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Measurement, Modelling and Subjective Responses to the sound decay from coupled volumes in the McPherson Room, St Andrews University

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ABSTRACT

We present room acoustics measurement and assessment results from a recital room with a coupled volume. We employ current techniques of modelling coupled volumes and compare these with measurements and the results from questionnaires completed by listeners hearing live music performances in the McPherson Room with and without the acoustic banners extended. An auditorium with a coupled volume can provide much sought-after room acoustics providing both Clarity and Reverberance. The subjective qualities “Clarity” and “Reverberance” are two of the key questions asked of listeners in questionnaires on room acoustics. Clarity for music correlates adequately with C80, but the subjective quality Reverberance does not currently have a defined physical parameter. Edwards’ approach to the coupled chamber at the McPherson room in the Laidlaw Building at St Andrews University, differs significantly from coupled volumes in his earlier auditoria such the Meyerson Symphony Center, Dallas and Symphony Hall, Birmingham. The design process for the McPherson Room included a VR presentation with acoustic simulations where the participant could sing and hear the resultant sound with and without the coupled chamber. This enabled the Client to proceed with confidence in the acoustic design even though it was without precedent.

Keywords: Reverberation, Schroeder, Decay

1 INTRODUCTION

The decay from coupled volumes in the McPherson Room, St Andrews University is studied.

2 DESIGN PROCESS

The brief for the McPherson Recital Room in the Laidlaw Music Centre, University of St Andrews was to build a room that is a joy to perform and listen in for a wide range of uses from rehearsals and performances of the many University and Town choruses to full orchestra rehearsals. And for use for recitals with an audience of up to 300.

The room is equipped with 88 motorized lifts each 2mx1m in plan with a travel of -0.6m to +1.05m to change the room format to suit the various uses, but we report here on the room acoustical adjustments that performers employ to adjust the acoustic to suit their requirements.

Edwards designed coupled chambers for concert halls such as the Meyerson Symphony Center, Dallas in the 1980’s and as the brief called specifically for choral uses, he recommended the use of a coupled chamber for this project. This is the first time a coupled chamber has been used in a recital hall. While for major concert hall projects adjustability of the opening between the two chambers is provided by reverberation chamber doors, for this recital room he proposed a simple non-adjustable ceiling with fixed openings between the chambers. The ceiling also provides catwalk surfaces for access to lighting and audio/recording equipment.

Edwards has observed that in a typical shoebox concert hall such as the Musikvereinssaal the sound decays in the upper (hard) part of the volume in different way than in the lower (audience-occupied) part – in other

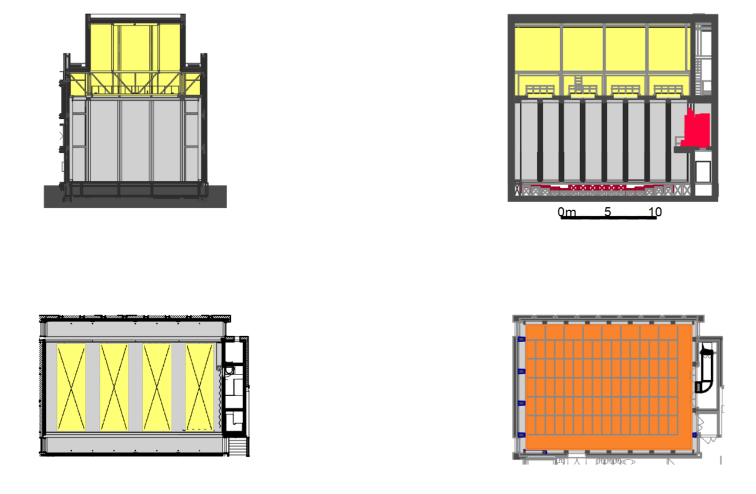


Figure 1. Design of the McPherson Recital Room in the Laidlaw Music Centre, University of St Andrews.

words, that the Musikvereinssaal is not a single, diffuse volume. His design for the McPherson room builds on this idea by reducing the coupling between the audience chamber and the reverberation chamber above.

For acoustical adjustability, Edwards provided acoustical banners in the audience chamber and an acoustical curtain in the reverberation chamber.

A VR presentation with real-time convolution was used to demonstrate the effect of the coupled chamber with closed-cup headsets so that the Client and one presenter could speak and sing in the virtual room and hear the result with and without the coupled chamber. In preparing the VR presentation, Edwards included the transition between discrete reflections from the room surfaces and the exponential decays from the two chambers. He designed for strong early reflections that would be powerful enough to balance the late sound from the coupled chamber, and so the walls, floor and ceiling are essentially the large flat hard surfaces. When the banners are retracted the sound initially reduces in strength according to the inverse square law rather than as an exponential decay. In the VR simulations, we estimated the impulse response at the transition between geometric and statistical acoustics models, and our purpose in this paper is to report on the measurements of that transition.

3 MEASUREMENT OF THE IMPULSE RESPONSE

3.1 Apparatus

The microphones used were Sennheiser MKH 8020 omnidirectional condensers. An omnidirectional sound source, NTi DS3 Dodecahedron Speaker, was used on a tripod. Amplification was provided by a NTi DSPA3 Power Amplifier with the signal source set to line. Audio input and output in the McPherson Recital Room in the Laidlaw Music Centre was achieved using an Allen & Heath DT168 Dante stage box in the room (with all microphone inputs set to a gain of +32 dB) and this was controlled from the Recording Room elsewhere in the same building using Reaper DAW software running on a MacBook Pro and an Allean & Heath SQ7 mixing desk with Dante card (for control of microphone gains). A Netgear ethernet switch enabled in the switch room enabled the Dante devices to communicate. The audio device in Reaper DAW software was set to Dante Virtual Soundcard.

3.2 Signals used

Measurements were performed using exponential sine sweep excitation enabling removal of the effects of harmonic distortion at the source [1]. The exponential sine sweep signal was generated as a wav file using Python

3 code with the numpy and scipy libraries. Sweeps were generated using the formula:

$$s_e[n] = \sin(K(\exp(t[n]/D) - 1)), \tag{1}$$

for integer sample number n where

$$t[n] = n/F_s,\ 0 \leq n \leq 2^M - 1, \tag{2}$$

with the sample rate being F_s and

$$D = \frac{T}{\ln\left(\frac{\omega_2}{\omega_1}\right)},\ K = D \times \omega_1, \tag{3}$$

with $T = 2^M/F_s$ being the duration of the measurement in seconds for a sweep of order M going between a starting frequency $f_1 = \omega_1/(2\pi)$ and a (higher) finishing frequency of $f_2 = \omega_2/(2\pi)$. A very long signal length of $M = 2^{23}$ samples was used running from $f_1 = 10$ Hz to $f_2 = 28$ kHz with a sample rate of $F_s = 48$ kHz. A linear fade in and fade out were applied over the first and last 40 milliseconds of signal respectively in order to prevent wide-band excitation at the start and end of the sweeps from first order differential discontinuities. The resulting sweep was played twice end to end, resulting in a source wav files of length 5 minutes and 50 seconds.

3.3 Measurement process

The sweep was loaded into a track on Reaper DAW and the recording button activated in Reaper with recording armed on tracks to capture microphone signals. The stop button only pressed manually after the (second sweep of) the wav file output had finished metering. More Python code was used to read in the wav file of the microphone signal and chop the resulting array to isolate the microphone signal during the second playback of the sweep within the source wav file to give the measurement signal, $y[n]$. The resulting array and the array containing a single sweep were then divided in the frequency domain to get the time domain impulse response:

$$h[n] = \mathscr{F}^{-1}\left(\frac{\mathscr{F}(y)}{\mathscr{F}(s_e)}\right). \tag{4}$$

where $\mathscr{F}$ and $\mathscr{F}^{-1}$ denote the use of numpy.fft.fft and numpy.fft.ifft respectively in Python. The use of a very long sweep (2^{23} samples at 48 kHz sample rate) has the advantage of localising the measured linear impulse response in the first few seconds of the h array, with the measurement noise diluted over the full 2 minutes and 55 seconds of the measurement. Truncation to a length of 12 seconds was then performed before saving wav files of the impulse response.

4 ANALYSIS OF IMPULSE RESPONSE MEASUREMENTS

4.1 Band pass and Schroeder backward integration

The time domain impulse responses generated were band pass filtered to limit the signal to an octave band of interest and then truncated to 11.5 seconds to remove the presence of a small non-causal tail at the end of the impulse response due to the frequency domain filtering used. Next Schroder backward integration [2] was performed to generate the energy decay curve, EDC, in this case by squaring every sample in the (filtered) impulse response and using cumulative summation from the end of the signal:

$$EDC[n] = \sum_{m=n}^{2^M-1} h^2[m], \tag{5}$$

and this can be achieved in one line of Python code: EDC = numpy.flip(numpy.cumsum(numpy.flip(h**2))).

4.2 Nosie slope removal

Energy decay curves can be plotted on a logarithmic scale giving straight line decays where exponential decay of energy is present[2]. Fitting of multiple slopes in reverberant decays performed has previously been done

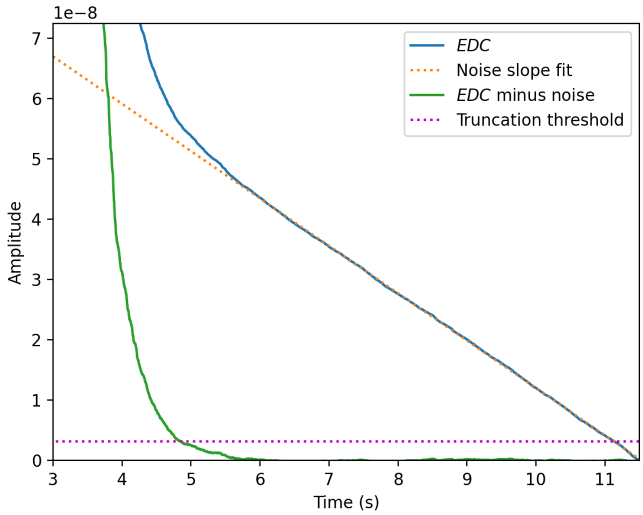


Figure 2. Zooming in on the (linear scale) Energy Decay Curve (*EDC*) (measured with banners retracted and curtains retracted in the McPherson Recital Room, 1 kHz octave band) to show the straight line fit to the Schroeder Backward integration of a constant background noise towards the end of the measurement. The result of subtracting the straight line fit from the *EDC* is shown in green.

on decay curves by optimisation of the sum of exponential decays and a straight line noise term as seen in Equation 6 and Equation 2 respectively in the works by Xiang and Goggans [3, 4]. The straight line term can be understood as the result of performing Schroeder backward integration on the square of the impulse response where there is a background noise signal of constant average energy over time and this is readily identified as a straight line down to zero at the end of a linear plot of *EDC* data in the time domain (or a time reversed logarithm graph when viewed on a decibel scale).

It is the current authors contention that simultaneously fitting the noise slope and exponential decays leads to minimal ability to measure low amplitude decays late in the signal even when these decays are visible above the background noise in the impulse response. In the current work it is demonstrated that removing the noise slope prior to curve fitting achieves improved ability to detect these late decays.

In order to identify the noise slope in the *EDC*, a least squares straight line fit was performed on the *EDC* data using the scipy.optimize.curve_fit function in Python. This straight line fit was performed over a wide range of time intervals (0 seconds through to 11.5 seconds, then 0.1 seconds through to 11.5 seconds, then 0.2 seconds through to 11.5 seconds and so on up to and including 11.0 seconds through to 11.5 seconds). The lowest standard deviation error in the slope was then used to determine the best straight line fit to the noise slope (where, in practice, this corresponded to the straight line fit over the largest range after the exponential decays had fallen below the noise floor) and this was subtracted and this deduced noise slope was removed from the *EDC*:

$$EDC \text{ minus noise} = EDC[n] - (gt[n] + c) \quad (6)$$

where g is the slope and c is the *EDC* axis intercept at $t = 0$. An example of the resulting noise slope removal process is shown in Figure 2.

A search was performed to find the first sample number, n_0, that had a value of *EDC* minus noise less than zero. The maximum absolute value of the *EDC* minus noise array in the range $n \geq n_0$ was then obtained. The *EDC* minus noise array was then truncated to the first point where ten times this noise level was reached (so where the green line crosses the magenta line in Figure 2) in order to enable plotting and curve fitting on a logarithmic (decibel) scale in the subsequent sections.

4.3 Double slope decay analysis

Once the EDC with the noise slope removed was obtained, this was normalised by dividing the EDC array by its maximum value and then the decibel value $10\log_{10}(EDC \text{ minus noise})$ analysed to fit a double exponential decay, $10\log(EDC_{fit})$ where:

$$EDC_{fit}[n] = A\left(\exp(-\alpha t[n]) + \gamma \exp(-\beta \alpha t[n])\right). \quad (7)$$

The variables to be fitted were the decay exponent of the first slope, α, the ratio of the two decay exponents, β, and the relative level of the second slope, γ and $A = 1/(1+\gamma)$. This minimum root mean squared curve fitting was performed using the scipy.optimize.curve_fit function in Python with the search ranges $0 < \alpha < \infty$, $0 < \beta < 1$. Since it is possible to find local minima of root mean squared error over a wide range of γ values, a fit was evaluated repeatedly for multiple orders of magnitude for γ using the formula $10^{-m-1} < \gamma < 10^{-m}$ where the values of m were taken to be integers in the range 0 to $\min(\log_{10}(EDC \text{ minus noise}))$. The Root Mean Square Error between EDC_{fit} and the measured EDC of each fit was stored in an array $RMSE[m]$. The index $m = m_{min}$ giving the lowest value of $RMSE[m]$ was determined. The best fit for plotting was determined to be $m = m_{min}$ while error bounds on α and β where determined using the maximum range of m values corresponding to fits with a root mean square less than twice the minimum root mean square error ($RMSE[m] < 2RMSE[m_{min}]$).

If $\gamma \ll 1$ and $\beta < 1$ then a double slope decay results. The reverberation time times associated with the two slopes will be:

$$T_{60}^{(1)} = \frac{\ln(10^6)}{\alpha}. \quad (8)$$

$$T_{60}^{(2)} = \frac{\ln(10^6)}{\beta\alpha}. \quad (9)$$

Examples of the EDC on a decibel scale including the resulting fit of a double exponential decay to the EDC minus noise data is shown in Figure 3 for the McPherson Recital Room in the Laidlaw Music Centre of the University of St Andrews with the banners in the main hall and the curtain in the coupled reverberation chamber fully retracted and fully extended. The very high dynamic range achieved by using a very long logarithmic sine sweep is clear, as is the ability of the noise slope removal procedure to display features that are largely obscured by the noise slope in the *EDC*.

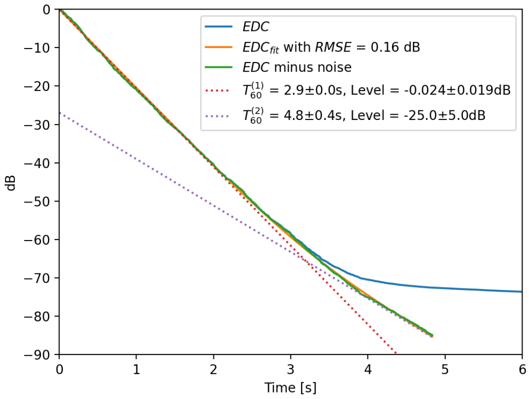
With the banners in the recital room retracted, extending the curtain in the coupled reverberation chamber (going from Figure 3a to Figure 3b) reduced the identified reverberation time associated with slope 1 from 2.9 seconds to 2.8 seconds. The reverberation time associated with slope 2 changed from 4.8 ± 0.4 seconds with the curtain retracted to 5.4 ± 0.6 seconds when the curtain was extended. Evaluating the intercept with the y axis of the decibel plot for slope 2 gives -25.0 ± 5 dB when the curtain is retracted and -35 ± 5 dB when the curtain is extended. While the uncertainty in the precise slope of the second slope is relatively large, the presence of the second slope would be completely missed if the noise slope had not been removed before applying curve fitting.

The two slope decay model clearly fails to completely describe the decay when the banners are extended (as in Figures 3c and 3d) due to the sound field being much less diffuse. It is therefore appropriate to treat these cases with other forms of curve fitting.

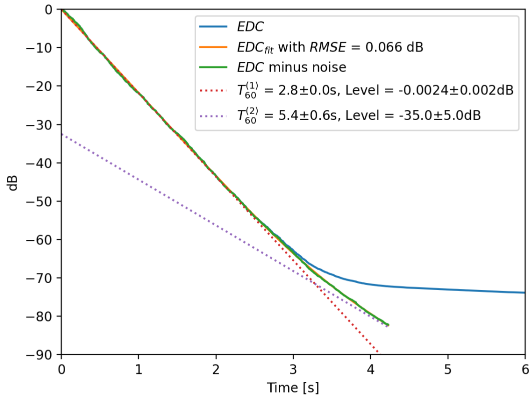
In order to prove that the data in the region where the noise slope is valid, a test the same technique was appleid to measure the Younger Hall in the University of St Andrews. The result is show in Figure 4 and shows a clear measurement of a straight line decay (including below the noise slope in the *EDC*). This should be expected for a successful measurement of the Younger Hall because there is no coupled volume and there is even distribution of damping material in the room. The double slope decay analysis deduces that there is considerable uncertainty in the best value for a second slope since a single exponential decay is adequate to describe this space.

4.4 Curved response analysis

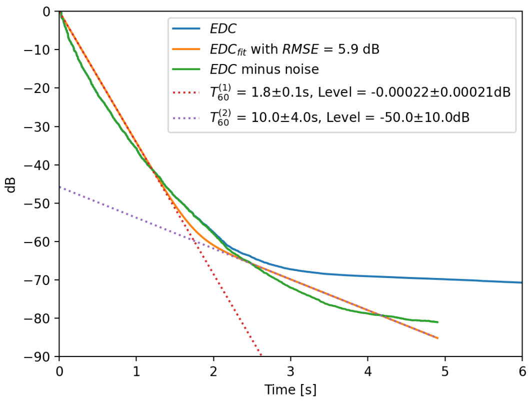
Response from -15 dB etc.?



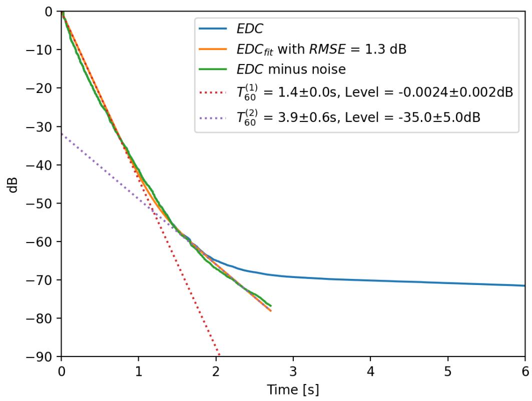
(a) Banners retracted and curtains retracted



(b) Banners retracted and curtains extended



(c) Banners extended and curtains retracted



(d) Banners extended and curtains extended

Figure 3. The Energy Decay Curve (*EDC*) and fit for measurement in the McPherson Recital Room with source-receiver distance of 9 metres for octave band centred on 1 kHz.

5 AUDIENCE QUESTIONNAIRE

We invited an audience (mainly members of one of the St Andrew's choruses) to listen in the McPherson room to a 3-minute performance of solo trumpet, with the room in four different room settings, arranged in Table 1 in ascending order relative to the amount of additional absorption:

Table 1. Room setting descriptions

Room Settings	Audience Chamber	Reverberation Chamber
Room Setting 1	Banners extended	Curtain extended
Room Setting 3	Banners extended	Curtain retracted
Room Setting 2	Banners retracted	Curtain extended
Room Setting 4	Banners retracted	Curtain retracted

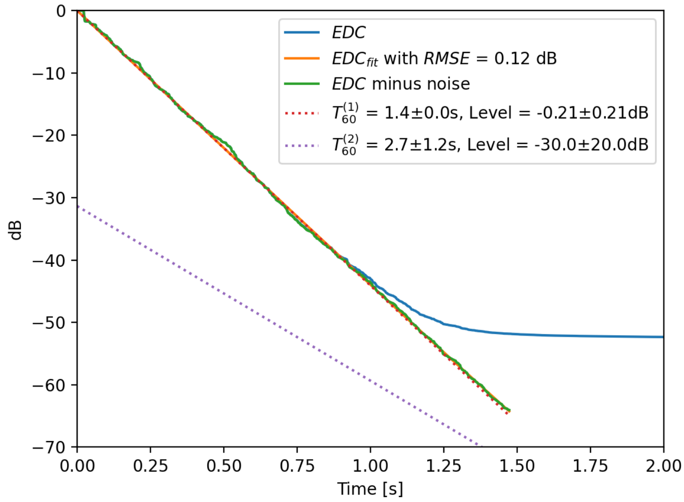


Figure 4. The Energy Decay Curve (*EDC*) and fit for measurement in the Younger Hall with source-receiver distance of approximately 9 metres for octave band centred on 1 kHz.

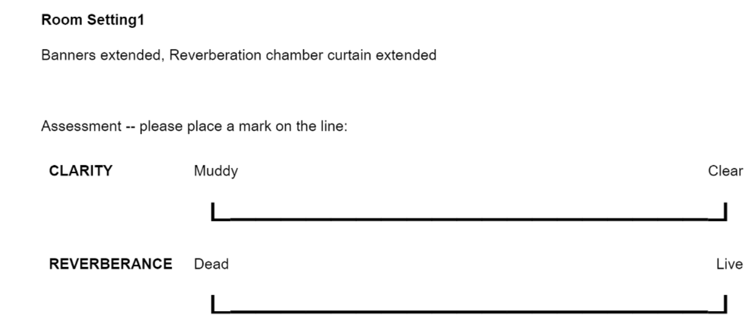


Figure 5. Excerpt from questionnaire.

An audience of 26 attended and completed an anonymous questionnaire based on the method used by Barron [5] - an excerpt is shown in Figure 5.

As this is a recital room rather than a concert hall, and as the performance was by a soloist rather than an orchestra, we are most interested in the audience responses regarding Clarity and Reverberance.

The acoustical differences between the room settings were noticeable, and the audience reported a significant change with the setting of the banners, and smaller changes with the setting of the curtains in the reverberation chamber, as shown in Figure 6.

While the audience questionnaire did not reveal much subjective change with extending/retracting the reverberation chamber curtain, this result will have been influenced by the source instrument being a solo trumpet. The setting of the curtain has been found to have an important but subtle effect in the use of the room.

We invited the audience to leave written comments, and one of them is this: “I'd like to hear how the settings with banners extended function for different instruments. I'd enjoy settings with the banners retracted for cello, I think, but I'd prefer settings with the banners extended for piano. The whole session had made me think I'd like to hear different pieces with different instruments in the different settings. What I'd enjoy most about those would be to focus on and appreciate the timbre of the specific instrument.”

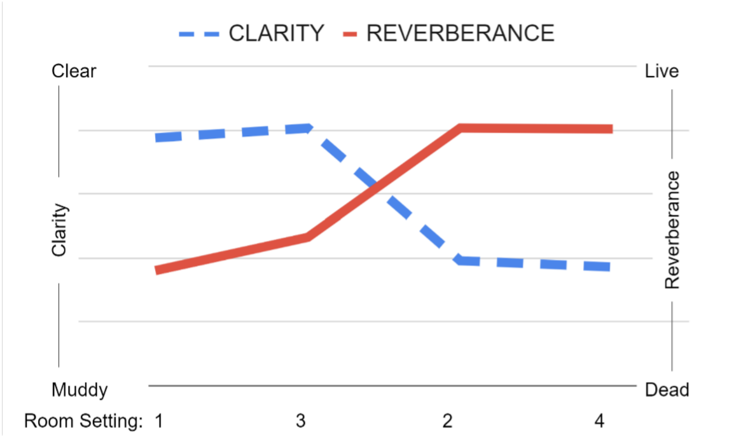


Figure 6. Average of audience responses to questionnaire.

6 CONCLUSIONS

It worked.

ACKNOWLEDGEMENTS

Thanks to everyone.

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