coefficients. The REDIR RT and RAMSETE reflection orders were exactly half those for the CISM model.

The reverberation time predictions for the classical formulae and the computer models are discussed separately, with the later discussion being further subdivided

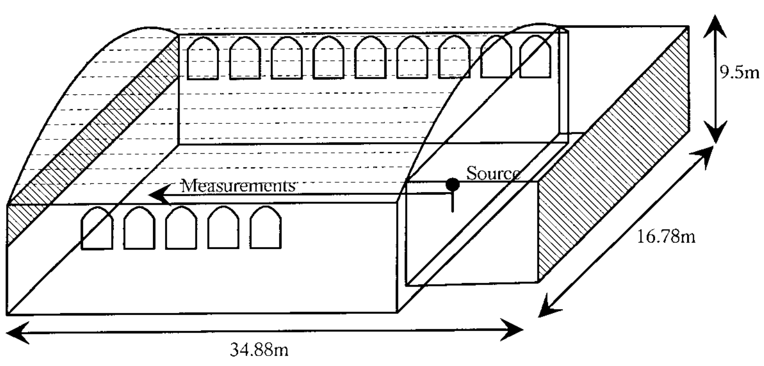

Fig. 4. An illustration of the concert hall with the source and measurement positions.

into Sabine and Millington based predictions. The sound propagation predictions for the computer models are discussed together.

6.3. Reverberation time results

Table 4 shows the average measured RT for each octave band and the formula predictions using the corresponding absorption coefficients. The Sabine and Eyring formulae using the standard absorption coefficients and the Millington formula taking the Millington absorption coefficients.

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 RT by between 0.2 and 1.0 s. 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 RT for each of the models using the standard and Millington absorption coefficients, respectively.

Table 4
Measured and predicted RT (s) in the concert hall, 125 Hz to 4 kHz

	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 5
Measured and predicted RT (s) in the concert hall using standard absorption coefficients, 125 Hz to 4 kHz

	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
REDIR RT	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 RT (s) in the concert hall using Millington absorption coefficients, 125 Hz to 4 kHz

	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
REDIR RT	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

Table 7
Average predicted SPL errors (dB) in the concert hall, 125 Hz to 4 kHz

Absorption	Model	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	Average
	REDIR RT	2.8	2.1	1.8	0.5	1.7	2.6	1.9
Standard	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
	REDIR RT	2.5	1.9	1.5	0.5	1.8	2.8	1.8
Millington	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

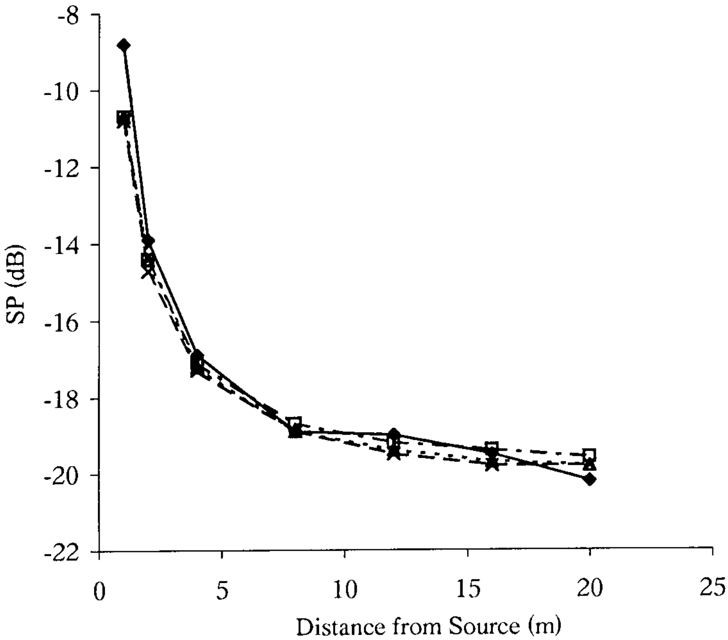

Fig. 5. The measured (—) and REDIR (- - -), CISM (· · ·), RAMSETE (-•-) predicted sound propagation using standard absorption coefficients, in the concert hall for the 1 kHz octave band.

Comparison of Tables 5 and 6 show 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 REDIR RT, CISM and RAMSETE, respectively.

Table 6 shows that using Millington absorption coefficients increased the average prediction accuracy of REDIR RT 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 REDIR RT, 11.7% for CISM and 11.0% for RAMSETE.

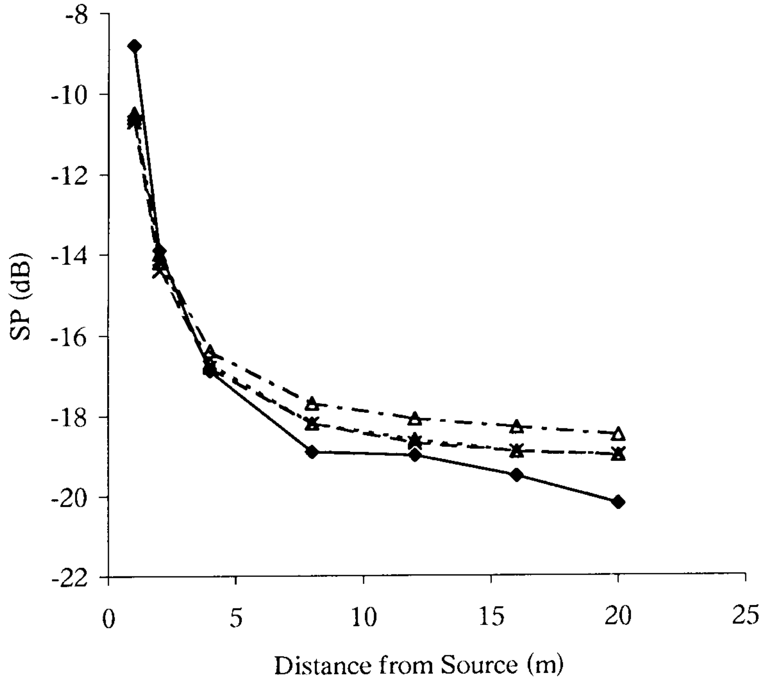

Fig. 6. The measured (—) and REDIR (- - -), CISM (· · ·), RAMSETE (-•-) predicted sound propagation using Millington absorption coefficients, in the concert hall for the 1 kHz octave band.

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 to be derived for each of the six octave bands. Only the SP curve for the 1 kHz octave band is presented, along with the summary of the predictions for all six octave bands.

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.

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 REDIR RT and CISM models produced similar predictions, giving a 1.8 dB average prediction error overall. RAMSETE was approximately 0.4 dB worse giving results which were on average 2.2 dB in error.

Fig. 5 shows the 1 kHz measured and predicted sound propagation curves using the standard absorption coefficients. It can be clearly seen that in the reverberant sound field, beyond 8 m 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 Fig. 6 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. Summary

The prediction accuracy of both classical formulae and computer models for the prediction of reverberation time has been investigated in two real spaces, a recording studio and a concert hall. 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.

Three computer models were tested for their suitability to the prediction of reverberation time a simple hypothetical space was designed. As the room was designed to be diffuse the Eyring formula was assumed to be accurate, and it was found that all models were within 14% on average of value calculated by the Eyring formula. In a concert hall sound propagation and reverberation time were simultaneously predicted twice, once using standard absorption coefficients and once using Millington based absorption coefficients. It was found that on average across six octave bands that REDIR RT and CISM models were improved by 7% and RAMSETE by 3% when Millington rather than standard based absorption coefficients were used. When predicting sound propagation in the concert hall all of the models were similarly accurate, within 0.5 dB on average, and thus it appears that temporal acoustic parameters are more difficult to predict than spatial acoustic parameters. There was no significant difference in sound level prediction accuracy when using standard or Millington absorption coefficients in any of the computer models.

Further research has been undertaken to determine the validity of the use of Millington absorption coefficients for highly absorbent material in computer models, especially in reverberant rooms. Hence the second part of this investigation reports on the predictions in a test room with at least one surface covered in absorption [38]. In addition it presents the results when only absorptive patches were mounted on the room surfaces. The third part describes the results obtained when predicting the insertion loss of an acoustic barrier in a factory space [39]. Also included are the results of a more refined model for approximating diffraction effects.

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