Enhancing the strength of symphonic orchestra in an opera house

Published Version:
D'Orazio, D., Fratoni, G., Garai, M. (2020). Enhancing the strength of symphonic orchestra in an opera house. APPLIED ACOUSTICS, 170, 1-10 [10.1016/j.apacoust.2020.107532].

Availability:
This version is available at: https://hdl.handle.net/11585/767206 since: 2021-02-24

Published:
DOI: http://doi.org/10.1016/j.apacoust.2020.107532

Enhancing the strength of symphonic orchestra in an opera house

Dario D'Orazio[a], Giulia Fratoni[a], Massimo Garai[a]

[a]*Department of Industrial Engineering - DIN, University of Bologna, Italy*

Abstract

Nowadays, historical opera houses are also employed for symphonic music, especially in a country like Italy where they are far more widespread than concert halls. The aim of the work presented here is to modify the acoustic conditions of an opera house by introducing an overhead reflector array and removing drapes from the stage, so to meet the requirements for an orchestral performance. The design process and the shape optimisation of the canopy layout were developed with a Geometrical Acoustic (GA++) model. In-situ acoustic measurements were used to calibrate the model, to adjust the tilt angles of the panels and to validate the software–aided design. Combining theoretical studies with practical needs, the results of this work give the opportunity to investigate the consequences of placing a reflector array in an opera house. A multi-decay analysis on measured impulse responses shows that the reflector array enhances the acoustic coupling between the stage house and the main hall. Finally, the blending effect on the orchestral sections caused by the reflector array was estimated through a simulation employing calibrated virtual instruments.

1. Introduction

An opera house is an acoustical system composed of several volumes that act as sub-systems: the stage tower, the orchestra pit, the main hall and the boxes (or the galleries) (1; 2; 3; 4). When symphonic music is played in an opera house, the orchestra usually is located on the stage and the high amount of sound absorption of side drapes leads to a "dead" acoustic effect, undermining the sound strength at the listeners. Consequently, the orchestral sound reaches the audience with low energy and fewer early reflections. Furthermore, it may be unbalanced in frequency due to sound absorption at mid-high frequencies in the stage tower (5). Inadequate values of reverberation time and an unbalanced orchestral timbre – too loud strings, with respect to low woodwinds and brass – are some of the resulting effects reported in literature (6).

For all these reasons, reflector arrays are often added to enhance the orchestral sound (7; 8) and to improve the mutual listening between the musicians and the conductor (9). The first examples of canopy date back to 1950s when Cremer and Keidel installed plexiglas sound reflectors for the acoustic improvement, respectively, of Herkules Hall in Munich and of the studio of the South German Radio Broadcasting Corporation in Karlsruhe (10). Subsequently, Bolt, Beranek & Newman designed acoustics arrays for the open audience of Koussevitzky Music Shed at Tanglewood (11) and for NYC Philarmonic Hall (12). In the 1960s several studies about the typical acoustic properties of reflector arrays appeared, regarding the interference patterns expected from regular panel arrays (13), the acoustic field around the single reflector due to diffraction effects (14), and the frequency switch phenomena when the ceiling is too densely covered (15). The Fresnel-Kirchoff (FK) approximation was used by Cremer to define the bandwidth in which the scattering effect of the canopy and the canopy themself is useful (16). While Cremer investigated the diffraction of the single reflection, Rindel explored the limit related to the total size of the reflecting surface when the whole array is small compared to the Fresnel Zone needed to transmit low frequency sound (17). Successively, Cox and Lam proposed further approximate prediction models concerning the scattering effects due to rigid plane and curved reflectors (18). More recently, the reliability of these theoretical formulations was verified through studies on scale models (19).

Following these experiences an overhead canopy was designed and installed in an opera house taken as case study. An array of demountable sound reflectors was proposed and then fabricated taking into account all the physical constraints due to the restricted space of a small stage tower. The installation of the reflector array is intended to be complemented by the removal of most of the absorbing curtains from the stage. A Geometrical Acoustic (GA++) model, calibrated with in-situ acoustic measurements, was used during the design phase. The effects of the overhead reflectors on the sound field are then described by means of measurements and simulations.

2. Method

The present study investigates the effects of an array of sound reflectors when installed in an opera house. The design of demountable panels allows to set the stage in two

Table 1: Geometrical features of the opera house at present time (2020).

Description	Value
Width stage tower (m)	14.7
Height stage grid (m)	12.7
Stage depth (m)	13.6
Volume of the main hall (m^3)	7400
Volume of the stage tower (m^3)	2500
V/seat ratio (m^3)	7.4
Occupancy (N)	1000
Height proscenium arch (m)	11.2
Width proscenium arch (m)	10.3

different configurations. The first configuration, which is more suitable for speech (opera), involves the presence of all the drapes and curtains on the stage and the removal of the canopy (fig. 1(a)). The second configuration, which is more suitable for music (symphonic concert), involves the removal of most of the drapes and curtains on the stage and the installation of the canopy (fig. 1(b)). The proposed reflector array, built for this purpose, is the final result of an optimisation process developed with a geometrical acoustic simulation approach and in-situ adjustements.

2.1. The case study

In public opera houses, occupancy, size and materials may vary depending on seasonal, geographical and societal factors (2). The theatres were used for ballets and parties as well as for opera. The buildings were designed and optimised specifically for these performances, thus not including symphonic music. When symphonic music became popular in Italy, around the 1920s, all opera houses had been already built.

For the present work, the opera house under study is the Duse theatre, located in Bologna, UNESCO City of music (20). Although it might look like recently built (see fig. 2(a)), the hall is a refurbishment of an earlier theatre dating back to the 17th Century. In the 1820s the main hall was expanded to its current size hosting up to two thousand people, distributed in three tiers of boxes (see fig. 2(b)). In 1940-42 the boxes were replaced by balconies and the chairs have progressively been refurbished using velvet instead of the original wood. At the same time the occupancy of the theatre was halved for safety reasons. Since the stage tower has never been expanded from the original construction, its current size in plan and its height are both small compared with modern stage towers. The main geometrical characteristics of the opera house at the present time are provided in table 1.

The acoustics of the hall shows properties in line with the typical behaviour of Italian opera houses. In particular they correspond to the "modern opera house" category according to the statistics (see fig. 3) (2). Nevertheless, since 2013 the Duse theatre has been hosting symphonic music seasons. The authors of the present paper were asked to improve the acoustic conditions in the opera house for symphonic performances.

2.2. Calibration of the model

In order to work with a calibrated model of the opera house, a campaign of acoustic measurements, complying with ISO 3382-1 (21), was performed in the unoccupied state. During the measurements the configuration of the stage was organised as during an opera, i.e. with the side drapes of the stage (*legs*) and the short curtains (*borders*) hung above the stage.

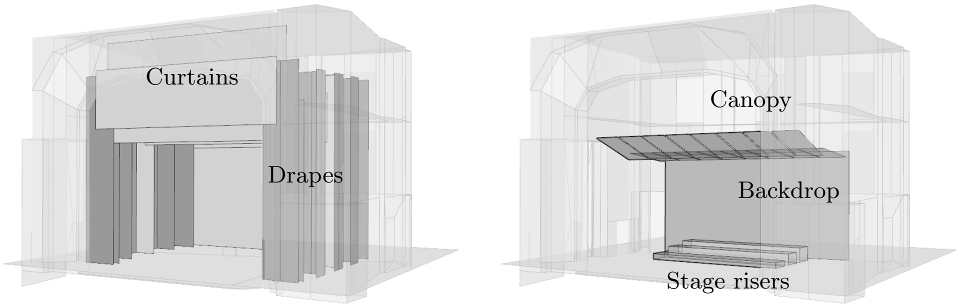
Figure 4 shows the positions of sound sources and receivers selected for the acoustic survey of the opera house. Three different locations on the stage were chosen as sound source positions in order to take into account both the asymmetry of the stage and the distinct location of the three main orchestra sections (first violins, woodwinds and percussion). Eighteen receivers positions were chosen in the audience area, spread throughout the stalls and the two galleries. Most of the receivers positions are below the overhangs of the balconies (gray areas in fig. 4).

Measurements were carried out using the following equipment: high–SPL dodecahedron as omnidirectional sound source (22); four Bruel & Kjaer 4190 half inch microphones as monoaural receivers; RME Fireface 800 at 24 bit / 48 kHz; laptop and custom software providing exponential sine sweep (ESS) 128K length as signal emitted.

The geometrical 3D virtual model of the hall was built with SketchUp software following the state-of-the-art guidelines (23; 24). The model consists of 3800 flat surfaces for a total surface area of about 7650 m^2 and a total volume of 9900 m^3.

A stage tower is a system composed of several elements, including trusses, ropes, and sceneries. Moreover, the absorption characteristics of the side drapes on the stage (25) can significantly vary depending on their actual position. Therefore, in order to quantify the equivalent absorption area of the most absorbing objects in the stage tower, measurements were also performed without drapes and curtains, placing receivers on the stage (26). Concerning the seats of the opera house under study, three typologies were differently treated depending on their different degree of upholstery (stalls, first and second gallery). Material properties have been provided by previous datasets (5; 27; 28) and then applied to the surfaces of the model. The scattering and absorption coefficients used in the GA++ simulation (29) are reported in table 2.

The calibration process was developed by evaluating the behaviour of early decay time (EDT) and sound clarity (C_{80}) values (3). All the sound source positions (first violins, woodwind and percussion) and the receivers divided in areas (stalls, first and second gallery) were considered, as shown in table 4. The calibration was considered achieved when most of the differences (90%) between



(a) Without canopy and with drapes (b) With canopy and no drapes

Figure 1: Configuration for opera (left) and configuration for symphonic music (right).

Table 2: Relative surface percentages (S%), scattering (s) and absorption (α) coefficients of the materials used in the simulations. Absorption values referred to "Stage tower" were estimated through the iteration process of calibration. Scattering values are provided at the mid–frequency 707 Hz, according to GA++ software algorithm (29).

	S%	s	α						Ref.
			125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	
Plaster	34%	0.30	0.01	0.03	0.03	0.04	0.06	0.06	(28)
Carpet	20%	0.05	0.04	0.07	0.15	0.20	0.25	0.30	(28)
Stage tower	12%	0.30	0.12	0.15	0.15	0.18	0.18	0.18	–
Wooden stage	7%	0.40	0.18	0.18	0.12	0.07	0.07	0.07	(27)
Drapes (*legs*)[1]	6%	0.15	0.20	0.20	0.25	0.40	0.45	0.45	(25)
Seats (1st gall.)	6%	0.60	0.52	0.60	0.78	0.88	0.70	0.65	(27)
Seats (stalls)	5%	0.60	0.48	0.50	0.50	0.58	0.58	0.60	(27)
Stage grid	3%	0.25	0.15	0.15	0.25	0.40	0.50	0.50	(5)
Marble	3%	0.02	0.01	0.01	0.02	0.02	0.03	0.03	(28)
Curtains (*borders*)[1]	2%	0.05	0.20	0.35	0.35	0.45	0.50	0.50	(25)
Seats (2nd gall.)	2%	0.60	0.35	0.38	0.55	0.62	0.52	0.52	(27)
Canopy[2]	1%	0.60	0.12	0.08	0.07	0.04	0.04	0.04	(27)
Backdrop (PVC)[2]	1%	0.05	0.06	0.06	0.03	0.03	0.02	0.02	(28)
Stage risers[2]	1%	0.30	0.12	0.10	0.10	0.08	0.08	0.08	(28)

[1]Elements partially removed when the reflector array is installed (see details in the text).
[2]Elements present only when the reflector array is installed.

measured and simulated values, in each octave band and for each source-receiver zone, was within twice the JND of EDT, i.e. 10% of the value, and within the JND of C_{80}, i.e. 1 dB (see tab. 3) (21; 30).

2.3. Optimization of the reflector array layout

The design process of the reflector array was constrained by practical needs: the cost of realisation of the panels, the ease of storage when they are not used, and the compatibility with stage-lighting requirements. For all these reasons, a design approach based on traditional solutions was chosen, taking wooden panels as sound reflectors. Respecting the tradition of Italian opera houses, no reflectors were proposed in the main hall over the stalls.

First of all, the dimensions of each panel were chosen as 3 x 1.5 meters, allowing a wide-frequency diffraction effect (7; 31). Secondly, given the size of the single panel, two rows of 8 panels were proposed in order to cover the orchestra area maintaining a coverage of about 80%, purposely leaving half of the first violins not covered (see fig. 5). All the panels were designed of the same size, to ensure greater ease of storage. The two rows of reflectors were intended to be hung from the stage trusses. The placement of the reflector array is also determined by the limited depth of the stage tower and by the need to have lighting fixtures between the proscenium arch and the upper part of the canopy. Given the dimensions of the chosen panels and the hall size, the Fresnel-Kirchoff approximation is suitable for the medium–high frequencies for all the seats of the case study's audience area (17).

After removing most of the drapes and curtains of the stage, the height of the whole array of reflectors has been chosen in two phases. A preliminary design was done by simulation and a final optimisation was done by in-situ measurements. Two rows of horizontal panels were simulated at three different heights: 6, 7 and 8 meters above the stage level (see fig. 6(a)). The corresponding simu-

Table 3: Configuration with drapes and curtains on the stage (without canopy): comparison between measured and simulated values. Mean values are referred to the unoccupied condition and to all the source-receivers pairs, shown in fig. 4. "M" and "3" subscripts identify, respectively, the average over the octave bands 500-1000 Hz and 500-1000-2000 Hz. 90% of differences between measured and simulated values are within twice the JND of EDT, i.e. 10% of the value, and within the JND of C_{80}, i.e. 1 dB (21; 30).

		EDT_M (s)			$C_{80,3}$ (dB)		
Sources	Receivers	Meas.	Simul.	Diff.	Meas.	Simul.	Diff.
	Stalls	1.33	1.22	0.11	4.9	4.3	0.6
1st viol.	1st gall.	1.08	1.07	0.01	3.0	4.3	**1.3**
	2nd gall.	1.16	1.28	0.12	2.8	2.3	0.5
	Stalls	1.40	1.33	0.07	2.9	3.5	0.6
Woodw.	1st gall.	0.97	1.11	**0.14**	5.6	5.0	0.6
	2nd gall.	1.10	1.15	0.05	4.9	4.4	0.5
	Stalls	1.37	1.35	0.02	4.0	3.9	0.1
Perc.	1st gall.	1.04	1.06	0.02	5.4	5.6	0.2
	2nd gall.	1.11	1.15	0.04	5.3	4.7	0.6

Table 4: Configuration with the canopy on the stage (without drapes and curtains): comparison between measured and simulated values. Mean values are referred to the unoccupied condition and to all the source-receivers pairs, shown in fig. 4. "M" and "3" subscripts identify, respectively, the average over the octave bands 500-1000 Hz and 500-1000-2000 Hz. All the differences between measured and simulated values are within twice the JND of EDT, i.e. 10% of the value, and within the JND of C_{80}, i.e. 1 dB (21; 30).

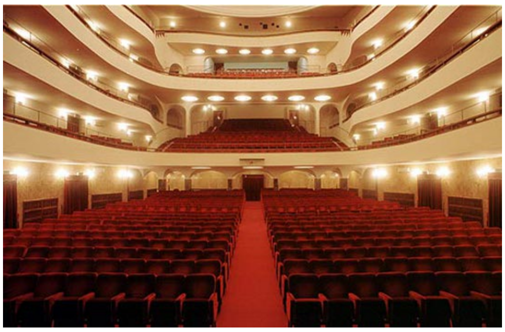
Sources	Receivers	EDT_M (s)			$C_{80,3}$ (dB)		
		Meas.	Simul.	Diff.	Meas.	Simul.	Diff.
	Stalls	1.49	1.41	0.08	3.2	2.8	0.4
1st viol.	1st gall.	1.34	1.28	0.06	1.9	2.8	0.9
	2nd gall.	1.39	1.39	0.00	1.1	1.6	0.5
	Stalls	1.54	1.45	0.09	2.1	1.7	0.4
Woodw.	1st gall.	1.21	1.30	0.09	3.3	2.9	0.4
	2nd gall.	1.42	1.33	0.09	2.4	2.8	0.4
	Stalls	1.57	1.51	0.06	1.9	1.7	0.2
Perc.	1st gall.	1.28	1.30	0.02	3.1	3.1	0.0
	2nd gall.	1.38	1.30	0.08	2.2	3.1	0.9

lated values of sound strength (G) and early support (ST_E) guided the choice.

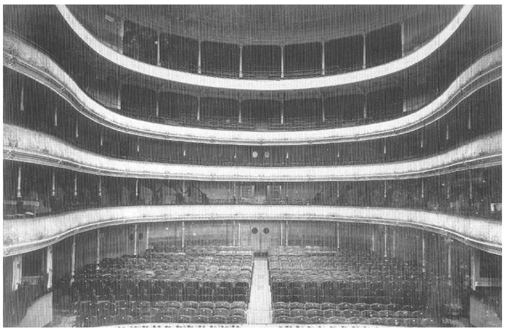
Within the range of assessed heights, the higher the reflector array, the higher the sound strength expected. As will be discussed in the following sections, this fact is due to the coupling effect between the volume of the stage house and the volume of the main hall. On the contrary, the higher the reflector array, the lower the ST_E values, due to the attenuation of the reflections from the panels.

Taking into account the constraints previously exposed, the optimisation process is a compromise that involves three more requirements, referring to the sound and to the blending of the orchestral sections. On one hand, the violinists need more ensemble conditions, whilst the audience needs a louder contribution from the woodwinds and all musicians need to better hear each other (32).

In order to test the three different heights of the reflector array (6, 7, 8 meters above the stage level), in this phase a receiver for each listener area was considered during the simulations (R4, R10, R16 in fig. 4). Mean G_M values were obtained averaging simulated results of 3 source-receivers pairs for each sound source. Mean ST_E values were obtained placing three virtual receivers at 1 meter from each sound source and then averaging the simulated results. The first target value is $G > 3$ dB at mid frequency, considering a mid-size orchestra playing *mezzo-forte* to achieve a value of sound pressure level equal to about 80 dBA at the listeners (33). The second target value is minimum of $ST_E > -13$ dB and mean value of $ST_E > -12$ dB, aiming at proper ensemble conditions for the musicians (32). Moreover, the reflector array should also balance the sound of the sections, which means keeping the mean G_M values homogenous between the orchestral sections (within 2 dB of difference). Without the canopy, the sound pressure level from the violins is much louder than from the other orchestral sections. Figure 7 shows the relationship between G_M and ST_E for the options assessed and the target area is highlighted in gray. According to the graph shown in figure 7, the best height proves to be 7 m. Therefore, this level above the floor was considered as the maximum height for the whole reflector array.

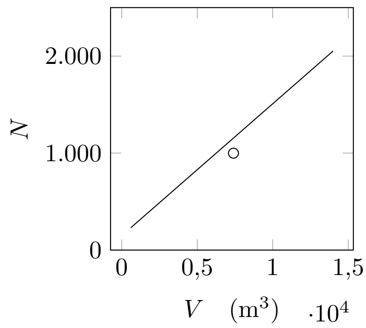


(a) View at the present time

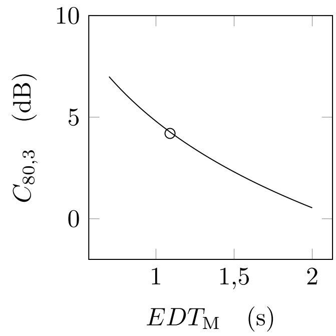


(b) View during 19th Century

Figure 2: Views of Duse theatre at the present time (left) and in 19th Century (right).



(a) N vs V



(b) $C_{80,3}$ vs EDT_{M}

Figure 3: Relation between main data measured in the case study: occupancy (N), volume of the main hall (V), sound clarity (C_{80}), and early decay time (EDT). Mean values of measured C_{80} and EDT are referred to the unoccupied condition and to all the source-receivers pairs, shown in fig. 4. "M" and "3" subscripts identify, respectively, the average over the octave bands 500-1000 Hz and 500-1000-2000 Hz. Curves are taken from the work by Prodi et al., category "modern opera houses" (2).

The two rows of panels were designed with small tilt angles, according to technical guidelines (6; 7; 28). However, this choice allows to also cover the galleries, due to diffraction effects (17; 18; 31). As a consequence of diffraction, there are secondary lobes outside the specular reflection angle which increase the performance of the canopy far beyond the geometrical reflection paths. This contributes to spreading the effect of the canopy not only to the geometrical focus - which is in the stalls - but also to the first and the second galleries (see fig. 6(c)).

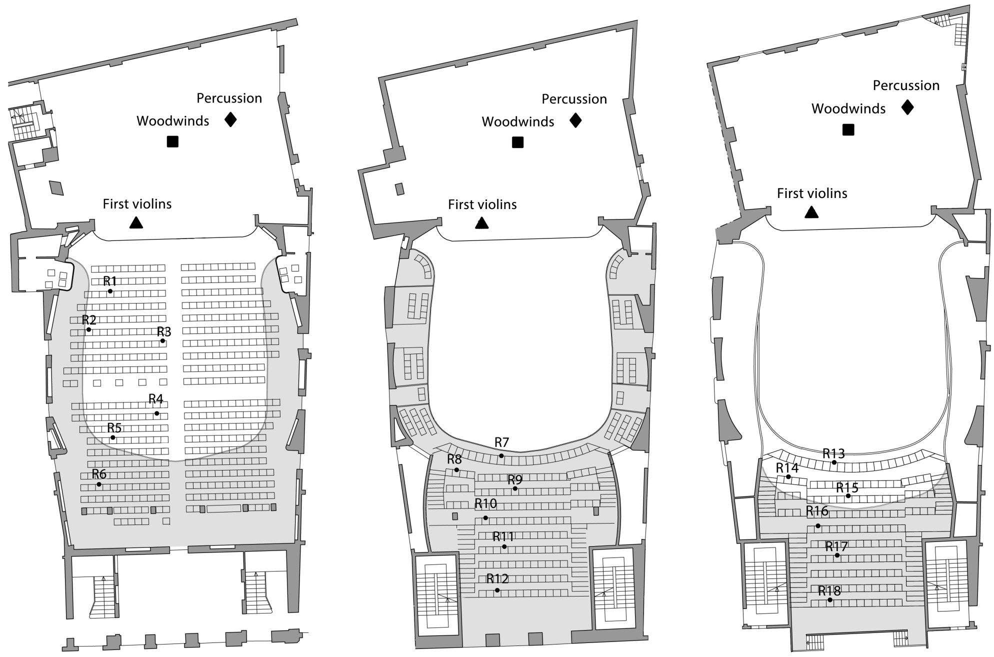
3. Results and discussions

3.1. Sound strength as performance metrics

Validation measurements were done with the overhead canopy installed and most of the drapes removed (see fig. 8). In this phase the tilt angles of the two rows of reflectors was further optimised in-situ (see figs. 6(b), 6(c)). The same positions of previous acoustic measurements were mantained for sound sources and receivers. The results of this second campaign of measurements are provided in table 4 and compared with the previously simulated values, in order to validate the whole design process.

In the audience area the canopy increases the early decay time values, fulfilling the requirements for symphonic music. In particular, the comparison of results in table 3 and 4 shows that the reflector array contributes to significantly increase the EDT values in case of woodwinds and percussion while it only slightly affects the EDT values in case of first violins. The different behaviour is in line with the distinct requirements of each orchestral section. While the instruments that are closer to the rear of the stage need higher EDT values, the instruments that are closer to the proscenium arch already show adequate EDT values, even without the canopy. Typically, the strings need more comb filtering effect (38) rather than further gain from the panels. Reflections from above contribute to producing the desired comb filtering and to blending the strings timbre that otherwise would be too "un-chorused", according to conductors.

Further remarks can be drawn from the measured sound strength values. Figure 9 shows the differences between sound strength values measured with and without the canopy, focussing on the consequent effects on early sound strength G_{E} and late sound strength G_{L}. The measured performances of the reflector array are comparable to the ones measured by Bradley (8). The acoustic absorption due to resonance effects of the wooden panels is responsible of the negative gain in the 125 Hz octave band. It should be noted that at this frequency an opera house like the one under study usually shows the highest values of reverber-



(a) Stalls (b) First gallery (c) Second gallery

Figure 4: Plans of the opera house (stalls, first and second gallery). Three positions of sound sources on stage and 18 receivers in the audience area were used in measurement procedures. Gray areas are below the overhangs of the balconies.

ation time and sound strength, providing adequate values for symphonic music with no need of further gain.

The variations in G_{E} and G_{L} increase more with the sound source placed in woodwinds position than in the first violins position. This behaviour contributes to compensate the "natural gain" provided to the different orchestral sections by the opera house. In fact, without any canopy, sections like woodwinds could not be adequately supported, due to high absorption of the stage. As shown in figure 9, the installation of the reflector array allows to make the loudness of woodwinds comparable to that of the string sections.

3.2. About the coupling effects

The increase of the sound strength in the seating area, shown in the previous section, is worth a further discussion in terms of coupling between stage tower and main hall. As shown in previous works and by the measurements results of the present case, decreasing the absorption of the stage tower in an opera house, i.e. by removing the side curtains, may vary the reverberation time at the listeners (26). Moreover, increasing the coupling area, i.e. removing the upper fly curtain and placing the array of reflectors, may vary the sound decay from nonexponential to exponential (40; 41). According to the classical theory of coupling by Cremer at el. (16), the sound energy in the seating area is governed by the coupling factor k_S, defined as:

$$k_S = \frac{S_c}{S_c + A_S} \tag{1}$$

where S_c is the coupling surface, in m^2, and A_S is the equivalent absorption area of the fly tower, in m^2. When the sound source is placed in the fly tower and the receiver is placed in the main hall, the sound energy density in the receiver volume can be expressed as:

$$E_R(t) = E_{S1}\frac{k_S}{1-\delta_{\mathrm{I}}/\delta_R}e^{-2\delta_{\mathrm{I}}t} + E_{R2}e^{-2\delta_{\mathrm{II}}t} \tag{2}$$

where the amplitude E_{S1} and E_{R2} of both decays refer to initial coupling conditions and $\delta_{I,II}$ are the eigenvalues of the coupling matrix (16; 40). Using the subscript S for source room, i.e. the fly tower, and R for receiver room, i.e. the main hall, the eigenvalues are:

$$\delta_{\mathrm{I,II}} = \frac{1}{2}(\delta_S+\delta_R) \pm \sqrt{\frac{1}{4}(\delta_S+\delta_R)^2 - (1-\gamma)^2\delta_S\delta_R} \tag{3}$$

where γ depends on the mutual coupling factor and δ_S and δ_R are related to as the sound decays of the two sub-rooms considered as uncoupled (37).

The availability of the numerical model and the material properties allows to quantify the relation between the equivalent absorption areas of the fly tower at mid frequency $A_{S,M}$:

$$A_{S,M,\mathrm{without}} \geq A_{S,M,\mathrm{with}} \tag{4}$$

where $A_{S,M,\mathrm{without}}$ is referred to the 'without canopy' configuration and $A_{S,M,\mathrm{with}}$ to the 'with canopy' configuration (see fig. 1 and tab. 5). The relation between the two conditions may also be expressed in terms of coupling surface S_c as:

$$S_{c,\mathrm{without}} \leq S_{c,\mathrm{with}} \tag{5}$$

Table 5: Absorption data of the fly tower in three configurations: without (w/o) canopy, with (w) canopy, and the intermediate in which the drapes were removed but the canopy was not installed. Reverberation time values $T_{M,S}$ were measured placing sound sources and receivers on the stage and averaging six source-receiver pairs. The volume in the 'with canopy' configuration – between brackets – is intended as the part of the stage volume surrounded by the reflector array and the backdrop. Subscript "M" means that the values are averaged over 500-1000 Hz octave bands.

		w/o canopy (w drapes)	w/o canopy (w/o drapes)	w canopy (w/o drapes)
V_S (m^3)	Volume fly tower	2500	2500	(1200)
$A_{S,M}$ (m^2)	Eq. abs. area fly tower	350	250	(130)
S_C (m^2)	Coupling surface	80	110	110
$T_{M,S}$ (s)	Reverb. time stage	1.15	1.55	1.40

because in the 'without canopy' configuration the upper fly curtains cover almost half of the coupling surface and in the 'with canopy' configuration the coupling surface corresponds to the whole area under the proscenium arch. It follows that in the 'without canopy' configuration there is a "weak" coupling, from eq. 1:

$$k_{S,\text{without}} \sim 0.1 \tag{6}$$

while in the 'with canopy' configuration the so-called "strong" coupling is realized:

$$k_{S,\text{with}} \geq 0.5. \tag{7}$$

With regard to the mentioned data, it is possible to point out some remarks, starting from equation 2. As a matter of fact, the acoustic absorption of the fly tower affects the sound energy distribution and the sound decays in the audience area. The more coupling, the more sound energy in the audience area. A decrease of sound absorption on the stage (condition of eq. 4) and a larger coupling surface (condition of eq. 5) are both required to improve the coupling between the orchestra on the stage and the audience. As a consequence, removing the side drapes and the upper fly curtains – to install the reflector array – should be intended as a single overall intervention, to fulfil both the equations 4 and 5 at the same time.

Further support to the found remarks can be provided by a multi-decay Bayesian analysis (36) applied to the measured impulse responses (see fig. 10). The impulse responses referring to the sound source in the first violins position and the receiver R10 in the first gallery (see plans in fig. 4) were analysed. The energy decay curve in the configuration without the canopy is composed by two terms, highlighting the coupling effect between the stage tower and the main hall (see fig. 10(a)). On the contrary, when the canopy is installed and most of the drapes are removed from the stage tower, the decay curve better fits a single slope decay (see fig. 10(b)). Concerning the parameters shown in fig. 10, $\mathbf{T} = T_1, T_2$ and $\mathbf{H} = H_1, H_2$ are the decay parameters which fit the Schroeder curve H_s for a large number of data points K:

$$H_s(\mathbf{H}, \mathbf{T}, t_k) = H_0(t_K - t_k) + \sum_{S=1}^{2} H_s e^{-13.8 t_k / T_s} \tag{8}$$

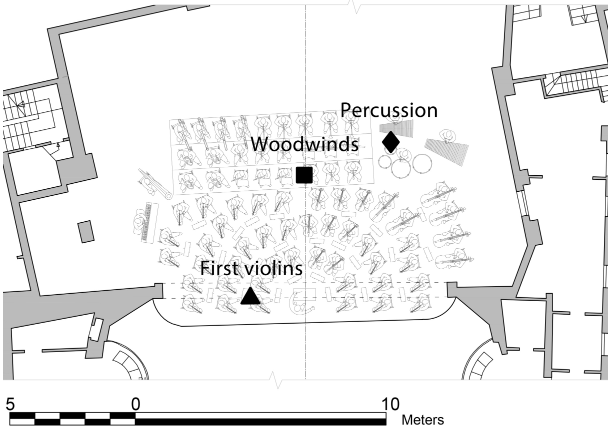
where H_0 is the background noise (not shown in fig. 10).

The variation of coupling effects with the installation of the canopy is also one of the reasons that contribute to the variation of the sound clarity, whose values are reported in tables 3 and 4. On one hand, with the reflector array the theatre shows more early reflections, that are the responsible for the rise of the numerator of the clarity criterion (21). On the other hand, the single slope energy decay increases much more the denominator, leading to a total drop of C_{80} values. The overall effect is a decrease from a range of 3 to 5 dB – suitable to speech/singing – to a range of 1 to 3 dB – suitable to music/symphonic concert.

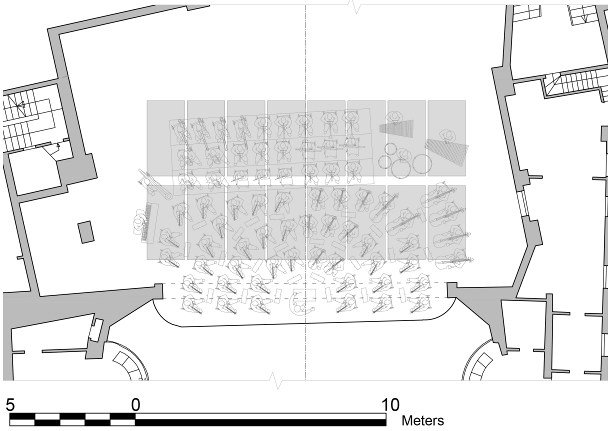
The influence of the canopy has been handled in terms of average values until now. A focus on the spatial consequences in the audience area is provided below. In particular, the spatial sound propagation of the woodwinds section is assessed. As already mentioned, the lack of woodwinds sound in the audience was one of the motivation of the canopy installation. The whole section of a mid-size orchestra was simulated: three flutes, three oboes, three clarinets and three bassoons, each one with its own directivity. Due to the use of multiple directional sound sources, the comparison in terms of G could becomes meaningless, so the SPL(A) was analysed (35). The sound sources were calibrated basing on average data of *fortissimo* dynamics provided by Weinzierl et al. (34). Results of simulation are shown in figure 11. In fig 11(b) it is possible to see a more uniform distribution and higher SPL(A) also in the side galleries. Moreover, it should be noted that the energy decays in the overhangs in the first and second gallery follow a 6 dB/doubling slope, according to (39). In other words, the coupling surfaces between the hall and the overhangs are secondary sound sources of spherical waves.

4. Conclusions

In an opera house the proscenium arch separates two acoustic volumes: the stage tower and the main hall. The first one is usually occupied by drapes, lighting fixtures and sceneries. The sound behaviour is optimised for speech and singing, and is less suited for the purpose of playing symphonic music.



(a) Virtual sound sources used in the simulation.



(b) Canopy layout with respect to the orchestra.

Figure 5: Sound sources positions used in the measurements and in the simulations. A mid-size orchestra was used as reference. Three sound source positions were considered: the music stand of the first violin below the proscenium arch, the first oboe (woodwinds) on the symmetry axis and the percussion off-axis below the canopy.

In the present case study, the authors studied the effect of removing the stage draperies and installing an overhead canopy in order to enhance the performance of symphonic music, both for listeners and musicians. A GA++ model, properly calibrated, was used as to optimise the configuration of an array of reflectors, based on target values of sound strength at the listeners and early support for the musicians. A final adjustement was done setting the tilt angles of the panels through in-situ measurements. The results of the validation measurements confirmed the performance of the canopy installed.

The canopy contributes to achieve the adequate values of acoustic room criteria needed for symphonic playing, increasing the EDT, decreasing C_{80} and blending the sound strength of the orchestral sections.

While an opera house is generally considered as two different acoustic volumes, a reflector array allows to consider the sound field similar to that of a single volume system. This is confirmed by Bayesian analysis of the measured impulse responses.

CAD models and impulse responses of configurations with and without the canopy, including measured impulse responses and material data, are freely available in repository (42).

Acknowledgements

The authors gratefully acknowledge the direction and the technicians of the Duse Theatre in Bologna. The works received useful feedbacks by Matteo Parmeggiani and Tommaso Ussardi, conductors of the resident Senzaspine Orchestra. Thanks to Simona De Cesaris, Federica Morandi and Lisa Loreti, who helped in the measurements, and to Carlotta Mirri, who provided an early version of the numerical model. Finally, the authors are indebted to Francesco Martellotta, who shared the multi-decay analysis software.

[1] Hidaka, T., and Beranek, L. L. (2000). Objective and subjective evaluations of twenty-three opera houses in Europe, Japan, and the Americas, *J Acoust Soc Am*, 107(1), 368–383.

[2] Prodi, N., Pompoli, R., Martellotta, F., and Sato, S. I. (2015). Acoustics of Italian historical opera houses, *J Acoust Soc Am*, 138(2), 769–781.

[3] Garai, M., Morandi, F., D'Orazio, D., De Cesaris, S., and Loreti, L. (2015). Acoustic measurements in eleven Italian opera houses: Correlations between room criteria and considerations on the local evolution of a typology, *Build Environ*, 94(2), 900–912.

[4] D'Orazio, D., De Cesaris, S., Morandi, F., and Garai, M. (2018). The aesthetics of the Bayreuth Festspielhaus explained by means of acoustic measurements and simulations, *J Cult Herit*, 34, 151–158. DOI: 10.1016/j.culher.2018.03.003.

[5] Kim, Y. H., Lee, H. M., Seo, C. K., and Jeon, J. Y. (2010). Investigating the absorption characteristics of open ceilings in multi-purpose halls using a 1:25 scale model. *Appl Acoust* 71(5), 473-478.

[6] Jaffe, C. (1973). Design considerations for a demountable concert enclosure (Symphonic shell), *J Audio Eng Soc*, 22(3).

[7] Holden, M. (2015). Acoustics of multi-use performing arts centers. CRC Press.

[8] Bradley, J. S. (1996). Some effects of orchestra shells, *J Acoust Soc Am*, 100(2).

[9] Dammerud, J. J., and Barron, M. (2010). Attenuation of direct sound and the contributions of early reflections within symphony orchestras. *J Acoust Soc Am*, 128(4), 1755-1765.

[10] Cremer, L. (1953). Die Plexiglas-Reflektoren um neuen Herkulessaal der Münchener Residenz, *Die Schalltechnik*, 13(5), 1–10.

[11] Johnson, F. R., Beranek, L. L., Newman, R. B., Bolt, R. H., and Klepper, D. L. (1961). Orchestra enclosure and canopy for the Tanglewood Music Shed, *J Acoust Soc Am*, 33(4), 475–481.

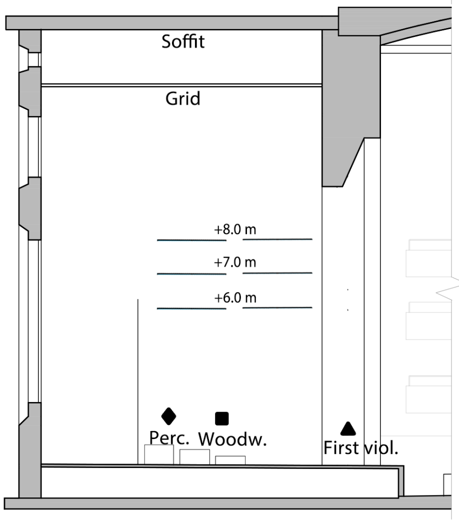
[12] Meyer, E. W. and Kuttruff, H. (1963). Reflexionseigensch aften durchbrochener Decken Modelluntersuchungen an der Reflecktoranordnung der neuen Philharmonic Hall in New York, *Acustica*, 13, 183–186.

[13] Watters, B. G., Beranek, L. L., Johnson, F. R., and Dyer, I. (1963). Reflectivity of Panel Arrays in Concert Halls, *Sound: Its uses and Control*, 2(3), 26–30.

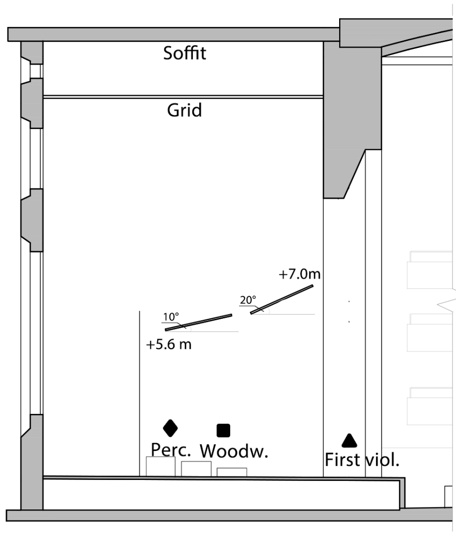
[14] Leonard, R. W., Delsasso, L. P. and Knudsen, V. O. (1964). Diffraction of sound by an array of rectangular reflective panels, *J Acoust Soc Am*, 36(12), 2328–2333.

[15] Meyer, E., Kuttruff, H., and Roy, N. (1967). Room-Acoustical Measurements in a Model of the Stadthalle Göttingen. *Acta Acust united Ac*, 19(3), 132-142.

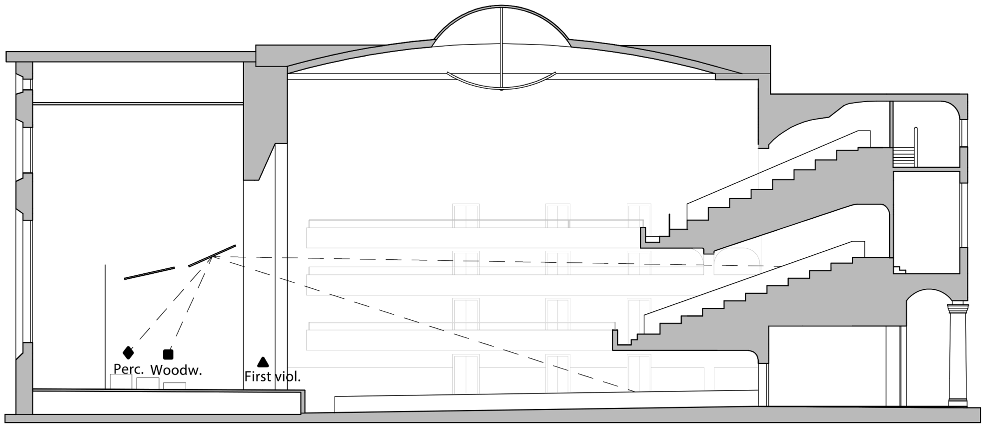
[16] Cremer, L., and Müller, H. A. (1982). *Principles and applications of room acoustics* (Vol. 1). Chapman & Hall.



(a) Step–by–step height optimisation.



(b) Optimised configuration.



(c) Example of specular reflections paths.

Figure 6: Options simulated for the height of the reflector array (top left), the final configuration (top right) and an example of reflection paths from the sound sources corresponding to woodwinds and percussion sections (below).

[17] Rindel, J. H. (1991). Design of New Ceiling Reflectors for Improved Ensemble in a Concert Hall, *Appl Acoust*, 34(1), 7–17.

[18] Cox, T.J., and Lam, Y. W. (1993). Evaluation of methods for predicting the scattering from simple rigid panels, *Appl. Acoust.*, 40, 123–140.

[19] Szeląg, A., Lewińska, M., and Rubacha, J. (2016). Verification of mathematical formulae applied to overhead stage canopy design, *Appl. Acoust.*, 110, 61-71.

[20] Cities of Music Network, UNESCO cities of music (available at https://citiesofmusic.net/city/bologna/, last seen July 7, 2020).

[21] ISO 3382-1 (2009), Acoustics - Measurement of room acoustic parameters - Part 1: Performance spaces, Geneva: International Organization for Standardization.

[22] D'Orazio, D., De Cesaris, S., Guidorzi, P., Barbaresi, L., Garai, M., and Magalotti, R. (2016). Room acoustic measurements using a high SPL dodecahedron, In *140^{th} AES Convention*, Paris.

[23] Bradley, D. T., and Wang, L. M. (2007). Comparison of Measured and Computer-Modeled Objective Parameters for an Existing Coupled Volume Concert Hall, *Build. Acoust.*, 14(2), 79–90.

[24] Savioja, L., and Svensson, U. P. (2015). Overview of geometrical room acoustic modeling techniques. *J Acoust Soc Am*, 138(2), 708-730.

[25] Pieren, R., Schäffer, B., Schoenwald, S., and Eggenschwiler, K. (2018). Sound absorption of textile curtains–theoretical models and validations by experiments and simulations, *Text Res J*, 88(1), 36–48.

[26] Jeon, J. Y., Kim, J. H., and Ryu, J. K. (2015). The effects of stage absorption on reverberation times in opera house seating areas, *J Acoust Soc Am*, 137(3), 1099–1107. DOI: 10.1121/1.4913772

[27] Vorländer, M. (2007). *Auralization: Fundamentals of Acoustics, Modelling, Simulation, Algorithms and Acoustic Virtual Reality*, Springer Science & Business Media.

[28] Cox, T. J., and D'Antonio, P. (2009). *Acoustic absorbers and diffusers: theory, design and application.* Crc Press.

[29] Odeon 12 Combined Edition. ODEON Room Acoustics Software, 2012.

[30] Vorländer, M. (2013). Computer simulations in room acoustics: Concepts and uncertainties. *J Acoust Soc Am*, 133(3), 1203-1213.

[31] Cox, T. J., and D'Antonio, P. (1997). Designing stage canopies for improved acoustics, *Proc. IOA*, 19(3), 153–160.

[32] Dammerud, J. J., Barron, M., and Kahle, E. (2011). Objective assessment of acoustic conditions for symphony orchestras. *Build. Acoust.*, 18(3-4), 207-219.

[33] Meyer, J. (1993). The sound of the orchestra, *J Audio Eng Soc*, 41(4), 203–213.

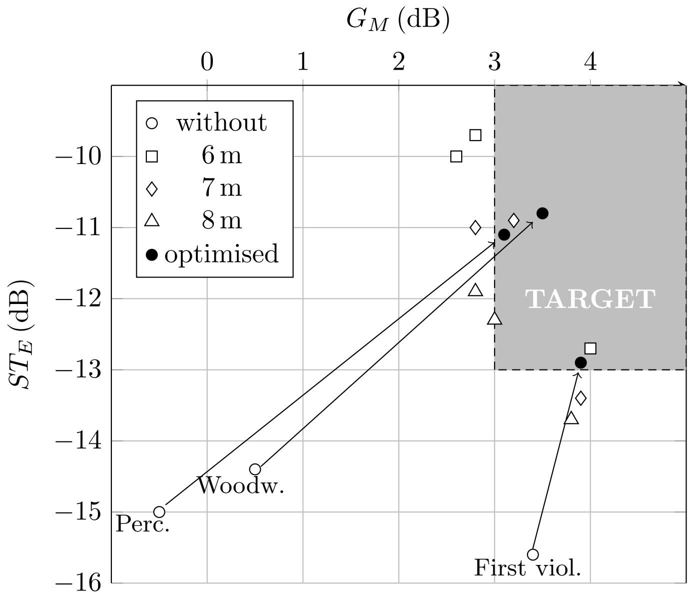


Figure 7: Simulated values of G_M and ST_E for the configuration without the canopy, the three different heights assessed and the final proposal. Gray area represents the target values considered during the optimisation process.

Figure 8: View of the stage during the validation measurements.

[34] Weinzierl, S., Lepa, S., Schultz, F., Detzner, E., von Coler, H., Behler, G. (2018). Sound power and timbre as cues for the dynamic strength of orchestral instruments, *J Acoust Soc Am*, 144(3), 1347-1355.

[35] D'Orazio, D., Fratoni, G., Rovigatti, A., Garai, M., (2020). A virtual orchestra to qualify the acoustics of historical opera houses *Build. Acoust.* DOI: 10.1177/1351010X20912501

[36] Xiang, N., Goggans, P., Jasa, T., and Robinson, P. (2011). Bayesian characterization of multiple-slope sound energy decays in coupled-volume systems. *J Acoust Soc Am*, 129(2), 741-752.

[37] Garai, M., De Cesaris, S., Morandi, F., and D'Orazio, D. (2016). Sound energy distribution in Italian opera houses. In *Proc Mtgs Acoust* 28, 015019. DOI: 10.1121/2.0000434

[38] Barron, M., and Marshall, A. H. (1981). Spatial impression due to early lateral reflections in concert halls: the derivation of a physical measure. *J Sound Vib*, 77(2), 211-232.

[39] Barron, M. (1995). Balcony overhangs in concert auditoria, *J. Acoust. Soc. Am.*, 98(5), 2580-2586.

[40] Bradley, D. T., Wang, L. W. (2005). The effects of simple coupled volume geometry on the objective and subjective results from nonexponential decay, *J. Acoust. Soc. Am.*, 118(3) Pt.1, 1480–1490.

[41] Ermann, M. (2005). Coupled Volumes: Aperture Size and the Double-Sloped Decay of Concert Halls, *Build Acoust* 12(1), 1–14.

[42] D'Orazio, D. (2019). Duse Theatre CAD and measured IRs, *Mendeley Data*, V1, DOI: 10.17632/br9x8hp52m.1

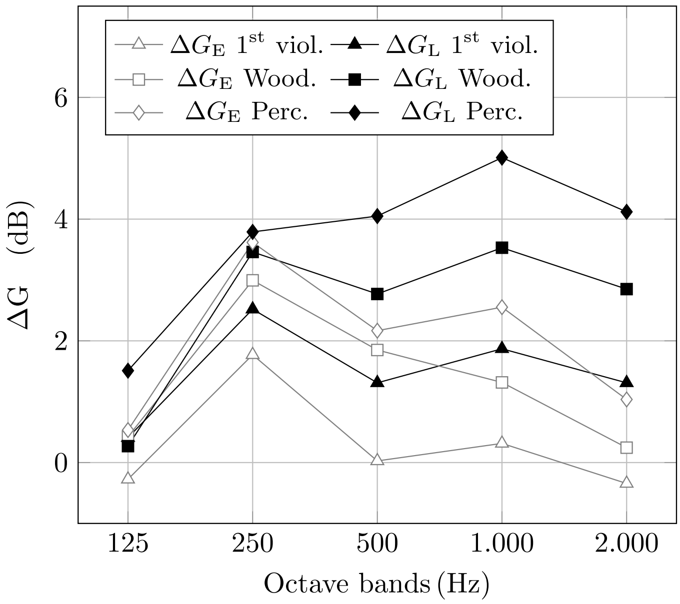
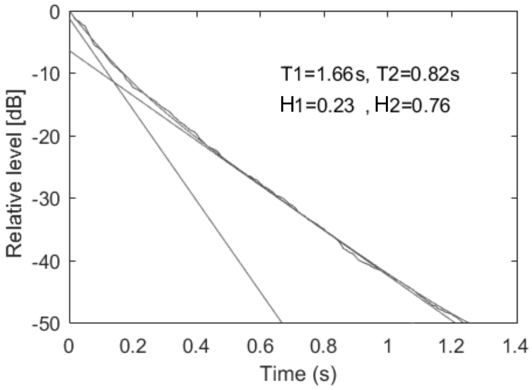
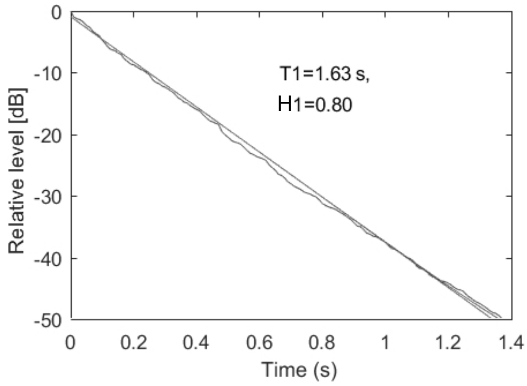


Figure 9: Change in early sound strength (G_E) and late sound strength (G_L) between the condition without and with the canopy. Results are provided for sound sources in first violins, woodwinds and percussion positions (see fig. 4).

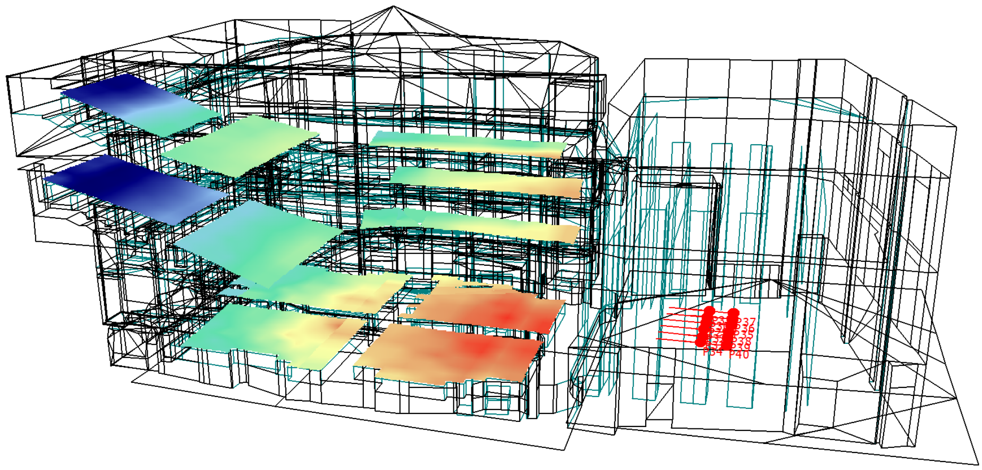


(a) Without canopy and with drapes

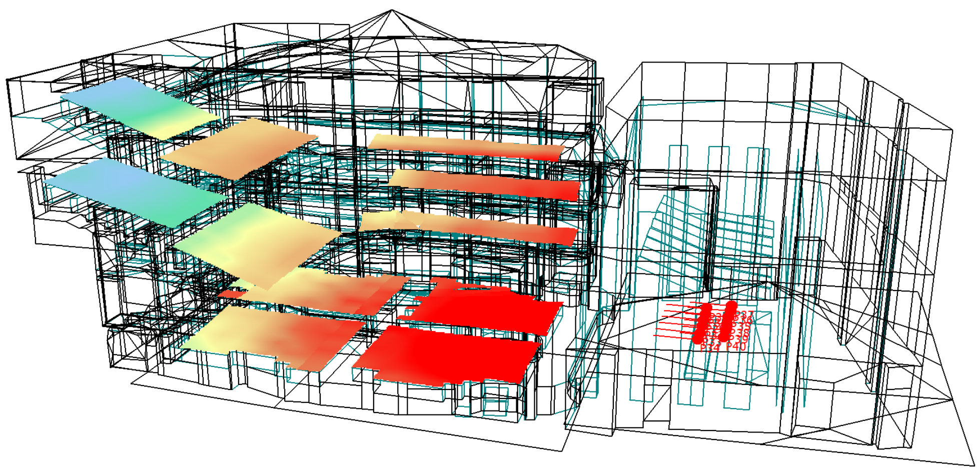


(b) With canopy and no drapes

Figure 10: Multi-decay analysis (36) on measured impulse responses filtered in the 500 Hz octave band, referring to the sound source in the first violins position and the receiver R10 in the first gallery (see plans in fig. 4).



(a) Without canopy and with drapes



(b) With canopy and no drapes

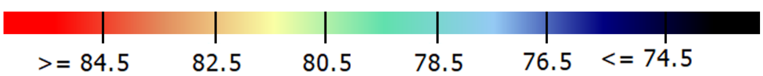


Figure 11: Simulated values of A-weighted sound pressure level, in dB(A).