# Reverberation Influences the Attack

Tor HALMRAST

Statsbygg and University of Oslo/Musicology, Norway



## ABSTRACT

The attack of a signal is of course best preserved if we hear the direct sound only, but that is not the case in a concert hall. Acousticians often remembers that long reverberation masks the entrance of the next onset, but more astonishing is the perceived and measured difference in timbre due to "smoothening"/"prolongation" of the attack, (also for a first note in a phrase). The paper will discuss general theory regarding how "diffuse field reverberation" influences the attack. The early response of a concert hall, is, however, seldom "diffuse". The paper discusses methods for measuring attack including Rise Time, Steepness etc. of the Integrated (Cumulative) Squared Step Response and also Spectral Flux, for both real halls and simulations (Odeon). Investigations were done for signals of different lengths and for different musical instruments which in itself have slow or fast note-onset. The most important question: Is it possible to reduce the smoothening of the attack due to reverberation by adding early reflections? Preserving the attack is important also because listeners nowadays are used to recordings where any wanted amount of direct sound is mixed with a late, long and (too?) smooth, non-correlated, digital reverberation.


Keywords: Attack, Reverberation, Smoothing

## 1. INTRODUCTION

When listening to musicians playing the same pieces of music in different acoustic settings in Stavanger concert hall (see 4.1), the perceived differences were astonishing. However, the measured overall changes in spectrum, level etc., were surprisingly small. Long reverberation of course increases the length of a tone, so that it masks the entrance of the next one, but probably most astonishing was the perceived difference in timbre due to changes of the attack, (also for a first note in a phrase).

The paper will discuss general theory of how an "ideal, diffuse field reverberation" influences on attack. The early response of a concert hall, is, however, seldom "diffuse". The paper will show measurements and simulations (Odeon) of attack with/without early reflections. Methods for measuring attack in concert halls is not as trivial as measuring Rise Time, Steepness etc. for ordinary electronic filters, and alternative approaches like Integrated (Cumulative) Squared Step Response and Spectral Flux is discussed. The importance of attack has been little discussed in concert hall design, but should be more and more important, also because listeners nowadays are used to listening to recordings where any wanted amount of direct sound is mixed with a long and (too?) smooth, non-correlated, (digital) reverberation. It is generally assumed that a fast attack is more brilliant, sounds more like if there are more high frequencies present than a "fade in".

First we must remember that a signal of course preserves it attack best if we just hear the direct sound only. This paper will show how reverberation always smoothens/prolongs the attack and discuss how this affects signals of different lengths, different musical instruments which in itself have slow or fast onset of note, and if it is possible to reduce the smoothening of the attack by early reflections.

## 2. ATTACK IN ROOMS WITH EXPONENTIAL DECAY

Following Schroeder[1], Jordan[2] discusses rise time etc. of concert halls. Assuming that the decay process in a hall follows the exponential function in eq.1, a corresponding (complementary) build-up process may be written as in eq. 2: (assuming a speed of sound of 344 m/s. $I_0$ is the intensity at zero time).

$$I_{t,decay} = I_0 e^{-\mathrm{k}t} = I_0 e^{\frac{-13.76t}{\mathrm{RT}}} \quad (1) \qquad I_{t,buildup} = I_0(1 - e^{\frac{-13.76t}{\mathrm{RT}}}) \quad (2)$$

Figure 1 shows equation 2 for different values of RT (Reverberation time). The value of **Rise Time** (*TR*) will correspond to the point of time where 50% of the total energy has arrived:

$$\frac{I_{TR}}{I_0} = 0.5 \quad \text{which is shown to give:} \quad TR \cong 0.05\, RT\ [s] \quad (3)$$

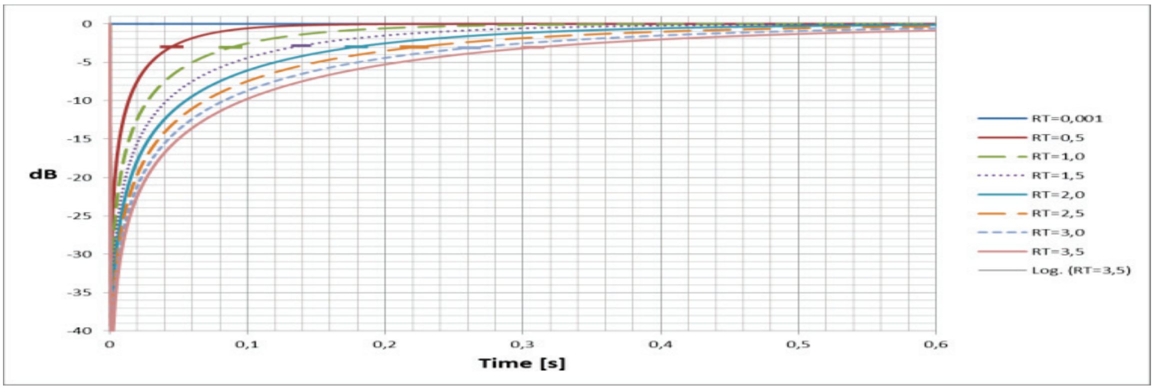


Figure 1 – Attack as a function of reverberation time following Eq.2

From Jordan[2] we find that:

$$10log\frac{I_{t,buildup}}{I_0} \sim 10log(1 - e^{\frac{-13.76t}{\mathrm{RT}}}) \tag{4}$$

It is further shown that at a level -5 dB below the stationary level, we get a calculated value of Steepness, $\sigma$ :

$$\sigma_{calc} = \frac{d}{dt}\left(10log\frac{I_{t(-5dB)}}{I_0}\right) = 0.0094\frac{13.76}{RT} \approx \frac{0.13}{\mathrm{RT}[s]} \;\; [\mathrm{dB}\ /\mathrm{ms}] \tag{5}$$

Schroeder[1] states that for enclosures with nearly exponential reverberation, the time $t_0$ at which the sound intensity during the build-up process has reached a level 5 dB below steady state, is typically 1/40 of the reverberation time $RT_{60}$. Schroeder further states that a more convenient and accurate method of measuring steepness is *'measuring the echo amplitudes of the enclosure near $RT_{60}$/40 after excitation'*.

## 3. ROOMS WITH NON-EXPONENTIAL DECAY (EARLY REFLECTIONS)

For standardised measurements of reverberation time, one often "forgets" the very first part of the decay, and starts the calculations after -5 dB decay. This is of course beneficial for the reproducibility of the measurement results, but we lose a lot of interesting information about possible coloration due to very early reflections etc., see Halmrast[3]. Regarding the shape of the build-up, Jordan[2] states: *'When one considers that the sound paths which are effective in determining the steepness are those which occur early in the build-up process and include the reflections with short time delays, it would seem possible to influence the value of steepness. If, for instance, reflecting surfaces were placed in some sound paths between source and receiver...... then this would correspond to a reduction of the effective mean free path in an early interval of the build-up process'.*

Several investigations conclude that measuring the Early Decay Time gives a better judgement of the perceived reverberation in a hall (especially for "running music"). Measurements including the first part of the decay, however, often give somewhat different results for different sender positions on stage. Such differences should in fact be considered important. (We should also remember that measurements on an empty stage often gives results that are repeatable, but not practically interesting).

## 4. LISTENING AND ANALYSING

### 4.1 Same music performed in different acoustic settings in Stavanger Concert Hall

For the IMS conference on musicology in 2016, the author had the possibility of playing with a group of musicians and recording the same short pieces of music in different acoustic settings in Stavanger Concert Hall (See Halmrast[5]). The same music was played on the same instruments for three settings in the Valen concert hall (a highly flexible hall, with both flexible absorbers on walls and flexible ceiling), and one "jazz-club"-setting in the flexible Zetlitz hall. The settings in Valen were named *2.Chamber* ($T60_{mid.frq}$=1.9s), *4.Amplified* (a setting used for amplified events) ($T60_{mid.frq}$=1.7s) and *6.Concert* ($T60_{mid.frq}$=2.5s). The musicians were instructed to keep same strength for all settings (as good as possible). The recordings were done at the same position on the 8$^{th}$ row, slightly off-centre, with the same recording level for all settings. The main results are given in Halmrast[3,4]. The music was: classical trumpet a cappella followed by a string quartet (and trumpet) (material from Mahler 5$^{th}$), jazz piano trio and rock guitar trio, both with trumpet soli.

All music was performed without the use of any house amplification (only guitar and bass personal amplifiers with exact the same levels etc. for all the acoustic settings of the hall). Analysing the recordings, we found that the differences, both in level and overall frequency content were surprisingly small. This could of course be discussed regarding “performology”, (how the musicians compensate for the acoustics, even when told not to do so), but for this paper, the most interesting result was that the “driest” settings sounded much more “brilliant”/high-frequency than the more reverberant settings. The note lengths were analysed, and they of course increase with increased reverberation time. For “the same” snare drum stroke, the length was 0,27 s in the dry *5.Zetlitz* setting, increasing to 0,40 (*2.Aplified*), 0,41 (*4.Chamber*) up to 0,44 s for the *6.Concert* setting. The increased length of each note due to reverberation of course gives that one note “masks” the attack of the next one (if the first one is not very, very short or the time between the notes are very long). This “masking” effect of reverberation is well known. The effect reverberation has on the attack also for the “the first note” is not so well known, and the main issue for this paper. (Close inspections on the spectrograms might indicate that in the most reverberate settings, the high frequencies “arrive later”, giving additional “smoothing” to the attacks). (see Halmrast[5]).

### 4.2 Convolution of “dry” recordings with impulse responses

We must remember that the general equations for the build-up of the attack in part 2 are only valid for long signals. Noise bursts: very short, longer and much longer, were convolved with Stavanger Concert Hall in most reverberant *6.Concert* setting. The following figure shows sound pressure level over time for increasing length of the noise burst. *Black:* dry noise bursts, *Lime:* Convolved with IR measured on stage (close reflections). *Blue:* Convolved with IR from stage to hall in Stavanger (most reverberant setting, *6.Concert*).

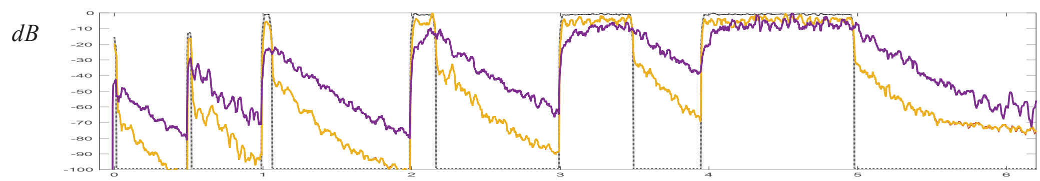


Figure 2 - Noise bursts of increasing length. *Black*=dry, *Lime*=short RT, *Blue*=Long RT

Seen from the left, fig.2 shows that very short notes are clearly detected without any prolonged attack phase, because they do not “build-up” in the reverberant room. For the longest reverberation, the attack for longer notes (to the right in fig. 2) are severely prolonged. The decays, however, are similar for all the situations. This simple analysis shows that the room´s influence on the attack not only depends on the reverberation time, but also on the length of the signal (and of course also on the instruments own “onset time”/“attack time”/ “fade in”).

The guitar is a good instrument for analysing attack. The guitar did not play any a cappella parts in the tests in Stavanger, but a dry guitar lick (without distortion pedal), was convolved with a very moderate reverberation (like in *5.Zetlitz*), and with the long impulse response measured in *6.Concert.* From the fig. 3 we clearly see how the reverberation smoothens and prolongs the attack.

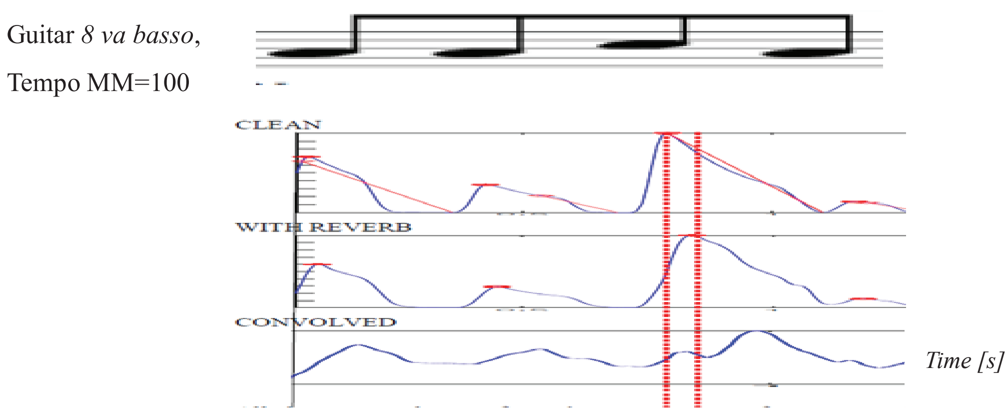


Figure 3 – Guitar Lick. *Upper*=clean/dry, *Middle*=Convolved short RT, *Lower*=Convolved Long RT

## 5. MEASURING ATTACK

At the moment, a lot of investigations on attack is done, for instance at the Ritmo[6] Centre at Dept. of Musicology at Univ. Oslo. However, most of this work is done regarding rhythm, finding the so-called *p-centre* of the musical event. The effect of attack on timbre is little discussed in literature, but a sharp (short) attack is usually said to be perceived as more "trebly". Hajda[7] mentions attack as: *´that period of the signal in which the global RMS amplitude is rising and the spectral centroid is falling after the initial maximum´…..'In general, three acoustical parameters repeatedly appear as correlates to dimensional solutions in timbre studies: 1. Amplitude-vs-time (temporal) envelope, usually expressed in terms of attack or rise times. 2. Spectral energy distribution across frequency components. 3. Spectral variance in terms of the amplitudes of frequency components.* Comment regarding 1*: Log-rise-time = log10($t_{max} - t_{thresh}$), where $t_{max}$ is the time from onset to maximum RMS amplitude and $t_{thresh}$ is the time from onset to a threshold taken as 2% of the amplitude at $t_{max}$'*. Here we see yet another, similar, but not identical definition of Rise Time. (See also Vos[8]).

A big problem when measuring timbre of attack is of course that the attack is so fast, and a good frequency analysis requires measurement over a long time ("window"). The next problem is uncertainty about our hearing: How long time do humans actually integrate over, when the sound is changing? Using very small time windows for the analysis will separate the direct sound and the very early/early reflections, and indicate longer attack duration with early reflections than without. Often one states that up to 80ms adds clarity for music, but that cannot be the case if the signal is very short. Often 20 ms is suggested for our integration time. We have analysed both for 10 ms and 20 ms, as very early reflection often arrives within such time limits. Some researchers use 7ms as the limit for "stage reflections" that is included in the direct sound, (even if they are not really direct sound).

Meyer[9] states*:"…..the perceived point of tone entrance lies about 10 dB below the final sound level, or the masking threshold (in the presence of pre-existing noise), and this is relatively independent of the speed of the attack. For very soft tones the point of attack can move as close as 7 dB to the final sound pressure level, i.e., it is sensed even later. For very loud tones, the tone entrance is already perceived at a sound pressure level of 15 dB below the final value".*

For the actual design of a hall, one should of course also pay attention to the direction of the reflection, and if a single, distinct reflection gives audible coloration (comb filter with a distance between the dips (or CBTB, Comb Between Teeth Bandwidth) that is in the order of the critical band, which means delays in the region 5-25 ms, see Halmrast[3].

In electronics, **Rise Time** is the time taken by a signal (step function) to change from a specified low value to a specified high value. These values may be expressed as ratios or as percentages or dB values with respect to a given reference value. In analogue and digital electronics, the percentages are commonly the 10% and 90% of the output step height, however, other values are commonly used. (Examples of "other values" are -5 /-3 dB mentioned in part 2). We shall see that these parameters often are too "general", so we need to examine the attack more in detail.

The method we found most convenient was to integrate the squared impulse response, which also might be called a Cumulative Step Response. This method has some resemblance with Griesinger[12] work on LOC (without the discussions about phase coherence and neural "firering"). Fig.4 shows the measurements in a shoebox hall with reasonable exponential decay, in University Aula, Oslo (empty). In the left pane, we see the squared impulse response (up to 2s) (blue) and the integral of this (red). The middle pane shows a zoom in of this Integrated Imp. Resp. (up to 0.4s). To the right is shown the common decay and the Schroeder curve.

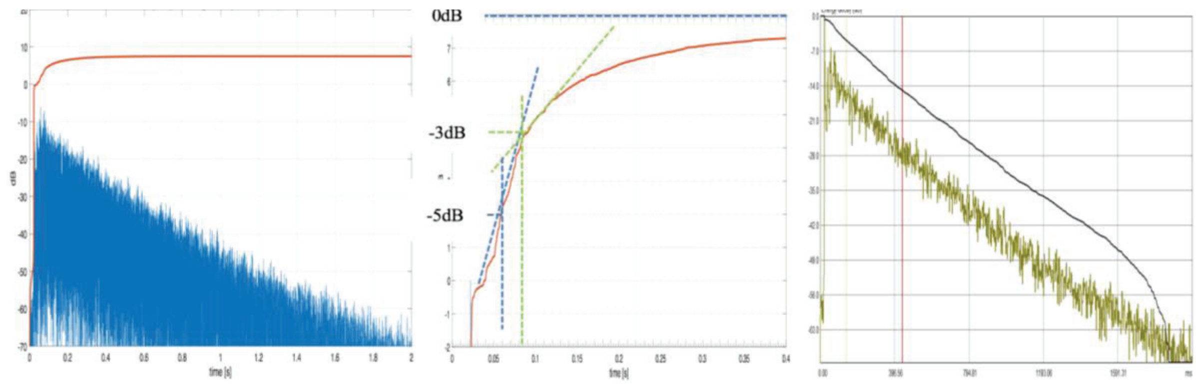


Figure 4 – *Left:* Imp.Resp. and Int.Imp.Resp. *Middle:* Variation of Steepness during attack phase. *Right:* Imp.Resp. and Schroeder curve.

The reverberation time (T30 and T20) for this hall is app. 2.2 s (empty, mid freq.). According to Jordan (in Part 2), Steepness should then be 0.13/RT= 0.13/2.2=0.059 dB/ms. From the middle pane in the figure above, we see that the steepness is changing during the attack, but we find a typical value around the -5 dB point of 0.087 dB/ms, and 0.033 dB/ms around the -3 dB point. The mean value of these might actually correspond quite well with Jordan. From the same figure, we find that Rise Time (up to -5 dB) is 38 ms. For the build-up unto -3 dB, we get a Rise Time of app. 60 ms. The calculated rise time, TR according to Jordan (up to -5 dB), should be 0.05 x 2.2 = 0.110 s= 110 ms. As a conclusion, both Steepness and Rise Time give measured values that deviate from the equations for exponential decay (and build-up). The hall is a moderately small regular shoebox, so this hall, if any, should be assumed to have exponential decay. One reason why even this hall differs from the equations might be that it actually has some (nice) early reflections. Keeping in mind that the measurements highly depends on where on the build-up curve we analyse these parameters, we should not relay too much on either Rise Time or Steepness before we have more measurements from different halls. For now, we should inspect the shape/curvature of the Integrated, Cumulative Squared Impulse Responses itself in order to find the interesting issues of attack.

## 6. MEASURING ATTACK IN ROOM ACOUSTIC MODEL

### 6.1 The model

A very simple, large hall was modelled in Odeon, with sidewalls and rear wall behind audience as reflective, highly diffusing/scattering. Dimensions: L x W x H = 46 x 31 x 20 m. Receiver: 30 m distance, 1m off centre, height 2 m. Three different settings of a "box" around the source were analysed, called; *Transparent*, *Reflecting* and *Absorbing*. Especially the two last ones will be discussed here. The following figure shows the room, the reflection patterns for settings *Reflecting* and *Absorbing,* up to 20 ms (when we see that the reflections from the sidewalls appear).

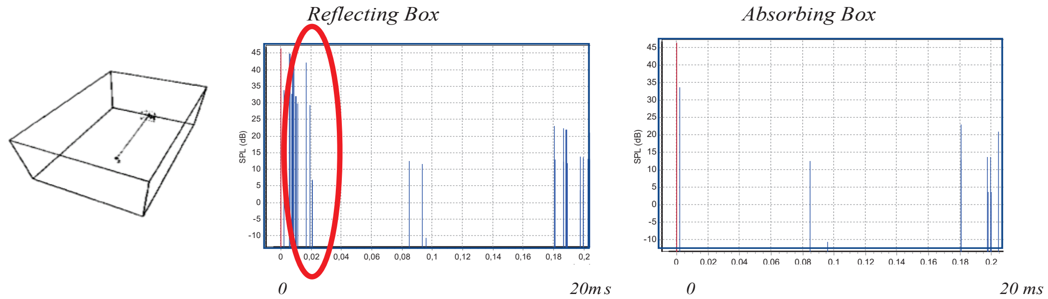


Figure 5 – Odeon model. Reflection pattern with/without early reflections

Fig. 6 shows both the impulse responses, up to 320 ms.
(PS! For the first part, the curves are identical, so the red curve is covered by the black one).

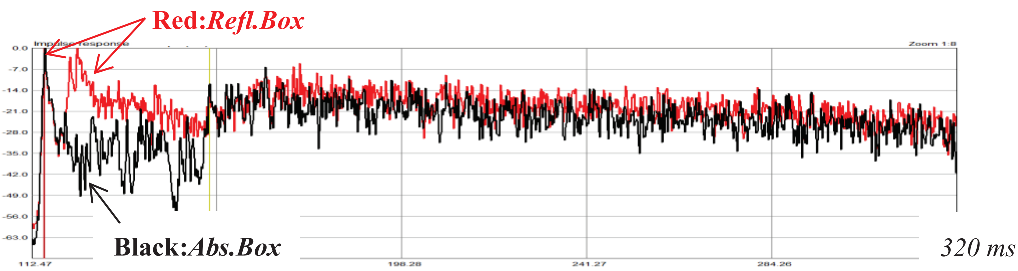


Figure 6 – Impulse response with/without early reflections (Odeon)

Comparing the common acoustic parameters for *Refl.Box* and *AbsorbBox,* we find that the close reflections give an increase in C50 and C80. Spectral centroid for the Impulse Responses is also increased from 7165 Hz to 7504 Hz due to the close reflections. The close reflections changes EDT more than RT. (For this simple simulation, it seemed like the close reflections gave an increase in EDT for 500 Hz and below, but a decrease for 1 kHz and above. This should be investigated further, together with close examination of the EDT algorithm in use, as the first reflection(s) actually might be stronger than the direct sound, and make confusions in choosing the exact time of arrival of the direct sound).

### 6.2 Analyses of attack from the room models

Fig. 7 shows the impulse responses (lower) and the integrated, squared response for *Reflective Box* (blue) and *Absorbing Box* (yellow) (up to 0.5s, 10 dB division).

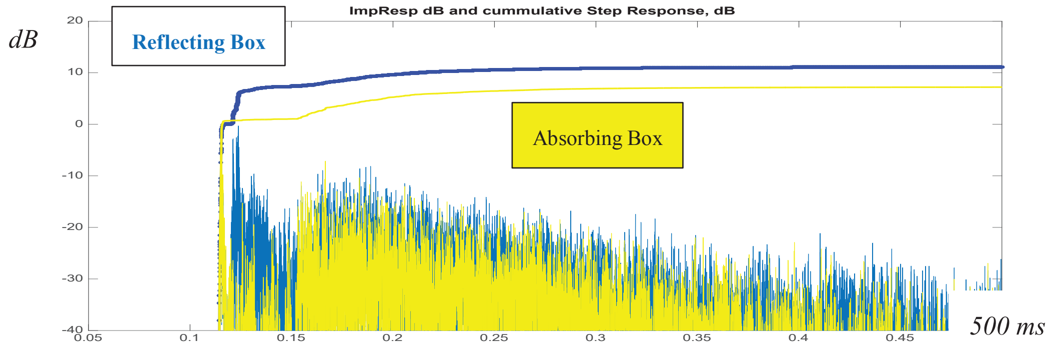


Figure 7 – Impulse Response and Integrated Impulse Response.
*Blue*=With early reflections, *Yellow*=without early reflections.

From fig. 7 (and fig. 4) we see that measuring attack time ("rise time") as the time for the signal to reach -5dB (or -3 dB) seems to be a much more complicated affair than stipulated for the theoretical exponential decay situation discussed in part 2. Measuring Steepness (dB/ms) is perhaps more convenient than Rise Time, but both are very problematic, since the slope of the attack changes radically over time, and in a different way with/without early reflections. The following figure shows the differences in the attack-curvature for the 3 settings, and we see that *Refl.Box* has the sharpest/fastest attack. (1 dB division).

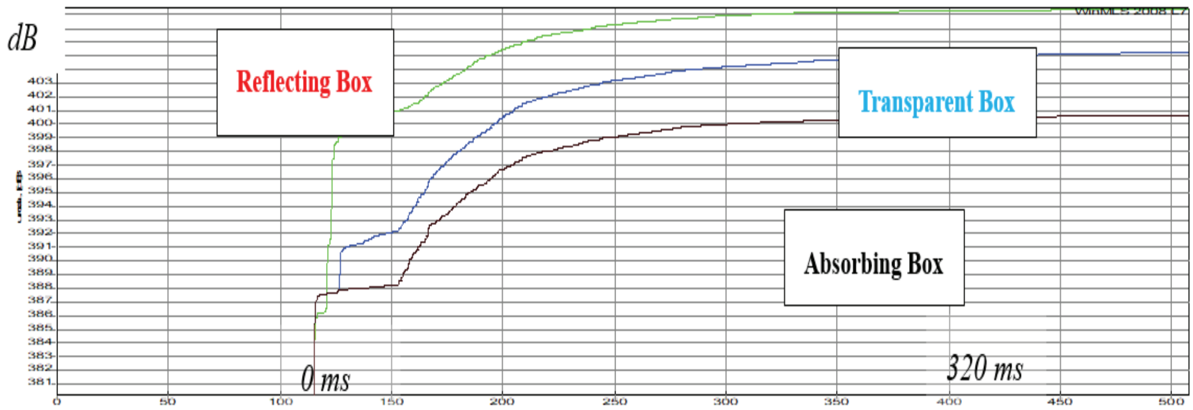


Figure 8 – Integrated Impulse Response. *Red*= with early reflections, *Black*=without early reflections: (*Blue*= with transparent box, not discussed)

We also did analysis of Spectral Flux, which might give indications of attack. See Halmrast[5] for discussions about Spectral Flux measurements using MIR Toolbox[10] and Mining Suite[11] compared to other methods, and the problems regarding choice of window lengths for Spectral Flux analysis of attack.

### 6.3 Note Length and Musical Instruments own attack time/build-up

Figure 9 shows a short musical phrase that was played by different instruments, "dry" and convolved with the measured impulse response from the most reverberant setting in Stavanger Concert Hall. The figure shows a comparison of the attacks for an instrument with very short sounds; a xylophone, compared with a "slow reacting" and long sustaining instrument; a bowed violin. We see that for the convolved curves, the attack is preserved as rather short for the xylophone, but prolonged for the violin. We also see that for the violin, the decay (and sustain) of one note masks the entrance of the next. Listening to these examples, each note is heard separately for the xylophone, and the first attack is rather well preserved, but the violin has a got an added build-up for the first note, and the second and especially the third note is almost not perceived as a new attack, but is masked by the first notes. (Total length is 1.5 s. Division is 5 dB).

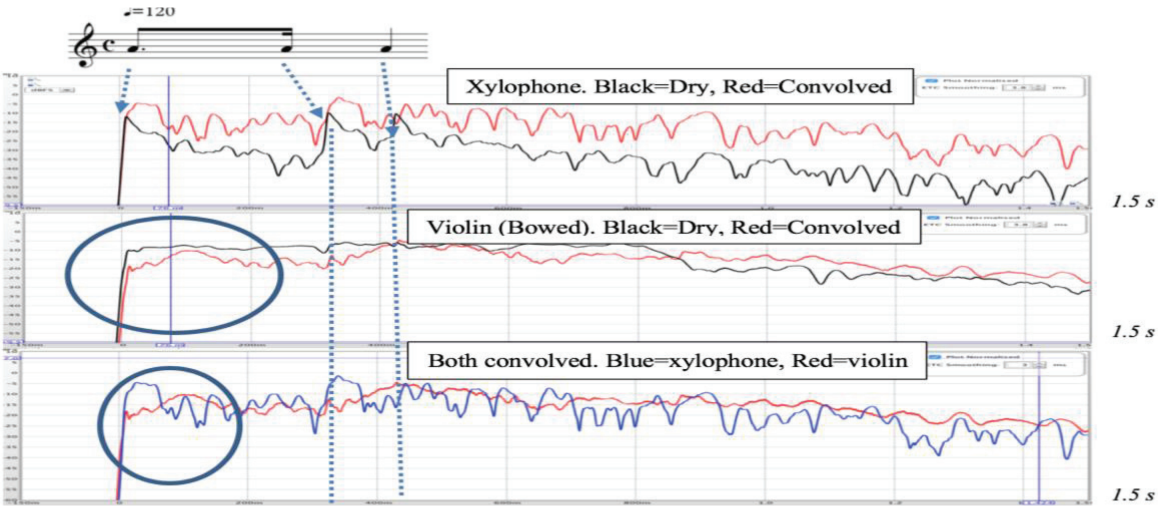

Figure 9 – Analysis of xylophone and violin playing the same music. Dry and convolved with long RT

Further investigation (see Halmrast[4]) shows the important decisions we have to make when analysing small differences in short attacks. If we assume that our ear has an integration time of 10 ms (or more), the setting with close reflections, *Refl.Box*, will be perceived with the "clearest" attack.

The bowed violin has very slow internal build-up so it would be more problematic to find the influence of close reflections in order to preserve the attack.

## 7. MEASUREMENTS IN A CHURCH

Stavanger Concert Hall has nice early reflection (that is why the hall works reasonably good also for percussive music in settings with long reverberation, and we can, of course not get rid of all these reflecting surfaces close to the stage for a quick comparative test). Measuring in a general room, we must also consider that the directivity of the source, possible floor reflections and surfaces close to the receiver/mic are of great importance in our simple analysis of the influence of close reflections on attack. For a simple test, impulse responses (handclaps) were recorded in a church with a reverberation time of app. 2.4 s. The following figure shows spectrograms for the first 0.3 s and the attack curve for sender position *Without* (aisle) and *With* close reflections (pulpit).

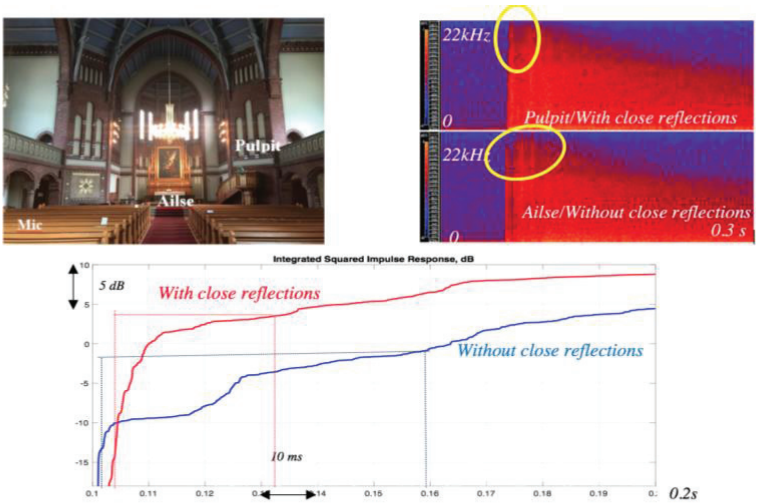


Figure 10 – Imp. Resp. measured in a church.
Spectrogram and Int.Imp.Resp. with/without close reflections

We see that the overall attack is faster with the close reflections. If we should want to measure the Steepness, we would need to closely define which part of the curve is interesting (especially for the blue curve). Quick estimations of Rise Time (to –5dB) gives: $TR_{WithCloseReflections}$ = *30ms,* and $TR_{WithoutCloseReflections}$=*58 ms.* Schroeder´s "rule of thumb" for exponential decay in Part 1 gives: $2.4s/40 = 60\ ms$ so, for this quick test, the agreement is nice for the measurement without close reflections, and the close reflection practically halves this attack time. However, until we have more analyses and simulations, we should inspect the shape of the attack curve in detail and compare with the typical note length, and not rely too much on parameters like Steepness and Rise Time.

## 8. CONCLUSION

Reverberation “smoothens/prolongs” the attack. For rooms with an exponential decay, the build-up of the attack can be determined from the decay. However, most interesting halls do not have exponential decay, especially in the early part, and we need to investigate the attack more in detail.

**Integrated, Squared Impulse Response** (Cumulative Step Response) is a good way of investigating attack. Parameters like Rise Time and Steepness can be derived from this, but for many interesting situations with early reflections, the curvature of the attack is non-uniform and we should inspect the actual shape of the curve rather than trust these parameters. It is shown from computer simulations and measurements in a church that **early reflections** in some cases might help preserving a somewhat short attack time for halls with long reverberation times.

The effect reverberation (and early reflections) have on attack is highly dependent on the type of musical signal. Extremely short, bright signals can be so short that they do not “build up” due to the reverberation at all. Instruments with long internal build-up/onset (like bowed strings) get a nice development from the smoothed attack due to long reverberation time in the hall. For most instruments in between these groups, there is a problem of “smoothing” due to prolonged attack from the reverberation. This can be reduced by introducing early reflections.

For the design of halls, however, we must also remember that distinct early reflection might give comb filter coloration (see Halmrast[3]), and take the direction and delay times of the early reflections into consideration (see Halmrast[13,14]). Preserving the attack is important also because listeners nowadays are used to recordings where any wanted amount of direct sound is mixed with a late, long and (too?) smooth, non-correlated, digital reverberation.

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