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ORCHESTRAL TIMBRE: COMB-FILTER 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 parameters show good results. In this paper, a closer look is taken at the reflections *within* the time intervals commonly used for the room-acoustic parameters, their contribution to coloration is investigated, and the results are compared with psycho-acoustic studies.

1. INTRODUCTION

The first part of this investigation shows that placing reflecting surfaces closer to the orchestra will improve the ensemble conditions, but might give undesirable coloration, as if the orchestra were "placed inside a small box". Such a coloration effect is called "box-klangfarbe".

In section 3 it is shown that coloration can be detected by analyzing 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 dips 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 the critical bandwidth. A strong/discrete reflection with a time delay of about 5–20 ms (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. In section 4 it is shown that the results are valid also for the audience area. In section 5 good agreement with psycho-acoustical studies is shown. In earlier studies, however, there seems to be an underlying assumption that all coloration must be "bad". In section 6, some practical/musical comments are given on "good" and "bad" coloration for orchestra platforms.

2. INVESTIGATIONS IN OSLO CONCERT HALL

This work on orchestra-podium acoustics started with investigations for the Oslo Philharmonic/Mariss Jansons in Oslo Concert Hall. This hall has a triangular shape, a very large ceiling height over the orchestra, and sidewalls placed far away from the orchestra; see reference [1] or reference [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 reference [3] and Appendix A): 7 flexible suspended reflectors, $2{\cdot}8 \times 2{\cdot}8$ m, height 6–7 m, over the orchestra; flexible walls on all sides; and "tilted tops" 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 tops" 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 Appendix A and reference [4]). Figure 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 tops 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, have been given by Ando [5].

Remarks were given that when introducing the suspended reflectors, "it sounds as 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 analyzed, 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].

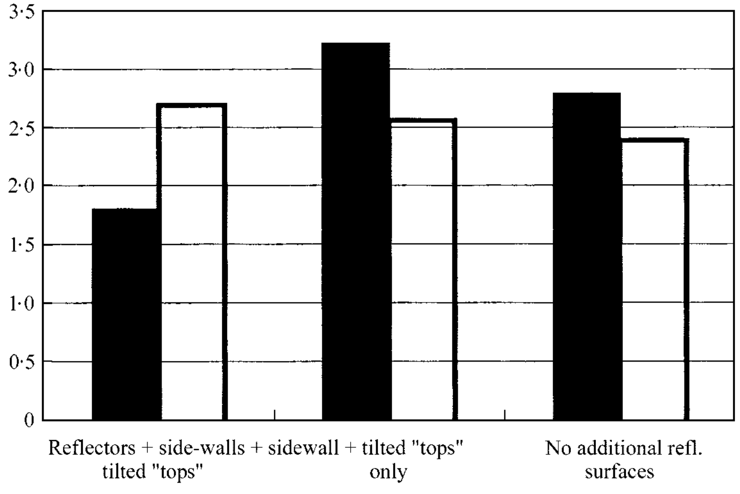

Figure 1. Score for the parameter "klangfarbe" (timbre). Mean values for orchestra □ and audience ■. Arbitrary score scale.

Even though coloration was most clearly stated from the audience area, measurements on the stage were used 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. It was decided to measure impulse responses through the orchestra, called TOR-measurements. In section 3, results from measurements to the audience area are given, showing similar conclusions as for the orchestra platform.

3. TOR-MEASUREMENTS

3.1. ABOUT TOR-MEASUREMENTS

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 references [7, 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 reference [8]) used by the Oslo Philharmonic, 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 were 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 reference [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 Olso w/suspended reflectors). For information about halls (1) and (2) see reference [9]. Note that for Munich/Gasteig, suspended plexi-glass reflectors over the orchestra have been introduced after Gade's investigations.

3.2. TYPICAL TOR-IMPULSE RESPONSE WITH SUSPENDED REFLECTIONS

A typical impulse response from TOR-measurements on an occupied stage with suspended reflectors or a low ceiling over the orchestra is shown in Figure 2: (a) direct sound; (b) very early reflections; (c) reflection from ceiling/suspended

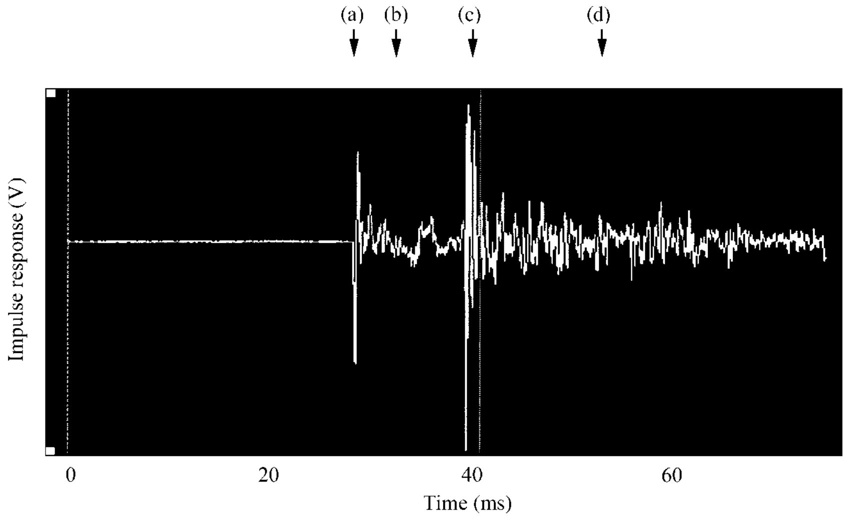

Figure 2. Typical TOR-impulse-response, for occupied orchestra, platform with suspended reflectors (measurement from Oslo Concert Hall).

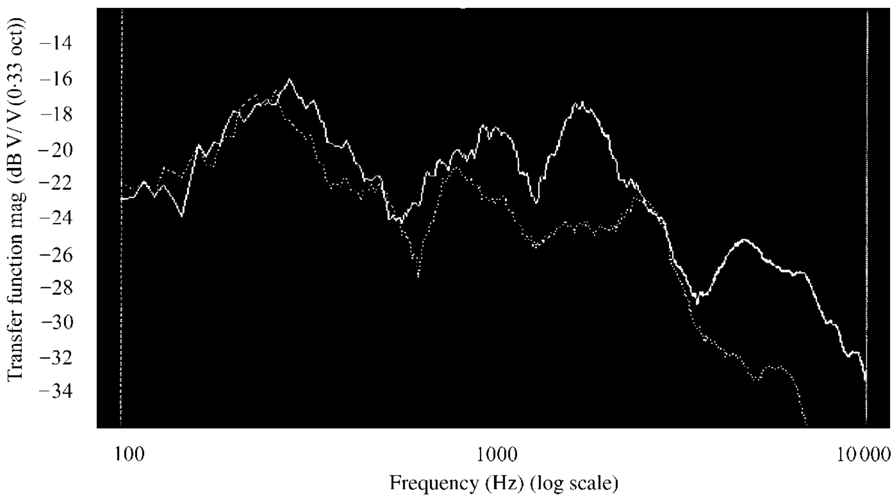

Figure 3. FFT of the whole Tor-impulse response in Figure 2 (approximately 2 s). With suspended reflectors (upper curve), without suspended reflectors (lower curve).

reflectors (note that with the orchestra on the platform, this reflection is stronger than the direct sound); (d) late early-reflections (> 25 ms after the direct sound).

3.3. FFT ANALYSIS FOR DIFFERENT TIME WINDOWS OF THE TOR-IMPULSE RESPONSE

Taking the FFT of the whole measuring time (approximately 2 s) gives no visual indication of the coloration-effect reported; see Figure 3. One 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 section 5.2. One can now investigate coloration using shorter time-windows for the FFT of the TOR-impulse response in Figure 2, successively increasing the time window. These short-time FFTs can be compared with the detailed information about klangfarbe given from the questionnaries and the distance/time delays from each reflecting surface introduced in the test [3].

Region b. Introducing surfaces that give *very-early reflections* in Figure 2 sidewalls close to musicians, etc.) were reported not to give any box-klangfarbe for the overall orchestra-klangfarbe. Figure 4 shows the FFT of The TOR-impulse response in Figure 2, taken for a time interval up to 7 ms after the direct sound. One can see some broad, but not clear, comb-filter effects. A strong/discrete reflection within time region *b* would, theoretically, create a broad comb-filter with more than some 300 Hz between the dips. Comb-filter coloration from very-early reflections is discussed further in section 5.

Region c. Introducing the suspended reflectors was reported to give box-klangfarbe. Figure 5 shows the short-time FFT of the TOR-impulse response in Figure 2, taken for a time window up to 13 ms after the direct sound, indicated by the cursor in Figure 2, just including the reflection from the suspended reflectors. One can see a clear comb-filter-effect. One thus can define the "comb-between-teeth-bandwidth" as the distance in Hz between two successive dips.

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 Figure 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.

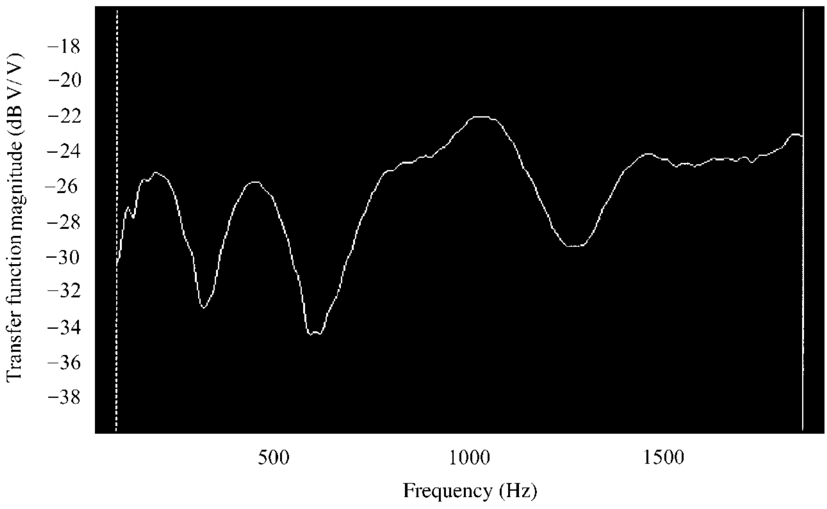

Figure 4. FFT of impulse response in Figure 2 (linear frequency scale). Time window up to 7 ms after direct sound.

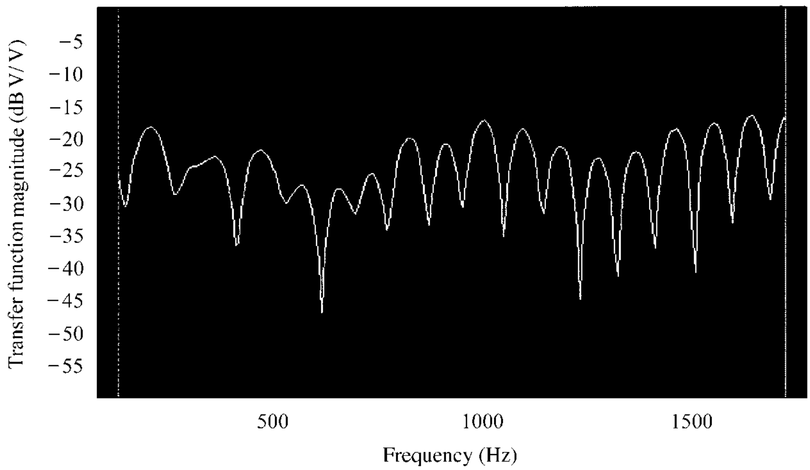

Figure 5. Short-time-FFT of impulse response in Figure 2. Time window up to 13 ms after direct sound. The |···|← "comb-between-teeth bandwidth" is indicated.

When one increases the time delay of the reflection further, one enters the "time-domain" region of sound perception, and a "lonesome" reflection will be perceived as an echo, not as coloration.

3.4. 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. Figure 6 shows the TOR-impulse response in Munich. Figure 7 shows FFT for a time-window just including the reflections from the suspended reflectors (up to the cursor position in Figure 6, at 25 ms after direct-sound arrival). One can see a more narrow comb-filter (smaller "comb-between-teeth-bandwidths") than in Oslo, due to higher placements of the suspended reflectors. (9 m in Munich, 6–7 m in Oslo). The results from Oslo and Munich verify the "rule of thumb" that suspended reflectors/ceilings should not be positioned lower than 8 m over the orchestra, corresponding to a time delay of some 17–22 ms after the direct sound, for the different positions on the stage (see reference [4]).

3.5. HALLS WITHOUT SUSPENDED REFLECTORS

The TOR-measurement in The Vienna Musikverein shows another type of impulse response, see Figure 8. In this hall there is a very high ceiling, and no suspended reflectors, so one does not get any strong, discrete reflector–reflection as in the other halls. One can notice the very smooth TOR-impulse response due to the many reflections arriving just after the direct sound (the region called b in Figure 2). The stagewalls/galleries/mezzanine give several reflections arriving in the

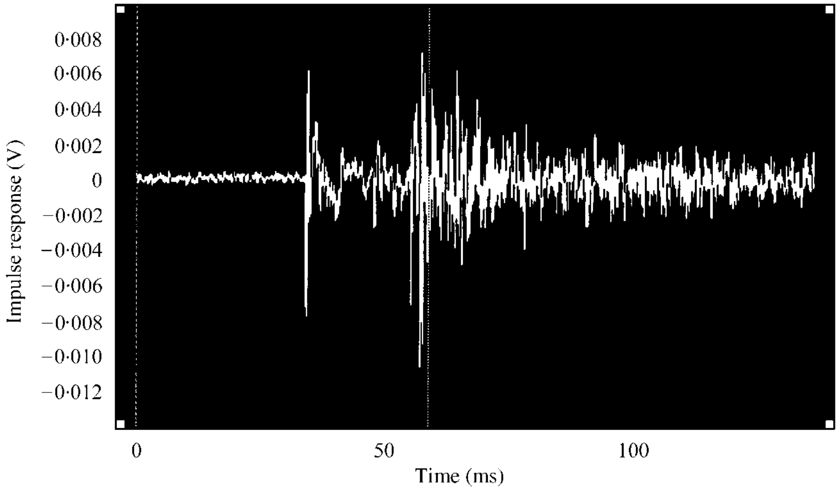

Figure 6. TOR-impulse-response, Munich (cursor at 25 ms after direct sound).

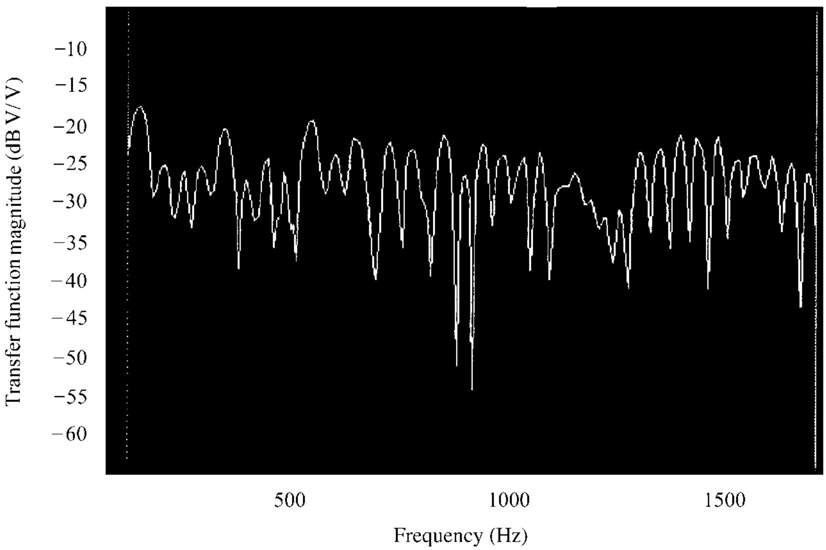

Figure 7. Short-time FFT of Figure 6 (up to 25 ms after direct sound).

time interval 0–25 ms after the direct sound (see also reference [11]). This gallery/mezzanine might be compared to the "tilted tops" in the flexible test arrangement for Oslo Concert Hall. In addition, the Vienna Musikverein has very nice modulated surfaces and statues along the sidewalls giving "diffuse"/scattered reflections. After some 70 ms one can 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 (see Figure 9) shows no "rhythmic behaviour". No box-klangfarbe was reported.

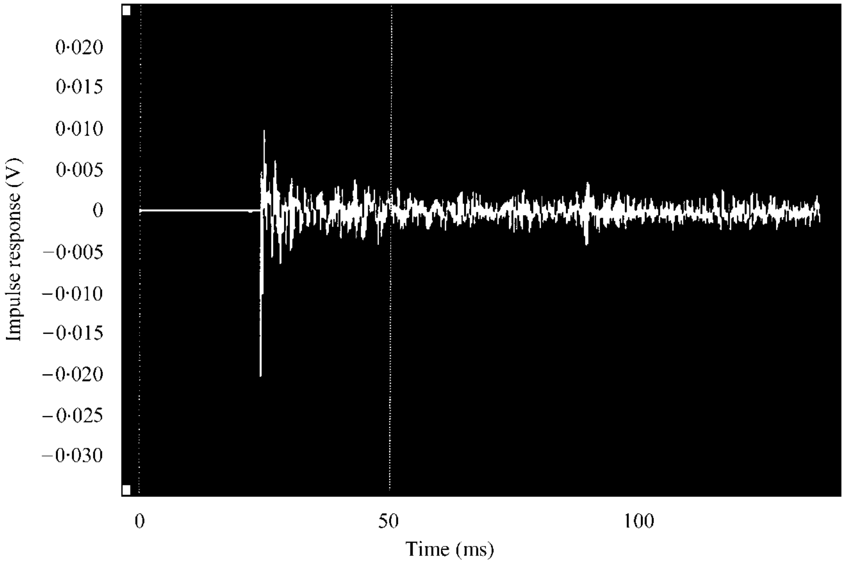

Figure 8. TOR-impulse response, Vienna.

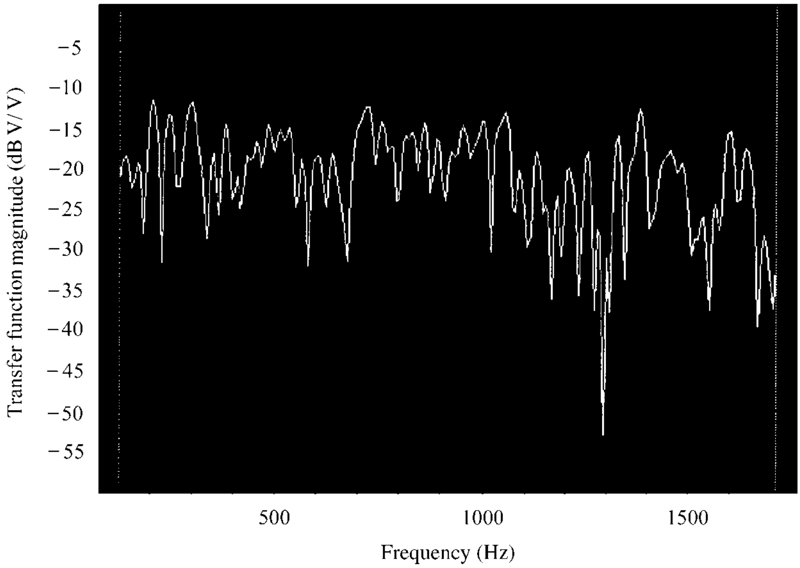

Figure 9. Short-time FFT of Figure 8.

3.6. 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 comb-filter (see Figure 10(b)), and some box-klangfarbe was reported both from the orchestra and the audience, but not as clearly as in Oslo with suspended reflectors. One can see that the dispersed surfaces of the orchestra

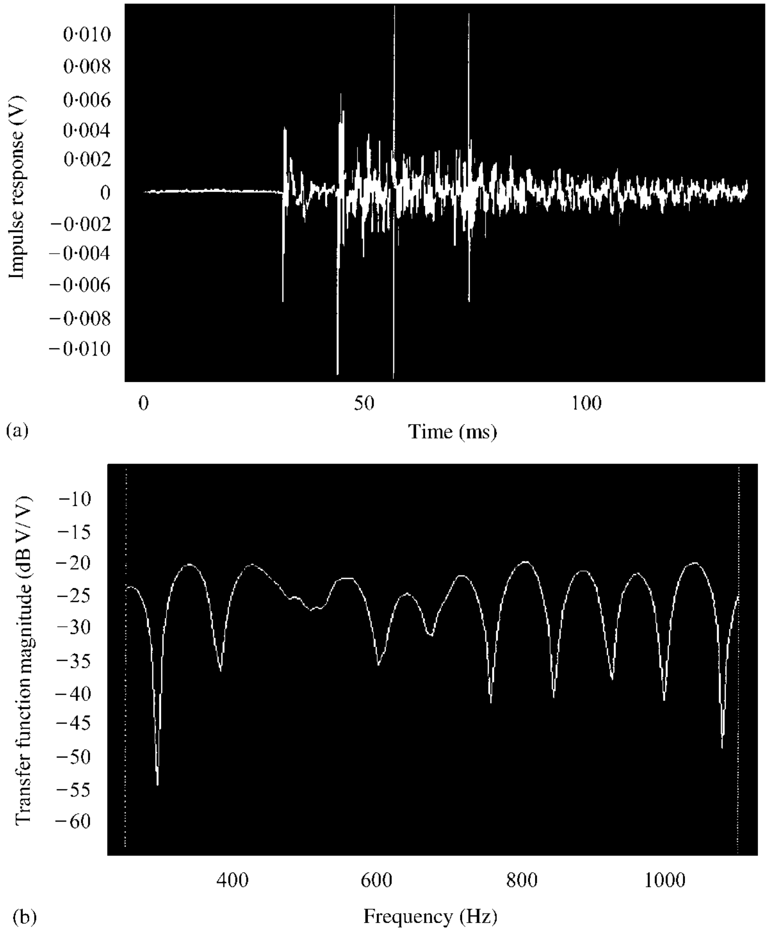

Figure 10. TOR-impulse response from Frankfurt and FFT up to 25 ms after the direct sound.

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 ms 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.

4. MEASUREMENTS FOR THE AUDIENCE

For the measurements on the orchestra platform (see sections 1 and 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 one will have a lot of additional surfaces that might contribute. However, Figure 11 shows that the main conclusions are the same for the audience

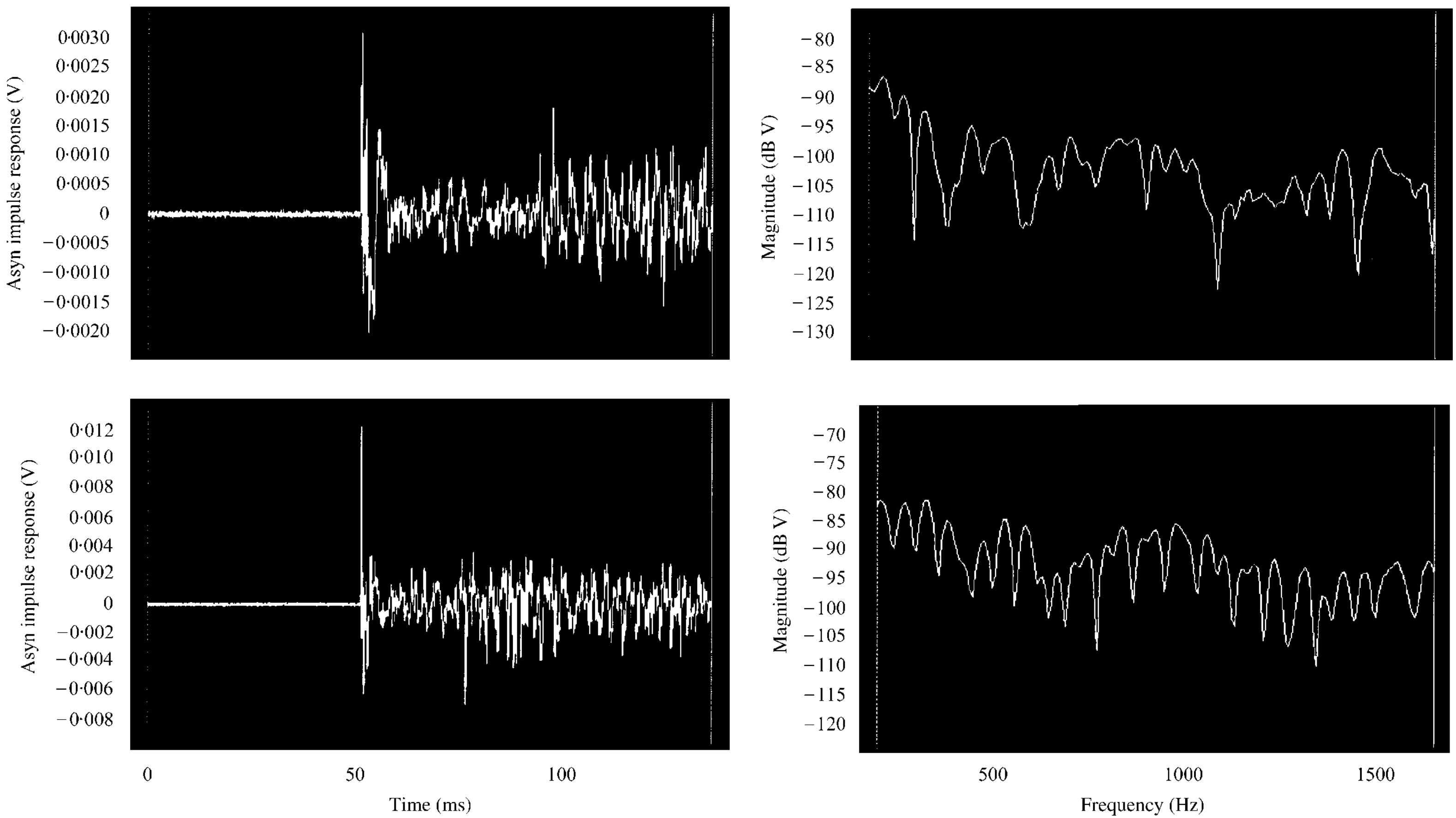

Figure 11. Impulse responses between stage and audience seat, and FFTs up to 25 ms after the direct sound. Upper figures, without reflecting surfaces close to the orchestra; lower figures, after introducing suspended reflectors.

area. Figure 11 shows the impulse response from the stage to a typical audience seat in Oslo Concert Hall (2/3 back, somewhat to the side), and the FFT of this impulse response taken up to 25 ms 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. One can see that a more clear comb-filter effect is shown in the lower FFT, indicating more coloration when introducing the suspended reflectors.

5. EVALUATIONS

5.1. 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? At the top of Figure 12 are given the results from the practical/musical test in the four halls, showing the time-delay regions of the most dominating reflections for the four orchestra platforms and remarks if box-klangfarbe was reported. The main part of Figure 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 metres this reflection must have travelled (in excess of the direct sound). Figure 12 is a mixture of time and frequency-domain results. Comparing the practical results on the top of the figure with the main curves, one can 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 Figure 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 this study shows that a strong, discrete reflection with a time delay of some 5–20 ms (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 Figures 8 and 9 from Vienna.

5.2. 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. From all these investigations it is concluded that coloration effects are generated in the early part of the received sound, defining the "short time spectrum" which confirms the use here of comb-filter investigations taking the FFT of the early part of the TOR-impulse response. The authors also defined an autocorrelation weighting function to

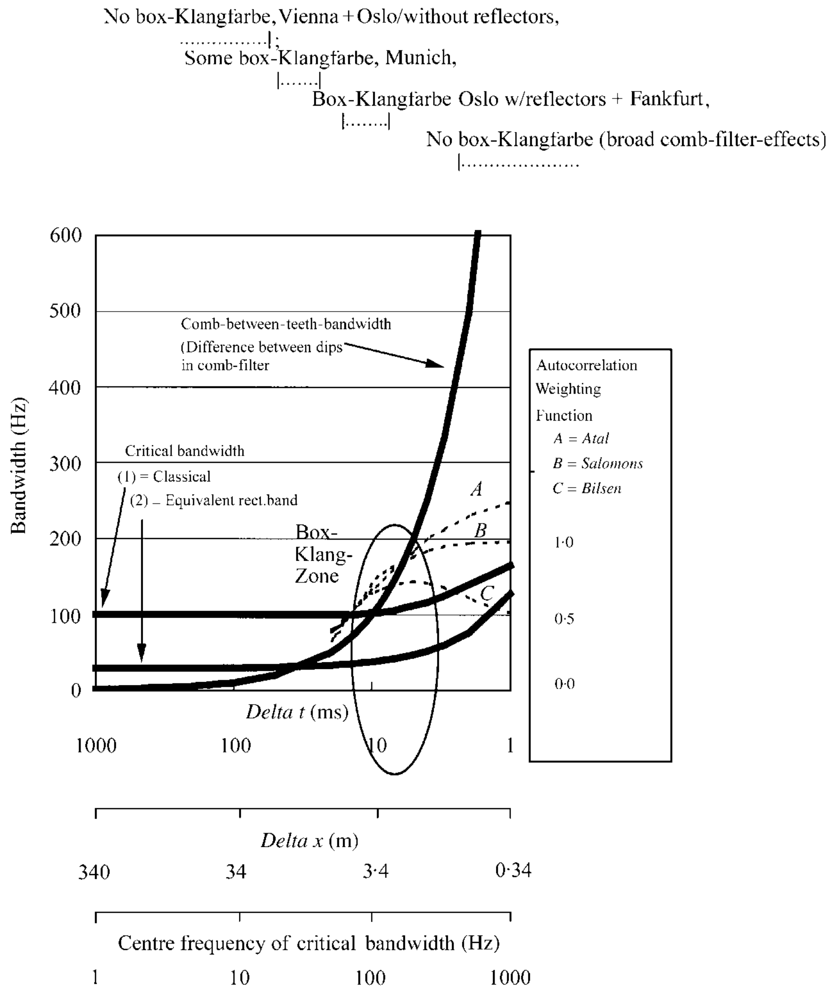

Figure 12. Comparison between practical/musical results and critical bandwidth. At top: delay-time regions for discrete reflections and comments on box-klangfarbe for four halls. Main figure: "Comb-between-teeth-bandwidth" for delayed discrete reflections compared with critical bandwidth for center frequencies 1/(*Delta t*). *X*-axis: *Delta t* (time delay between direct sound and reflection), also given as *Delta x* (excess travelling distance of reflection). *Y*-axis: 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 shown the autocorrelation weighting functions for different time delays, proposed by three authors.

describe the hearing organ. A broader discussion about whether to use a frequency- or time-domain criteria for coloration, or if they are equivalent, is given in references [10, 13, 14, 16]. Here one can just point out for which region of time delay(/quefrequencies) this autocorrelation weighting function has its highest values, indicating that coloration is most likely to appear. The autocorrelation weighting functions in Figure 12 are after Salomon [15]. They show that there has been some uncertainty about this weighting function for short delay times. Figure 12 shows all three results. The results are shown on the same time-delay axis as the present 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 region coloration was found most likely to appear in the psycho-acoustic studies, and compare this with the present practical study. One can see that the present results and the psycho-acoustic studies agree that coloration is most likely to appear for discrete reflections within some 5–25 ms 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 *et al.* [10] and Salomons [15] (curves A and B in Figure 12), which show coloration also for shorter time delays than what is given for the present musical study indicated as the box-klang-zone.

For such short time delays one should, however, take some practical/musical aspects into consideration. Reflections on an orchestra platform with such short time delays might give some coloration (as shown in Figure 4), but not necessarily an overall orchestra box-klangfarbe.

6. 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 Figure 2) are often bass instruments like double bass and timpani (see reference [8]). The frequency spectrum radiated from these instruments are far from the broadband-noise signals used in the psycho-acoustic-experiments (see references [17–19]). 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, 17, 16]. The "comb-between-teeth-bandwidth" of such reflections are some 300–1000 Hz, indicated as "*no box-klangfarbe* (*brand comb-filter-effects*)" at the top of Figure 12. One example of such "good" coloration is given in Appendix A (Figure A1) 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 references [4, 16]. Examples of improvements of the design of suspended reflectors are given in Appendix C.

7. CONCLUSIONS

On an orchestra platform a strong, discrete reflection arriving some 5–20 ms 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 ms will reduce box-klangfarbe.

The present results on coloration for orchestra show good agreement with psycho-acoustical studies on coloration, upon taking practical/musical situations into consideration.

8. FURTHER WORK

This is only the beginning of the investigations of coloration in concert halls and operas. Further investigations should be made on the following: 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; standardization of measurements of "diffusing"/"scattering" reflections from surfaces; multi-channel-playback/auralization 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/time delay 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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APPENDIX A: THE PRACTICAL/MUSICAL TEST IN OSLO CONCERT HALL

The Oslo Philharmonic Orchestra played extracts from the following compositions: Wagner "*Prelude to Tristan and Isolde*". Strauss "*Zaratuhstra*", Stravinsky. "*The Golden Bird*", Beethoven "*Symphony Number* 3 *Third movement*, Brahms "*Symphony Number 3*, *Third movement*". 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 as follows: no reflecting surfaces close to the orchestra; suspended plexi-glass reflectors over the orchestra; hard-board sidewalls; 90° tilted tops on the sidewalls; hard-board orchestra back wall; 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*.

In addition was "*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 continuous 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 Figure A1.

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

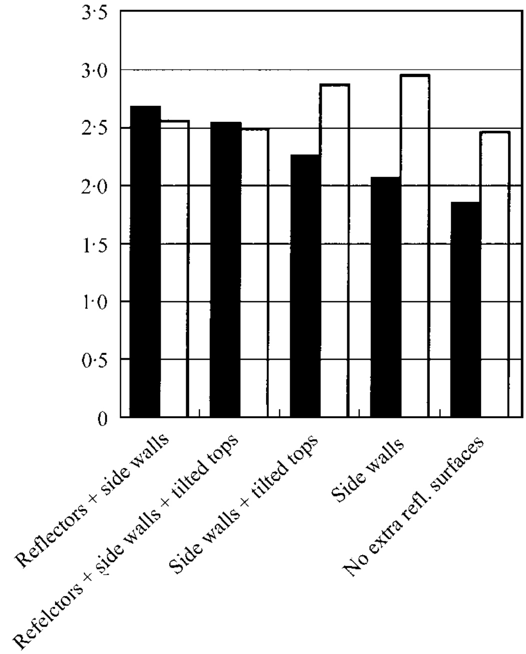

Figure A1. Mean score, all musicians ■/audience □. Arbitrary “score” scale.

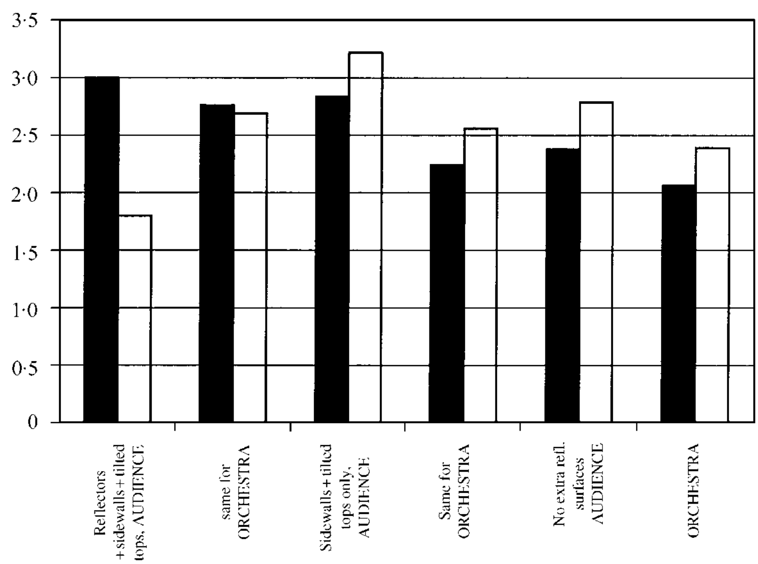

Figure A2. The scores for the parameters “klangfarbe” □ and “punch” ■, for several settings of the reflecting surfaces around the orchestra, given for orchestra and audience areas.

distinct/strong response, that will give the listener a feeling of a “direct kick” instead of just an overall diffuse increase of bass “noise”. Figure A2 shows that “punch” is increased when introducing surfaces close to the (bass) instruments. Figure A2 also shows the conflict between klangfarbe and “punch”, and that the best compromise between these two parameters is achieved with sidewalls and “tilted tops”, without suspended reflectors. The reflections from the sidewalls, etc., is an example of “good coloration”.

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 a more or less circular room, see Statsbygg, Akustikk-Rapport no. 40/1996 [20]), or too “rhythmically”, but give “randomness” in the TOR-impulse response. As an example, a rhythmic reflection pattern of 8, 9, 10, 11, 12, 13, 14, … ms will, theoretically, give a clear colorating audible peak at 1000 Hz. Several simulations and listening test verified this also for musical signals [16]. 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 Bilsen (1968) [14]. A possible way of reducing the comb-filter-effect from suspended reflectors by making them smaller has been proposed by Rindel [22, 23]. 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!