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Modelling of sound fields in enclosed spaces with absorbent room surfaces
Part II. Absorptive panels

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Abstract

This is the second part of a report on the modelling of sound fields in enclosed spaces with absorbent room surfaces. Both Sabine and Millington absorption coefficients are used to further investigate which approach produces the most accurate predictions. Classical formulae and geometric acoustic models, previously detailed, were used to predict the reverberation time in a test room with highly absorbent room surfaces. In addition the test room was configured with a partially absorptive surface. This configuration has previously only been predicted inaccurately. It was shown that the Millington formula predicted more accurately than either the Sabine or the Eyring formulae in the configurations of the room investigated. Verification of the previous results were confirmed when two of the computer models gave consistently more accurate predictions using Millington absorption coefficients than Sabine absorption coefficients. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

In the first part of this report on the influence of absorption coefficients in mathematical models of enclosed spaces [1], it was seen that the Eyring reverberation time formula produced inaccurate predictions when absorbent material was unevenly distributed around the room surfaces. It was shown that the REDIR RT [2], RAMSETE [3] and CISM [4] mathematical models could simultaneously predict sound levels and reverberation time under these conditions. All three models were considered accurate for both spatial and temporal acoustic parameters. The use of

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Millington absorption coefficients in the models gave more accurate predictions than the use of standard absorption coefficients.

In this paper, prediction of reverberation time in spaces with highly absorbent material, such as might be sold for noise control purposes, for example acoustic tiles or acoustic baffles, is specifically investigated. The reason for examining the effects of extreme values of absorption coefficient is that these most commonly give inaccurate results. An extensive investigation into predicting the reverberation time in a room fitted with absorptive material on the room surfaces was undertaken by Mehta and Mulholland [5]. This room was subsequently used by Arau-Puchades [6] in his determination of an improved reverberation time formula specifically for uneven distribution of absorbent material. In both cases it was concluded that the Eyring formula [7] was inaccurate under these conditions.

Seven configurations of this same room were used in the research described here. The models predicting the reverberation time using standard absorption coefficients, that is absorption coefficients taken from standard texts based on international standard measurements, and absorption coefficients derived from the Millington reverberation formula. In addition to determining the accuracy of each approach it was possible to establish which of the two absorption coefficients gave the most consistently accurate results.

The seven room configurations measured by Mehta and Mulholland have been used for predictions by three computer models and various reverberation time formulae, so that the accuracy of each approach could be determined. All methods used the two types of absorption coefficients described previously [1], the standard and those derived from the Millington RT formula [8]. It has previously been stated that it could be said that the mathematical basis of both the Eyring and the Millington RT formula is correct [9].

The computer models used for the predictions were REDIR RT [2], RAMSETE [3] and CISM [4]. All three models are based on geometric acoustics assumptions although their individual implementation is different, in that the technique used are ray-tracing, beam-tracing using pyramids and method of images, respectively. For completeness the following formulae were used to predict RT: Arau-Puchades, Eyring, Sabine and Millington, with only the Millington formula using Millington absorption coefficients. The Arau-Puchades results have been included for comparison only. His work was based on the directional sound decay for the initial, intermediate and final reverberation decay in a room. Assuming a non-uniform dispersion of absorption the initial slope the rate of decay is described by,

$$D_i = \bar{D}d \tag{1}$$

where $\bar{D}$ is the mean decay rate and d is the dispersion factor, as given below

$$d = \text{antilog}\sqrt{\frac{x}{S}(\lg \bar{a}_x)^2 + \frac{y}{S}(\lg \bar{a}_y)^2 + \frac{z}{S}(\lg \bar{a}_z)^2 - \left[\frac{x}{S}\lg \bar{a}_x + \frac{y}{S}\lg \bar{a}_y + \frac{z}{S}\lg \bar{a}_z\right]^2} \tag{2}$$

where x, y and z are the surface area for one particular orientation, S is the total surface area of the room,

$$\begin{aligned}\bar{a}_x &= -\ln(1-\bar{a}_x)\\ \bar{a}_y &= -\ln(1-\bar{a}_y)\\ \bar{a}_z &= -\ln(1-\bar{a}_z)\end{aligned} \tag{3}$$

where $\bar{a}_x$ is the average absorption coefficient of the surfaces in the x plane, and so on.

The intermediate slope, $\bar{D}$ the mean decay is given by $60/T$,

$$T = \frac{0.16V}{S\bar{a}_x^{-x/S}\bar{a}_y^{-y/S}\bar{a}_z^{-z/S}} \tag{4}$$

where V is the volume of the room

The final slope, D_f is given by

$$D_\mathrm{f} = \frac{\bar{D}}{\mathrm{d}} \tag{5}$$

It should be noted that for this work the definition of an accurate prediction in terms of RT is considered to be a prediction within 14% of the measured value. This is based on the relative difference between Sabine and Eyring predicted reverberation times when an absorption coefficient of 0.2 is used. This is similar to Hodgson's suggestion of an engineering accuracy of 2 dB for sound levels and 10% for reverberation time [10].

2. Millington absorption coefficients

The Millington reverberation time formula is very similar to that of Eyring, except that each individual surface is considered, in terms of surface area and absorption coefficient, rather than simply taking the average value. The formula for reverberation time, T, is

$$T = \frac{0.161V}{-\sum_i S_i(1-\alpha_i)} \tag{6}$$

where V is the room volume, S_i is the room surface area for each individual surface and α is the absorption coefficient for the associated room surface.

To enable the Millington formula to be used correctly a conversion graph has been created, see Fig. 1, so that Millington absorption coefficients can be simply found from the standard absorption coefficients.

3. The test room configurations

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 [11].

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. The other five configurations, Cases 1–5, are listed below:

- Case 1: absorption on the long walls.
- Case 2: absorption on one long wall.
- Case 3: absorption on the floor and the two short walls.
- Case 4: absorption on the floor and on one short wall.
- Case 5: absorption on three mutually perpendicular surfaces.

These five configurations are illustrated in Fig. 2. In addition to these five cases, two further cases which could not be predicted by Arau-Puchades were predicted.

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

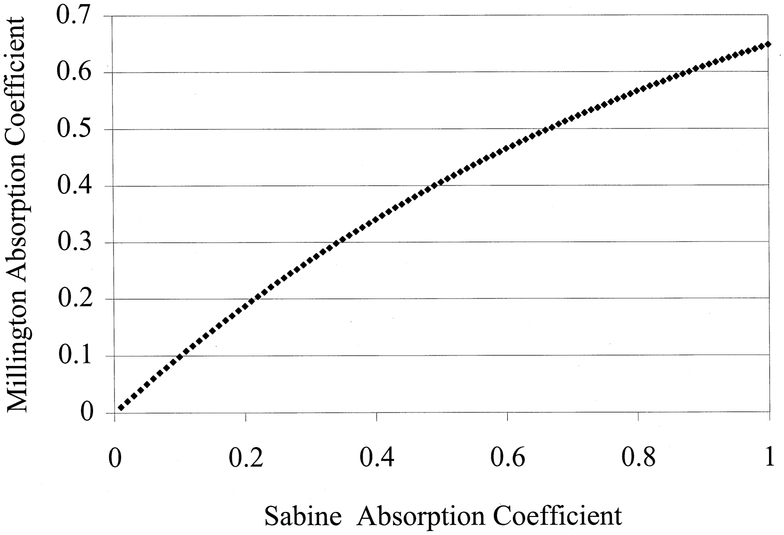

Fig. 1. The Sabine to Millington absorption coefficient conversion graph.

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.

4. Formulae based predictions

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

4.1. Case 0: empty configuration

All four 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.

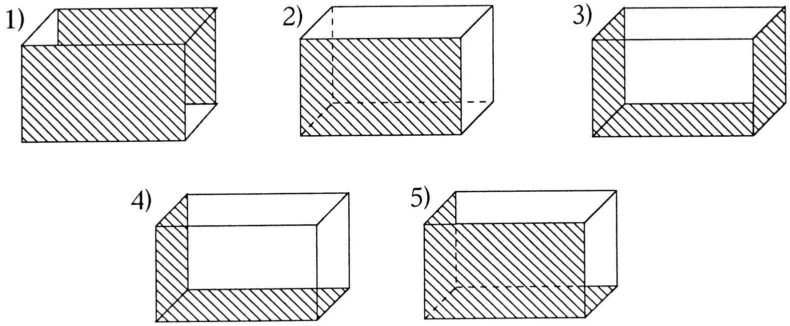

Fig. 2. The five configurations of the Mehta and Muiholland experimental room with absorptive material on the room surfaces.

Table 1
The measured and predicted reverberation times (s) 1 kHz

Case	Measured	Arau-Puchades	Eyring	Sabine	Millington
0	2.20	2.07	2.18	2.23	2.18
1	0.52	0.51	0.20	0.24	0.23
2	0.71	0.79	0.39	0.43	0.41
3	0.29	0.28	0.16	0.21	0.20
4	0.40	0.37	0.23	0.27	0.26
5	0.17	0.14	0.14	0.18	0.17

4.2. Case 1: absorption on 2 long walls

With absorption panels on the two longest walls the Arau-Puchades formula is significantly more accurate than any of the classical formulae which 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.

4.3. Case 2: absorption on a long wall

With absorption on just one long wall the reverberation time was 0.19 s longer than in Case 1, when both long walls were absorptive. This difference was accurately predicted by the three classical formulae. However, only the Arau-Puchades formula was accurate in absolute terms.

4.4. 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 s, which was accurately predicted by Arau-Puchades and under that predicted by the classical formulae by approximately 0.1 s. This again demonstrates the limitations of the classical approach to RT prediction when the sound field is less diffuse.

4.5. 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, whereas the Arau-Puchades formula predicted accurately. The predicted differences between the reverberation times in Cases 4 and 3 were consistent for all the classical formulae at 0.06 s, compared to the measured difference of 0.11 s. The prediction error was approximately 35% for all the classical formulae.

4.6. Case 5: absorption on 3 adjacent room surfaces

When three adjacent surfaces were covered in absorptive material the Arau-Puchades produced the least accurate prediction, a 17.6% error, although as the measured reverberation time was so small the error becomes marginal. The Millington formula was the most accurate, predicting the reverberation time exactly.

Overall, ignoring the empty configuration of the room, the Arau-Puchades formula gave a 8.3% prediction error, and was significantly more accurate than any of the classical methods which produced 42.3, 31.8 and 32.9% average errors for the Eyring, Sabine and Millington formulae, respectively. 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.

5. Computer model predictions

The computer models used in the following predictions are described in Part I of this paper.

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

5.1. Case 0: empty configuration

Prediction of all three computer models were consistent with those for the hypothetical space used in Part I of this investigation [1]. REDIR RT 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 RT was the same for both sets of absorption coefficients for each model.

5.2. 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; REDIR RT 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.

5.3. 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 s. Only RAMSETE predicted this increase accurately, 0.20 s, using both the standard and Millington based absorption coefficients. REDIR RT and CISM both predicted a greater difference

Table 2
Measured and predicted reverberation times (s) using both standard and Millington absorption coefficients, 1 kHz

		RAMSETE		CISM		REDIR RT	
Case	Meas.	Standard	Millington	Standard	Millington	Standard	Millington
0	2.20	1.38	1.38	2.24	2.24	2.13	2.13
1	0.52	0.32	0.44	0.34	0.50	0.29	0.47
2	0.71	0.52	0.64	0.58	0.77	0.58	0.73
3	0.25	0.18	0.27	0.18	0.28	0.19	0.29
4	0.40	0.24	0.35	0.24	0.37	0.26	0.39
5	0.17	0.09	0.18	0.10	0.20	0.11	0.20

ranging from 0.24 to 0.29 s. 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 REDIR RT using the Millington based absorption coefficients, with an average error of 2.8%.

5.4. 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.

5.5. 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 REDIR RT using the Millington absorption coefficients, which gave an error of 2.5%.

5.6. 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 REDIR RT 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.

Considering the classical formulae for the prediction of reverberation time, as discussed in Section 4, it can be seen that the Millington formula is at least as accurate as the other classical formulae, although the accuracy was inconsistent. Of all methods, the results using the Arau-Puchades formula were marginally the most accurate, with 8.3% error compared to 9.7% error for the most accurate computer model. However, the Arau-Puchades method was not applied to certain configurations of the space, which Mehta and Mulholland's original computer model could not predict accurately. In the next section the application of the three computer models to two cases, which the Mehta and Mulholland model was unable to predict accurately is described.

6. Configurations with partial absorbent

There were two configurations of the room which were not accurately predicted by Mehta and Mulholland and were not mentioned by Arau-Puchades. These cases formed an appropriate test for the three computer models REDIR RT, CISM and RAMSETE using the Millington absorption coefficients. Both involved arrangements of panels of absorptive material 1.25 by 0.90 m in size, rather than having entire room surfaces covered with absorbent. In order to maintain a reasonable reflection order it was necessary to reduce the energy discontinuity percentage from 99 to 90% for the CISM model. Otherwise the representation of the space was as before. The two cases are referred to here as Cases 6 and 7 whereas Mehta and Mulholland referred to them as Cases 2 and 5, respectively.

6.1. Case 6: single panel on the floor

In this case a single panel of absorptive material was positioned at various locations on the floor and walls of the room. Mehta and Mulholland found that the measured reverberation time, 1.20 s, did not vary with the location of the sample of absorptive material, whereas their model predictions did vary, giving on average a RT of 1.50 s. As Mehta and Mulholland do not state exactly where the sample was positioned or where the sound source was located, for this investigation it was decided to use two sound source positions, nine panel positions and eight receiver locations, as shown in Fig. 3. This gave 144 prediction positions in total. The average of which was taken to be the reverberation time of the room. The reverberation time was predicted using the classical formulae. The computer models predicted early decay time, the room being two small and reflective for the computer models to accurately predict reverberation time itself.

The Millington formula using the Millington absorption coefficient gave a reverberation time of 1.41 s compared to 1.46 s for the Eyring formula using the standard absorption coefficients. This demonstrates that there is a limit to the application of

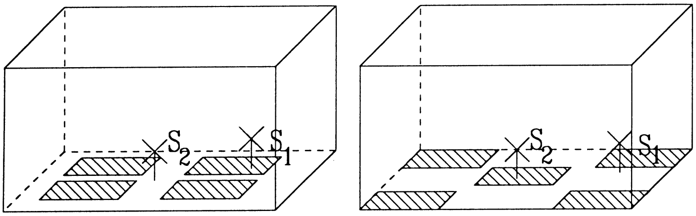

Fig. 3. The Mehta and Mulholland experimental room showing the nine locations where the absorptive sample was positioned and the two sound source positions, S.

the classical formulae, as the predictions were outside the defined accuracy limits, with 17.5 and 21.7% errors for the Millington and Eyring formulae, respectively.

Table 3 shows the predicted early decay times with standard deviations for the three computer models using standard and Millington absorption coefficients.

From Table 3 it can be clearly seen that none of the computer models produced a significant variation in the predicted early decay times across the 144 different source-receiver-panel combinations. Thus in this respect these predictions agree with the measurements of the room.

The REDIR RT model predicted the reverberation time with the smallest average error, 1.2% when a Millington based absorption coefficient was used, compared to 8.6% using the standard absorption coefficient. Similar results were predicted by CISM, with average errors of 2.7 and 5.3% for the Millington and standard absorption coefficients, respectively. RAMSETE, as previously, under-predicted the early decay time in this highly reverberant room, giving an average error of 10.0 and 16.7% for the Millington and standard absorption coefficient predictions.

In this case of a single absorptive panel partially covering the floor, the use of a Millington absorption coefficient produced only a marginal improvement in prediction accuracy, as the absorptive panel covered under 2.0% of the total surface area of the room. The improvement in prediction accuracy using Millington absorption coefficients was on average 5.7% for the three computer models, compared with the results using standard absorption coefficients.

6.2. Case 7: one panel per wall and floor

In this case five absorptive panels were placed on the room surfaces, one on each wall and one on the floor. The reverberation time measured by Mehta and Mulholland was 0.60 s. Again, no precise details were disclosed by Mehta and Mulholland, so the same procedure was used as before, for the source and receiver locations, but the samples were assumed to be all centrally located on their respective room surfaces. The predicted reverberation times are thus the average of the eight predictions. There was no variation in measurements mentioned by Mehta and Mulholland, hence no standard deviation data is presented for the predictions.

The Millington formula predicted a RT of 0.67 s, whereas the Eyring formula predicted a 0.65 s reverberation time. Each of the formulae can be considered to be accurate, Millington giving an error of 11.7% compared to 8.3% for Eyring.

Table 4 shows the predicted early decay times for the three computer models using standard and Millington absorption coefficients.

Table 3
Case 6: one absorptive panel. Predicted early decay times (s) and standard deviations (s), 1kHz

	REDIR RT		CISM		RAMSETE	
	Standard	Millington	Standard	Millington	Standard	Millington
Average EDT	1.096	1.186	1.168	1.263	1.00	1.08
Standard deviation	0.007	0.023	0.009	0.014	0.010	0.011

Table 4
Case 7: five absorptive panels. Predicted early decay time (s) 1 kHz

	REDIR RT		CISM		RAMSETE	
	Standard	Millington	Standard	Millington	Standard	Millington
Average EDT	0.53	0.60	0.51	0.65	0.46	0.51

As for the previous results the REDIR RT model predicted the reverberation time with the smallest average error, 0.0%, when a Millington based absorption coefficient was used compared to 11.7% using the standard absorption coefficient. Similar results were predicted by CISM, with 8.3 and 15.0% average errors for the Millington and standard absorption coefficients, respectively. RAMSETE as before under-predicted the early decay time in this highly reverberant room, giving average errors of 15.0 and 23.3% for the Millington and standard absorption coefficient predictions, respectively.

In this case with five absorptive panels the use of a Millington absorption coefficient produced a slightly greater improvement in prediction accuracy than in Case 6, which just had one panel. In Case 7 the area of the absorptive panels represented 9.5% of the total surface area of the room. The improvement in prediction accuracy when using Millington absorption coefficients over standard absorption coefficients was on average 8.9% for the three computer models.

7. Conclusions

An extensive investigation into the accuracy of reverberation time predictions in a room configured with an uneven distribution of absorptive surfaces has been carried out. Predictions have been made using different formulae and computer models, and in each case both standard and Millington based absorption coefficients have been used.

The Eyring and Millington classical formulae were unable to predict accurately the reverberation times in the room, in any of the five absorptive surface cases investigated. When the room was reconfigured with small individual absorptive panels the prediction accuracy of the Eyring and Millington formulae improved, the difference between them being minimal due to the small surface area of the absorptive panels. Although neither formulae was accurate in this space the Millington formula was at least as accurate as the Eyring formula, and approximately 10% more accurate when there was a significant amount of absorbent material.

Using three computer models to predict early decay time in the cases where entire room surfaces were covered in absorptive material the average error accuracy of the predictions using standard absorption coefficients was approximately 33%, reducing to 10% when Millington absorption coefficients were used. In the two configurations of the room with individual absorptive panels the predictions from the three computer models using Millington absorption coefficients were approximately 6% more accurate than those using standard based absorption coefficients.

REDIR RT was the most accurate model, followed by CISM and RAMSETE, although all three could be considered accurate at predicting the reverberation time in the room when Millington absorption coefficients are used. As has been previously determined the RAMSETE model has been found to significantly under-predict the reverberation time in highly reverberant rooms.

It is necessary to further validate the idea that using Millington absorption coefficients, for highly absorbent material, provides significantly more accurate predictions than applying standard absorption coefficients based on industrial measurements. Part III of this investigation compares the use of the two types of absorption coefficients in the modelling of noise control, using an acoustic barrier to reduce sound levels [11]. The modelling of diffraction is also fully investigated.

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