060928 Model investigations – preliminary

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1 Introduction

Three different issues have been tested with scale modelling: The reflection from a cornice (both the frequency response and sound level), the reflection from a finite width panel (directivity and level) and how the sound field and acoustical parameters (ST and RT) change according to different stage configurations. For more detailed information about these investigations, see previous internal reports [3] – [10] and the transfer report [13] for most recent details on investigation tools and results.

Where relevant, a computer model of the scale model configuration has been developed to compare results from the two modelling techniques.

2 Frequency response of cornice reflection

The procedure of this study has been to measure the frequency response of a cornice reflection and relate it to simplified theory and a hypothesis for this particular cornice reflection. A cornice reflection can take place underneath a balcony or other horizontal elements that are attached to a wall. It can also take place where a vertical element is attached to the ceiling (or in principal also the floor). See figure 1 for a general situation with a cornice reflection generated by a balcony. The element attached to the wall can be referred to as a soffit.

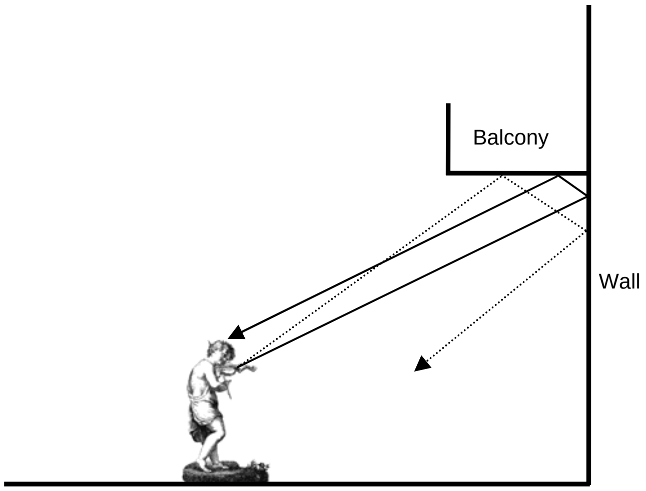


Figure 1: Cornice reflection at the stage enclosure.

The solid line represents sound reflection back to the musician, while the dashed line represents reflection back to the fellow musicians. At which positions on stage the cornice can reflect back, depends of the source position and the width of the soffit. The frequency response of this reflection will be determined by the dimensions of the soffit.

2.1 Measurement setup

The measurements have been carried out in a 1:25 scale model consisting of a (stage) floor, wall and two removable panels that create the cornice reflection. The panels can be attached at different heights on the wall.

Because of problems with floor reflections interfering with the cornice reflection, the measurements were carried out without the floor. To minimize other interfering reflections, the wall was placed up side down to allow the spark source and microphone to hang freely from above without any mounting attached to the spark source. See figure 2 for illustration of the measurement configuration.

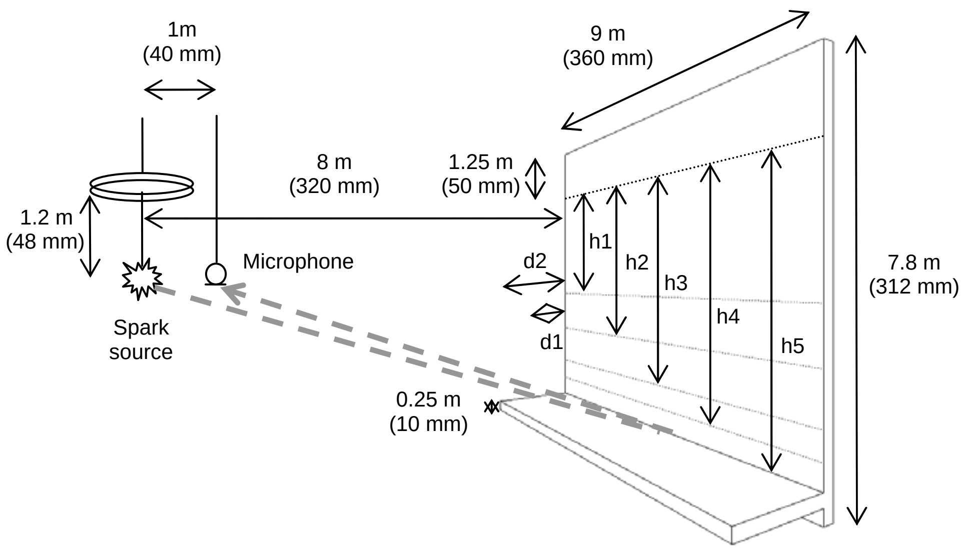


Figure 2: Measurement set-up for evaluation of cornice reflection.

The spark source and microphone were hung at the same height. The base of the spark source was 1.25 m (50 mm) below the upper edge of the wall, at a distance of 8 m (320 mm) from the wall. The microphone had a distance of 1 m (40 mm) from the spark source. The spark source's base is made of Plexiglas and has a diameter of 2" (1.27 mm (50.8 mm)). Both spark source and microphone hang on the vertical centre line of the wall.

The microphone position was chosen on front of the spark source to minimize disturbing reflections from the spark source. Two different flat panels were attached to the wall at various heights to create a cornice reflection. The wall was much larger than the panel, so the wall could be treated as a large surface. The height of the panel (h) was varied from 3 to 6 m (120 to 240 mm) as is presented by h1 to h5 respectively (measured from the floor normally situated 1.25 m (50 mm) from the top of the wall). Two different panel widths were tested: 1 and 2 m (40 and 80 mm), denoted as d1 and d2 respectively. The thickness of both cornices is 0.25 m (10 mm). See table 1 and 2 below for details on the variable dimensions in the test.

	Height (mm)
h1	3 m (120 mm)
h2	4 m (160 mm)
h3	5 m (200 mm)
h4	5.5 m (220 mm)
h5	6 m (240 mm)

Table 1: Cornice heights.

	Depth (mm)
D1	1 m (40 mm)
D2	2 m (80 mm)

Table 2: Cornice depths.

2.2 Expected frequency response

Due to diffraction, a reflection from a finite panel will only take place above a certain frequency given by the size of the panel. The lowest frequency for complete reflection is called the limiting frequency. Above this limiting frequency the frequency response is roughly flat, and below this frequency the response decreases with 3 dB per octave. For an object of length L and depth D, both dimensions L and D will introduce a limiting frequency and the frequency response will drop 6 dB below the lowest limiting frequency (see figure 3). For the panels in our investigation, the length is much larger than the depth, so only one limiting frequency is relevant. The wall itself will also have limiting frequencies, but due to its size they are at very low frequencies, so the wall can be treated as reflecting at all frequencies of interest in this test.

Above the limiting frequency there will be comb filter effects caused by edge reflections from the panel interfering with the main cornice reflection. This is not shown in this simplified expected response.

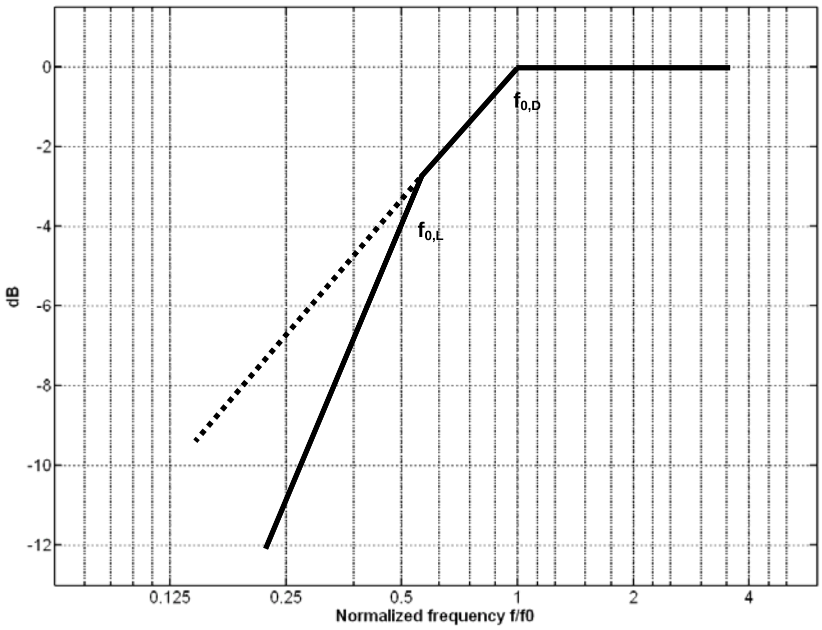


Figure 3: Simplified theoretical frequency response of reflection from an object with dimensions D and L, L being the largest dimension. Dotted line represents a much larger dimension L.

2.3 Expected limiting frequencies

The limiting frequencies can be calculated according to the equation given below.

$$f_0 = \frac{c}{\left(\frac{1}{s} + \frac{1}{r}\right) \cdot \left(D \cdot \cos\theta\right)^2} \qquad (1)$$

Where:

s is the distance between the source and the reflecting object

r is the distance between the receiver and the reflecting object

D is the dimension (depth) of the reflecting object

θ is the incidence angle of the sound

D·cosθ can be said to represent "apparent depth" of the object. This relation was proposed by Rindel [1] and the version presented in equation 1 was presented by Barron [2].

With the panel attached to a large wall, the wall will enhance the apparent depth of the panel. This enhancement seems to be represented as a doubling of the panel's depth, see figure 4. If this is true, the limiting frequency will shift two octaves down.

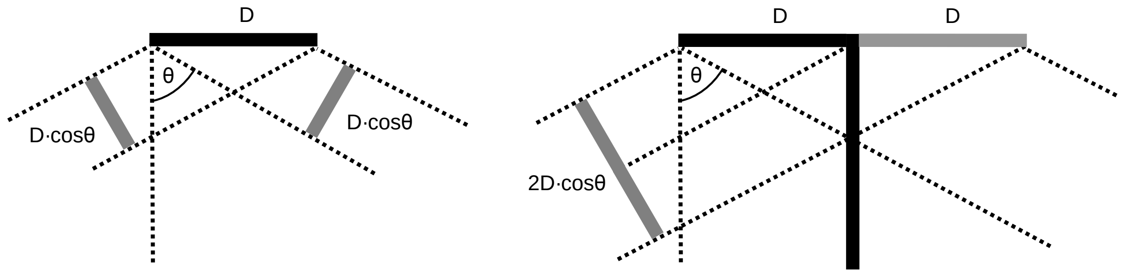


Figure 4: Apparent width of panel with wall absent and present.

The hypothesis to be tested can be formulated as: The limiting frequency for a finite size panel is extended two octaves lower when the other surface is a large reflecting wall (surface).

2.4 Analysis of the frequency response of the cornice reflection

The frequency response of the measured cornice reflection was found by taking the Fourier transform of the cornice reflection. The cornice reflection was isolated by use of a time window. To eliminate the influence of noise, a measurement with no panel present was done for each configuration. This measurement representing the background and was subtracted from the measured impulse response with panel present to improve the isolation of the cornice reflection. Since a Fourier transform of the measured impulse response will be affected by the frequency response of the spark source itself, a relative frequency response was calculated. The frequency response of the cornice reflection is compared to the frequency response of the wall reflection. Since the wall is large, this reflection is expected to have a flat frequency response.

2.5 Results

Figure 5 – 8 show measured frequency responses for panel depths of 1 metre and 2 metres at a height varied from 6 to 3 meter. The frequency axis is normalized to the calculated limiting frequency. The dashed straight lines show the simplified expected response.

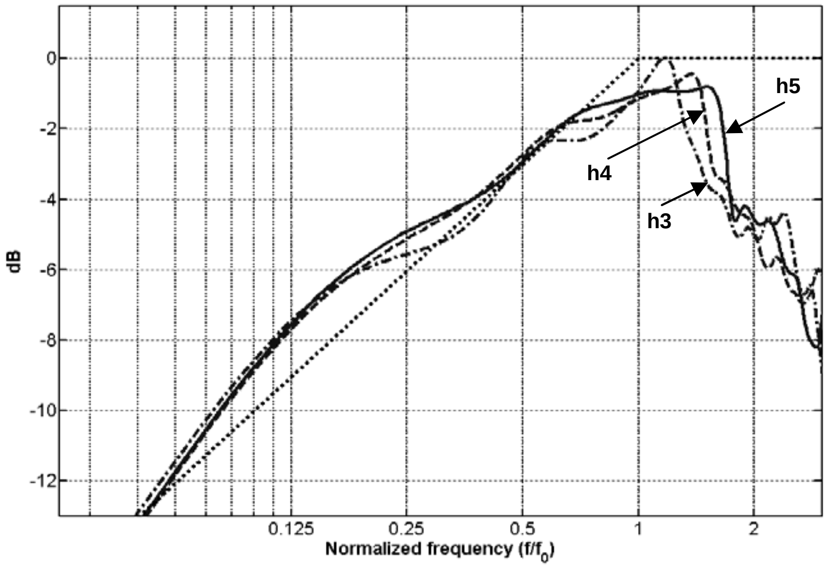


Figure 5: Measured and expected normalized frequency response with 1 m panel depth at 6 (h5), 5.5 (h4) and 5 (h4) metres height. Dashed straight lines show simplified expected responses.

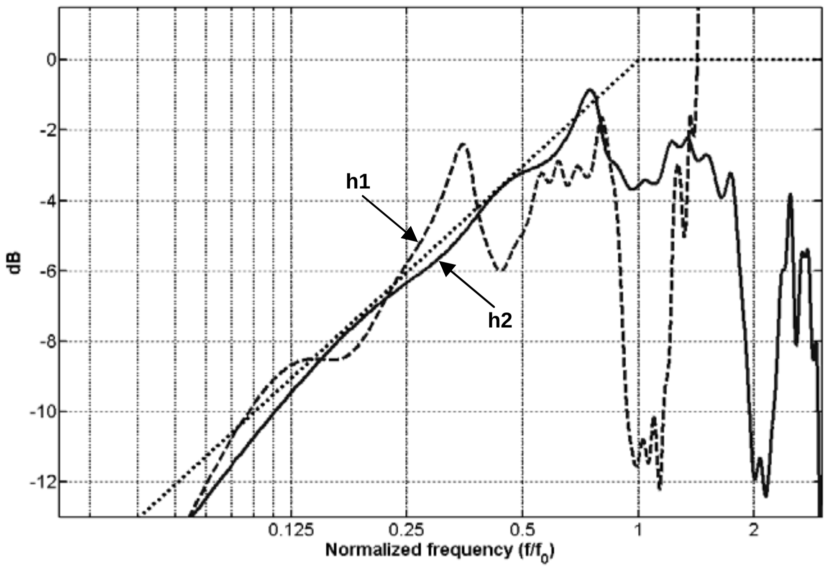


Figure 6: Measured and expected normalized frequency response with 1 m panel depth at 4 (h2) and 3 (h1) metres height. Dashed straight lines show simplified expected responses.

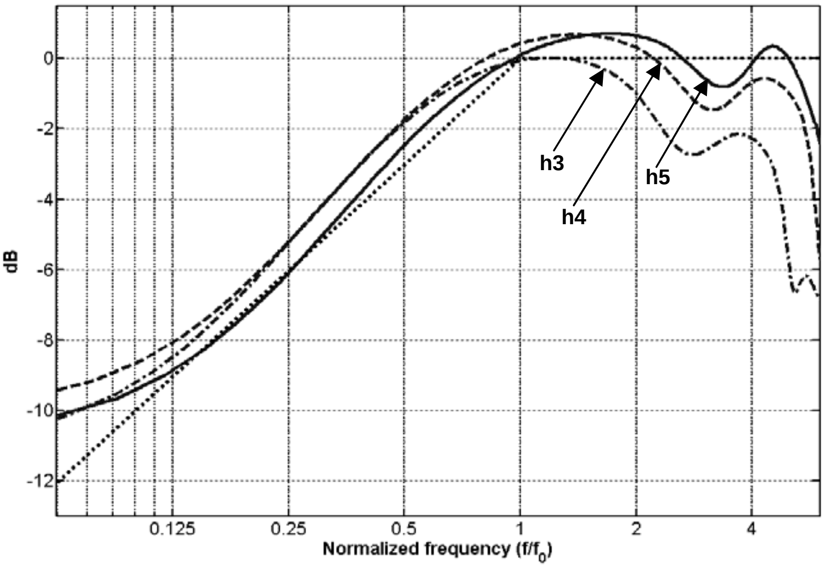


Figure 7: Measured and expected normalized frequency response with 2 m panel depth at 6 (h5), 5.5 (h4) and 5 (h4) metres height. Dashed straight lines show simplified expected responses.

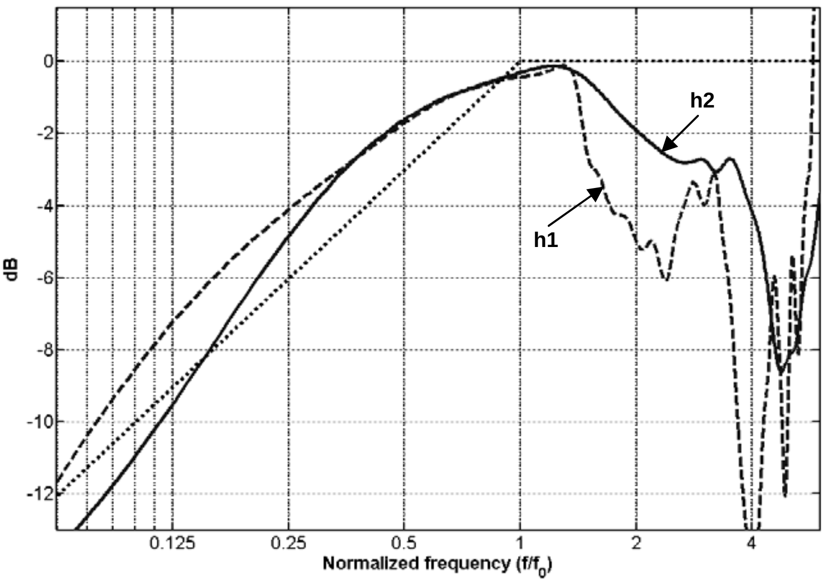


Figure 8: Measured and expected normalized frequency response with 2 m panel depth at 4 (h2) and 3 (h1) metres height. Dashed straight lines show simplified expected responses.

See table 3 for a summary of results for all the heights and both cornices and the ration between calculated and measured limiting frequency (measured divided by calculated).

Cornice height (m)	Limiting frequency (Hz)					
	Cornice depth d1 (1 m)			Cornice depth d2 (2 m)		
	Calculated	Measured	Ratio	Calculated	Measured	Ratio
6 (h5)	1434	1450	1.01	358	380	1.06
5.5 (h4)	1643	1730	1.05	411	350	0.85
5 (h3)	1945	1950	1.00	486	550	1.13
4 (h2)	3122	-	-	781	850	1.09
3 (h1)	6809	-	-	1702	1800	1.06

Table 3: Measured limiting frequencies with wall present.

Note that the calculated limiting frequency is above the bandwidth of the spark source (1720 Hz) for a panel depth of 1 metre at heights of 3, 4 and 5 metre. One third octave corresponds to a frequency ratio of 1.19 / 0.84 (up or down).

2.6 Discussion of results

For the four highest positions of the reflecting panel (creating the cornice reflection), the measured frequency responses match well expectations based on the simplified theory. The obtained responses above 2 kHz are questionable since the peak frequency of the spark source is at 1720 Hz. Above this frequency the spectrum drops off abruptly and gives low signal to noise ratio. This leads to problems with verifying the hypothesis for the two lowest panel heights. At these heights (3 and 4 metre height relative the floor) using the 1 metre wide panel, the expected limiting frequency is above the frequency bandwidth of the spark source (1720 Hz). All measured limiting frequencies are within 1/3 octave up/down from the calculated frequency.

Redoing the experiments by using the 5 mJ spark source (instead of the 47 mJ source used) will move the peak frequency from 1720 Hz to 2000 Hz (50 kHz in the 1:25 scale model). To confirm the calculated limiting frequencies at the two lowest heights with the 1 metre panel the minimum peak frequency is 78 kHz and 170 kHz respectively. So changing spark source will not help much for these two positions.

To improve the accuracy of the measurements, the reflections from the spark source could be tried minimized. This can be done by removing the Plexiglas disc and attaching a curved surface to cover the ceramic base which the three legs of the spark source are mounted to (as was done for the panel reflection investigations, section 4). Measured frequency responses using the 1 metre panel don’t reach 0 dB above the limiting frequency. This could be caused by the measurement configuration. The ideal configuration would be with the source and receiver at equal distance from the wall and on the axis of geometric reflection from the cornice. With the microphone 1 metre (40 mm) in front of the source, the microphone is not at the main direction of the cornice reflection. It was tried to have the microphone at same distance as the source, but shifted 1 m (40 mm) to the side, but because of disturbing reflection(s) from the spark source mounting, this more ideal configuration gave worse results in the calculated responses. Reducing reflections from the spark source could make this ideal position showing good results and may as well remove the observed level shift. The reason for this shift in level occurring for the 1 m panel only, could be caused by the limiting frequencies being 2 octaves higher for this panel, above 25 kHz physically in the scale model. At such high frequency sound waves behave much as rays and non-ideal transducer position could be more in the "shadow" of the reflected sound wave with this panel.

The reference used to obtain the frequency response of the cornice reflection, is the reflection from the wall. This should be valid with no floor present. If the floor had been present, this reference reflection would be partly disturbed by the floor reflection.

2.7 Concluding remarks

One hypothesis was tested in this experiment: the bandwidth of a reflection from a finite surface is extended two octaves down when the surface is attached 90° to a large reflective surface, compared to hanging it freely suspended. The frequency bandwidth of the reflection is defined by a lower limiting frequency. Measured limiting frequencies of the reflection from 1 and 2 metre deep panels at a height from 3 to 6 metres, support this hypothesis. The configuration with a 1 metre wide panel could not be verified with a height of 3 and 4 metres due to source bandwidth limitations

3 Sound level of cornice reflection

As described, the frequency response of a cornice reflection has been investigated with different soffit heights. These same measurements have been used to look at the level of such a reflection, and to look for an optimal soffit height to maximize the average sound level of the reflection.

The sound level of the cornice reflection has found by using the simplified theory for the frequency response of a soffit reflection.

3.1 Calculated frequency response

See figure 9 for the simplified expected frequency response from a surface with finite width, D and corresponding integrated octave band values of the sound level.

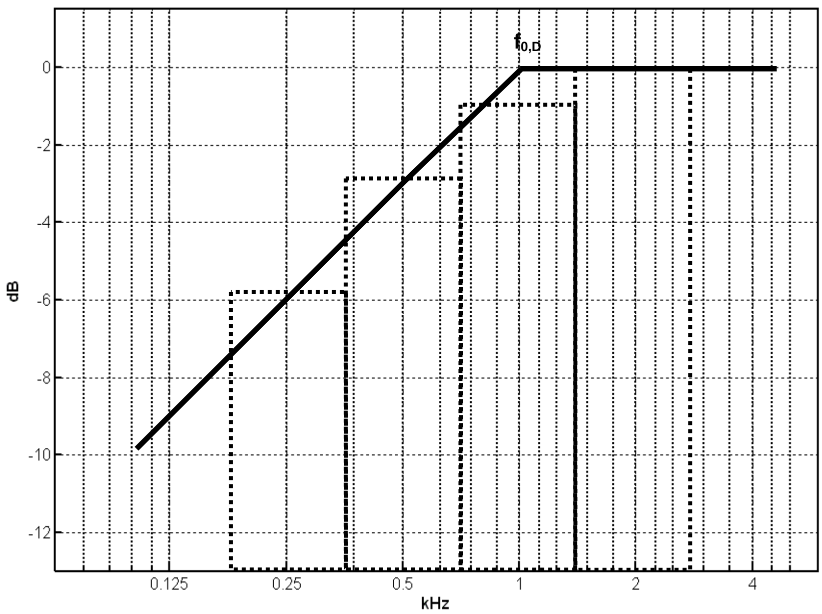


Figure 9: Simplified theoretical frequency response of reflection from an object with the limiting dimension D and integrated octave band values.

3.2 Calculated levels based on the simplified frequency response

If we know the frequency response, we can try to figure out what the octave band values and average (arithmetic) or total sound level will be. The levels can be found relative to a reflection from an infinite flat surface at a similar distance or with the source-receiver distance taken into account as well. The latter will be more realistic for comparing the level from varying soffit heights, since the soffit moves farther away when increasing the height. Because of the increased distance the level will decrease, but it will cause the limiting frequency to shift down in frequency which will contribute to increase the level. This means we have two factors that work in opposite directions, an optimal height should exist. The following method has been used to find octave band values:

- If the limiting frequency is above the upper boundary of the actual octave band, the level is set to 0 dB or according to the source-receiver distance
- If the limiting frequency is within the octave band, equation 2 below is applied
- If the limiting frequency is above the octave band, equation 3 below is applied

$$f_0 < f_c/\sqrt{2} \Rightarrow \qquad \Delta L_{f0} = 0 \qquad (2)$$

$$f_c/\sqrt{2} < f_0 < f_c \cdot \sqrt{2} \Rightarrow : \qquad \Delta L_{f0} = 10 \cdot \log\left(\frac{f_0}{f_c}\right) \qquad (3)$$

$$f_0 > f_c \cdot \sqrt{2} \Rightarrow \qquad \Delta L_{f0} = 10 \cdot \log\left(\frac{f_0}{f_c/\sqrt{2}}\right) \qquad (4)$$

If the source-receiver is taken into account as well, the following term is added:

$$\Delta L_{srd} = 20 \cdot \log\left(\frac{1}{s + r}\right) \qquad (5)$$

This is done for the octave bands 250, 500, 1k and 2k Hz.

The average level is calculated over these four octave bands. With the source-receiver distance taken into account, the levels in each octave band and the average are normalized to the maximum level. The total level could also be found by summing the sound energy in each octave band, which would give a different total level. This has not been done in this investigation.

3.3 Calculated levels based on measurements

The levels for the measured cornice reflections are obtained by filtering and summing the energy for each octave band, 0.25 – 2 kHz on the isolated cornice reflection. The levels are here compensated for the detected source-receiver distance (which gives the levels relative to a large reflecting surface at an equal distance), so the obtain values correspond to theoretical values based on ΔL_{f0} only. (The level is found by comparing the level from cornice and wall reflection and compensating for different distances.)

3.4 Comparison of calculated and measured levels

Table 4 and 5 show the difference between calculated and measured reflection levels (measured minus calculated). This is without the source-receiver distance taken into account (showing the effect of the limiting frequency only)

Cornice height (m)	Sound level (dB)					Limiting frequency (Hz)
	250 Hz	500 Hz	1 kHz	2 kHz	Average	
6	+2	+1.1	+0.1	-0.9	+0.6	1434
5.5	+1.9	+1.1	+0.3	-0.4	+0.7	1643
5	+2.0	+0.7	+0.2	0.0	+0.8	1945
4	-0.1	+0.5	+0.4	-0.9	0.0	3122
3	-3.1	-0.4	+0.1	-0.1	-0.7	6809

Table 4: Difference between measured and calculated reflection levels from a 1 metre wide panel at different heights (measured – calculated).

Cornice height (m)	Sound level (dB)					Limiting frequency (Hz)
	250 Hz	500 Hz	1 kHz	2 kHz	Average	
6	+1.0	+0.6	+0.3	+0.3	+0.3	1434
5.5	+1.7	+1.1	-0.7	-0.9	+0.3	1643
5	+1.7	+1.4	+1.7	-2.4	-0.3	1945
4	+2.1	+1.1	-0.2	-2.2	+0.2	3122
3	+2.6	+2.3	+1.3	+0.4	+1.6	6809

Table 5: Difference between measured and calculated reflection levels from a 2 metre wide panel at different heights (measured – calculated).

3.5 Search for an optimal soffit height

With both frequency response and source-receiver distance taken into account, we can try to find an optimal height of the cornice on a general basis. The reflection level is from a panel height ranging from 2 to 14 metres. This is based on a source-receiver distance equal to 10 + 10 metres (half the width of an average stage, as presented in section 3.3.2), both at a height of 1.2 metre. The maximum levels and associated soffit heights are indicated in bold.

Tables 6 to 8 show the results for a 1, 2 and 3 metre deep soffit (respectively).

Cornice height (m)	Sound level (dB)					Limiting frequency (Hz)
	250 Hz	**500 Hz**	**1 kHz**	**2 kHz**	**Average**	
14	-1.1	-1.1	-1.1	-1.9	-1.2	1118
12	-0.4	-0.4	-0.4	-1.1	-0.5	1168
10	**0**	**0**	**0**	-0.2	**0**	1304
8	-0.1	-0.1	-0.1	**0**	-0.1	1635
6	-1.3	-1.3	-1.3	-1.1	-1.2	2532
4	-4.5	-4.5	-4.5	-2.9	-4.1	6108
2	-14.7	-14.7	-14.7	-13.0	-14.2	67470

Table 6: Calculated reflection level for source and receiver 10 from the wall with a 1 m wide panel attached to wall.

Cornice height (m)	Sound level (dB)					Limiting frequency (Hz)
	250 Hz	**500 Hz**	**1 kHz**	**2 kHz**	**Average**	
14	-2.4	-1.9	-3.3	-3.6	-2.4	279
12	-1.8	-1.1	-2.5	-2.7	-1.6	292
10	-1.4	-0.2	-1.6	-1.8	-0.8	326
8	**0**	**0**	-0.8	-1.0	**0**	409
6	-1.1	-1.1	**0**	-0.2	-0.2	633
4	-4.4	-2.9	-2.8	**0**	-2.1	1526
2	-14.5	-13.0	-12.9	-8.6	-11.8	16855

Table 7: Calculated reflection level for source and receiver 10 from the wall with a 2 m wide panel attached to wall.

Cornice height (m)	Sound level (dB)					Limiting frequency (Hz)
	250 Hz	**500 Hz**	**1 kHz**	**2 kHz**	**Average**	
14	-2.4	-3.3	-3.9	-3.9	-2.8	124
12	-1.6	-2.5	-3.0	-3.0	-2.0	130
10	-0.7	-1.6	-2.2	-2.2	-1.1	145
8	**0**	-0.8	-1.3	-1.3	-0.3	182
6	-1.1	**0**	-0.6	-0.6	**0**	281
4	-2.9	-2.3	**0**	**0**	-0.7	678
2	-13.0	-10.9	-10.0	-5.4	-9.2	7491

Table 8: Calculated reflection level for source and receiver 10 from the wall with a 3 m wide panel attached to wall.

3.6 Discussion of results

Comparison between measured and calculated levels shows good agreement. The maximum difference between measured and calculated average level is 1.6 dB. This implies that the simplified theoretical model is valid to use in further experimentation with reflection level from flat finite surfaces (cornice reflection). A lower level of about 1 dB above the limiting frequency for the 1 m wide panel is observed here as well (as discussed in the previous section).

When looking at optimum height of cornice reflection, the ideal height will be controlled by the frequency bandwidth of the reflection that is useful for the musicians. If only the 1 and 2 kHz octave bands are relevant for hearing one-self and each other, the ideal height will be shifted 1 – 3 metres compared to a reflection bandwidth from 0.25 to 2 kHz. For a bandwidth of 0.25 to 2 kHz the optimal soffit height for a soffit width of 1, 2 and 3 metres were found to be 10, 8 and 6 metres (respectively).

These calculations have been verified with measurements with 1 and 2 metre wide panel at a height from 3 to 6 metres. The calculation of reflected sound level at other heights is under the assumption that the formulas for calculating the level and frequency response are valid at extended heights. This could be verified by looking at reflection levels from real halls where such cornice reflections take place or by building scale models with corresponding dimensions.

3.7 Concluding remarks

A simplified method of calculating octave band and average levels of a cornice reflection is developed. It shows good agreement with measured reflection levels.

Some experimentation on different soffit heights has been done with the source and receiver at the centre of a stage with an average width (20 m). The results show that with a 1 metre wide soffit the optimum height is 10 metre (for a maximum average reflection level). Increasing the width to 2 and 3 metres, lowers the optimum height to 8 and 6 metres, respectively. These optimum heights are for the total sound level from 0.25 to 2 kHz. If only a bandwidth 1 to 2 kHz is shown be relevant for such reflections, the optimum height is shifted 1 – 3 metres down (9, 5 and 4 m for 1, 2 and 3 m width).

4 Directivity and level of panel reflections

On stage in a concert hall there are often overhead reflectors, balcony overhangs (soffits), vertical elements installed along the sides of the stage or other elements with a finite width. It is interesting to investigate to which degree such reflections can be useful for the musicians. To have an objective investigation of this, the level, frequency response and directivity of panels have been measured in a 1:25 scale model.

The level and frequency response of such a reflection will be seen in relation to an infinite flat surface at an equal distance. Due to diffraction there is a lower frequency limit for a complete reflection from the panel (as described in section 1.2). For an infinite long panel this limiting frequency (f_0) is controlled by the width of the panel, the panel's distance from the source and the receiver, and the incidence angle. "Infinite" will in practice mean that the length of the panel is much larger than the width (causing in practice the width to be the only limiting dimension). Below the limiting frequency, the reflection level is expected to drop 3 dB per octave.

Since the bandwidth of the reflection is dependent of source-receiver distance measurements have been done with two different configurations of source-receiver-distance, both relevant distances on an actual stage. To have a brief look at the case of a cornice reflection, measurements of 50° incidence have been done. To see the directivity of the panel reflection, the reflection has been measured at a 10 degree step from -90 to 90° and polar plots generated.

To describe the resulting reflected levels and directivity, a reflection from a large flat surface is used a reference. Such a large flat surfaces will follow principles of geometrical acoustics to a high degree, and will give a specular reflection (according to ray theory). The coverage angle of the reflection from the panel is seen in relation to a specular (geometrical) reflection from the panel.

To see how a computer model is able to model the behaviour investigated, a computer model with the same geometrical properties was created in CATT-Acoustic.

4.1 Measurement setup

Vertically standing panels of minimum height of 31.3 m (1250 mm) have been used for these tests. The spark source and the microphone were placed 10.6 (425 mm) above a reflecting surface (serving as a base for the panel and the mounting of the spark source and the microphone). See figure 10 for a picture of the measurement configuration and the computer model of the same configuration. In the computer model figure, the source and receiver distance is indicated as S and R. The area for a specular (geometrical) reflection is also indicated. The coverage angle of the specular reflection can be found using Snell's law from optics (treating sound as rays).

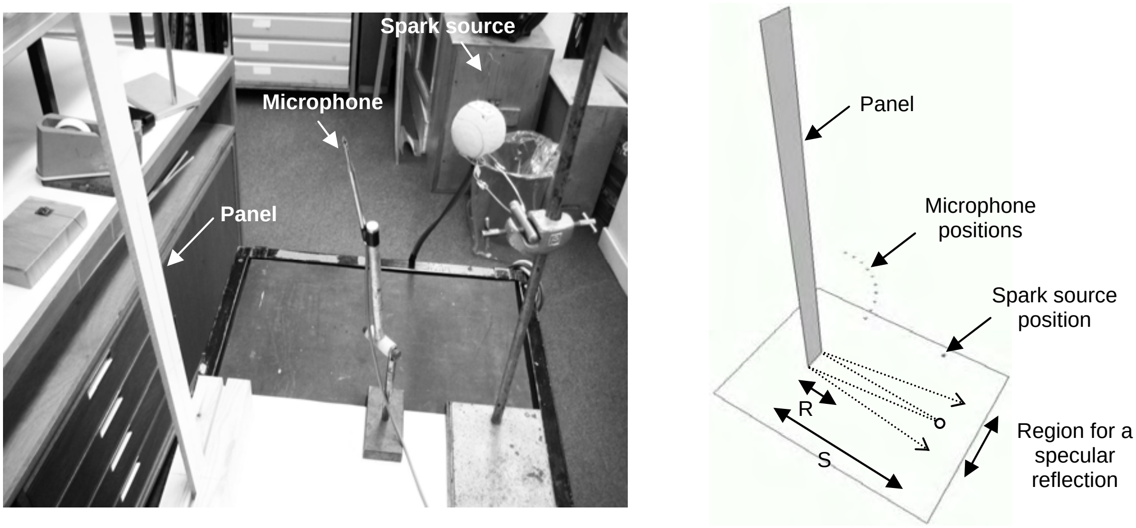


Figure 10: Picture of the measurement setup and the corresponding computer model.
S and R represent source and receiver distance relative to the panel.
The region for a specular (geometrical) reflection is indicated.

To minimize the reflection from the spark source mounting, a tennis ball has been used to serve as a spherical diffusing base. The porcelain base is exposed on top of the tennis ball, which could give some weak disturbing reflections.

The position of the microphone is moved along a circle at a constant distance from the panel. 10° steps have been used for the positioning of the microphone. The spark source was at a fixed position for all microphone positions. The two following configurations were investigated:

	Spark source distance from panel (m)	**Microphone distance from panel (m)**	**Total sound path (m)**
Setup 1	5 (200 mm)	3 (120 mm)	8 (320 mm)
Setup 2	11 (440 mm)	5 (200 mm)	16 (640 mm)

Table 9: Source-receiver distances used, with scale model dimensions given in brackets.

Two different panel widths were tested: 1 and 2 metre (40 and 80 mm). To serve as an "infinite" wall reference a 11.75 m (470 mm) wide panel was used. See table 10 below for more details.

	Width (m)	Height (m)	Thickness (m)
Panel 1	1 (40 mm)	31.2 (1250 mm)	0.175 (7 mm)
Panel 2	2 (80 mm)	31.2 (1250 mm)	0.175 (7 mm)
Panel 3 (reference)	11.75 (470 mm)	21.9 (875 mm)	0.175 (7 mm)

Table 10: Panels used, with scale model dimensions given in brackets.

See figure 11 for a sketch of the measurement setup seen from above.

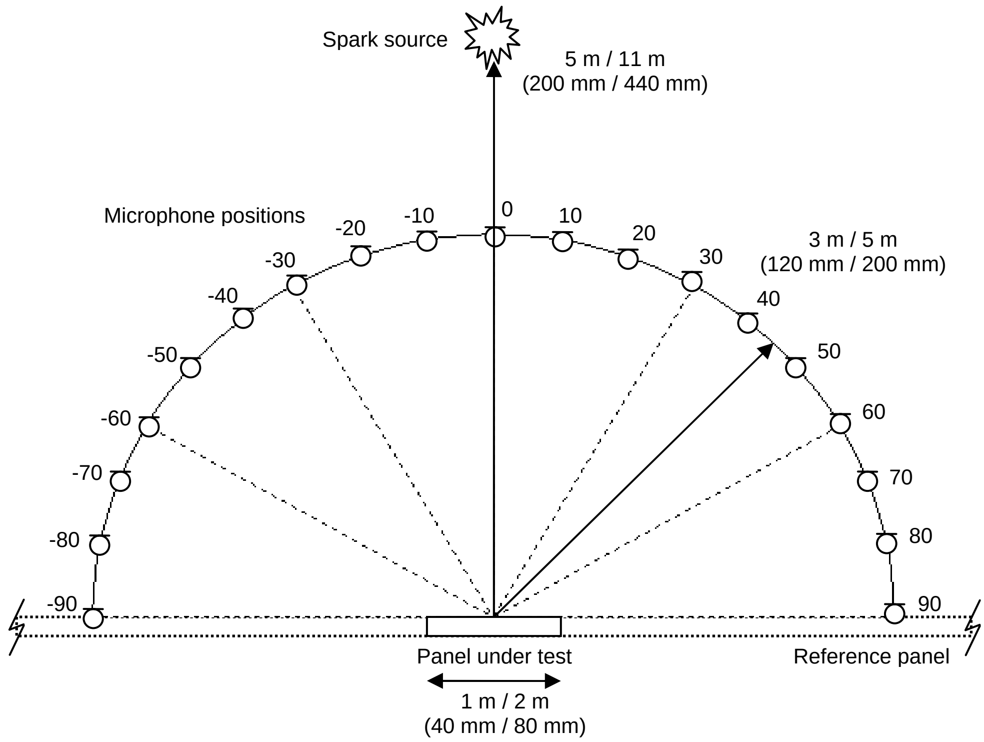


Figure 11: Configuration for measurement of directivity and sound level of panel reflection.

This results in a total of 19 measurements being done for each configuration. At these first investigations only the angles -90° to 0° have been measured, since the directivity pattern will be symmetric (with 0° incidence).

Both the spark sources were used the 5 + 3 metre configuration (for further comparison of the two sources) and the 47 mJ source only for the 11 + 5 metre configuration. Only the results from the 47 mJ source measurements are shown in this report, see [7] for all results.

At each microphone position three measurements were done; with panel 1 and 2 and no panel present. The measurement of no panel present was done to be able to get a better isolation of the panel reflection by subtracting the response with no panel present from the panel measurement (like for the investigation of the cornice reflection described in section 1.1). The position on the line between the receiver and panel (0° or 50°, “on –axis”) includes measurement of response with panel 3 as well. This measurement serves as a reference reflection level from a large wall. Each measurement is done by taking the average of 4 individual captured impulse responses.

4.2 CATT simulation

See right part of figure 10 for the CATT model of the scale model measurement configuration. Two different simulations were done CATT-Acoustics. The first was done with no edge diffusion modelling, while on the second simulation, this feature was enabled. In both situations the panel was modelled as a hard non-absorbing and non-scattering surface. CATT-Acoustic version 8.0e build 3.01 was used. The edge diffraction is implemented by applying scattering coefficient along the edges of the surface. The width of the scattering edges is set to one quarter wavelength to imitate diffraction effects along the edges. See [12] for more details on how the edge diffusion is implemented in CATT-Acoustic.

4.3 Observed coverage angles and polar plots

To describe the directivity of the panel, we can observe the coverage angle of the panel reflection. This is generally done for common sound sources like loudspeakers. The coverage angle is the “beam width” of the reflection seen in relation to the main direction of the reflection (often referred to as “on-axis” direction). The most common way of representing coverage angles for sound sources is by using the -6 dB level as outer limits (for loudspeakers etc.). This means that the sector where the main reflection level is not less than the 6 dB in level relative to the on-axis level will define the coverage angle of the source. The -6 dB limit is used because the sound from the speakers is normally expected to be in phase related to each other when being placed next to each other. Looking at the -6 dB points will then help getting an even level with more than one speaker combined. (Two sources in phase of similar sound level raise the overall level by 6 dB, compared to only one source).

Looking at reflecting elements on a stage, the phase relation between the different reflections is not known. Hence, when summing reflections we must sum energy not sound pressure. When summing sound energy, two sources of equal level raise the overall level by 3 dB. For this reason coverage angles using the -3 dB level as outer limits are referred to in the results. The -3 dB level is seen relative to the large wall reflection (panel 3).

The directivity of the panel reflection is illustrated by polar plots. The curve that represents the directivity runs from -90° to 90° and the curve's distance from the centre represents the sound level of the reflection for the particular angle (- 90 to 90). 0 dB in the polar plot represents that the level of the measured panel reflection has the same level as the reflection from an infinite surface at the same distance as the panel tested.

Figure 12 shows how the coverage angle is estimated from polar plot of the panel reflection. Two polar plots are included: One for the reflection at low frequencies and one for the reflection at high frequencies. The calculated specular coverage angle is also included. For the low frequency reflection the detected -3 dB angles are indicated with white dots and the coverage angle for this reflection is line up with black dotted straight lines. The detected -3 dB points for the high frequency reflection is indicated with the black dots. The -3 dB points are found visually.

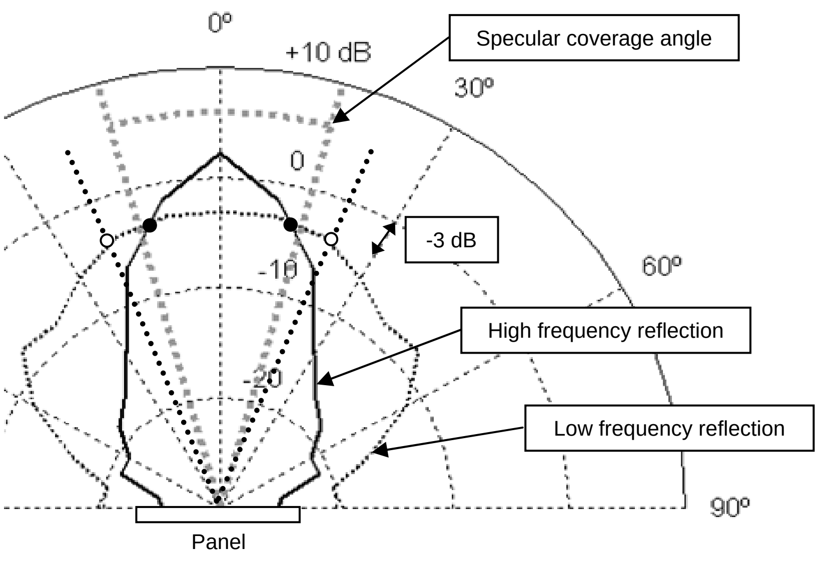


Figure 12: Estimation of coverage angle from polar plot of panel reflection

As can be seen in figure above the detected coverage angle is almost the same for the low and high frequency reflection, even though the reflection patterns (directivity) are rather different. This illustrates the limitation of using the coverage angle as a descriptor of the directivity of the reflection. At low frequency the reflection is much wider than the calculated specular reflection, while the reflection is close to the specular reflection at high frequencies (about 30° coverage angle). If the -3 dB point is not seen relative to a large wall reflection but relative to on-axis level, the -3 dB points would have been more to the sides for the low frequency reflection, resulting in almost 70° coverage angle. The advantage of calculating the coverage angles as illustrated in figure 35, is that it will help us find the zones of a stage where reflections take place that have a level within -3 dB relative to a large wall reflection at all frequencies.

4.4 Results

See figures 13 to 18 for the resulting polar responses for the different configurations. Only polar plots are presented here while observed coverage angles are mentioned in the discussion (for full detail on coverage angles see [7]).

Reflection from 1 m wide panel

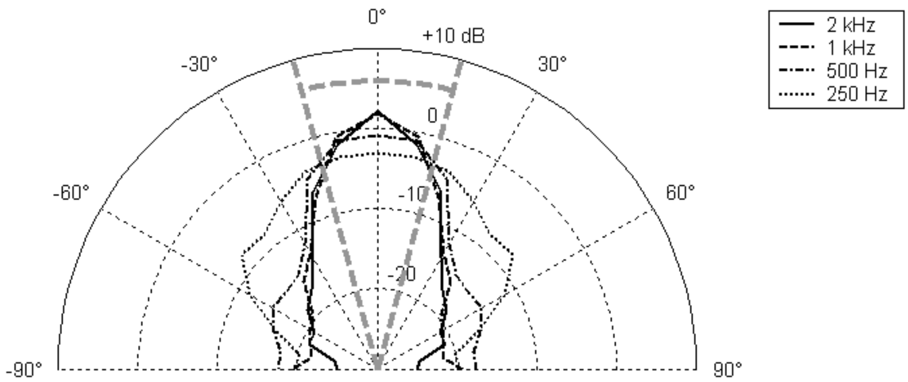


Figure 13: Reflection from a 1 m (40 mm) wide panel at 250, 500, 1k and 2 kHz. Measured with 47 mJ spark source. Source 5 metre and microphone 3 metre from panel.

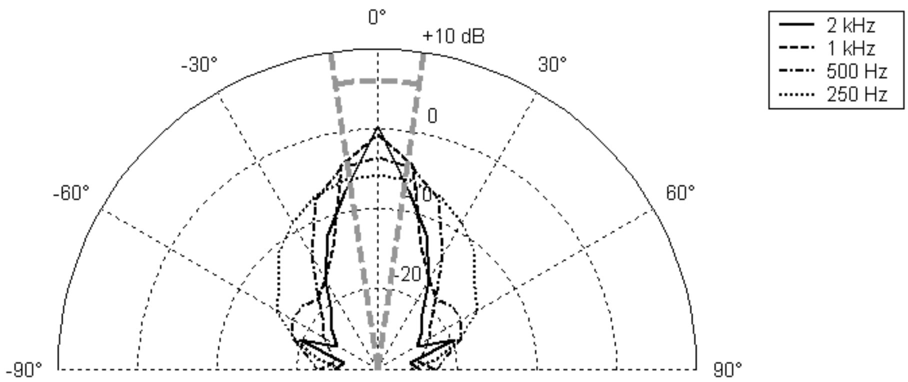


Figure 14: Reflection from a 1 m (40 mm) wide panel at 250, 500, 1k and 2 kHz. Measured with 47 mJ spark source. Source 11 metre and microphone 5 metre from panel.

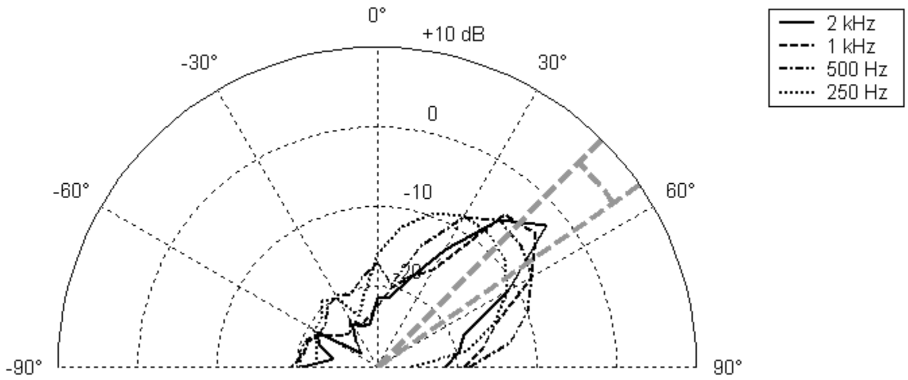


Figure 15: Reflection from a 1 m (40 mm) wide panel at 250, 500, 1k and 2 kHz. Measured with 47 mJ spark source with -50° incidence. Source 11 metre and microphone 5 metre from panel.

Reflection from 2 m wide panel

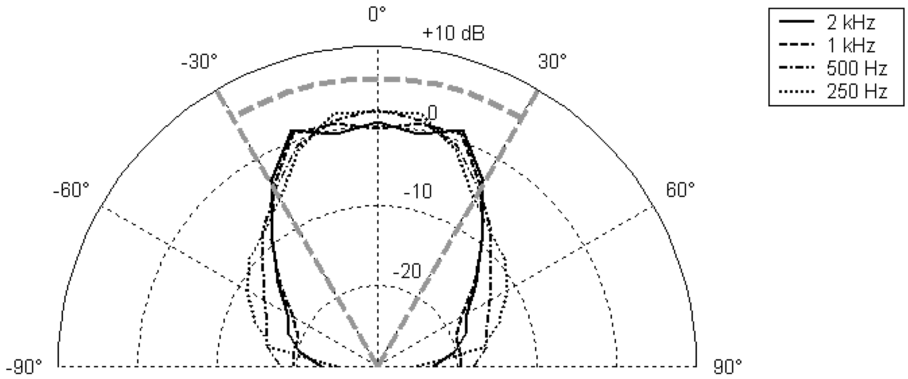


Figure 16: Reflection from a 2 m (80 mm) wide panel at 250, 500, 1k and 2 kHz. Measured with 47 mJ spark source. Source 5 metre and microphone 3 metre from panel.

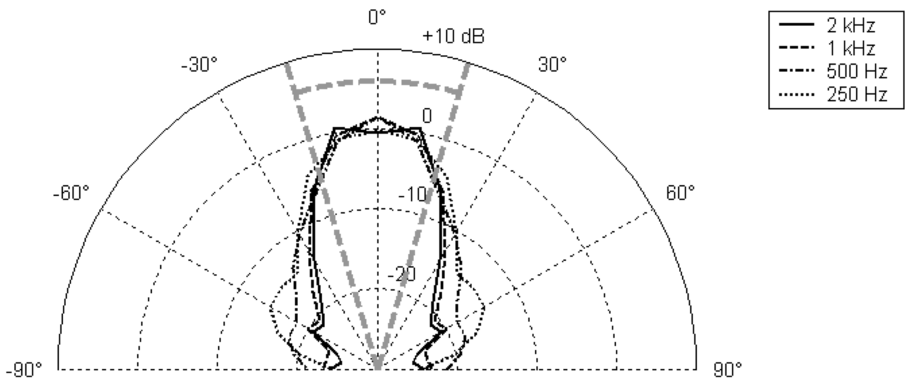


Figure 17: Reflection from a 2 m (80 mm) wide panel at 250, 500, 1k and 2 kHz. Measured with 47 mJ spark source. Source 11 metre and microphone 5 metre from panel.

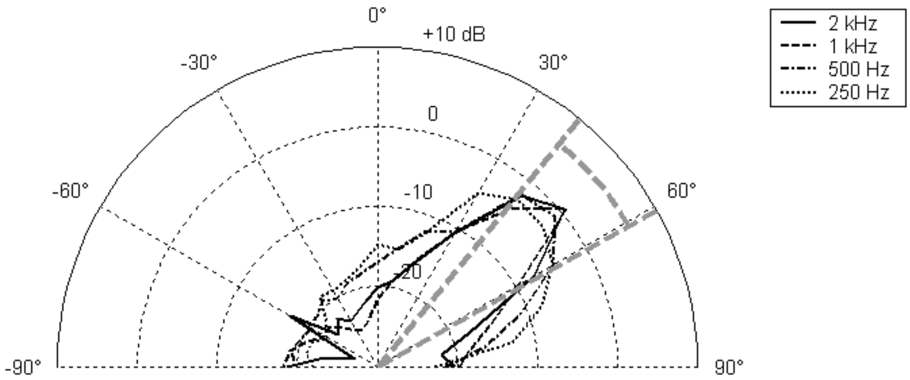


Figure 18: Reflection from a 2 m (40 mm) wide panel at 250, 500, 1k and 2 kHz. Measured with 47 mJ spark source with -50° incidence. Source 11 metre and microphone 5 metre from panel.

4.5 Results from the CATT simulation

For comparison with computer simulation, the results in CATT-Acoustic are shown for the prediction of the 2 metre wide panel with source-receiver distance 5 + 3 metre. Figure 19 shows the results with flat panel without edge diffusion modelling, while figure 20 shows the results with edge diffusion enabled.

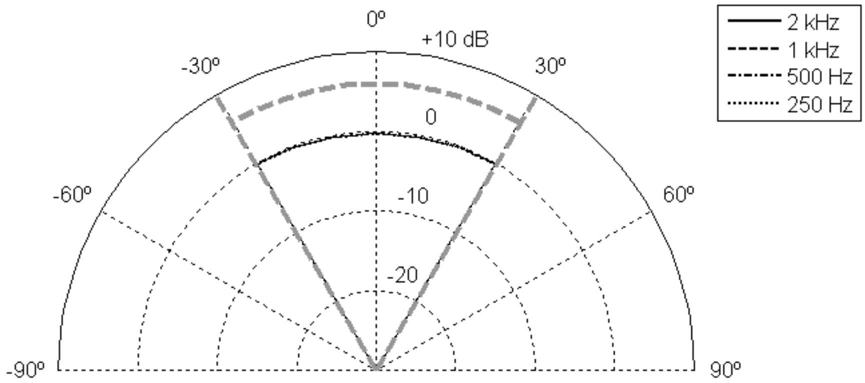


Figure 19: Reflection from a 2 m (80 mm) wide panel at 250, 500, 1k and 2 kHz. Simulated in CATT-acoustic with edge diffusion disabled. Source 5 metre and microphone 3 metre from panel.

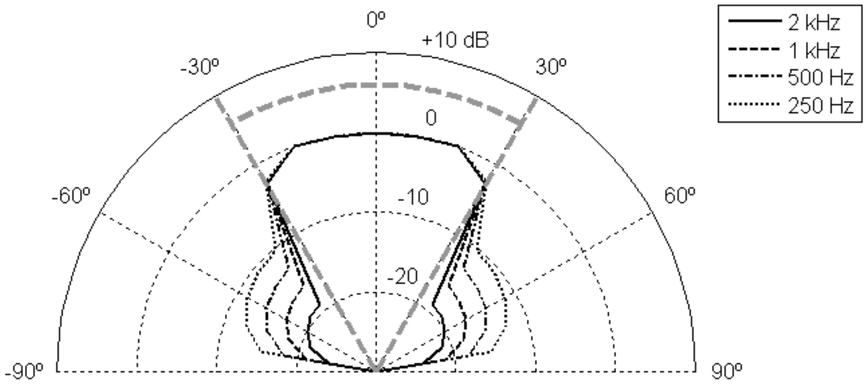


Figure 20: Reflection from a 2 m (80 mm) wide panel at 250, 500, 1k and 2 kHz. Simulated in CATT-acoustic with edge diffusion enabled. Source 5 metre and microphone 3 metre from panel.

4.6 Discussion of results

When looking at the panel reflection, several aspects are interesting: the reflection pattern compared to a specular reflection off the panel, the on-axis reflection level compared to the reflection level from a large wall and the coverage angle of the reflection. The on-axis reflection level at various frequencies will be affected by the width of the panel. If the frequency is below the limiting frequency of the panel (as described in section 5.1) the reflection level is expected to be lower in level than a reflection from a large wall. Above the limiting frequency we can expect the reflection to behave according to geometrical acoustic (ray theory). We can here expect the coverage angle of the panel to be close to specular coverage angle. This is seen in the results. For the octave bands above the limiting frequency, the coverage angle is at least 71 % of the theoretical specular coverage angle, except for the 1 metre wide panel with a source-receiver distance of 11 + 5 metres (47 % at 2 kHz).

For frequencies above the limiting frequency, on-axis level is in most cases 1 – 2 dB above the level from a large wall. This is believed to be caused by constructive interference between the reflected and diffracted components from the finite surface. For frequencies high above the limiting frequency (see for instance figure 16), this increased level is not observed. This could be explained by the panel being large enough compared to the wavelengths involved to give a almost perfect specular reflection (and weak diffraction components) with 0° incidence. Some destructive interference can also be observed above the limiting frequency (see also figure 16) which is in agreement with what Rindel found, [1].

Below the limiting frequency, the levels appear to drop according to -3 dB per octave. This is only investigated on-axis. This is according to the theoretical behaviour. The coverage angle is wider (over 100 % of specular coverage angle) at these octave bands, and approaching omni-directionality as the frequency decreases (with minor side lobes).

Outside the specular coverage angle the reflection level is about -15 dB if the angle is doubled. This means that if the specular coverage angle is 15° to each side (as in figure 36), the reflection level is about -15 dB at 30° to one of the sides. Geometrical acoustics will not predict any reflection at all at this angle. At 125 Hz the level is slightly higher than -15 dB at the doubled angle. Any quantitative knowledge about the importance of this raised coverage (compared to a specular reflection) is not known.

Due to the angle resolution the observed coverage angles can in fact be higher, since the theoretical coverage angle falls between two 10° steps. To improve this, the angle resolution of the measurements can be increased in the region where specular reflection is expected and to some point beyond that. For incidence angles above 0° or at far distance, this will be increasingly critical, so coverage angles for the 50° incidence cannot be treated as reliable values, while for 0° incidence the result of this test can serve as a valid indication of the actual polar pattern of the reflection.

When comparing measured polar patterns with the one obtained with computer simulation in CATT-Acoustic, it is clear the reflection pattern with edge diffraction enabled, does not have the same shape as the measured patterns. This is due to the scattering model in CATT (Lambert's cosine law for statistical distribution of the direction of scattered sound). The reflection level just outside the specular coverage angle drops off much faster in the CATT results, which can lead to the level being under predicted for the areas on stage that is just outside the specular reflection from the panel. With edge diffusion enabled we see that only a specular reflection is taking place, which is what we would expect from the ray/cone tracing.

4.7 Concluding remarks

Measurements of the level and the directivity have shown:

- Above the limiting frequency of the panel, the reflection behaves much like a specular reflection (according to geometrical acoustics) and the level is about the same as from an infinite (large) flat surface. On-axis the level is normally slightly higher due to edge diffraction effects. The coverage angle is found to be 75 – 98 % of the specular coverage angle for 0° incidence. For 50° incidence this ratio is found to be only 36 – 48 %. The actual measurement setup gives limited angular resolution to detect these ratios.
- Below the limiting frequency the on-axis reflection level behaves close to the law of -3 dB per octave. The coverage angle is here wider than the specular

coverage angle. The ratio between these two angles seems to be just about doubled per octave.

With the guidelines given above, tools based on geometrical acoustical can be used to investigate the contribution of reflection from finite width flat surfaces. The limiting frequency needs to be calculated for each reflection path.

A panel width of 1 metre seems to be useful for energy above 1 kHz only. These results are valid for typical source-receiver distance on stage. A panel width of 2 metres reflects well for all four octave bands investigated (250 – 1k Hz) with 0° incidence. With 50° incidence the effective width of the panel is about halved and it comes in the same category as the 1 metre wide panel with 0° incidence, but these values serve just approximate values due to limited angular resolution.

If the polar pattern of such reflections is to be further investigated, the measurements should be done with a higher angular resolution especially in the region where specular reflection is expected. To verify the measured values, the measurements could be done on both sides of the symmetry line of reflection to check for symmetry in the results.

The use of scattering coefficients to imitate diffraction in the computer model does not give similar directivity of the panel reflection, compared to scale model results. This can lead to an underestimation of the reflection level just outside the region for the specular reflection from the panel.

5 The effect of stage configuration on the sound field on stage

The stage configuration in our scale model hall has been varied to see how this affects the sound field on the stage. The elements being varied on stage are: orchestra absent or present, with or without the orchestra on risers and flat or diffusing stage side walls and back wall.

The transducers were chosen on stage according to recommendations for measuring the stage parameters ST_{early}, ST_{total} and ST_{late}. The impulse response itself will also be investigated to get a more detailed description of how the sound field changes.

Since both spark sources have limited bandwidth (assumed to be about 3 octaves), both sources have been used to investigate in which octave bands the two sources give corresponding results (and hence can be treated as reliable in those octave bands).

5.1 Measurement setup

See figure 21 for a description of the panel types used in the main hall.

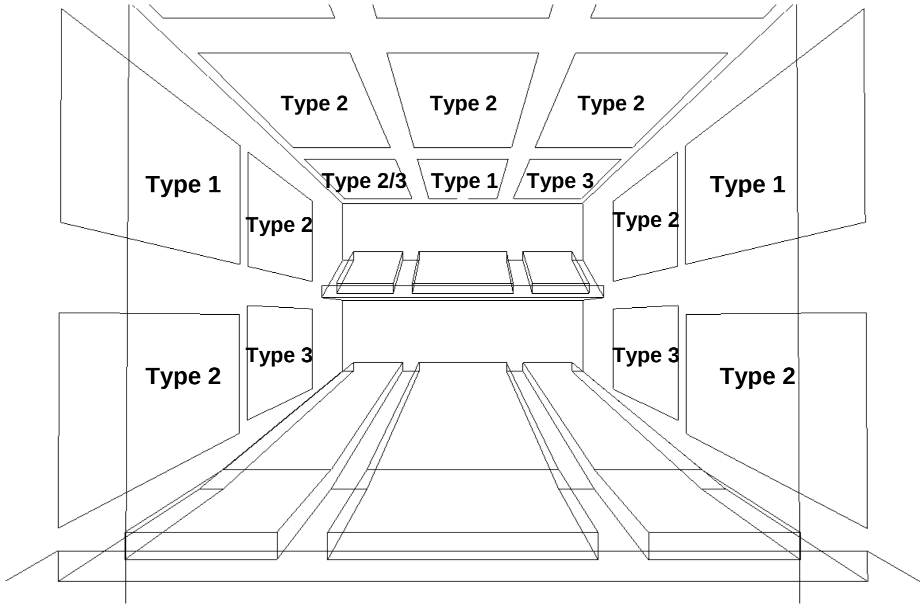


Figure 21: Panels in the rest of the hall.

Due to lack of panel type 3, both panel type 2 and 3 on the left side ceiling at the back have been used. Since this is so far away from the stage, this change between different measurements is believed to have little effect.

See [13] for more details on our scale model of a general rectangular concert hall.

5.2 Measurements

For each stage configuration, a total of 12 measurements have been done at position E. The sequence is E1, E2, E3 and E4. This is repeated twice (giving a total of three “rounds”). These three rounds have been done to check the variation in the results at each microphone position and the average over the four microphone positions.

With the orchestra present, the musicians are moved between each measurement to fulfil the requirement of minimum distance of 2 m from the transducers to the musicians. This was done to have as many musicians on the stage as possible. The number of musicians on stage was constant.

Figure 22 below shows a measured impulse response with configuration 1 at E1. We can see from this figure that at this microphone position the wall reflection arrives after 20 ms (the wall being more than four metres from the transducers).

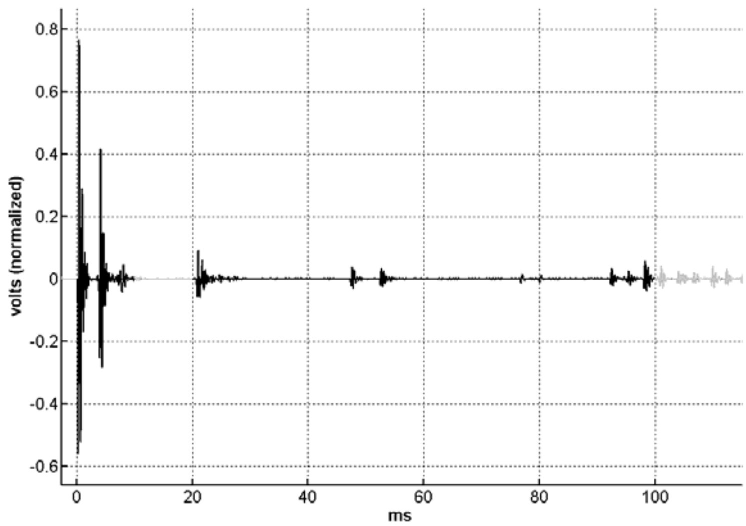


Figure 22: Measured impulse response at E1 with setup 1. For calculating ST_{early}.

The black parts of the impulse response shown above, are the parts of the response used for calculating ST_{early} (0 – 20 ms and 20 – 100 ms). The first strongest impulse shown is the direct sound, and it is followed by the floor reflection. This represents the reference energy emitted from the source. The response from 20 to 100 ms consists of the early reflections on the stage.

When calculating of ST values, the non-linearity of the source is compensated for (see appendix B for details). Correction values are applied to the direct sound and the floor reflection to compensate for this non-linear behaviour of the source. See also Dammerud [3] for more details. For details on how ST was calculated based on the measured scale model impulse responses, see Dammerud [4].

5.3 Computer simulation of the scale model

To see how well the acoustics on stage can be modelled on the computer, a computer model of our scale model of a general concert hall has been developed. With exactly the same source and receiver positions, results have been compared between these two models. The acoustical parameters reverberation time (RT, T30 and T15) and support (ST_{early}, ST_{total}, ST_{late}) have been compared on overall average, between receiver positions and overall average octave bands.

When we have measurement data from real halls, computer models of these stages can also be made to compare simulated results against measured. CATT-Acoustic has been used for the computer modelling to provide impulse responses and the acoustical parameters are calculated by CATT-Acoustic. MATLAB has been used to calculate ST values while WinMLS has been used to calculate reverberation times from the scale model impulse responses.

5.3.1 Model details

The computer model has been created by manual measurement of the physical dimensions of our existing scale model hall. The acoustical properties of the materials used in the scale model are based on estimated values from literature where available and reverberation chamber measurements of materials.

As mentioned, the scale model has removable panels on the walls (except the back wall due to attached balcony) and the ceiling to change the acoustical qualities of the hall. These panels are also included in the computer model. Figure 23 and 24 show musicians on risers of the stage of the hall – in the scale model and the computer model.

The design of the musicians in CATT is shown on the right hand side in figure 25. The scale model is included for comparison. The design of the musicians in the computer model is a compromise between detail and acoustical representation, and the design shown is a first suggestion on how to model the musicians. The vertical element of the back is included to model the body of the musician when seen from the side, while saving the number of surfaces used to model the whole musician. The lower part of the legs can be argued to be too “solid” compared to the real world situation (in both the scale model and the computer model).

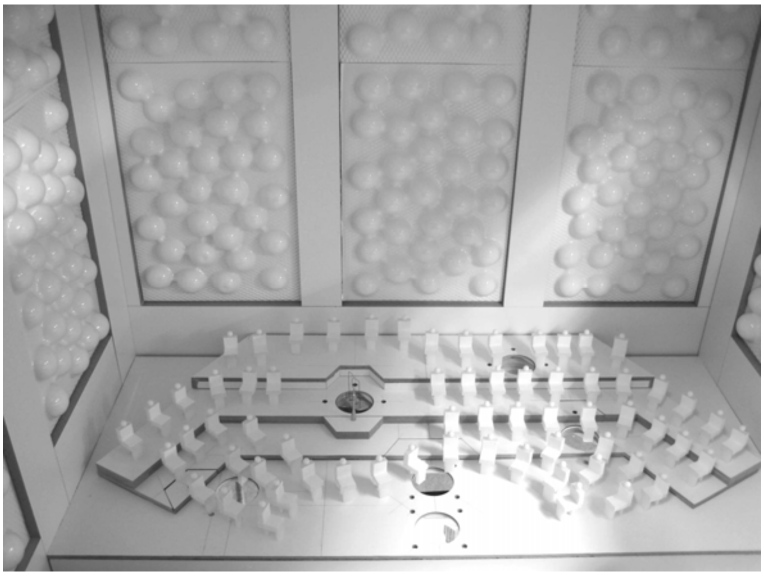


Figure 23: Musicians on risers in the scale model while measuring at source position E.

Figure 24: Musicians on risers in the CATT model with simulations at source position E.

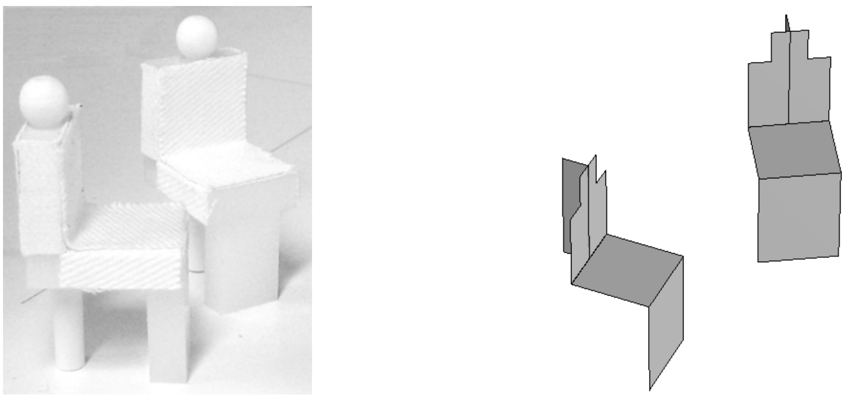


Figure 25: Musicians modelled in scale model and CATT-Acoustic.

The sound absorption of the musicians in the scale model has been measured in a scale model reverberation chamber and compared to values estimated for a real orchestra (Chiles, [11]).

5.3.1.1 Acoustical properties in the CATT model

Data for absorption coefficients of the materials used in the model are based on Chiles' and Barron's data [11], [2], see table 11.

Material	**Absorption coefficient (α)**					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Hard wall	0.05	0.04	0.02	0.02	0.02	0.02
Panel type 1	0.05	0.04	0.02	0.02	0.02	0.02
Panel type 2	0.05	0.04	0.02	0.02	0.02	0.02
Panel type 3	0.05	0.04	0.02	0.02	0.02	0.02
Audience	0.32	0.50	0.73	0.87	0.85	0.85
Musicians	0.13	0.20	0.37	0.64	0.78	0.78

Table 11: Absorption coefficients used in the CATT model.

For the musicians a transparency coefficient is used to represent the diffraction of sound transmitting through the orchestra. These values are just roughly estimated. See table 12 for the coefficients used.

Material	**Transparency coefficient**					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Musicians	0.85	0.70	0.40	0.20	0.10	0.02

Table 12: Transparency coefficients used in the CATT model.

Based on the same references stated above, the scattering properties of the materials have been set, see table 13.

Material	**Scattering coefficient (α)**					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Hard wall	0.10	0.10	0.10	0.10	0.10	0.10
Panel type 1	0.10	0.10	0.10	0.10	0.10	0.10
Panel type 2	0.25	0.40	0.50	0.50	0.50	0.50
Panel type 3	0.35	0.60	0.70	0.70	0.70	0.70
Audience	0.10	0.20	0.35	0.50	0.70	0.70
Musicians	0.70	0.70	0.70	0.70	0.70	0.70

Table 13: Scattering coefficients used in the CATT model.

5.3.2 Modelling parameters in CATT-Acoustic

Below are shown the settings in CATT used for these simulations.

Diffuse reflection: Diffuse with edge diffusion

Acoustic environment: 20 °C, 50 % relative humidity, 1.20 kg/m^3 density (default)

Full detailed calculation: 20364 rays (auto), 5500 ms truncation time, late part ray-tracing enabled for situations with the orchestra present, i.e. disabled for configuration 1 and 2

CATT-Acoustic version 8.0e (build 3.01) was used. The ST and RT values from the computer model have been calculated in CATT. (MATLAB functions have been developed for calculating ST based on impulse response from CATT, but this has yet not resulted in corresponding values.)

5.3.3 Stage configurations used

The same stage configurations have been used as for the investigations performed in the real scale model. See figure 26 for illustrations and details on the different stage configurations used.

5.4 Configurations tested

Figure 26 show the different stage configurations that have been tested.

5.5 Results

Figure 27 shows measured impulse response at E1 including Schroeder curves.

The impulse responses presented are based on one single measurement at position E1. The Schroeder curve is the backward integration of the impulse response, and show how the sound level drops off according to time/distance. It can also serve as an indication of how diffuse the sound field is (an ideal diffuse room will have its Schroeder curve as a straight decaying line.

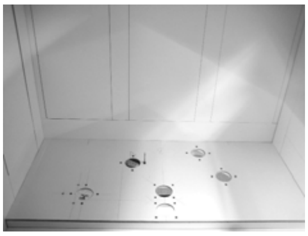
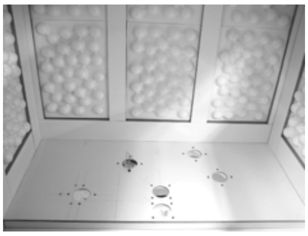
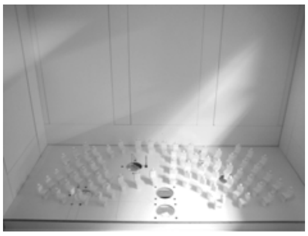
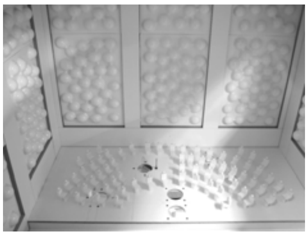
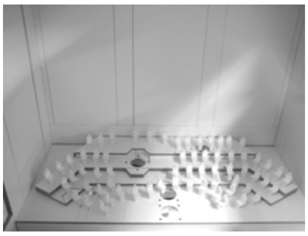
Config. nr	Description	Picture of configuration
1	No orchestra Flat walls	
2	No orchestra Diffusing walls	
3	Orchestra on flat floor Flat walls	
4	Orchestra on flat floor Diffusing walls	
5	Orchestra on risers Flat walls	
6	Orchestra on risers Diffusing walls	

Figure 26: Stage configurations used in investigation.

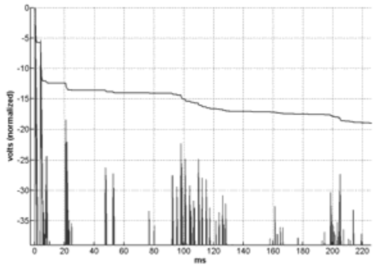
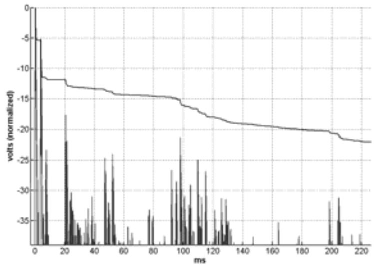
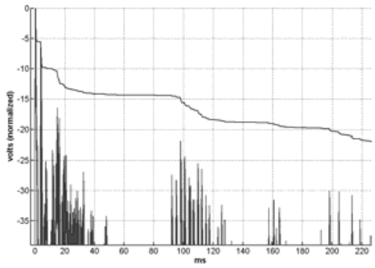
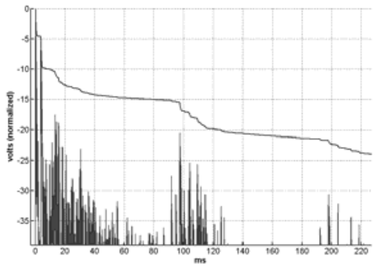
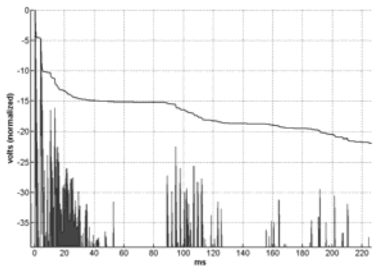
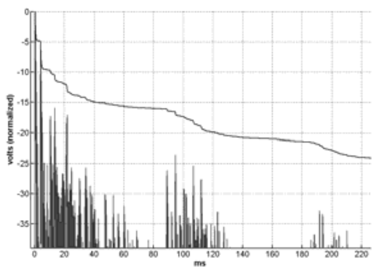
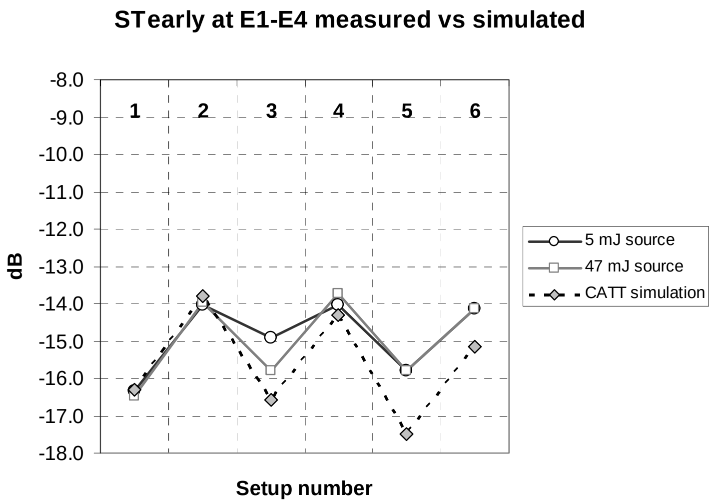
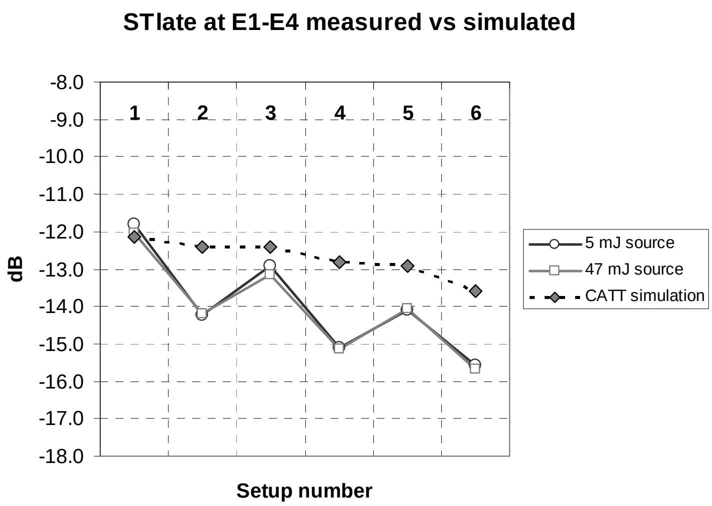
Config. nr	Description	Impulse response
1	No orchestra Flat walls	
2	No orchestra Diffusing walls	
3	Orchestra on flat floor Flat walls	
4	Orchestra on flat floor Diffusing walls	
5	Orchestra on risers Flat walls	
6	Orchestra on risers Diffusing walls	

Figure 27: Measured impulse responses at position E1 with Schroeder curve drawn as solid line. The vertical range is 0 to – 40 dB, while the horizontal range is 0 to 220 ms.

5.5.1 Comparison of scale model and computer model results

Figure 28 shows measured and calculated ST values.





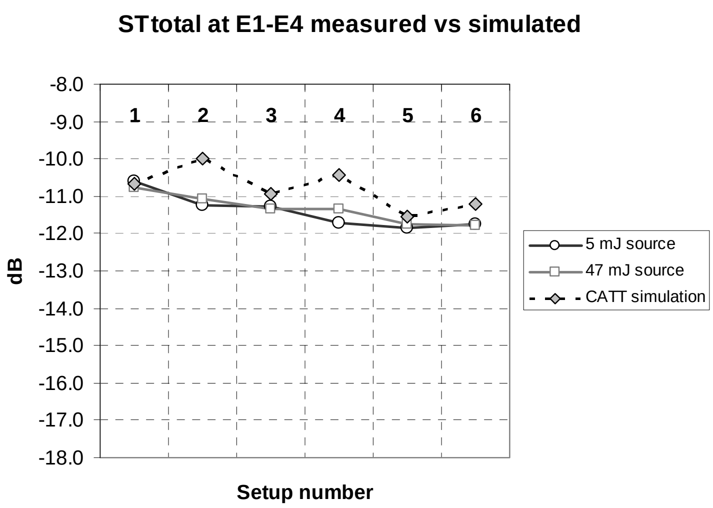
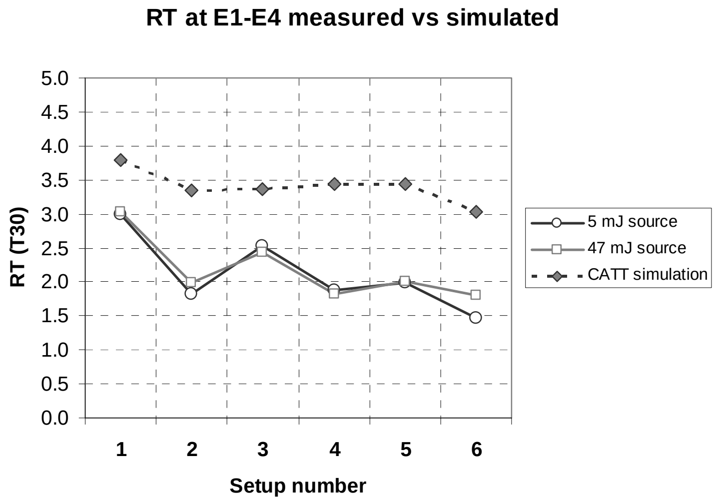


Figure 28: Measured and simulated ST parameters on stage.

Figure 29 shows measured and calculated reverberation times (T30 and T15). Reverberation time is defines as the time it takes for the sound level to drop 60 dB after the sound source has been switch off. T30 is defined as the time for the impulse responses to level drop from -5 to -35 dB multiplied by 2 (to give the standard 60 dB fall time). T15 is defined as time for the impulse response level to drop from -5 to -20 dB multiplied by 4. The results shows are average reverberation time over the four octave bands 250 Hz to 2 kHz. Both 5 mJ and 47 mJ spark source measurements in the scale model are included. A more detailed analysis of the differences between measured and simulated is given in [8] (some errors occur in that report – refer to updated figures in this report).



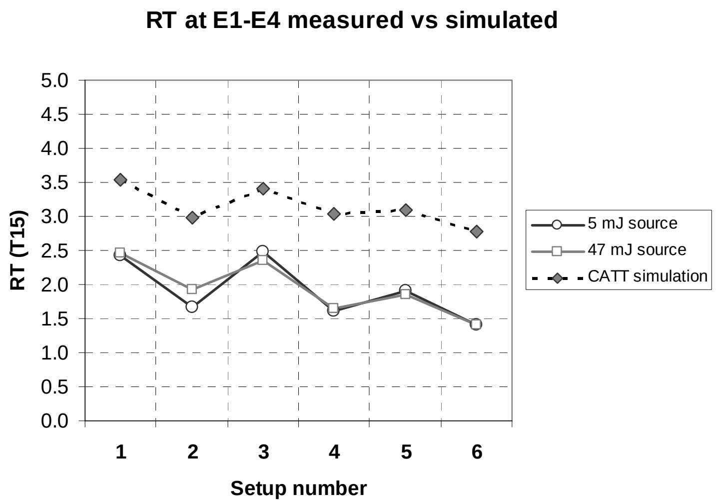


Figure 29: Calculated reverberation time (0.25 – 2 kHz) from scale model measurements and CATT modelling.

5.6 Discussion of results

The scale model represents an average rectangular concert hall. The size and shape of the stage will vary much between different stages, but the relative changes between the different stage configurations can give information relevant for real stages.

5.6.1 Changes in impulse responses measured in the scale model

Figure 27 shows that the diffusing panels add reflections after 20 ms (up to 40 ms). The orchestra adds reflections mostly between 10 to 35 ms. The sound energy after 90 ms is almost identical for all the six stage configurations used. Reflections from the two side walls on the stage arrive at 50 and 79 ms. The corner reflections at the back of the stage arrive at 54 and 82 ms. It can be seen that these reflections almost disappear with the orchestra present (lowered more than 10 dB). The back wall reflection also seems to be lowered with the orchestra present. The diffusing panels seem to restore these reflections to some degree. With risers these side reflections are seen to be restored as well, but to a smaller degree compared to the diffusing side walls.

The broadband impulse responses presented have an emphasis of higher frequencies (above 1 kHz (25 kHz)), since the spectrum of the source is dominated by higher frequencies. So the shadowing effect of the orchestra for the wall reflections might not be as large as indicated by measured responses. With the orchestra present high frequencies are easily blocked by lower frequencies will diffract through the orchestra. The energy at lower frequencies might not be seen in the broadband impulse responses for the reason given above. Performing octave band filtering of the impulse responses or inverse filter the response of the spark sources will give a more valid picture of changes between the stage configurations. But changes seen in ST and RT parameters will be valid, since they are based on relative differences within the same octave band filtered impulse response.

The ceiling on stage gives reflections in the region 100 ms to 111 ms. The ceiling reflections are not much affected by the changes on stage. Some changes are seen with orchestra and risers on stage, but this could due to variation between the measurements. The impulse responses shown in figure 26 are based on only one measurement for each configuration, so small variations cannot be related to the different configurations alone. The time delays referred to here are cannot directly be generalized to other stages, since the delays are controlled by the dimensions of the stage. But some of the trends seen could be valid for other stages as well.

5.6.2 The effect of stage configuration on ST_{early} in scale model

Stage configuration 1 and 2 show the largest differences (empty stage with and without diffusing side walls). With configuration 1 the stage is very non-diffusing and adding diffusing panels has a large impact and increases the ST_{early} value by 2 dB. When introducing the orchestra the value decreases about 1.5 dB. This could be explained by the orchestra seems to give reflections arriving before 20 ms and it obscures the wall reflections. By adding diffusion side walls with the orchestra present, ST_{early} is raised up to the same region as for diffusing walls without the orchestra. The risers do not seem to make a significant change of the value.

5.6.3 The effect of stage configuration on ST_{late} in scale model

There is a significant change in the late sound on stage between configuration 1 and 2. Introducing the diffusing panels causes this value to drop about 2 dB. Both orchestra and risers cause the level to drop 1 dB each, when being present, but with both diffusing walls and orchestra present, the situation seems to “saturate”, showing only 1 not 2 dB reduction of the value when risers are being introduced.

5.6.4 The effect of stage configuration on ST_{total} in the scale model

The overall sound level on stage appears to go down when adding diffusing panels, orchestra and risers. The orchestra will add absorption to the stage, and more diffusion on the stage will scatter the sound and project it more towards the audience (which will be absorbed by the audience before coming back to the stage). But the effect is marginal: the value is 1 dB lower with all elements present compared to the empty stage.

5.6.5 The effect of stage configuration on RT in the scale model

The trends in calculated reverberation times are seen to similar to the trends for ST_{late}. Introduction of diffusing side wall, orchestra and risers contribute to lower the reverberation time. The observed reduction is about 1 second with all elements present on stage compared to the empty stage. Going from an empty stage to and empty stage with diffusing side walls give the largest change of reverberation time.

5.6.6 The validity of the scale model

The validity of the model related to conditions on real stages is affected most significantly by the scattering properties of the diffusing panels, the design of the musicians and the risers. The diffusing panels will represent a general 2-dimensional scattering (both horizontal and vertical diffusion). The vertical scattering will contribute to give reflections down towards the musicians which are seen in the impulse response. Such a reflection could be provided by balcony overhangs, or special designed reflectors as well as shape (diffusing properties) of the wall itself.

The design of the musicians in the model will affect mainly the side wall reflections. The musicians can have been built with too solid legs (with solid Plexiglas) compared to a real situation. Replacing this part with two cylindrical elements will better represent the legs and the sound propagation that will take place between the musicians and the floor. On real stages music stands are present. These will also affect the sound transmission within the orchestra (depending on type of music stand) and should be included in future modelling. Future investigation of the sound transmission through a group of people sitting on chairs (with or without music stands) could give information on this. See appendix A for suggested design of music stands for the scale model.

5.6.7 Comparison between scale and computer modelling results

When comparing between the scale model and the computer model, it is important to bear in mind that the measurements from the scale model can have discrepancies as well (not only the computer model). This includes the spark source, microphones, background noise, compensation for air absorption, 12 bit DA converters, etc. The most significant technical limitation is maybe the bandwidth of the spark source (to give a sufficient signal-to-noise ratio for all 4 relevant octave bands after compensation of air absorption). The results obtained from the scale model can because of this not be treated as the full truth about the acoustical qualities in the scale model when comparing with the computer model. But it is believed to be close enough to give a relevant comparison with the computer model.

The main challenge with computer modelling is to set the acoustical properties correctly for the materials in the scale model. This involves the absorption and scattering by the panels (on ceiling and walls), the musicians and the audience. For the musicians a good geometrical representation is also important. The audience can normally be modelled as a large box with the same absorption and scattering properties. This cannot be done for the musicians on stage since the sound transmission through the orchestra is important and by simple modelling the orchestra as one box will not give any shadowing effects within the orchestra. Further comparison between real situations, scale models and computer models are needed to evaluate the validity of the how the musicians are computer modelled.

The agreement between measured and simulated configurations is also affected by the arrangement of the orchestra and how close the musicians are to the source and the microphone positions. But by looking at average values over 4 positions, the effect of these variations can be expected to be smaller than the variations between the different stage configurations.

As mentioned, the octave band analyses illustrate that there are disagreements within the scale model measurements. The 5 mJ source doesn't give reliable data for the 250 Hz octave band (large variations in measured reverberation time). At 2 kHz the reverberation time is consistent with both sources (see [8] for details). This indicates that the 47 mJ source is more reliable than the 5 mJ source as a reference against computer modelling results.

For the early sound (ST_{early}) the agreement between the two models are in some cases surprisingly good. The same trends can be seen between the two models, except for the 250 Hz octave band, where the values show larger variations. The good agreement with configuration 1, 2 and 4 indicates that the computer modelling of the diffusing panels is good. With the orchestra on stage the values are lower in the computer model. According to the impulse responses the orchestra seem to block side wall reflections. This indicates that the musicians in the computer model could have been modelled too solid (non-transparent) (compared to the scale model musicians, not necessary real musicians). The modelling of the risers should be reasonable valid due to its simple geometry, but the diffraction component on the risers' edges may be the reason for the differences observed.

The values for ST_{late} show lower values with the computer model with diffusing walls present. The agreement of ST_{early} values, indicated that the absorption and scattering coefficients of the diffusing panels are good (looking on 0.25 – 2 kHz averages). STlate in the computer model could be higher due to errors in the modelling of the main hall. The diffusing panels will direct more sound to the main hall and how the main hall is modelled will largely affect the late sound. This is also seen in the reverberation time values. T30 is 1 to 1.5 seconds higher in the computer model and the average reverberation time is almost not changing between different configurations. For T15 the same trends are seen between the two models, but the computer model give generally 1 second longer reverberation time. This supports the observation of scattering and absorption being reasonably modelled on stage, but that the acoustical properties of the main hall need to be revised.

As demonstrated in section 4 the modelling of scattering in CATT-Acoustic (using Lambert's law) will lead to different directivity of the scattered sound. Impulse responses from the computer model are not presented here, but the level of the scattered reflections can be expected to be different in the two models. This illustrates some of the advantages of scale modelling to see the reflected sound field on stage.

5.7 Concluding remarks

Measurements done on stage in the scale model of a general shoe-box shaped concert hall, show significant differences in the impulse response and calculated parameters (ST and RT). Since the measurements were made at only one source position the results cannot be generalised to yield for other positions or other concert hall stages. But there are indications of the following:

- The presence of the orchestra adds reflections mostly between 10 and 35 ms (dependent on width and depth of the stage).
- Side wall reflections and corner reflections from the back of the stage almost disappear with the orchestra present. The back wall reflection is also lowered. Having diffusing panels on the side walls and back wall seem to restore these reflections to some degree. These observed changes are likely to be exaggerated by the frequency response of the spark sources. The risers were

also seen to help restoring these reflections but to a smaller degree than diffusing walls, but doesn't raise ST_{early} significantly.

- By introducing diffusing walls and the orchestra, the late sound is lowered. The most significant difference in the late sound is caused by the property of the walls, but the orchestra contributes as well.

The changes in the impulse response at 10 – 35 ms and 50 ms with an orchestra present or absent illustrate the problems involved with measuring impulse responses on an empty stage.

The results listed above may possibly be influenced by the modelling of musicians and the absence of music stands. The representation of the musicians in the scale model may be too solid. This will lead to an overestimation of the "shadows" of sound caused by the orchestra. Further investigations are needed to verify the validity of the scale modelling.

5.7.1 Comparison between scale and computer modelling

A comparison between ST_{early} values measured in the scale model and computer model shows good agreements, but with the orchestra on stage this value is lower in the computer model. This indicates that the early sound seems to be adequately well modelled in CATT-Acoustic (in terms of absorption and scattering properties), but that the transparency used to model the orchestra needs revision. Further investigations are needed to find out how the sound transmits through an orchestra (in real situations).

For the late sound field (beyond 100 ms) and reverberation time (T30 and T15) there are large differences between the scale model and the computer model. The late sound field is generally overestimated in CATT, but the same overall trends for the different stage configurations are seen with T15. The better agreement of T15 values also supports that the early sound is better modelled than the late in CATT. This seems to be due to differences in the acoustical properties of the materials in the hall (mainly the audience).

In general for making valid computer models of real stages, the main challenges will be to represent the acoustical properties of the different surfaces on stage and to model the orchestra. By having measurements from the stage and audience area of the real hall will help setting the acoustical properties of both the stage and the main hall. Measurements of sound transmission through real orchestras need to be done to validate the modelling of the orchestra (both in computer and scale model). Description of the directivity of most musical instruments in the orchestra exists, enabling us to investigate the sound from orchestral instruments on stage with the orchestra present using computer models. Scale modelling will be preferable to investigate in detail of the sound field on stage, due to the simplified sound scattering model in the computer model.

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Appendix A – Music stand modelling

To represent the situation on stage better, the music stands on stage should be included in the model. This could be made out of plastic. A support for the stand could be implanted by folding the material or by gluing the stand to a horizontal base. Figure A.1 shows suggested design.

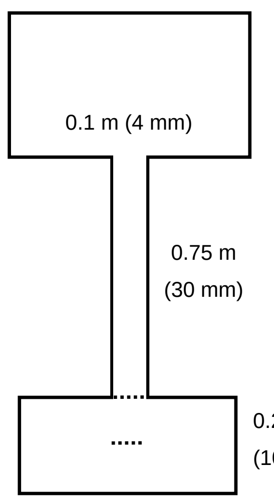

Figure A.1: Music stand for scale model.

This layout gives a total height of 43 mm (1.08 m full scale) and a full scale width of 0.5 metre.