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TRANSPARENT CONCERT HALL ACOUSTICS

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ABSTRACT
April 15, 2005 the new concert hall for symphonic music, Casa da Música in Porto, Portugal, has been inaugurated. The architectural concept of a transparent shoebox-shaped hall in combination with program requirements challenged the acoustics in many ways. By just pressing a button the acoustics of the hall is changed from excellent for symphonic music to adequate for amplified productions. All kind of technical provisions have been introduced in the design: lighting bridges, movable canopy, acoustic curtains, a moving bridge etc. In fact we believe a new type of multifunctional halls has been built. Will this be the future and, if so, what are the consequences for the field of acoustics?

The main auditorium, with a capacity of 1250 seats, has a transparent vertically movable and cantilever canopy. Canopy positions have been studied to optimize the support on the stage with respect to the playing ensemble.

QRD diffusers have been applied to create a diffuse and equally distributed sound field. Because of architectural issues the standard 734 diffusers have been modified. Instead of the 0-deep well in the sequence 0–1–4–2–2–4–1, a 7–deep well is used. This modification proved to have an impact on the acoustic performance of the diffusers, thus the acoustics of the hall.

INTRODUCTION
The main auditorium of Casa da Música is a shoebox-shaped hall, designed by the Office of Metropolitan Architecture, with a capacity of 1250 seats. The volume of the hall is approximately 17,000 m^3. The width of the hall is 22 m, the depth is 53 m and the maximum height is 17.5 m. The stage is rectangular shaped with a width of 22 m and depth of 11 m. The audience is arranged with raked continental seating in front of the stage. Behind the stage, on an elevated balcony, extra seats are intended for the choir. Both ends of the auditorium have large windows. Vertical placed QRD diffusers and a transparent canopy of 8 m by 12 m above the stage control the stage acoustics. Well-arranged QRD diffusers, balconies, lighting bridge and sinusoidal shaped glass control the auditorium acoustics. In front of the glass, in the front and rear wall, curtains control the light and variable acoustics.


Figure 1. Main auditorium


Figure 2. Stage of main auditorium with canopy

ROOM ACOUSTICS

Since the inauguration of Casa da Música in Porto, room acoustic measurements have been carried out to fine tune and establish the acoustical quality of the auditoria and rehearsal rooms. The acoustic quality of a room can be described by using parameters like reverberation time, clarity, support etc. From the impulse response, room acoustic parameters like Early Decay Time (*EDT*), Reverberation Time (T_{20} and T_{30}), Clarity (C_{40} as well as C_{80}) and the Support (ST_1) have been determined. These objective (measurable) acoustic parameters can be correlated to the subjective appreciation. For room acoustics the early, middle-late sound is important. For performing musicians, the (very) early sound is important. This is referred to as stage acoustics. The objective stage parameter Support (ST_1) reflects the ease of playing ensemble. The 'transparency' (Clarity) reflects to what extent details in music are audible. The Clarity C_{40} expresses the 'transparency' on the stage better than the Clarity C_{80}. *CS*, the Clarity measured at 1 meter from the source, can also express the 'ease' of playing ensemble. The ST_1 and *CS* are important stage parameters.

A new stage acoustics parameter

As both ST_1 and *CS* are defined for a microphone at 1 m from the source, these parameters mainly indicate how well a musician can hear himself compared to the rest of the orchestra. To be able to evaluate how other instrument groups can be heard, a special modified version of the clarity, $C_{cm,}$ is developed. In the C_{cm} parameter, the energy in the early reflections (7 ms to 40 ms) is compared to the energy in the late reflections (40 ms to ∞). Special is that the direct sound (0 ms - 7 ms) is omitted in this parameter, as the direct sound is only a function of distance to the source and otherwise - due to its strength - might mask the variation in supporting reflections. C_{cm} gives a good impression of how effective (and even) the distribution of early reflections is on stage. At this moment, the exact time windows of C_{cm} are still subject to research, as a way to compare C_{cm} for different halls.

CANOPY POSITIONS

To study the influence of the canopy position, measurements have been performed in the auditorium as well as on stage. The measurements for all combinations of source and receiver positions have been carried out for the canopy positions as indicated in fig 3 to fig 6.

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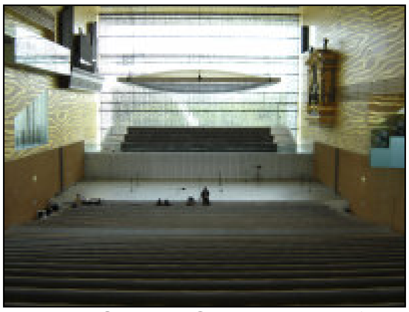

Figure 3.Canopy @: rear 8.6 m - front 8.6 m

Figure 4.Canopy @: rear 8.6 m - front 9.3 m

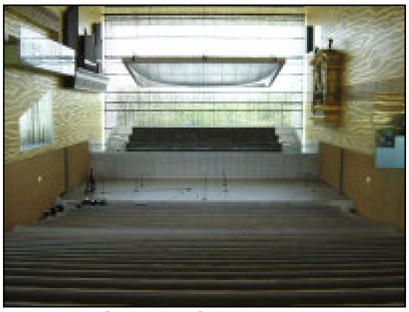

Figure 5.Canopy @: rear 8.6 m - front 10 m

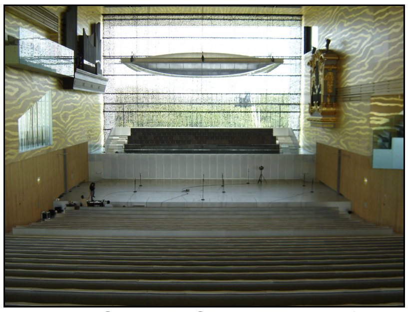

Figure 6.Canopy @: rear 10 m - front 10.m

During the measurements the canopy had its nominal pressure of 1.6 mbar. The acoustic curtains were pulled both up. The height of the omni directional source and the reference microphone was 1.35 m. For the auditorium measurements three source positions have been used. Apart from the reference microphone at 1m, also a microphone was placed at the conductor's position and six receiver positions were chosen in the auditorium. Microphones 3 – 7 were placed in the main audience area, while microphone 8 was located in the choir seats behind the stage. The measured impulse responses are used to determine the C_{80} in the audience area. The Clarity Factor (average 500, 1000, 2000 Hz) C_{80} for all six receiver positions for the different canopy positions are given in table 1. The Clarity Factor of the large auditorium is about –0.5 dB, with very little variation due to canopy position. We may conclude that for the Clarity in the audience area these canopy positions are not critical.

Table 1. Clarity Factor C_{80} [dB[for the canopy positions.

Canopy Position	*CF C_{80}*
8.6-8.6	**-0,48**
8.6-9.3	**-0,56**
8.6-10	**-0,64**
10 - 10	**-0,58**

Stage acoustics

To be able to describe the acoustic quality of the stage, measurements have been carried out with the different instrument groups represented by an omni-directional sound source on the stage. For this nine source positions have been used. For each source position, at 6 microphone positions on stage (height 1.2 m), one at the conductor's position (at a height of 2.0 m to simulate the conductor's position) and a reference position at 1 m distances from source the impulse response is registered. The stage acoustic measurements were performed for the same canopy conditions and positions as the measurements of the auditorium acoustics. The measured impulse responses have been used to determine the mean value for CS_{40} and the mean value for the Support for the different canopy positions, as these parameters give the a qualification of the acoustic quality on the stage. The measured values are presented in table 2. Table 3 gives an overview of measured Support.

Table 2. CS_{40} [dB] for the canopy positions.

Canopy position	*Average*
8.6-8.6	**11.8**
8.6-9.3	**11.8**
8.6-10	**12.0**
10-10	**11.8**

Table 3. Support [dB] for the canopy positions

Canopy position	*Average*
8.6-8.6	**-11.8**
8.6-9.3	**-11.6**
8.6-10	**-11.6**
10-10	**-11.9**

To analyze the influence of the canopy for the playing ensemble and the sensitivity of the musician's position on the stage the C_{cm} is determined at every receiver position for all source positions. In table 4 to 7 the Clarity Factor for the C_{cm} [dB] at four different receiver positions are given for the four different canopy positions and all the source positions.

Table 4. Clarity factor C_{cm} at the receiver position 2

Source	*8.6-8.6*	*8.6-9.3*	*8.6-10*	*10-10*
1	-3.6	-3.3	-3.3	-4.1
2	-4.2	-5.9	-5.1	-5.2
3	-5.7	-6.6	-6.8	-7.4
4	-2.5	-1.9	-2.6	-3.1
5	-4.9	-5.5	-5.4	-6.9
6	-4.6	-4.5	-4.9	-3.5
7	-2.9	-3.3	-2.4	-3.6
8	-4.2	-4.2	-4.2	-4.7
9	-2.8	-2.0	-2.5	-3.9

Table 5. Clarity factor C_{cm} at the receiver position 3

Source	*8.6-8.6*	*8.6-9.3*	*8.6-10*	*10-10*
1	-0.6	-1.3	-1.3	-1.7
2	-4.1	-3.9	-5.3	-5.4
3	-3.4	-3.9	-4.0	-5.0
4	0.8	0.8	0.9	0.7
5	-3.3	-3.8	-3.1	-4.1
6	-4.3	-4.4	-4.9	-5.1
7	0.3	1.0	0.7	-0.1
8	-2.8	-2.6	-2.5	-2.6
9	-4.4	-3.4	-4.2	-2.8

Table 6. Clarity factor C_{cm} at the receiver position 5

Source	8.6-8.6	8.6-9.3	8.6-10	10-10
1	-2.2	-1.9	-1.4	-2.8
2	0.0	-1.9	-0.5	-1.2
3	-0.4	0.2	-0.7	-0.8
4	-1.2	-1.5	-1.0	-1.3
5	-1.6	-0.6	-1.9	-1.4
6	0.1	-0.3	-0.4	3.3
7	-1.1	-2.0	-1.6	-1.3
8	-2.9	-2.6	-2.7	-3.1
9	0.5	0.5	0.8	0.1

Table 7. Clarity factor C_{cm} at the receiver position 7

Source	8.6-8.6	8.6-9.3	8.6-10	10-10
1	-1.4	-1.4	-1.7	-1.5
2	-3.7	-5.2	-4.0	-5.7
3	-3.8	-4.0	-2.1	-4.0
4	-1.9	-1.8	-0.3	-2.0
5	-3.3	-4.1	-3.5	-4.3
6	-3.3	-3.6	-2.7	0.4
7	-1.1	-1.3	-0.2	-1.2
8	-2.4	-2.6	-1.8	-3.1
9	-0.8	-0.6	-0.3	-0.5

Observations

The average of the results for the Clarity as well as the Support (250 – 2000 Hz) is about the value, normally reached for these parameters in concert halls. The different canopy positions don't influence these parameters. Table 4 to 7 show clearly the influence of the canopy position for the playing ensemble. As can be seen the position of the conductor (receiver 2) is the most sensitive for the canopy position. Source position 2 refers to the violins and position 3 to the celli. For the maestro the best canopy position is the horizontal one on 8.6 m. The values in the table also show that the canopy position is less critical for the musicians. The results also show that the canopy performs as was aimed for.

REFLECTION / ABSORPTION CANOPY

One of the issues with respect to acoustics of the large auditorium is the behavior of the canopy. Measurements on a scale model [1] of the canopy already showed the influence of the correct pressure of the canopy. To be able to measure the reflection and absorption of the canopy a special measurement setup is used. The canopy is placed in the horizontal position at 8.6 m height. A sound source is placed on the stage directly under the center of the canopy. A microphone is placed halfway the source and the canopy. The impulse response is measured. From the measured impulse response, the incoming sound and the reflected sound can be isolated. By comparison of these signals, the frequency content of the reflection can be determined.The first measurement is carried out with the canopy not under pressure, then the canopy has been pressurized to its nominal pressure (1.6 mbar) and the measurement has been repeated.

Figure 7 gives the frequency response for the reflection under non pressurized (red) and pressurized (green) conditions.

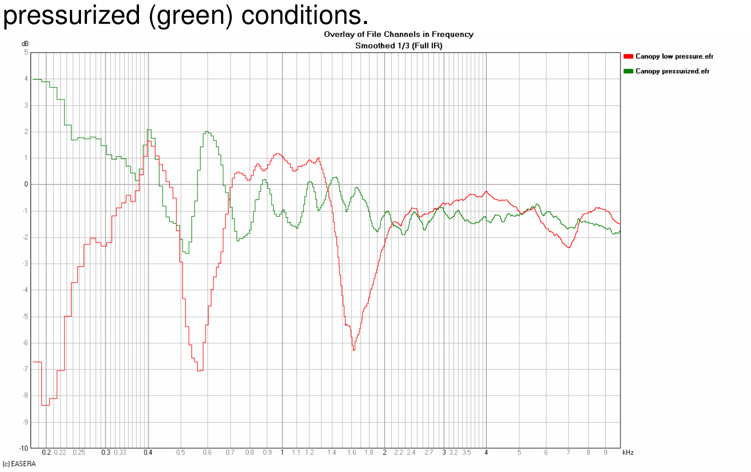

Figure 7. Measured frequency responses directly under the canopy.

Observations.

From the results it is clear that in the non-pressurized condition, the reflection from the canopy varies significantly over frequency and thereby exhibits coloration. It goes without discussion that this is undesirable in a concert hall. The coloration effect disappears when the canopy is under the correct pressure. Therefore, the canopy must be pressurized to its designated nominal pressure whenever the auditorium is used.

QRD DIFFUSERS

In the main auditorium, QRD diffusers are applied. Because of the architectural requirements, the standard QRD 734 diffusers have been modified in coordination with the supplier. The wells, which normally have a zero depth, are replaced by wells with a 7-depth. According to theory on which these diffusers are based, this should give the same acoustic result.

Figure 8. Modified QRD-diffuser.

Figure 9. Modified QRD-diffuser, side pane is missing.

After installation of the diffusers, it proved that the installed diffusers were not according to what DHV had agreed upon. From the diffusers, one pane – invisible but essential - was omitted, which might be the cause for low frequency absorption. As the large auditorium shows a bit short reverberation in the 250 Hz octave band, it has been investigated if this could be due to the change in the diffusers.

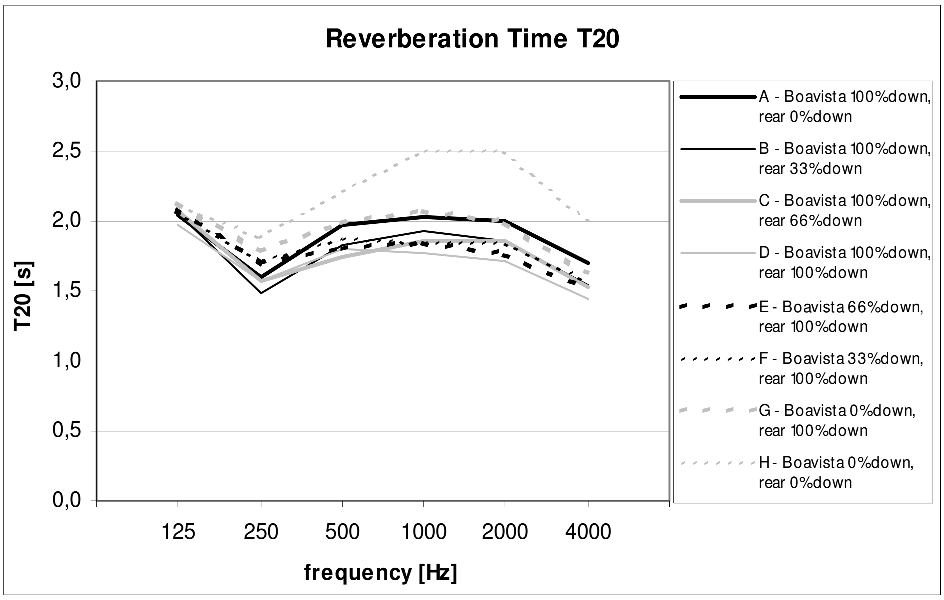

Figure 10. Measured reverberation times in the main auditorium of Casa da Música

The diffusers have been tested in the laboratory of Eindhoven University of Technology in the following configurations:

- Original QRD 734 Diffuser (Figure 11)
- CdM Diffuser, as installed in Casa da Música (Figure12)
- CdM Diffuser, side closed as modified by DHV (Figure 13)
- CdM Diffuser, side & 7-well closed (Figure 14)

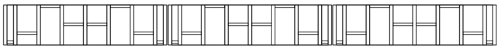

Figure 11. Original QRD 734 Diffuser

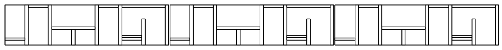

Figure 12. CdM Diffusers, as installed

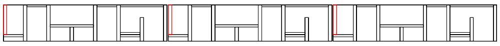

Figure 13. CdM diffuser, side closed

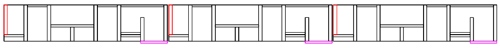

Figure 14. CdM diffuser, side & 7-well closed

The measured absorption of the diffusers is given in 1/3 octave bands in figure 15.

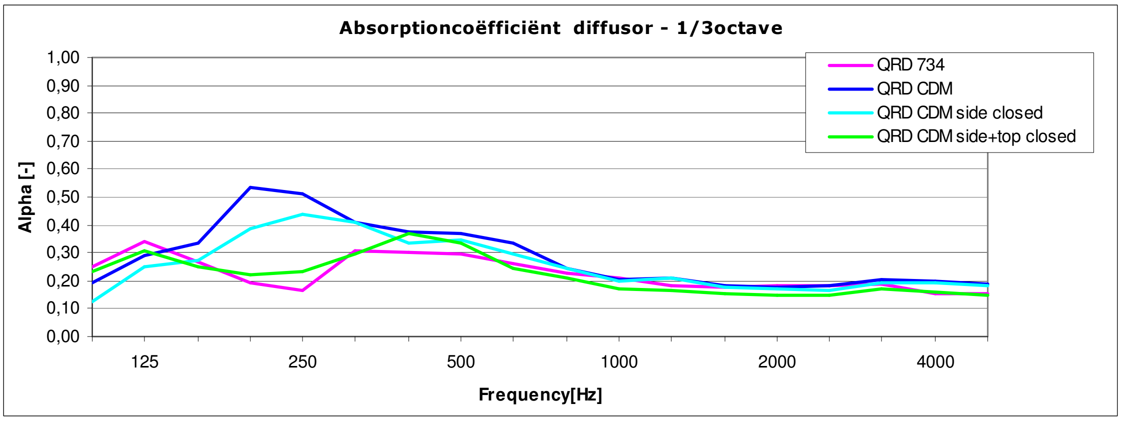

Figure 15. Measured sound absorption coefficients for the four diffuser types.

Observations

It appears that the modified diffusers, as supplied and installed, exhibit a significant higher absorption at low frequencies than the original product. This extra absorption fully accounts for the short reverberation time in the 250 Hz octave band. Adding the 'missing leg', as originally intended, corrects partly for this extra absorption, but not fully. It appears that also the modified 7-deep well introduces low frequency absorption. By closing the 7-deep well the effect disappears.

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