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Reverberation times in school halls: measurement oddities and modelling

Daniel Wallace

Apex Acoustics, Gateshead, UK

Jack Harvie-Clark

Apex Acoustics, Gateshead, UK

Summary

Rooms in which the majority of the absorption is on one surface - typically the ceiling - are common in school assembly and sports halls. These room types can exhibit reverberation time characteristics that vary with measurement technique and are difficult to predict due to non-linear decays. ISO 3382-2 does not have directionality constraints for sound sources used to measure the reverberation time in ordinary rooms to an engineering level of accuracy. This paper explores the effect of using a directional cabinet speaker for reverberation time measurements in halls. The modelling of reverberation time in these rooms is also investigated using CATT-Acoustic software, and some of the difficulties arising during the modelling are discussed.

Significant differences are measured between a cabinet loud speaker used in one orientation only and an omni-directional sound source. Measurements made with a cabinet speaker pointing both horizontally and vertically more accurately represent the results obtained with an omni-directional loudspeaker.

A method for determining the potential level of uncertainty in modelled reverberation time predictions is discussed.

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1. Introduction

The problem of accurately predicting reverberation times in empty school halls is well known, and has even lead to proposals to change the assessment criterion for these spaces [1] to avoid measuring this property. Rooms in which the majority of the absorption is on one surface - typically the ceiling or soffit - are common in schools, as classrooms and halls. These room types exhibit reverberation time characteristics that can vary with measurement technique and be difficult to predict.

1.1 Background

The National Physical Laboratory commissioned a study into standards for architectural and building acoustics in October 2000. [2] As part of this study, participants were required to take a number of reverberation time measurements in a large recording studio, and to note the variation in T_{20} when different aspects of the measurement procedure were changed. One participant examined the effect of using directional sources. The studio was fitted out with absorbent wall panels and diffusion from seating, measurement equipment and lighting trusses. The effect of the orientation of directional sources was briefly explored.

1.2 Interpretation of acoustic response

In spaces such as school halls where the majority of absorption is concentrated on one plane, the decaying sound field may be non-diffuse. In such spaces, the sound field can be described in terms of the grazing and non-grazing components [3]. The grazing components have no significant component in the vertical direction – the angle chosen as the limit for grazing modes effectively defines the proportion of modes in each set. From this model, the energy can be considered as travelling parallel to the ceiling, grazing the surface, or normal to the ceiling in the non-grazing set.

A sound source that has strongly directional characteristics, such as a cabinet loud speaker, may excite the grazing or non-grazing sound field with more or less energy depending on its orientation. When using the interrupted source measurement technique for reverberation time, the balance between the energy in the grazing and non-grazing sound fields may affect the reverberation time measured. The effect of source orientation on reverberation time,T_{20} has not been explored in this type of space.

1.3 Modelling

Prediction of the reverberation time of this type of room is known to be difficult using reverberation time formulae [4]. Calculations either assume a diffuse sound field, which leads to a linear decay, or make corrections to this assumption based on empirical results and mathematical analysis. As all decays possess different degrees of non-linearity, the improvement these corrections make can vary in effectiveness from room to room, and in themselves be difficult to predict. Geometrical acoustic (GA) models suffer from inherent limitations in predicting late reverberation, though in many visually simple rooms, uncertainty in room coefficients input into the model has been found to be the cause of unreliable prediction, rather than algorithms used in the software [5]. Recommendations on the successful modelling of sports halls and similar non-diffuse spaces are suggested.

2. Hall

2.1 Description

The hall used for measurements was a multi-purpose hall in a primary school, completed in 2012. The dimensions are 17.7 × 10.0 × 6.1 m. It has a perforated plasterboard ceiling with two roof lanterns and radiant panels inset. There is a 2.4 m high band of 25 mm thick absorbent wall panels on battens around three walls, which are plasterboard on masonry. One end wall is fully glazed curtain walling.

The hall was empty of building materials / equipment, and contained only the two persons present making the measurements.

Figure 1: Hall used for measurements

3. Measurement results

These measurements are the arithmetic mean of a range of source and receiver positions. The horizontal measurements are an average of loudspeaker positions in the corner and middle of the long side of the room, with the loudspeaker pointing in towards the wall.

Oct band / type	**125**	**250**	**500**	**1 k**	**2 k**	**4 k**
Horizontal	1.65	2.40	2.65	2.20	**1.70**	**1.51**
Vertical	1.58	2.65	2.76	2.17	**1.39**	**1.14**
Average	**1.61**	**2.53**	**2.70**	**2.19**	**1.55**	**1.33**
St. Dev.	0.20	0.26	0.18	0.13	0.18	0.21
Omni-directional	**1.60**	**2.49**	**2.69**	**2.04**	**1.63**	**1.33**
St. Dev.	0.28	0.22	0.16	0.13	0.06	0.09

Table 1: T_{20} values (seconds) from the hall with the cabinet and omni-directional sources. Standard deviations are calculated for all source positions and loudspeaker orientations.

Vertical measurements were taken in the same positions, but with the loudspeaker cone oriented towards the ceiling.

3.1 T-Tests

Statistical analysis of the measurements was undertaken to assess whether the reverberation time measured with a horizontal source was longer than that measured with a vertical source. Seventy-five decays were captured for each source orientation, in a variety of source locations and receiver positions, to give a large sample size suitable for this type of analysis. Student's T-Test returns a p-value, the probability that two samples are taken from the same underlying population. A p-value less than 0.05 indicates that one can state with greater than 95% confidence that the two samples are from different populations. Specifically for these comparisons, a p-value less than 0.05 would show that measuring T_{20} using horizontally and vertically oriented sources gives a statistically different result.

Octave band centre frequency / Hz					
125	**250**	**500**	**1 k**	**2 k**	**4 k**
2×10^{-2}	1×10^{-9}	1×10^{-4}	7×10^{-2}	1×10^{-47}	9×10^{-48}

Table 2: P-values from Student's T-Test comparing T_{20} measured with a horizontal and vertical orientated cabinet speaker. Values less than $5\text{x}10^{-2}$ show there is a significant difference between measurements.

3.2 Discussion of results

At 125 Hz the standard deviation with the omni-directional source is higher than the directional source, but this is unlikely to be significant, and the directional source is fairly omni-directional in this frequency band. It should be noted that the standard deviation at 2 kHz and 4 kHz is much higher with the directional source, as measured T_{20} varied considerably at high frequencies depending on the orientation of the loudspeaker.

The results of the T-test show a significant difference between measurements, with a notable result at 2 kHz and 4 kHz, where there is a vanishing probability of the horizontal and vertically orientated speaker giving the same T_{20}. The p-value at 1 kHz, falls just outside the 95% confidence interval required for statistical significance.

The key difference in measured reverberation times can be attributed to the differing decay rates of two superposed sound fields, grazing and non-grazing. Changing the orientation of the loudspeaker will affect the steady state balance of sound energy in the room. Increasing the proportion of energy present in the grazing component will reduce the time when the non-grazing to grazing transition occurs in the decay curve, which increases the measured reverberation time. As the decay rate of the grazing field is less than that of the non-grazing field due to less absorption on the walls, the reverberation time increases. The non-grazing field has been demonstrated [6] to dominate steady state levels, as there are more modes in this category than the grazing field; this is why the initial decay in this schematic model is dominated by the non-grazing field.

While noise is being produced by a sound source, the sound field in the room is reasonably diffuse [3] as all surfaces will offer a small amount of acoustic scattering. After the source is switched off, the sound field becomes increasingly non-diffuse as the non-grazing modes incident on the absorbent ceiling are absorbed.

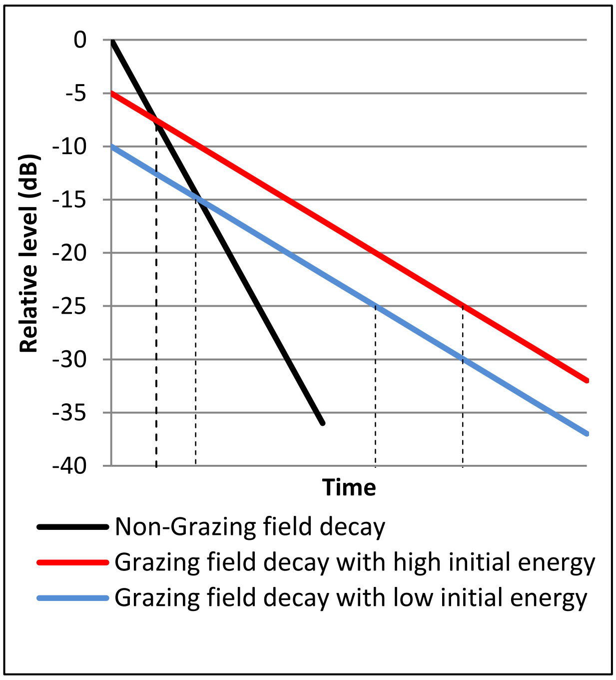

Figure 2 - Schematic diagram of decay rate of grazing and non-grazing sound fields. Note how delaying the non-grazing / grazing transition by altering steady state level balance can lead to a difference in T_{20}.

The results show that although at 2 kHz and 4 kHz, there is significant variation in T_{20} between vertical and horizontal source orientations, when the two are averaged, the omni-directional T_{20} result is recovered to within 5% over most frequency bands. This is an important result, as it demonstrates that room conditions measured by an omni-directional sound source can be approximated by measuring with a cabinet loudspeaker used in a range of orientations.

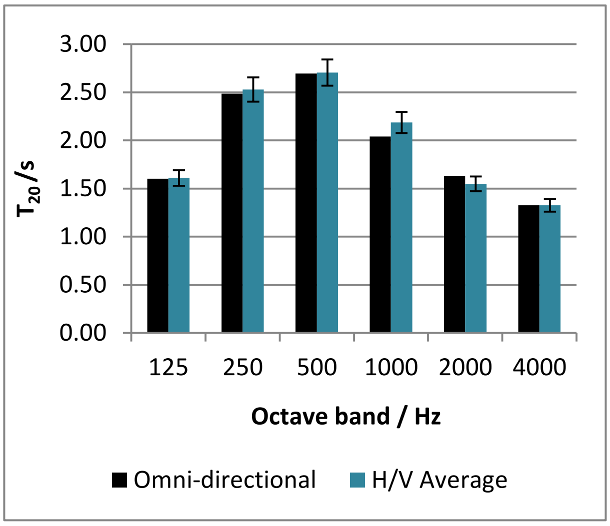

Figure 3 : T_{20} measurements for Omni-directional and Directional sources, averaged over a range of positions and orientations. Error bars are set at 5%, the nominal accuracy of ISO 3382's engineering method, which has been followed.

4. Geometrical Acoustic prediction

ISO 3382-2 maintains that reverberation time directly affects perceived acoustic qualities such as speech intelligibility, privacy and steady state levels as well as providing a correction term for other acoustic measures. The standard explicitly mentions sports halls as a room type where reverberation time is a meaningful parameter to measure. An acoustic prediction model was made in CATT to investigate if the measured results could be replicated. Bengt-Inge Dalenbäck, the developer of CATT, provided many useful comments and suggestions to increase the accuracy of the model.

4.1 Scattering and Absorption dependence

In certain spaces, it is known that adjusting the scattering coefficients can have a much more marked effect on predicted measures than changing absorption [7]. With this in mind, the scattering / absorption dependence of the room was evaluated by inputting a wide range of high and low coefficients, and recording how the predicted reverberation time (T_{20}) changed as a result. The effect of the plasterboard walls was found to be strongly dependent on both scattering and absorption coefficients

As a starting point, standard absorption coefficients from a range of sources were used in the model. The large, flat, reflective surfaces in the room were given a scattering coefficient of 10% across all frequency bands [8]. Roof lanterns, due to many small features such as window frames were given a higher scattering coefficient, increasing at high frequencies. Table 3 shows the coefficients used in the model.

Directivity data for the 10" cone diameter cabinet loudspeaker used in the measurements was not available for use in CATT, though information for a similar sized, but nominally slightly more directional loudspeaker was available, and was used in the modelling.

Absorption coefficient (%)	Octave Band / Hz					
	125	**250**	**500**	**1 k**	**2 k**	**4 k**
Plasterboard	2	2	2	2	2	2
Glazing	10	7	5	3	2	2
Wall Panels	20	70	99	99	99	99
Doors	14	10	6	8	10	10
Perforated Ceiling	10	35	70	90	80	65
Scattering Coefficients (%)						
Large surfaces	10	10	10	10	10	10
Skylights	10	20	30	35	40	50

Table 3: Absorption and scattering coefficients used in initial model

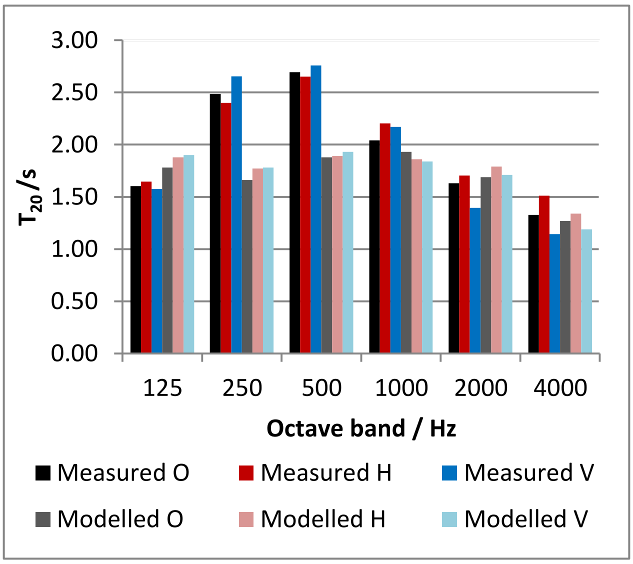

Figure 4 - Comparison of modelled T_{20} with measured T_{20} for all sources. O = Omni-directional, H = directional source oriented horizontally, V = directional source oriented vertically.

The modelled results fit the measurements to a reasonable degree of accuracy in most octave bands, though at 250 Hz and 500 Hz the predicted reverberation time is significantly different to the measurements to suggest an error in the set-up of the model.

A number of problems arise when altering the model by significantly changing the absorption and scattering coefficients; firstly, if an acoustically inaccurate model is forced to fit a T_{20} value, other measures of the response of the space could be driven far from their actual values. Without an understanding of the general trends in frequency dependent scattering coefficients for common materials, and realistic minimum and maximum values across octave bands, a model could be tuned to fit the measured results fallaciously. Clearly, modelling room dimensions accurately must come first.

4.2 Bounding T_{20}

While making a model that accurately predicts T_{20} remains elusive, finding a possible range of values by inputting maximum and minimum scattering and absorption coefficients is more achievable. This technique was initially used to assess the dependency of the room on scattering and absorption coefficients, but when the T_{20} could not be determined effectively, this method allowed the reverberation time to be bounded within calculated limits.

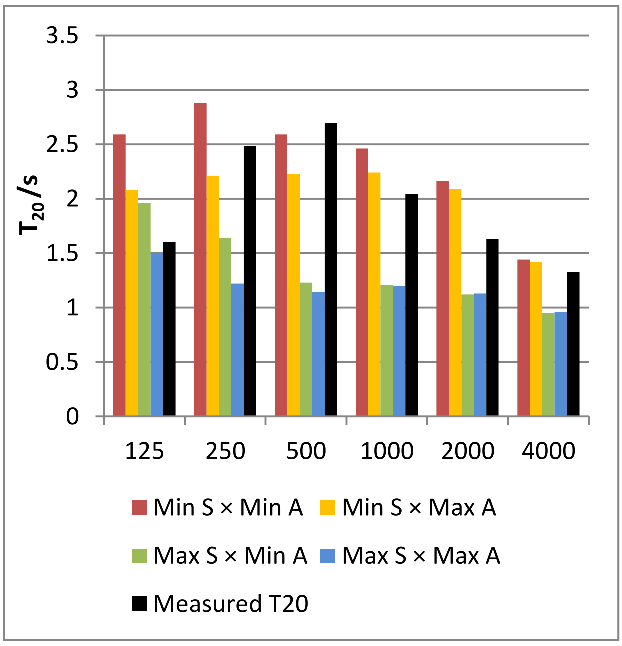

Figure 5: Comparison of T_{20} for minimum and maximum realistic scattering (S) and absorption (A) coefficients in the GA model, alongside the measured result.

At low frequencies, the prediction is equally dependent on absorption coefficients and scattering, as Min S × Max A and Max S × Min A, the yellow and green bars, nearly coincide. When the room is modelled diffuse and absorbent, the reverberation time is more than a second lower than the prediction with low scattering and absorption. Such a wide range of reverberation time values may not be of much use to the consultant, though with experience of modelling many spaces like this, this range should be able to be reduced.

The max/ min method may be used to assess the potential uncertainty in the prediction; the wide range of predicted results may make this unattractive, but it may nevertheless be realistic.

Discussion with Dalenbäck has led to the conclusion that because T_{20} is a difficult statistic to model confidently, it becomes a somewhat unhelpful measurement to obtain. Rooms with similar T_{20} can sound very different to users, as the perceived reverberation time is dependent on the earliest part of the decay, which is omitted from the calculation of T_{20}. [9]

4.3 A study of scattering coefficients

In cases where the sound field is non-diffuse, careful modelling of scattering is important. While there is a wealth of numerical data available for absorption coefficients, data on scattering coefficients for GA modelling is much scarcer. Instead, suggestions are made [5] [10] as starting points based on room models, and the use of engineering judgment and understanding of what causes sound to be scattered in a room is encouraged. Indeed, because different prediction methods define and handle the scattering of sound in slightly different ways, [11] no one scattering coefficient will work for all rooms and models. Even if laboratory measured scattering coefficients exist for a given surface material, applying these coefficients in non-diffuse spaces may still give errant results.

The following statements come from communication with Dalenbäck, and are applicable to CATT-Acoustic software, when modelling large spaces such as sports halls. Users of other geometrical acoustic prediction software may still benefit from this guidance, though the handling of wave effects and the particular algorithms used vary from program to program.

- Large flat, hard surfaces should start at about 10% scattering across all octave bands.
- If a surface is completely flat, and made of one material, the scattering only comes from edge diffraction, the effect of which decreases at high frequency. Edge diffraction is included as a setting in CATT.
- If a faceted surface is modelled geometrically, the high frequencies will be scattered as they are in reality by the geometry, however the low frequencies will be mixed incorrectly. In reality, low frequency waves will “see” a flat surface and “ignore” the facets. If a surface like this is present in the real room, it is easiest to geometrically model a flat surface with scattering coefficients peaking at the frequency corresponding with the "roughness scale" of the surface. All features similar in length scale to an acoustic wavelength make for difficult modelling.
- In order to check the model, set all scattering coefficients to 99% and check if the Eyring reverberation time prediction matches the ray-traced reverberation time.
- Resonant objects such as plate glass windows and plasterboard on battens will offer low frequency scattering.
- The scattering coefficient of large planes that are broken up by objects and holes like skylights should be increased, as the diffraction effects that these items cause in the real room will not be modelled.
- Flat surfaces with absorption will have more scattering than flat, hard surfaces, for which the specular reflection will be “clean”, with less diffusion of the sound. Absorption is a complex process with lots of phenomena, such as resonance, waves travelling through the material, and impedance mismatch at edges. These features reduce the proportion of sound energy that is reflected specularly.
- EDT, the time taken for sound levels to decay from 0 to -10 dB, is more easily predicted by GA software, as it does not rely on the end part of the decay; this measure can even be well predicted by Eyring calculations.

5. Conclusions

It has been demonstrated that there can be a significant relationship between directional source orientation and measured T_{20} in a room where the acoustic absorption is not evenly distributed, when using the interrupted source method. This phenomenon is noted most significantly in the 2 kHz and 4 kHz bands. As the particular directional loudspeaker used had a fairly constant directivity at low frequencies, here less difference was observed between sound source types.

The engineering method in ISO 3382-2 states a nominal accuracy of 5%, though there is no guidance on source directivity given. If a directional cabinet loudspeaker is used in just one orientation, the measured reverberation time in these tests regularly lies more than 5% from the omni-directional result, here taken as a reference. When such a directional loudspeaker is used in a range of orientations and the T_{20}s are averaged, the results come appreciably closer to the omni-directional T_{20}.

This feature of the acoustic response is not so evident in models, where the uncertainty of scattering coefficients can lead to an inaccurate model. In the room under test, 250 Hz and 500 Hz octave bands were significantly underpredicted, and these results cannot be simply explained.

Predicting T_{20} using acoustic models requires engineering judgement and careful application of measured coefficients. For models very sensitive to small changes, it may only be possible to determine a wide range of predicted reverberation times, rather than a single figure. Estimating the uncertainty of the prediction can be achieved by calcualting the limiting performance anticipated for scattering and absorption.

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