Acoustics 2008
Geelong, Victoria, Australia 24 to 26 November 2008

Acoustics and Sustainability:

How should acoustics adapt to meet future demands?

Avoidance of noise-related errors in the analysis of room impulse responses

Santiago Ortiz, Hong-Jiun Nieh and Densil Cabrera

Faculty of Architecture, Design and Planning, University of Sydney, NSW 2006, Australia

ABSTRACT

Room impulse responses can be analysed to yield several room acoustical parameters, such as reverberation time, early decay time, clarity index and strength factor. Despite the considerable noise immunity of modern impulse response measurement techniques (such as swept sinusoids), it is common for room impulse responses to have sufficient noise to have some effect on the derived room acoustical parameters. The effect of noise is typically seen by a change in the slope of the late part of the decay function (derived from Schroeder's reverse integration method), that can be detected using a series of short term correlation coefficients over the course of the decay function. By describing a room acoustical parameter error with a correlation coefficient value, a mathematical model can be established to correct errors from a calculated correlation coefficient over the 20 or 30 dB decay range used to calculate reverberation time. Such a technique is ideally suited for room soundfields that exhibit exponential decay, and needs to be used carefully in real room level decay functions. The method is evaluated using real room impulse responses with artificially introduced noise at various levels.

INTRODUCTION

The importance of the room impulse response in room acoustical measurements is well known. An impulse response fully describes a noiseless linear time-invariant system, and so provides much useful information in assessing the sound of rooms for a range of source-receiver positions. All of the room acoustical parameters in common use, such as reverberation time, early decay time, strength factor, clarity index, and definition, can be derived from the impulse response (ISO3382: 2000). However, background noise can be a major cause of inaccuracy in calculating such parameters.

Over the years, sophisticated instruments have been developed to record the room excitation with accuracy. In combination with highly specified equipment and the abundance of computing power, various room excitation methods have been developed to reduce the intrusion of noise at an early stage of measurement. One famous example is the logarithmic sine sweep method, adopted and developed by Farina (2000). The technique cross-correlates the logarithmic sweep played through the room with a sweep possessing a 6 dB per octave correction to linearise the spectral bias. This method can be viewed as playing and extending the impulse over a much longer period, and hence improving the signal to noise ratio (SNR) of the measurement by 3 dB per doubling of measurement duration. This method also has high immunity to harmonic distortion in the measurement system.

In terms of the analytical phase, Schroeder (1965) developed the backward integration method. This method transfers the impulse response data from the pressure domain into the integrated energy domain. The generated decay curve is smooth and repeatable as it represents the average of many decay curves from ideal interrupted noise. However, background noise contained in the impulse response introduces irregularities in the decay curve and hence reduces the precision when it is used to calculate various acoustical parameters. This scenario has been highlighted by Katz (2004) in a round robin test of current room acoustical measurement software. To reduce this error, Faiget et al. (1996) suggested a truncation point at the intersection between the true decay and the background noise should be used to reduce the contamination of noise before backward integration Various other methods of reducing errors from the background noise have also been considered, such as Chu's subtraction of noise in its mean-square values (Chu, 1978), and Xiang's approach of applying non-linear regression to the decay curve (1995).

A common approach of assessing the linearity of energy decay curves (in decibels) is to perform a correlation between level and time, and so yield a correlation coefficient (where -1 is ideal due to the negative slope of the decay). Using this simple device it is possible to detect non-linearities in the decay curve caused by the presence of noise, and so detect and quantify the quality of Schroeder's decay curve (1965). This approach is explored in the present paper in two ways. Firstly we consider how the point at which background noise influences on the measurement can be detected, using short-term correlation coefficient. Secondly we consider an error correction procedure based on correlation coefficient values for the T20 and T30 evaluation range of the energy decay curve.

EFFECT OF BACKGROUND NOISE ON SHORT TERM CORRELATION COEFFICIENT

Backward integration is a process of describing total energy decay of ideal interrupted noise. For a perfect impulse response with no background noise, with perfect measurement envelope (extending to infinite time), the very first point of Schroeder's curve represents a total summation of energy through the measurement period at a measurement position. As time goes by, the total summation of energy gradually decreases as a certain amount of energy is consumed in each sample time frame. This decreasing pattern forms the energy decay curve, which when expressed in decibels is close to a straight line with a negative slope. In practice, the integration period will be finite, yielding a steepening slope towards the end of the decay curve.

As there is noise in the impulse response, when the backward integration is performed, the total energy summation in the very first term would already contain noise from throughout the impulse response, although the initial decay rate may still be approximately correct. Nevertheless, there will be a point where the integrated noise and integrated ideal decay yield an appreciable change in the decay rate, which is exhibited as a reduction in the steepness of the slope, or a "raised ramp" (Karjalainen, 2002). This has the potential to induce errors in the calculation of room acoustical parameters such as reverberation time.

In the following experimental work a succession of short term correlation coefficients are used to detect the raised ramp that appears in the decay curve due to the presence of background noise in the measurement.

Experimental procedure

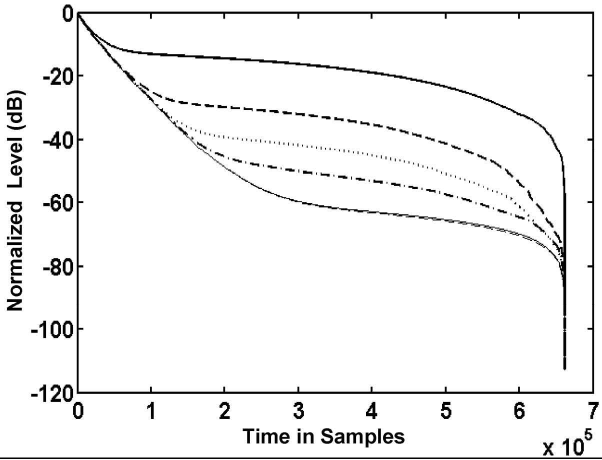
By using the logarithmic sine sweep method several impulse responses were measured in a reverberation chamber of 130 m^3. At first, an impulse response was measured with no added background noise. Several impulse responses were then measured, each with increments of 5 dB of pink noise inserted to the reverberation chamber. The impulse responses were then processed through a Matlab Mfile to generate the Schroeder's decay curve and calculate the correlation coefficient (r) values.

A short term correlation coefficient value was calculated for the following range of points in the decay curve: 0 dB to -5 dB, -1 dB to -6 dB, -2 dB to -7 dB, and continuing in 1 dB steps to -40 dB to -45 dB. A plot of these short term correlation coefficient values was generated and compared with the decay curve in order to see if it effectively detects the erroneous curvature created by noise.

Results

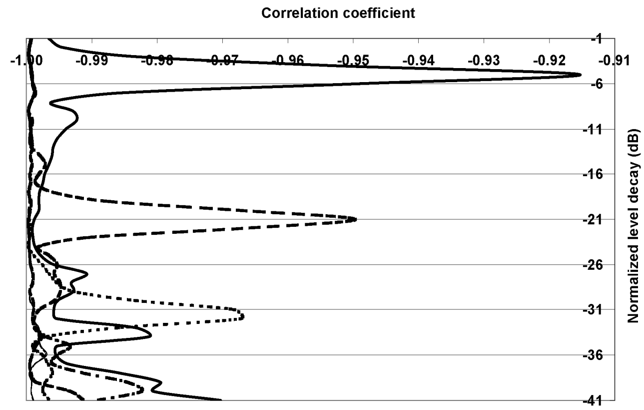
When no noise is introduced in the reverberation room, the correlation coefficient plot shows values that are very close to -1. This means the overall linearity of the decay curve is good (although there is a small reduction in steepness towards the end, probably due to pre-existing background noise, and there is also a small increase in the short term correlation coefficient values at this point shown in Figures 1and 2).

As expected, the addition of noise results in changing the shape of the later part of the decay curve, and the shape change of the decay curve is detected by the short term correlation coefficient plot. The short term correlation coefficient plots show a 'peak' point indicating a reduction in the linearity of the decay function. These peaks correspond to the parts of the respective decay curves where background noise is causing the decay slope to change. As more noise is introduced, the nonlinearity starts earlier in the decay and the peak values in the short term correlation coefficient plot follow accordingly (Refer to Figures 1 and 2). Another aspect of 'peak' value is that it increases as the error in the curve increases.



Level of pink noise added:
+60 dB, +50 dB, +40dB, +30dB, +10dB, 0dB (ref.)

Figure 1. Noise introduced in an impulse response creates a raised ramp in the decay curve, creating errors in the acoustical parameter calculation. The one with 0dB was the original decay curve without any pink noise added (but with some pre-existing noise).



Level of pink noise added:
+60 dB, +50 dB, +40dB, +30dB, +10dB, 0dB (ref.)

Figure 2. A short term correlation coefficient over the decay curve can detect the erroneous raised ramp in the decay curve. Again, 0dB means the original decay with no added pink noise.

NOISE CORRECTION USING CORRELATION COEFFICIENT OVER THE T20 AND T30 DECAY RANGE

The work presented in this section examines the extent of noise-induced errors in reverberation time measurements derived from impulse responses. By relating the error to the correlation coefficient associated with the entire reverberation time evaluation range, we propose a model for error correction. This model is first derived from ideal decays and perfectly steady state noise, so we then examine the vulnerability (and hence usefulness) of the model to characteristics associated with realistic reverberant decays and noise.

Experimental procedure

Various artificial impulse responses where created by applying the reverse procedure of Schroeder's backward integration to a descending straight line. As the decay is set to be a straight line right at the start, the impulse responses generated would have a correlation coefficient value of -1 across their entire decays (notwithstanding minor rounding errors, and the initial build-up of backward integration at the tail end of the decay).

In order to test the sensitivity of the correlation coefficient value to noise at different reverberation times, ideal decay curves possessing a range of reverberation times ranging from 0.5 to 5.0 seconds were generated. To avoid any significant influence of noise or from the initial build-up of the backward integration, all the artificial decays were given a range of 120 dB. These yielded correlation coefficient values that were extremely close to -1.

After the artificial impulse responses were generated, noise with different levels relative to the initial decay level was inserted to the impulse responses. Two types of noise were used in the experiment for comparison. We used pink noise as it is a simple representation of background noise (possessing a fine structure of fluctuations) and we also used a straight line to represent noise (i.e., with zero fluctuation).

A minimum of 250 noise gains where used for each set of impulse responses. For each gain, the reverberation time T30 and T20 values were calculated from the decay curve according to ISO 3382 (1997). Correlation coefficient values for the respective evaluation ranges of T30 and T20 were calculated, and signal to noise ratio was calculated to examine the consistency of the experiment. The calculated reverberation time values were compared to the designated reverberation time value from the original decay (without noise added), and its deviation was calculated in percentage form. Finally, these percentage differences are compared and related to the correlation coefficient values

Results

It was found that by adding linear noise (instead of pink noise) the relationship between the acoustical parameter error and the correlation coefficient value was independent of reverberation time. On the other hand when we used pink noise this relationship varied, although without any systematic relationship with reverberation time. Hence, the random level variation of pink noise over time is what causes the chaotic results, rather than the reverberation times themselves. The results obtained for both pink and linear noise are show in Figures 3 and 4.

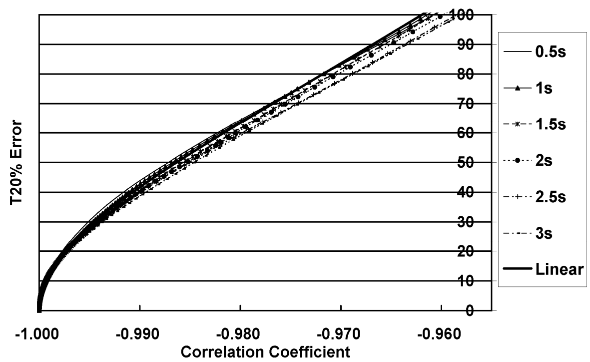


Figure 3. Correlation coefficient values related to percentage error in the T20 calculation using linear and pink noise.

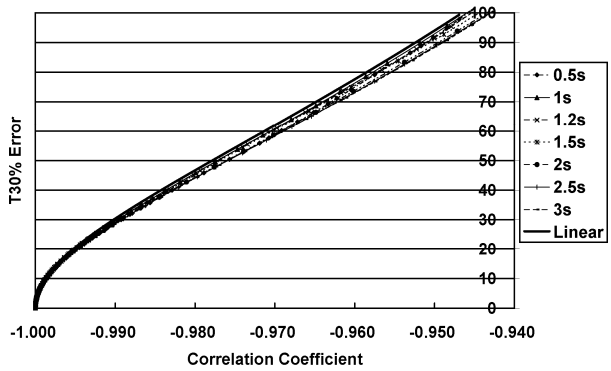


Figure 4. Correlation coefficient values related to percentage error in the T30 calculation using linear and pink noise.

Results show that exponential decays that exhibit correlation coefficients greater than -0.998 in the T20 and T30 decay range, contain less than 10% error (assuming the impulse response should have a perfectly linear decay) Correlation coefficients lower than -0.98 may contain more than 40% error, therefore output quite unreliable reverberation times.

Table 1. Relationship between error and correlation coefficient.

SNR (dB)	*Error %*	*correlation coefficient*
120 to 69	<1%	>-0.99999
69 to 53	1% to 10%	-0.99999 to -0.998
52 to 48	10% to 40%	-0.998 to -0.98
48 to 46	40% to 100%	-0.98 to -0.94
46 to 0	>100%	<0.94

Modelling

The following mathematical model is aimed at correcting errors created by background noise in the T20 and T30 acoustical parameters. By modelling the experimental results obtained in Figures 3 and 4 (linear noise curves), we can derive an equation to find the error by calculating a correlation coefficient over the T20 and T30 decay range.

As can be seen from Figures 3 and 4 the behaviour of all the curves is similar to that of a hyperbola (a curve that gradually becomes a straight line). To model the linear noise curve (that represents percentage error at all reverberation times) we can use the hyperbola formula:

$$\frac{(x-h)^2}{a^2} - \frac{y^2}{b^2} = 1 \quad (1)$$

Therefore, y can represent the percentage error and x the correlation coefficient value (r) in the following manner;

$$T20_{\%\,error} = \sqrt{b^2 \times \frac{(r-h)^2}{a^2}} \quad (2)$$

$$T30_{\%\,error} = \sqrt{b^2 \times \frac{(r-h)^2}{a^2}} \quad (3)$$

Where a, b and h are constants that define the curvature. The best fit for the linear noise curvature is represented by the following constant values;

$$T20_{\%error} = \sqrt{-23.28^2 \times \frac{(r+1.016)^2}{-0.016^2}} \quad (4)$$

$$T30_{\%error} = \sqrt{-49.84^2 \times \frac{(r+1.032)^2}{-0.032^2}} \quad (5)$$

Note – by inserting the constant values into the formula the *h* value in equation (4) and (5) is now being added to correlation coefficient due to its negative value.

Figure 5 shows the accuracy of equations 4 and 5 compared to the original experimental results. The models are accurate at representing errors up to 50% for T30 and up to 65 % for T20. For errors greater than 50% and 65% respectively, the experimental results seems to take a slightly different direction to that of the hyperbola model, due to the fact that the experimental results exhibit a small curvature that differs from the hyperbola asymptote creating a small gap at high percentage errors.

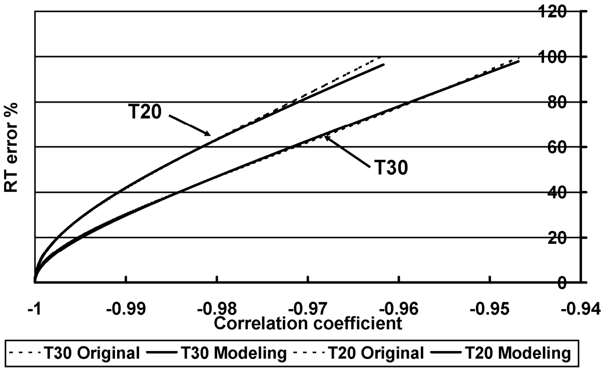


Figure 5. Error correction accuracy.

The above model can be used as a noise corrector when calculating T20 and T30. By calculating a correlation coefficient over the T20 and T30 decay range we can calculate the percentage error using equations (4) and (5). With this percentage error we can find a corrected reverberation time using the following formula;

$$T20corrected = \left(\frac{T20_{\%error}}{100}\right) + 1 \quad (10)$$

$$T30corrected = \left(\frac{T30_{\%error}}{100}\right) + 1 \quad (11)$$

It is recommended to use 6 decimal places when calculating the correlation coefficient in order to make use of the high sensitivity of the method and to be able to detect small errors up to 1%.

Validation of the model

In the following section the model proposed is examined using real impulse responses to check the validity in realistic applications.

Three impulse responses measured with the logarithmic sine sweep where used, all having a reasonably good signal to noise ratio. The first impulse response tested was measured in a 300 m^3 reverberation chamber, and being a small room it is expected to exhibit a high density of reflections, and so yield a close to perfect exponential decay when no background is contained in the measurement. The other two impulse responses where measured in large rooms by Angelo Farina (2000), the 'Opera di Pergola' and 'Santa Lucia", being large rooms they are expected to exhibit lower reflection densities, and hence more irregular exponential decays (which might be seen as steps in the backward integration).

Pink noise was artificially added gradually to each of the IRs. After every noise addition T30, T20 and a correlation coefficient was calculated for the analysed range. Using equation (4) and (5) a percentage error was estimated, and from this percentage error a T20 and T30 correction was calculated using equations (6) and (7).

Finally, a reference reverberation time was also calculated using the 'Aurora' plug-in in the program Adobe Audition, this was only done to the noise free impulse response. The reference values obtained where as follows; reverberation chamber 5.00 s, 'Opera di Pergola' 1.27 s and 'Santa Lucia' 5.26 s. These reference values are useful to compare the efficiency of the model to commercially available room acoustical parameter software.

It was found that the error correction method is accurate when correcting small percentage errors for the small room that exhibits close to linear exponential decays. Tables 2 and 3 show how the corrected values are very close to the reference (5 sec) for percentage errors up to 15% with good consistency.

The model correction is not accurate for percentage errors higher than 20% as the corrected values differ considerably from the reference value, although still correcting to a certain extent. The amount corrected without referring to the reference can also be seen by comparing the T20 or T30 measured from the T20 or T30 corrected in Tables 2 and 3.

Table 2. T20 correction for Reverberation Chamber 300 m^3. The reference reverberation time is 5.00 s.

T20 Measured	Correlation coefficient	Error%	T20 corrected
5.298	-0.99976796	5.967	5.000
5.302	-0.99976434	6.014	5.001
5.339	-0.99966240	7.203	4.980
5.449	-0.99945435	9.172	4.991
5.779	-0.99840798	15.792	4.991
10.960	-0.98331866	56.613	6.998
13.945	-0.98427643	54.641	9.018

Table 3. T30 correction for Reverberation Chamber 300 m^3. The reference reverberation time is 5.00 s.

T30 Measured	Correlation coefficient	Error%	T30 corrected
5.298	-0.99976796	3.979	5.095
5.302	-0.99976321	4.020	5.097
5.449	-0.99945435	6.132	5.134
5.779	-0.99840798	10.640	5.223
10.960	-0.98331866	41.463	7.747
15.612	-0.94715242	97.431	7.908

There was not much consistency found in the noise correction method when analysing larger rooms. The corrected values vary every time indicating a different behaviour is occurring to that being expected. In the initial stages the model is correcting more than it should, given lower values than the reference. This can be seen in tables 4 and 5 for error percentages less than 21%, were the corrected values are lower the 1.27 reference. The same can be seen in Table 7 for 'Santa Lucia' where the consistency of the model is also very variable and some results are also lower than the 5.26 reference.

Table 4: T20 correction for 'Opera di Pergola IR'. The reference reverberation time is 1.27 s.

T20 Measured	Correlation coefficient	Error%	T20 corrected
1.227	-0.99956187	8.212	1.134
1.234	-0.99953580	8.455	1.137
1.256	-0.99940375	9.592	1.146
1.296	-0.99906075	12.070	1.156
1.366	-0.99802046	17.660	1.161
1.484	-0.99512725	28.300	1.156
1.635	-0.99099761	39.586	1.171
1.828	-0.98607577	50.843	1.211
2.023	-0.98265083	15.971	1.281
2.215	-0.98094280	61.384	1.373

Table 5: T30 correction for 'Opera di Pergola' IR. The reference reverberation time is 1.27 s.

T30 Measured	Correlation coefficient	Error%	T30 corrected
1.290	-0.99925503	7.186	1.203
1.314	-0.99889110	8.816	1.207
1.398	-0.99727627	14.150	1.224
1.542	-0.99412496	21.704	1.267
1.693	-0.99134281	27.297	1.330
1.828	-0.98985509	30.085	1.404
1.950	-0.98859402	32.375	1.473
2.058	-0.98761415	34.115	1.535
2.157	-0.98650164	36.058	1.585
2.254	-0.98527772	38.160	1.631

Table 6: T20 correction for 'Santa Lucia' IR. The reference reverberation time is 5.26 s.

T20 Measured	Correlation coefficient	Error%	T20 corrected
5.290	-0.99993482	3.148	5.128
5.342	-0.99994016	3.026	5.185
5.508	-0.99981294	5.356	5.228
5.831	-0.99902028	12.331	5.191
6.373	-0.99672073	22.950	5.183
7.230	-0.99195300	37.184	5.270
8.210	-0.98738037	48.001	5.547
9.124	-0.98532455	52.444	5.985
10.653	-0.98596422	51.082	7.051
11.243	-0.98680908	49.256	7.533

Table 7: T30 correction for 'Santa Lucia' IR. The reference reverberation time is 5.26 s.

T30 Measured	Correlation coefficient	Error%	T30 corrected
5.287	-0.99993971	2.023	5.182
5.936	-0.99874757	9.390	5.427
6.704	-0.99584048	17.844	5.689
7.406	-0.99387117	22.242	6.059
8.027	-0.99223373	25.570	6.392
8.586	-0.99040588	29.066	6.652
9.081	-0.98819461	33.088	6.823
9.991	-0.98305065	41.910	7.040
10.399	-0.98002470	46.882	7.080

DISCUSSION

It is already widely recognised that correlation coefficient has a useful role in evaluating the quality of room impulse responses, but this study has presented two possible further applications for correlation coefficient – the identification of slope change due to noise, and the correction of the influence of steady state background noise on reverberation time measurements. Potentially these two approaches could be combined to increase the robustness of the derivation of reverberation time. As was mentioned at the outset, other room acoustical parameters may also be affected by noise within impulse response recordings, and a correlation-coefficient based approach to error correction might be applied.

The initial underestimation of the correction procedure for large room impulse responses with steady state noise is to be expected from the fact that the decay has a stepped fine structure (while a linear coarse structure). It should be possible to filter out the fine structure, or else to use the extent of fine structural deviation in a more complex error correction formula. An important advantage here is that the stepping is likely to be most prominent at the start of the impulse response, whereas the effect of noise is at the end.

Another circumstance where correlation coefficients will move away from -1 is when the room possesses a two-slope decay, for example in coupled rooms. Although it is difficult to define reverberation time in such circumstances, clearly if an error correction procedure is applied blindly to such decays, the correction will not be helpful.

In addition to the problem of stepped and two-slope decays, an issue with the practical implementation of this is that background noise in impulse response recordings is not necessarily steady state. For example, an impulsive noise introduced into a swept sinusoid recording results in a multitone descending sweep mixed in with the deconvolved impulse response.

By investigating the behaviour and reasons of minor deviations in the decay curve, the model can be modified with increased accuracy for real life application.

CONCLUSION

The short term correlation coefficient method is useful at determining the straight part of Schroeder's decay curve and at identifying any non linearity that is difficult to perceive visually. If we select the useful part of the curve by using the short term correlation coefficient method we can produce a more exact linear regression over the decay curve, thereby reducing the error in the reverberation time calculation. However, it is also important to note that although the regression line fitting can be optimized using correlation coefficient there can still be errors in the slope due to an incorrect integration time limit.

A clear pattern is shown between RT error and long term correlation coefficient values when straight line noise is used to eliminate the minor deviations in the pink noise. By using this result, we can have some success in correcting errors due to noise in realistic impulse responses.

REFERENCES

Schroeder, M. R. 1965, "New method for measuring reverberation time," *J. Acoust.Soc. Am.* 37, 409-412

Chu, W.T. 1978, "Comparison of reverberation measurements using Schroeder's impulse method and decay curve averaging method," *J Acoust Soc. Am*. 63, 1444-1450

Xiang, N. 1995, "Evaluation of reverberation times using a nonlinear regression approach," *J. Acoust. Soc. Am.*98, 2112-2121

Faiget, L, Ruiz, R and Legros, C. 1996, "The true duration of the impulse response to estimate reverberation time," IEEE, 0-7803-3192-3/96

Farina, A. 2000, "Simultaneous measurement of impulse response and distortion with a swept-sine technique," 108^{th} Audio Eng. Soc. Conv,

Katz, B.F.G. 2004, "International round robin on room acoustical impulse response analysis software 2004," Acoustics Research Letters Online 5, 158

Matti Karjalainen, Poju Antsalo, Aki Mäkivirta, Timo Peltonen, and Vesa Välimäki. 2002 "Estimation of modal decay parameters from noisy response measurements," *J. Audio Eng. Soc.* 50(11):867–878.