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# ORCHESTRAL TIMBRE
# COMBFILTER-COLORATION FROM REFLECTIONS

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Coloration is defined as changes in Timbre/"Klangfarbe". Coloration might be the reason why an orchestra-/opera-hall sounds bad, even if all the common room acoustic parameter show good results. In this paper we will take a closer look at the reflections within the time-intervals commonly used for the room acoustic parameters, investigate their contribution on coloration, and compare our results with psycho-acoustic studies.

Part 1 shows that placing reflecting surfaces closer to the orchestra will improve the ensemble-conditions, but might give undesirable coloration, like if the orchestra was "placed inside a small box". Such a coloration effect is called "Box-Klangfarbe".
In Part 2 it is shown that Coloration can be detected by analysing the Frequency Response of the first part of the Impulse Response between members of the orchestra. Such Through Orchestra Impulse Response (TOR)-measurements must be done with an orchestra on the platform to give information about coloration and ensemble conditions. We will call the difference between the successive dip´s in a comb-filter the "Comb-Between-Teeth-Bandwidth". It is shown that Box-Klangfarbe is likely to appear only when reflections give a "Comb-Between-Teeth-Bandwidth" that is comparable to Critical Bandwidth. A strong/discrete reflection with a time-delay of about 5-20 msec (Comb-Between-Teeth-Bandwidth of 200-50 Hz) will give Box-Klangfarbe. This time-delay region is called the "Box-Klang-Zone". It is shown that adding more reflections into this zone will reduce the Box-Klangfarbe. Part 3 shows that the results are valid also for the audience area. Part 4 shows good agreement with psycho-acoustical studies. In earlier studies, however, there seems to be an underlying assumption that all coloration must be "bad". Part 5 gives some practical/musical comments on "good" and "bad" coloration for orchestra platforms.

## 1) INVESTIGATIONS IN OSLO CONCERT HALL

Our work on orchestra-podium acoustics started with an investigations for the Oslo Philharmonic/Mariss Jansons in Oslo Concert Hall. This hall has triangular shape, a very large ceiling height over the orchestra, sidewalls placed far away from the orchestra, see Jordan [1] or Halmrast [2] for drawings and general information about the hall. Investigations for improving the musicians ability to hear each other were carried out in a full-scale test with the orchestra playing short musical examples, and in sequence introducing reflecting surfaces closer to the orchestra; (see [3] and App.A):

- *7 Flexible Suspended Reflectors, 2,8x2,8m, height 6-7m, over the orchestra,*
- *Flexible Walls at all sides, and*
- *"Tilted Top´s" of the sidewalls.*

The subjective impressions of these changes were reported in questionnaires by both orchestra and public seats. Sidewalls closer to the orchestra and "Tilted Top´s" on these were appreciated both by the orchestra and the audience. Suspended reflectors over the orchestra were appreciated by the orchestra, but not by the audience. (See App.A and [4] ). Fig. 1 shows that the questionnaire parameter "Klangfarbe"(Timbre) was improved for both the audience and the orchestra when introducing sidewalls closer to the orchestra and the tilted top´s of sidewalls, but reduced for the audience when adding the reflectors over the orchestra. Similar results, indicating that coloration is most likely remarked from the audience, is also given by Ando [5].

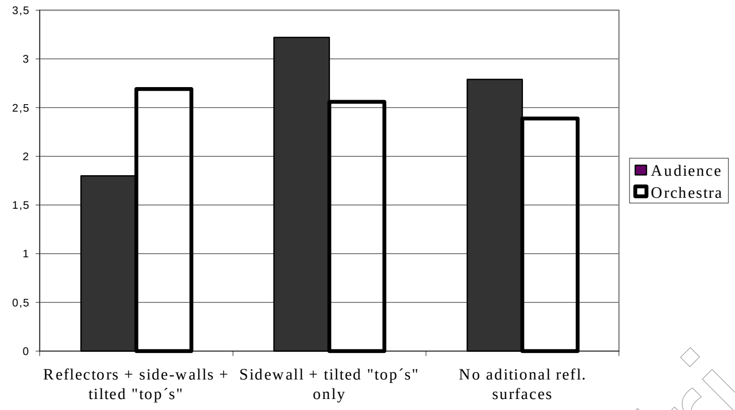


*Fig. 1 Score for the parameter "Klangfarbe" (Timbre).*
*Mean values for Orchestra and Audience. Arbitrary Score scale.*

Remarks were given that when introducing the suspended reflectors, "it sounds like if the orchestra is placed inside a bucket or a small box". The term "Box-Klangfarbe" will be used for this type of coloration. All the common room-acoustic parameters were analysed, but no significant changes indicating coloration were seen when introducing the reflectors over the orchestra, neither in the Odeon computer model [6], [4] nor in the room-acoustic measurements [3]. Even though coloration was most clearly stated from the audience area, we started using measurements on the stage in order to find the reason for the "Box-Klangfarbe", because the surfaces on the stage were the only ones changed during the test, and because the measuring-situation on the stage is much more controlled and gives more easy investigations of each reflection path. We decided to measure Impulse Responses Through the Orchestra, called TOR-measurements. In part 3 results from measurements to the audience area is given, showing similar conclusions as for the orchestra platform.

## 2) TOR –measurements (<u>T</u>hrough <u>O</u>rchestra impulse <u>R</u>esponse)

<u>2.1 About TOR-Measurements</u>

TOR-measurements are MLS Impulse Response Measurements used to investigate the acoustic conditions between different members of the orchestra. For information about the measuring equipment, see [7] and [3]. The TOR-measurements should of course be done between as many musicians as possible, but the most important measurements for overall orchestra acoustics and "klangfarbe" are the ones taken diagonally across the stage [3]. For the variation of the American Seating Order of the orchestra (see Meyer [8]) used by the Oslo Phil., the TOR-measurements were measured from the leftmost violin 1 to the right/rearmost double-bass/bassoon diagonally on the other side of the orchestra platform. All the TOR-measurements shown in this article are taken between such positions. Orchestra podium measurements should always be done with an orchestra on the platform, not for empty platforms, otherwise one will include a lot of reflections that will be absorbed by the other musicians, and this will reduce the possibility of detecting the reflections giving coloration, see [4].

TOR-measurements were performed for all the different stage settings in Oslo Concert Hall, and on tour with the Oslo Philharmonic in the following halls:

| |
|---|
| **1) Munich , Gasteig,** A hall with suspended reflectors over the orchestra in the same way as for the practical tests in Oslo Concert Hall. Some box-klangfarbe was reported. |
| **2) Vienna , Musikverein,** A reference hall. No suspended reflectors. No Box-Klangfarbe reported. |
| **3) Frankfurt , 100 Jahr-Halle, Hoechst**, A highly dispersed /scattering orchestra-shell combined with a very low-reverberant hall. Some Box-Klangfarbe was reported, (more than from Munich, but less than in Oslo w/suspended reflectors). |

For information about halls 1) +2) see Gade[9]. Note that for Munich/Gasteig, suspended plexi-glass reflectors over the orchestra have been introduced after Gades investigations.

2.2) Typical TOR-Impulse-Response with suspended reflectors

A typical Impulse Response from TOR-measurements on an occupied stage with suspended reflectors or a low ceiling over the orchestra is shown in fig 2.

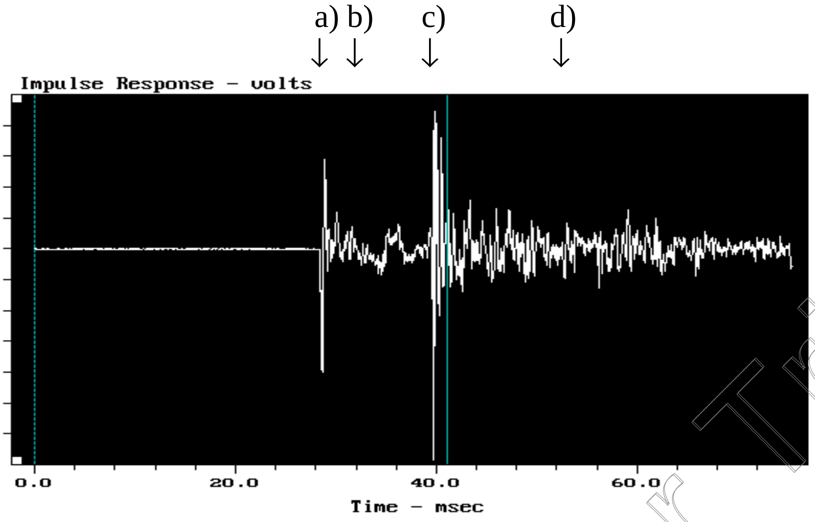


*Fig.2 Typical TOR-Imp. Response, for occupied orch. platform w/suspended reflectors (measurement from Oslo Concert Hall)*

- a) **Direct Sound**
- b) **Very Early Reflections**
- c) **Reflection from Ceiling/Suspended Reflectors**
  Note that with the orchestra on the platform, this reflection is stronger than the direct sound.
- d) **Late Early-Reflections** (> 25 msec after the direct sound)

2.3) FFT analysis for different time windows of the TOR-Impulse Response.

Taking the FFT of the whole measuring time (app.2 sec.), gives no visual indication of the coloration-effect reported, see fig.3:

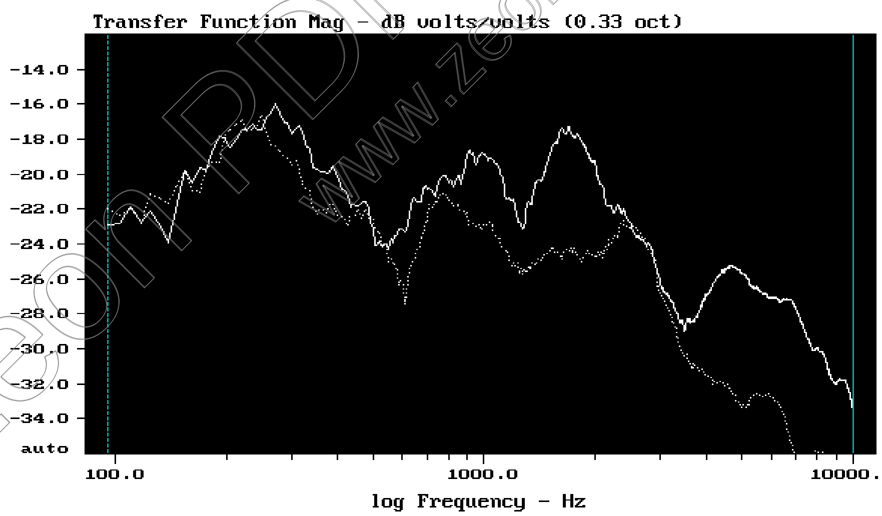


*Fig.3. FFT of the whole Tor-Impulse Response in fig.2 (app. 2sec)*
*With suspended reflectors (upper curve)*
*Without suspended reflectors (lower curve)*

We must use shorter time-windows for the FFT to see the "colorating" comb-filters. This corresponds to the fact that coloration appears rather shortly after the direct sound [10], see also Part 4.2.

We will now investigate coloration using shorter time-windows for the FFT of the TOR-Impulse-Response in fig. 2, successively increasing the time window. We will compare these Short-Time FFT´s with the detailed information about klangfarbe given from the questionnaires and the distances/time-delays from each reflecting surface introduced in the test [3].

*Region **b***: Introducing surfaces that give Very-Early-Reflections in fig.2 (sidewalls close to musicians etc.) were reported not to give any Box-Klangfarbe for the overall orchestra-klangfarbe. Fig. 4 shows the FFT of The TOR-Impulse-Response in fig. 2, taken for a time interval up to 7 msec after the direct sound. We see some broad, but not clear, combfilter-effects. A strong/discrete reflection within time region ***b*** would, theoretically, create a broad combfilter with more than some 300 Hz between the dip´s. Combfilter-coloration from Very-Early-Reflections is discussed further in Part 5.

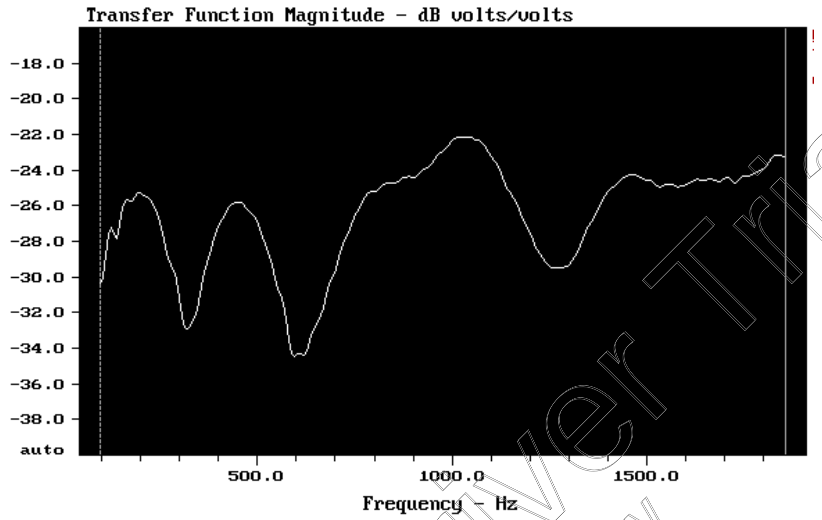


*fig. 4. FFT of Impulse Response in fig. 2. (linear frequency scale)*
*Time window up to 7 msec after direct sound*

*Region **c***: Introducing the suspended reflectors was reported to give Box-Klangfarbe. Fig. 5 shows the Short-Time-FFT of the TOR-Impulse-Response in fig.2, taken for a time window up to 13 msec after the direct sound, indicated by the cursor in fig.2, just including the reflection from the suspended reflectors. We see a clear Comb-Filter-effect. We define the "Comb-Between-Teeth-Bandwidth" as the distance in Hz between two successive dip's.

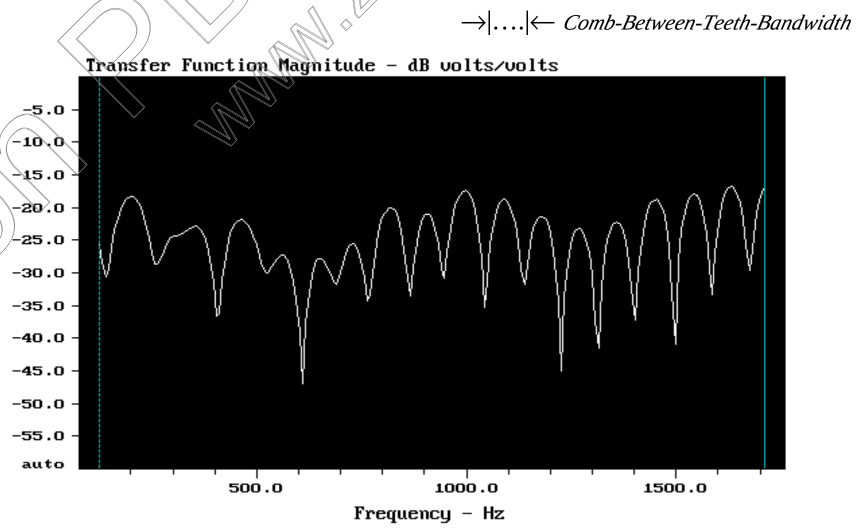


*Fig.5. Short-Time-FFT of Impulse Response in fig.2.*
*Time window up to 13 msec after direct sound. The "Comb-Between-Teeth Bandwidth" is indicated.*

*Region **d***: "Late-Early-Reflections". No reports of Box-Klangfarbe was given due to introducing reflecting surfaces with a time-delay in this region . The TOR-FFT-analysis including this time region shows no clear comb-filter, only additional small "ripples" to the main "envelope" created by the reflections in the earlier parts , like the "ripples" in fig. 3. If a hall had a "lonesome", discrete reflection in this time-region it would create a “Comb-Between-Teeth-Bandwidth” of less than 30 Hz. When we increase the time delay of the reflection further, we enter the “time-domain”-region of sound-perception, and a “lonesome” reflection will be perceived as echo, not as coloration.

2.4) The influence of the height of the suspended reflectors

The hall in Munich was reported to give somewhat less Box-Klangfarbe than Oslo w/reflectors over the orchestra. Fig. 6 shows the TOR- Impulse Response in Munich. Fig. 7 shows FFT for a time window just including the reflections from the suspended reflectors (up to the cursor position in fig. 6, at 25 msec after direct-sound-arrival). We see a more narrow comb-filter (smaller “Comb-Betwen-Teeth-Bandwidth´s”) than in Oslo, due to higher placements of the suspended reflectors. (9m in Munich, 6-7m in Oslo). The results from Oslo and Munich verifies the ”rule of thumb” that suspended reflectors/ceilings should not be positioned lower than 8m over the orchestra, corresponding to a time delay of some 17-22 msec after the direct sound, for the different positions on the stage (see [4]).

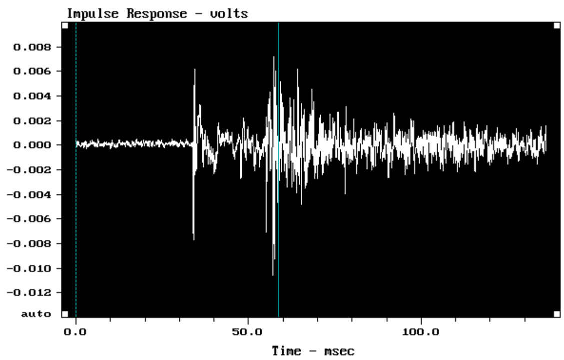


*fig. 6 TOR Imp. Resp. Munich*
*(cursor at 25 msec after direct sound)*

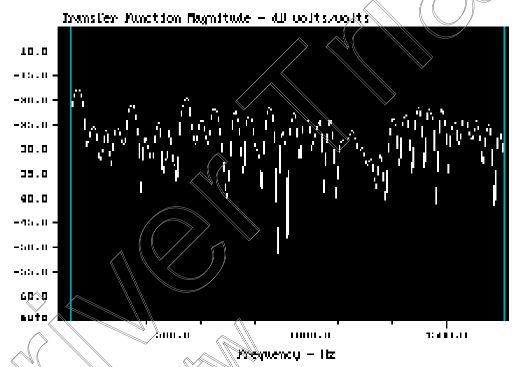


*fig.7 Short-Time FFT of fig.6*
*( up to 25 msec after direct sound)*

2.5) Halls without suspended reflectors

The TOR-measurement in Vienna/Musikverein shows another type of Impulse Response, see fig.8.

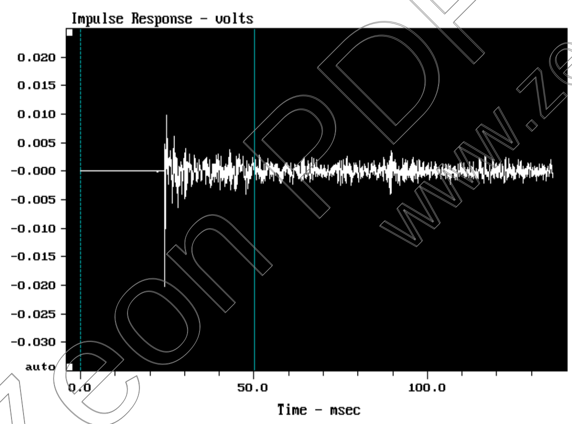


*fig.8 TOR-Imp.Resp. Vienna*

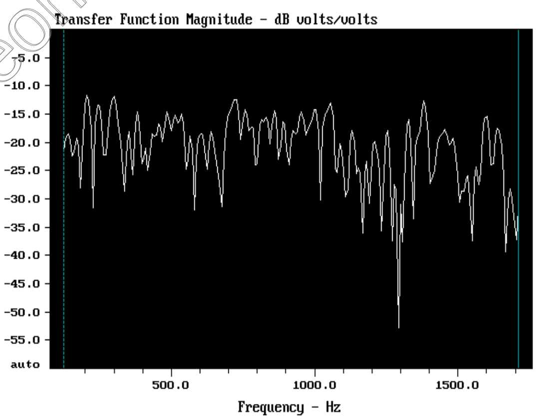


*fig.9 Short-Time FFT of fig.8.*
*(up to 25 msec after direct sound)*

In this hall there is a very high ceiling, and no suspended reflectors, so we do not get any strong, discrete reflector- reflection as in the other halls. We notice the very smooth TOR-Impulse-Response due to the many reflections arriving just after the direct sound (the region called ***b*** in fig.2.) The stagewalls/ galleries/mezzanine give several reflections arriving in the time interval 0- 25 msec after the direct sound. (see also Barron [11]). This gallery/mezzanine might be compared to the "tilted top´s” in the flexible test arrangement for Oslo Concerthall. In addition, Vienna/Musikverein has very nice modulated surfaces and statues along the sidewalls giving “diffuse”/scattered reflections.

After some 70 msec wee see the reflection from the roof of the hall, which would give a clear echo if the reflections arriving before that time were not so rich and well distributed in time. The FFT of the early part of the TOR-Impulse-Response in Vienna, (fig.9) shows no “rhythmic behaviour”. No Box-Klangfarbe was reported.

2.6) Will a "diffuse"/scattering orchestra-shell eliminate Box-Klangfarbe?

The roof and the sidewalls of the orchestra shell in Frankfurt/Hoechst are dispersed to provide "diffuse"/scattering reflections. Nevertheless, the short-time FFT still shows a clear combfilter (see fig.10b), and some Box-Klangfarbe was reported both from the orchestra and the audience, but not as clearly as in Oslo with suspended reflectors.

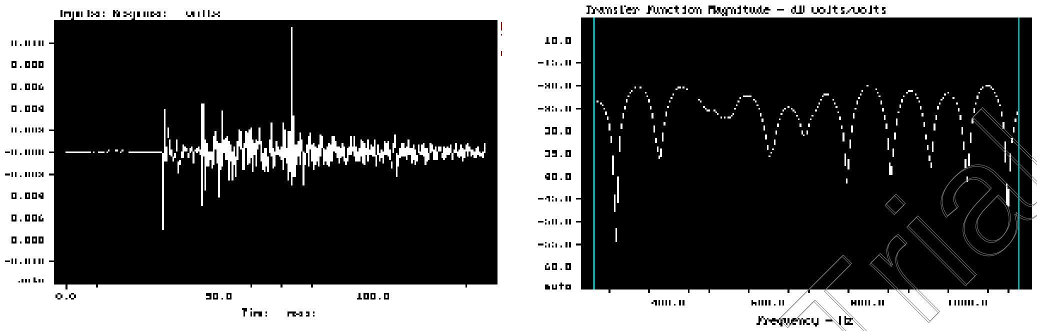

*fig.10a+b TOR-Impulse Response from Frankfurt and FFT up to 25 msec after the direct sound*

We see that the dispersed surfaces of the orchestra shell give somewhat more reflections in the time interval of interest for Box-klangfarbe, but not enough to avoid Coloration. One might notice the reflection arriving 45 msec after the direct sound. This comes from the hall, and gives (almost) an echo. This is of course disturbing in the time-domain, but does not give any coloration effect.

## 3) MEASUREMENTS FOR THE AUDIENCE

For the measurements on the orchestra platform (part 1+2), it was rather easy to find the "travelling path" of each of the reflections found in the Impulse Responses measured, and investigate the changes reported when introducing reflecting surfaces closer to the orchestra**.** When investigating the Impulse Response from the stage to the audience area in the hall, this might be more complicated, as we will have a lot of additional surfaces that might contribute. However, fig.11 shows that the main conclusions are the same also for the audience area. Fig. 11 shows the impulse response from the stage to a typical audience-seat in Oslo Concert Hall (2/3 at the back, somewhat to the side), and the FFT of this impulse response taken up to 25 msec after arrival of the direct sound. On top is shown the measurement without reflecting surfaces close to the orchestra, and below is shown the same after introducing the suspended reflectors. We see that a more clear combfilter-effect is shown in the lower FFT, indicating more coloration when introducing the suspended reflectors.

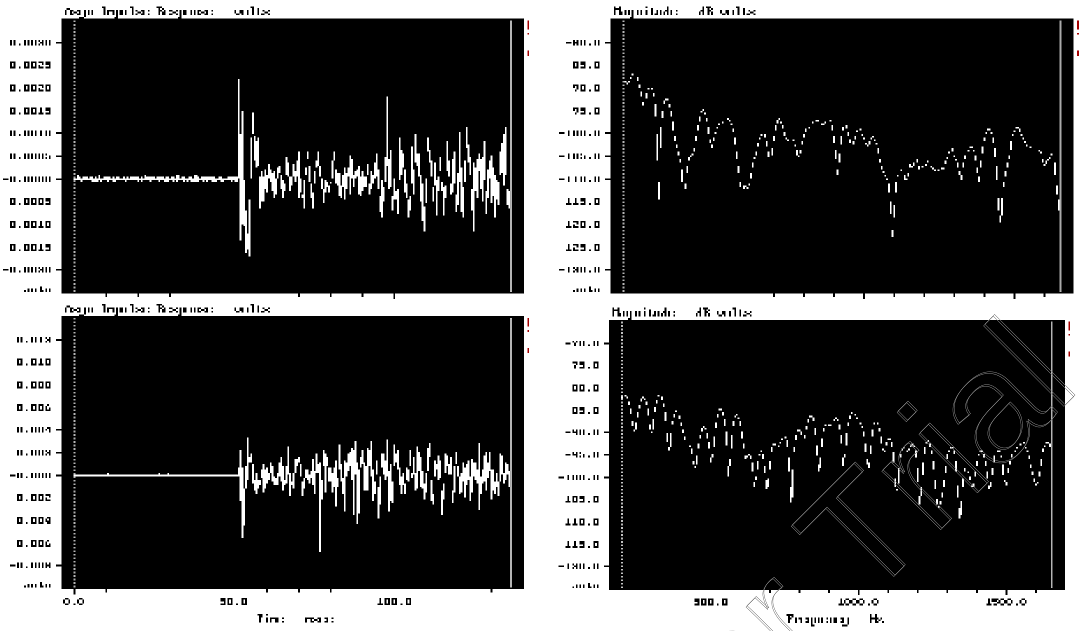

*fig. 11. Impulse Responses between stage and audience seat,*
*and FFT´s up to 25 msec after the direct sound.*
*Upper figures: Without reflecting surfaces close to the orchestra*
*Lower figures: After introducing suspended reflectors*

## 4) EVALUATIONS

4.1) COLORATION AND CRITICAL BANDWIDTH

A reflection arriving with a certain time delay after the direct sound will always give a comb-filter. The question is: Will Box-Klangfarbe be perceived? On top of fig.12 is given the results from the practical/musical test in the 4 halls, showing the time-delay-regions of the most dominating reflections for the 4 orchestra platforms and remarks if Box-Klangfarbe was reported. The main part of fig.12 shows a comparison between the calculated "Comb-Between-Teeth-Bandwidth" for a reflection arriving with a delay (*Delta t)* after the direct sound, and Critical Band for centre frequencies 1/(*Delta t*). The Critical Band is shown both as "Classical" and "Equivalent Rectangular Band" [12]. *Delta x* is also given, indicating the extra meters this reflection must have travelled (in excess of the direct sound). Fig. 12 is a mixture of time-domain and frequency-domain results. Comparing the Practical Results on the top of the figure with the main curves, we see that our results might have a psycho-acoustic reason:
For an orchestra on a platform, Box-Klangfarbe is perceived when a discrete reflection gives a clear comb-filter having a "Comb-Between-Teeth-Bandwidth" that is comparable in size to the Critical Bandwidth. This is indicated as a "Box-Klang-Zone" in fig. 12. The Box-Klang-Zone is simply "The region of time-delays that is likely to give Box-Klangfarbe for a strong/discrete reflection on an orchestra platform*".*
The exact borders of this Box-Klang-Zone must be further investigated, but our study shows that a strong, discrete reflection with a time-delay of some 5-20 msec (Comb-Between-Teeth-Bandwidth of some 200-50 Hz) will give Box-Klangfarbe. Adding more reflections in a random order into this Box-Klang-Zone, will smooth the TOR Impulse Response. The periodic behaviour of the Short-Time-FFT will then be more "unclear", and the chances of Box-Klangfarbe will be reduced, as shown in fig. 8+9 from Vienna.

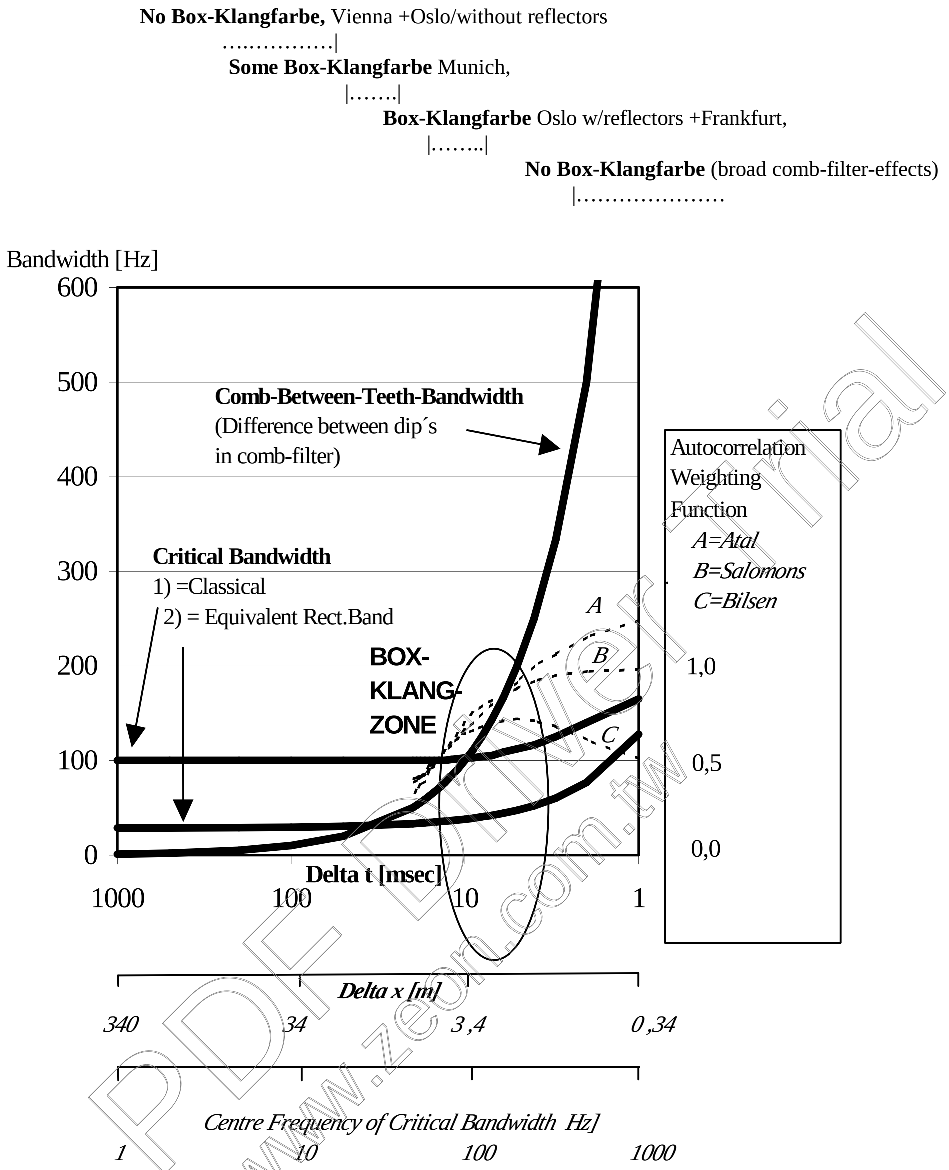


*Fig.12 Comparison between practical/musical results and Critical Bandwidth.*
*<u>On top</u>: Delay-time-regions for discrete reflections and comments of Box-Klangfarbe for 4 Halls.*
*<u>Main figure</u>: "Comb-Between-Teeth-Bandwidth" for delayed discrete reflections compared with Critical Bandwidth for Centre Frequencies 1/(Delta t).*
*<u>X-axis</u>: Delta t (time delay between direct sound and reflection), also given as Delta x (excess travelling distance of reflection)*
*<u>Y-axis</u>: Bandwidth (Critical Bandwidth and Comb-Between-Teeth-Bandwidth)*
*A "Box-Klang-Zone" is indicated showing the region of time delays that is most likely to give Box-Klangfarbe. On the right is showed the Autocorrelation Weighting Functions for different time-delays, proposed by 3 authors*

4.2) COMPARISON WITH PSYCHO-ACOUSTIC STUDIES

Atal et al [10], Bilsen [13],[14] and Salomons [15] have investigated coloration in listening tests for broadband noises with delays. These investigations all conclude that coloration effects are generated in the early part of the received sound, defining "Short Time Spectrum" which confirms our use of Comb-Filter investigations taking the FFT of the early part of the TOR Impulse Response. They also defined an Autocorrelation Weighting Function to describe the hearing organ. A broader discussion about whether to use a frequency-domain or time-domain criteria for coloration, or if they are equivalent, is given in [10], [13],[14] and [19]. Here we will just point out for which region of time-delay(/quefrequencies) this

Autocorralation Weighting Function has its highest values, indicating that coloration is most likely to appear. The Autocorrelation Weighting Functions in fig.12 are after Salomons [15]. They show that there has been some uncertainty about this Weighting Function for short delay times. Fig.12 shows all three results. The results are shown on the same time-delay-axis as our studies. Of course, there is no direct relationship between bandwidth and Autocorrelation Weighting Function, the figure is just meant to show for which time-delay-regions coloration was found most likely to appear in the psycho-acoustic studies, and compare this with our practical study. We see that our results and the psycho-acoustic studies agree that coloration is most likely to appear for discrete reflections within some 5-25 msec after the direct sound. For shorter time delays the comparison is good for the results from Bilsen[13] (curve C), but not for the investigations of Atal [10] and Salomons [15] (Curve A and B in fig.12), which shows coloration also for shorter time-delays than what is given for our musical study indicated as the Box-Klang-Zone. For such short time-delays we should, however, take some practical/musical aspects into consideration. Reflections on an orchestra platform with such short time delays might give some coloration (as in fig. 4), but not necessarily an overall orchestra Box-Klangfarbe.

## 5) PRACTICAL/MUSICAL DISCUSSION

The uncertainty reported for the very short time-delays in the psycho-acoustical studies can be somewhat eliminated for common orchestra platforms. Instruments placed as close to podium walls etc. to give reflections with such short time-delays (region ***b*** in fig. 2) are often bass-instruments like double bass and timpani (see Meyer [8]). The frequency-spectrum radiated from these instruments are far from the broadband-noise signals used in the psycho-acoustic-experiments (see [16] ,[17] ,[18]). For such instruments, the reflections from nearby surfaces should be considered as a part of the instrument, and this "total instrument" might very well include some "good" coloration. This was reported in the tests in Oslo Concert Hall [7],[16],[19]. The " Comb-Between-Teeth-Bandwidth" of such reflections are some 300-1000 Hz, indicated as "*No Box-Klangfarbe (broad comb-filter-effects)"* on the top of fig. 12.
One example of such "good" coloration is given in App.A, fig. 13, giving extra "punch" to the double-basses etc**.** in Oslo Concert Hall [4]. Other examples of "Good Coloration " and their use for chorused instruments are given in [4] ,[19] . Examples of improvements of the design of suspended reflectors are given in App.C.

## CONCLUSIONS

- ***On an orchestra platform a strong, discrete reflection arriving some 5-20 msec after the direct sound will give a Box-Klangfarbe. For such reflections, the "Comb-Between-Teeth-Bandwidth" is comparable to the Critical Bandwidth.***

- ***Adding more "diffuse"/scattered reflections with time delays of some 5-20 msec will reduce Box-Klangfarbe.***

- ***Our results on coloration for orchestra shows good agreement with psycho-acoustical studies on coloration, taking practical/musical situations into consideration.***

## 6) FURTHER WORK

This is only the beginning of the investigations of coloration in concert halls and operas.
Further investigations should be made on:

- The conflict/priority between coloration and ensemble for the orchestra
- The exact borders of the Box-Klang-Zone
- The number/distribution of additional reflections necessary in the Box-Klang Zone to avoid Box-Klangfarbe
- Standardisation on measurements of "diffusing"/"scattering" -reflections from surfaces
- Multi-Channel-Playback/Auralisation for listening studies on music that makes it possible to use different time delays for the different instruments/seats/musicians of the orchestra
- Coloration for the audience-area
- Coloration from an orchestra pit in an opera hall,
  taking into consideration reflections from proscenium/balconies and their timbre/delay-time from instruments not seen from the audience, not just the screening-effect of the wall between the pit and the audience.

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*(*)= In Norwegian*

## APPENDIX A

## THE PRACTICAL/MUSICAL TEST IN OSLO CONCERT HALL

The Oslo Philh. Orchestra played extracts from the following compositions:.

*Wagner "Prelude to Tristan and Isolde."*

*Strauss "Zaratuhstra" Stravinsky "The Golden Bird",*

*Beethoven "Symf. 3, 3.mov".*

*Brahms "Symph,.3, 1.mov"*

Each musician filled in a questionnaire while the stage crew changed the surfaces around/over the orchestra, and then the orchestra played the same "repertoire" in the new acoustic settings, and so on. Similar questionnaires were filled in also by 10 sound technicians/ ton-meisters and musicians placed in the audience area of the hall. The different situations tested were:

***No reflecting surfaces close to the orchestra***

***Suspended Plexi-Glass Reflectors over the Orchestra***

***Hard-Board Sidewalls***

***$90^0$ Tilted Top´s on the Sidewalls***

***Hard-Board-Orchestra Back Wall***

and different combinations of these. All the questionnaires included the following questions:

*1) Clearness/"distinctness".*

*2) Spaciousness*

*3) Punch**

*4) Bass*

*5) Brilliance*

*6) Balance (between instruments/groups)*

*7) Klangfarbe/Timbre.*

Addition: *"Do you hear any specific instrument/group specifically good/bad. ?"*

The orchestra also replied to the following questions:

*A) Hearing others, B)Hearing yourself/own instrument group, C)"Klangfarbe" other instruments,*

*D)"Klangfarbe" own instrument.*

All the questions were to be marked on a continuos line-scale:

***Little/bad,*** ……..through … ***Some, Mediocre……*** and …..***More/Better*** …... to ***Much/Good.***

The position of the marking on the line was measured for each question, and used for the analysis. The main result from the test is given in fig.13.

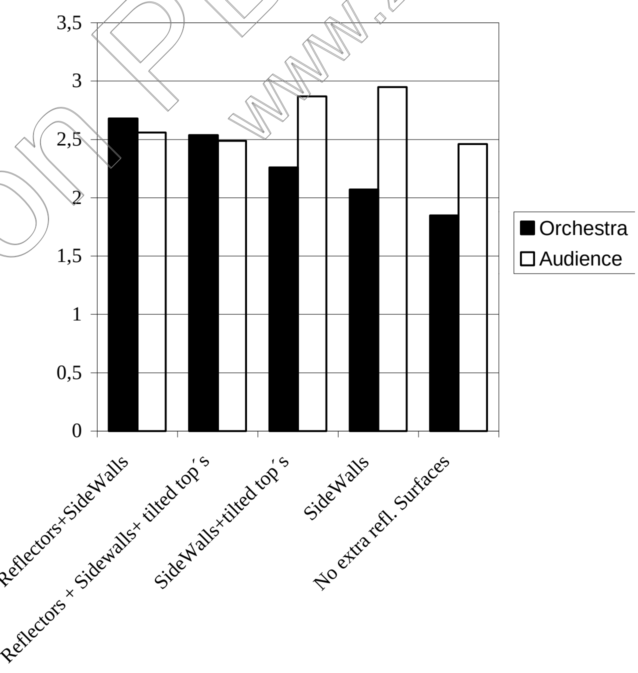


*fig.13. Mean score, all musicians/audience. Arbitrary "score"-scale.*

*The parameter "punch" might be unconventional. It was introduced in order to see if reflecting surfaces behind/over the double-basses etc. might give a distinct increase for the bass-instruments that could compensate somewhat for the low reverberation in the bass in the hall. The description “Punch” is commonly used by studio-engineers, and might be defined as low-frequency signal with a distinct/strong response, that will give the listener a feeling of a “direct kick” instead of just an overall diffuse increase of bass-“noise”. Fig. 14 shows that “Punch” is increased when introducing surfaces close to the (bass) instruments. Fig. 14 also shows the conflict between Klangfarbe and “Punch”, and that the best compromise between these two parameters is achieved with sidewalls and “Tilted Top´s”, without suspended reflectors. The reflections from the sidewalls etc. is an example of “good coloration”.

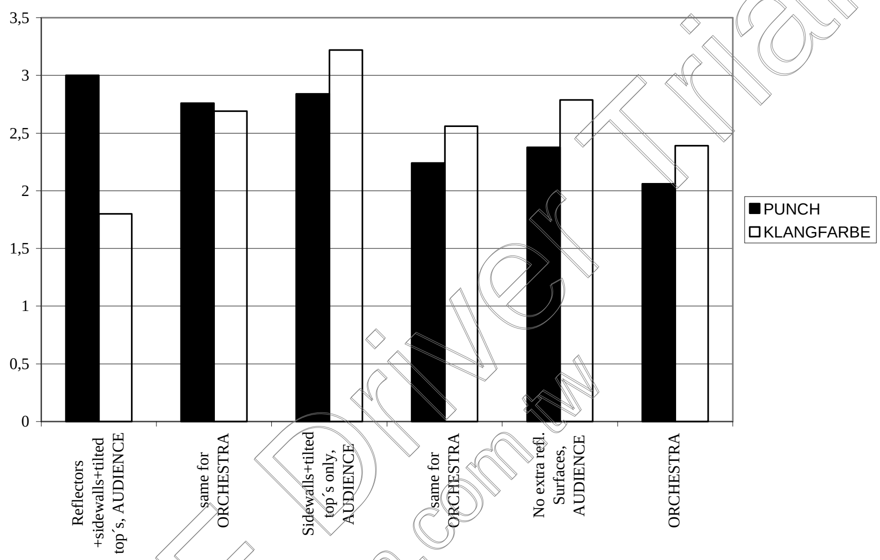


*Fig. 14. The scores for the parameters “Klangfarbe” and “Punch”, for several settings of the reflecting surfaces around the orchestra, given for orchestra and audience areas.*



**APPENDIX B**
**MULTIPLE REFLECTIONS**

In order for additional reflections to reduce Box-Klangfarbe, they must not arrive too close to each other in time (as in more or less circular room, see[20]), or too ”rhythmic”, but give ”randomness” in the TOR-Impulse-Response. As an example, a rhythmic reflection pattern of 8,9,10,11,12,13,14…… msec will, theoretically, give a clear colorating audible peak at 1000 Hz. Several simulations and listening verified this also for musical signals [19]. The “flutter-echo” is a typical example of “rhythmic-multiple-reflections”. Such rhythmic reflections might also be the result of evenly spaced “irregularities” of walls etc. in concert-halls and studios [4], [21].

**APPENDIX C**
**IMPROVING THE DESIGN OF SUSPENDED REFLECTORS**

Some guidelines for design of orchestra platforms/suspended reflectors are given in [14].
A possible way of reducing the comb-filter-effect from suspended reflectors by making them smaller is proposed by Rindel [23] [24]. More curved reflectors will also reduce the Box-Klangfarbe.
Such improvements were not possible in our flexible test in Oslo Concert Hall, due to practical reasons for the stage machinery. However, this practical limitation gave us the possibility of investigating coloration effects on orchestra podiums in a more general manner!