Detection of Colouration in Rooms by use of Cepstrum Technique

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Introduction

Colouration is an unwanted effect in rooms for speech and music. While very easy to hear when present, it is difficult to measure objectively. Examples of colouration problems include orchestra stages with suspended overhead reflectors, meeting rooms and talks studios with parallel hard walls. While colouration can easily be detected by listening, it is difficult to measure objectively. The cepstum technique is suggested as a method that can indicate a possible problem with colouration. The method has been applied successfully to a number of examples not only with measurements, but also by analysis of simulated impulse responses.

Colouration

Colouration can be caused by a single sound reflection that interferes with the direct sound. If the time delay of the reflection is Δt, the frequencies $f_n = n/\Delta t$ are amplified, while other frequencies in between are attenuated. This is also called a comb filter, and the effect can be quite disturbing when listening to speech or music. Colouration can also be caused by multiple reflections, like a flutter echo between parallel walls.

The cepstrum technique

The cepstrum of a signal is the inverse Fourier transform of the logarithm of the spectrum. Thus it brings the signal from the frequency domain to a new domain with the unit seconds (or preferably ms). In order to distinguish from the time domain, the independent variable in the cepstrum is called quefrency. It is noted that the terms have been made by reversing the order of the first letters in the words spectrum and frequency. The first use of the cepstrum was in the 1960'ies for echo detection in seismology [1], for speech analysis [2] and for echo removal [3]. Later the technique was applied to machine diagnostics by Randall [4, 5].

The cepstrum analysis is very efficient to find any periodic behaviour of the spectrum. So, a single peak in the cepstrum at quefrency Δt is an indication that the spectrum contains harmonics with frequency spacing $1/\Delta t$. The idea to use cepstrum for detecting colouration was first presented by the author in ref. [6], where it was used to evaluate the effect of reflector panels over the orchestra stage in a concert hall. In that reference the typical threshold for audible colouration was found to be a peak value 0.5 to 1.5 dB at a quefrency Δt between 5 and 50 ms. At that time the B&K 2032 analyser was used for the cepstrum analysis, and the ordinate was in dB relative to the average minimum of the cepstrum. More precisely, the mean log spectrum was subtracted from the log spectrum before calculating the cepstrum.

Implementation in ODEON

Measurements

Room acoustic measurements have been implemented i ODEON using an exponential sine sweep to generate the room impulse response in accordance with ISO 18233 [7]. An FFT of the impulse response provides the transfer function. The cepstrum is implemented as the inverse Fourier transform of the natural logarithm of the squared amplitude of the spectrum. It is noted that the unit of the ordinate is not normalised in the current version (ODEON 14 beta, February 2016).

Simulations

In order to apply the cepstrum analysis to a simulated result, the impulse response is generated with a unity filter instead of the HRTF filter normally used for binaural auralisation. Then the simulated impulse response is loaded as if it were a measured impulse response, and the further analysis is identical to that of a measured signal.

Case – a meeting room

A small, box shaped meeting room is used as an example case, see Figure 1.

Figure 1: The meeting room with sound source and microphone on opposite side of the table.

The dimensions are $L * W * H$ = 6,56 * 3,07 * 3,00 m. While the ceiling has some absorption, the other surfaces are hard and reflective. The two walls with the shorter distance are a smooth brick wall with painted plaster and a smooth drywall. A table with height 0.83 m is in the middle of the room. Reverberation time T_{20} is around 0,8 s with minor variation with the frequency, see Figure 2.

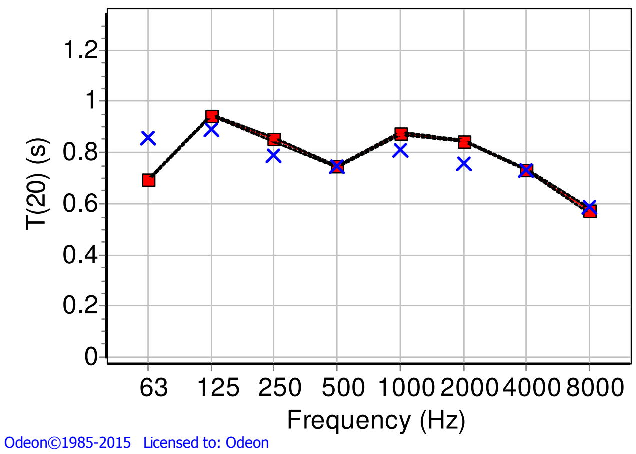

Figure 2: Reverberation time T20 in octave bands; measured (blue crosses) and simulated (red dots).

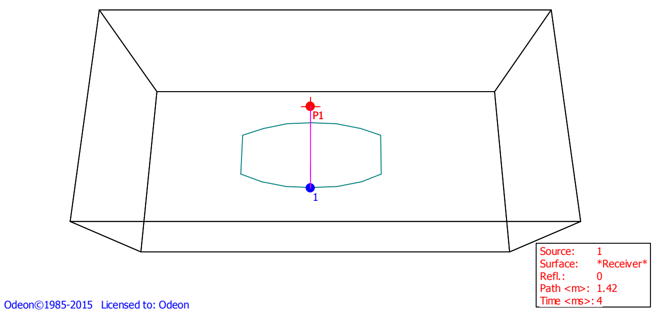

Figure 3: Model of meeting room with source (red) and receiver (blue).

A sound source and a microphone were placed at a height 1.2 m above the floor and in a distance of 1.42 m on either side of the table as shown in Figure 3. The direction of the direct sound between source and receiver was perpendicular to the longer side walls. The distance between the reflective side walls is 3.07 m which corresponds to a time delay of 8.9 ms. A flutter echo or colouration effect with this period could be expected.

The first reflection due to the table has a time delay of 0.5 ms. This reflection might cause a comb filter effect and thus an audible colouration. The first reflections from the nearest walls have time delays of 4.5 and 5.0 ms, respectively. These reflections may also cause some colouration.

The measured and simulated transfer functions are seen in Figure 4. It is not possible to see whether or not there is any periodicity in these spectra. Above 125 Hz the measured and simulated transfer functions looks similar, but at lower frequencies there are obvious differences. This is partly due to the reduced sound power of the loudspeaker at low frequencies.

The two cepstra derived from the measured and the simulated transfer functions, respectively, are seen in Figure 5. The ordinate axis is not calibrated and the units are quite arbitrary. In both cepstra is seen a peak around 9 ms as expected due to the parallel side walls

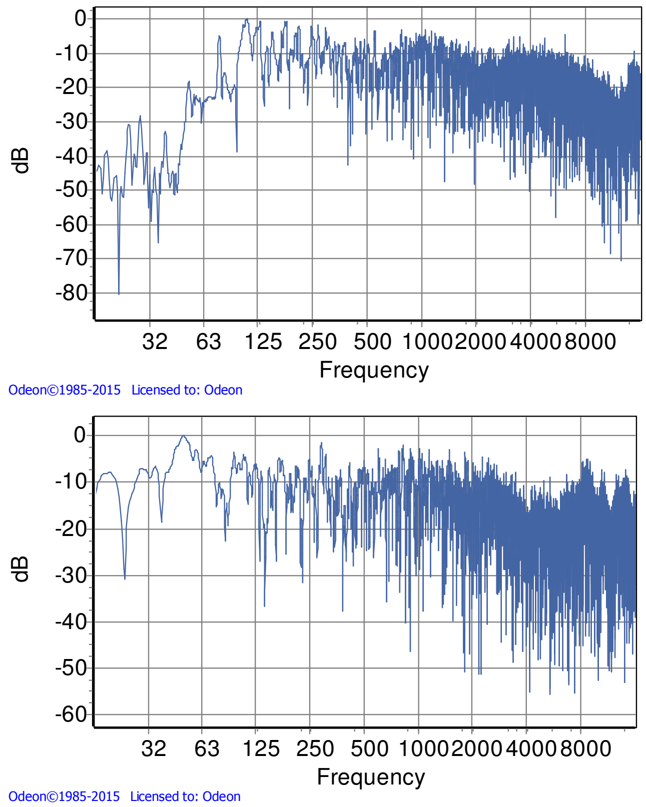

Figure 4: Transfer function between positions in Figure 1. Above; measured. Below; simulated.

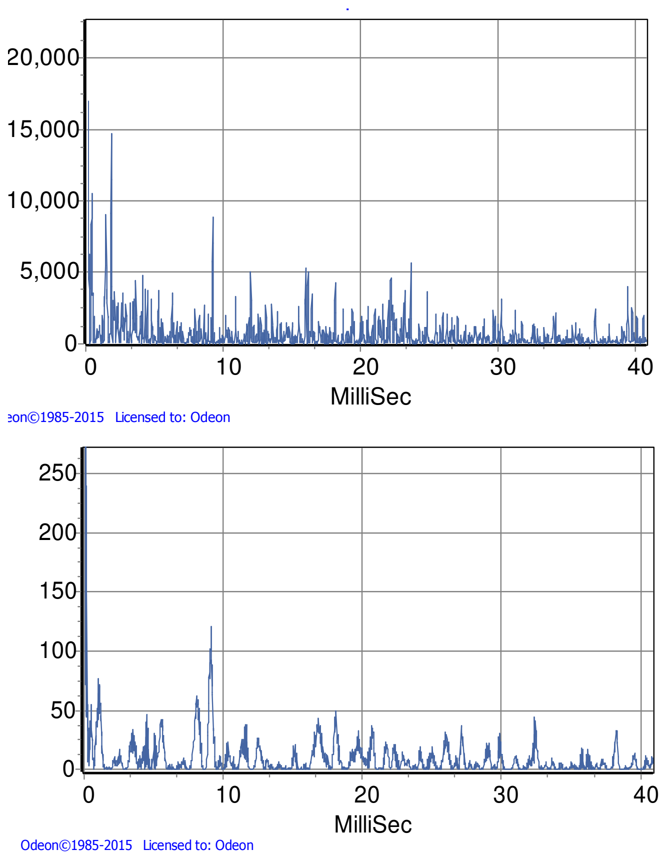

Figure 5: Cepstrum derived from the transfer functions shown in Figure 2. Above; measured. Below; simulated. Both show a peak at 9 ms.

Measures against colouration

Colouration, which is due to multiple reflections between parallel surfaces, can be reduced or removed in different ways just like measures to avoid flutter echo:

- Increase sound scattering, i.e. the rough structure of the surfaces
- Angling or tilting the surfaces a few degrees to avoid parallel surfaces.
- Increase sound absorption of the surfaces

In the case studies here the scattering coefficient of the sidewalls at mid frequencies was set to s = 0.01. This represents very smooth surfaces. (In ODEON the scattering coefficient due to roughness of a surface is automatically set to increase with frequency in accordance with typical measured data).

A new simulation was made with the scattering coefficient of the side walls increased to s = 0.10 at mid frequencies. The cepstrum derived from this simulation is seen in Figure 6. The peak around 9 ms is now reduced and has almost disappeared.

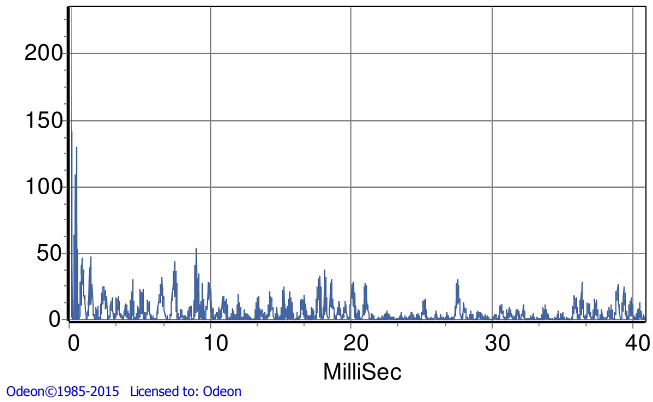

Figure 6: Cepstrum from simulation with increased scattering on the sidewalls; s = 0,10 at mid frequencies. The peak at 9 ms has almost disappeared.

Angling one sidewall by 5° was also tried, and the cepstrum derived from the simulation is seen in Figure 7. The peak at 9 ms has disappeared, meaning that the colouration due to parallel sidewalls has been avoided.

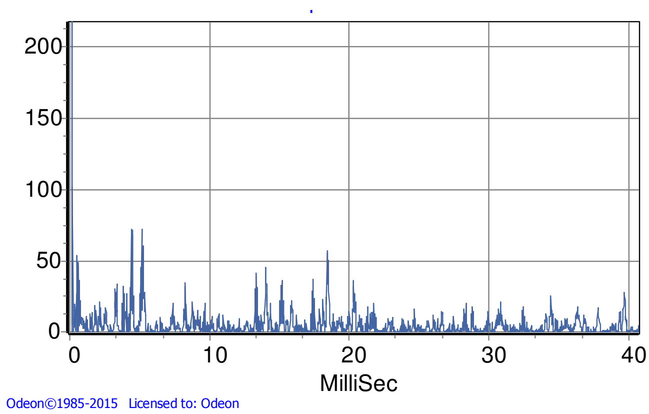

Figure 7: Cepstrum from simulation with one of the sidewalls angled 5°. The peak at 9 ms has disappeared, while the peaks at 4.5 and 5 ms are more pronounced.

While the angling of one wall efficiently removes the colouration due to multiple reflections, the colouration due to the first reflection from each of the sidewalls remains, and seams more pronounced than before.

The absorption coefficients at 1 kHz of the sidewalls were 0.02 and 0.09, respectively. A new simulation was made with the absorption coefficient of the sidewalls increased to 0.20 at all frequencies. The cepstrum derived from this simulation is seen in Figure 8. Again, the peak around 9 ms is significantly reduced. Instead, peaks are seen around 5 ms, which may be due to the first reflection from the nearest wall.

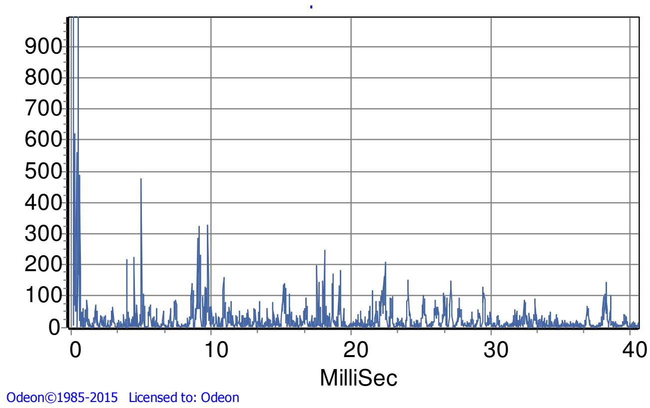

Figure 8: Cepstrum from simulation with increased absorption on the sidewalls; α = 0.20. The peak at 9 ms is reduced.

In Figure 9 the previous cepstrum is zoomed to show the peak at 0.5 ms. This is expected and represents the colouration due to the table reflection. Actually, this can be found in all the cepstra from the previous figures. The peak at 0.5 ms disappears when the table is removed from the room (not shown).

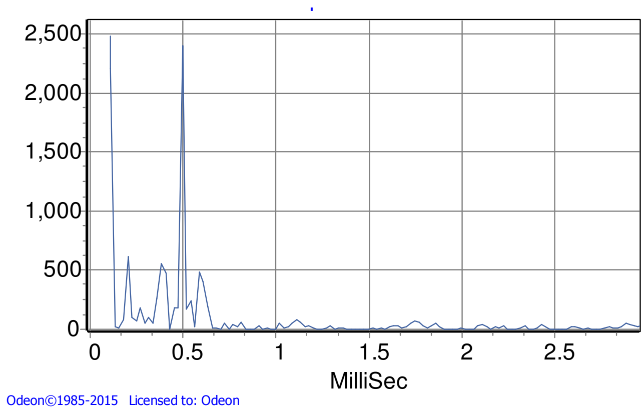

Figure 9: Zoom of cepstrum in Figure 8. The peak at 0.5 ms represents the comb filter effect due to the reflection from the table.

Conclusion

Colouration can be caused either by a single reflection with short time delay or by multiple periodic reflections. While flutter echoes are audible in the time domain as a series of repeated reflections, a flutter echo with sufficiently short periodic time delay is heard in the frequency domain as a colouration of the sound.

It is shown that the cepstrum analysis may offer a method for objective evaluation of possible colouration in a room. In a meeting room with parallel walls, the cepstrum showed a peak at a quefrency equal to the time for sound to propagate between the walls. This peak and thus the colouration can be reduced in three different ways; increased scattering of the walls, angling the walls, or increasing sound absorption of the walls.

It is also shown that the colouration due to a single early reflection from a table is detected as a peak in the cepstrum.

The cepstrum can be derived from measured or from simulated impulse responses. However, further work is needed on the implementation. Especially the ordinate axis seems to be quite arbitrary, and a solution is needed for a proper scale on the ordinate. When this is solved, the threshold for audible colouration should be determined through listening tests.

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