ACOUSTIC CORRECTION OF A RENAISSANCE PERIOD HALL

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Résumé

Les salles médiévales et Renaissance sont souvent utilisées pour des événements musicaux ou des conférences. Ces salles ont des plafonds voûtés, tandis que les surfaces sont recouvertes de plâtre et de marbre. L'acoustique de ces lieux n'est pas optimale pour écouter des performances musicales ou des conférences. Pour rendre ces environnements acoustiquement utilisables, une correction acoustique doit être effectuée. Une salle construite à la Renaissance et utilisée pour des manifestations culturelles a été considérée comme une étude de cas. Il ressort des mesures acoustiques, le temps de réverbération est d'environ 4,5 secondes. L'évaluation de la correction acoustique a été réalisée avec un logiciel pour l'acoustique architecturale. Le modèle virtuel a été analysé d'abord dans la configuration initiale, puis avec l'insertion de panneaux insonorisants sur les murs et sous le plafond avec la voûte. Ensuite, la correction acoustique a été réalisée en installant des panneaux insonorisants dans la pièce. Des mesures acoustiques ont été prises avec cette nouvelle configuration, en l'absence du public, et le temps de réverbération aux moyennes fréquences a été réduit à 2,0 secondes, comme indiqué dans le projet de conception.

Mots clefs : Salles Renaissance, acoustique de la salle, tube d'impédance, temps de réverbération, correction acoustique

Abstract

Medieval and Renaissance halls are often used for musical events or conferences. These rooms have vaulted ceilings, while the surfaces are covered with plaster and marble. The acoustics of these places are not optimal for listening to musical performances or conferences. To make these environments acoustically usable, an acoustic correction must be made. A room, built during the Renaissance period used for cultural events, was considered as case study. From the acoustic measurements, it results that at mid-frequencies the reverberation time is about 4.5 seconds. The evaluation of the acoustic correction was carried out with a software for the architectural acoustics. The virtual model was analyzed first in the initial configuration and then with the insertion of sound-absorbing panels on the walls and under the ceiling with the vault. Subsequently, the acoustic correction was performed by installing sound-absorbing panels in the room. Acoustic measurements were taken with this new configuration, in the absence of the audience, and the reverberation time at the mid-frequencies was reduced to 2.0 seconds as presented in the design project.

Keywords: Renaissance halls, room acoustic, impedance tube, reverberation time, acoustic correction

1 Introduction

Ancient buildings, with artistic and historical value, could be used for social, cultural and tourist activity and so, they could be used to increase the development of the region as cultural attractors. Musicals, meetings, conferences could catch the attention of many people. In these historical buildings there are chambers that could be used for different kinds of musicals or conferences. So the rooms built during the Middle Ages and Renaissance, in the logic of improving the historical and artistic heritage, are often used for musical events, exhibitions or conferences.

These types of rooms generally have vaulted ceilings, that were dictated by constructive needs of the time. From an acoustic point of view, monumental rooms are complex places, due to the presence of vaulted or barrel ceilings, niches and vaults, as well as acoustically reflecting surfaces of the walls such as plaster, stucco, along with the presence of marble floors. The acoustics of these places are not suited for listening to musical performances and conferences, since the large dimensions, plastered walls, marble floors and particular geometries cause a long sound tail that negatively affects the listening of the music or understanding of speech.

The audience that attended the events, while appreciating the historical and architectural qualities of the rooms as well as the suggestiveness of the places, is not satisfied with the acoustics due to the presence of excessive reverberation. To make these spaces acoustically usable, an appropriate acoustic correction must be made by inserting sound-absorbing material panels [1, 2]. For conference rooms, where the comprehension of speech is fundamental, a short sound tail is required, i.e. a reverberation time of about 1 second. While for those dedicated to listening to music, a reverberation time of about 2 seconds is required, so that the

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sound reflections can improve the direct components of the sound field and make the listening more pleasant [3 - 6].

This paper presents a case study of a room located inside a monastery, built during the Renaissance period. Following restoration work, which involved re-plastering the walls, restoring the floor with marble tiles, the room was used for conferences and screening films. The room has a width of about 6 metres, a height that varies between 2.5 to 5 metres and a vaulted ceiling about 20 metres long. The volume is about 5,000 m^3. There are large side windows and the back wall, upon which films are projected, was made of plasterboard. Furthermore, there are thirty wooden and fabric chairs arranged in six rows installed. Figure 1 shows the interior of the room at the end of the restoration work. While Figure 2 shows the plan with the most significant geometric dimensions, Figure 3 shows the section. The users of the room complained of poor speech understanding during the lectures and a poor quality of listening to musical performances. Acoustic measurements were taken to evaluate the acoustic characteristics of the room. Analysis of the results showed that at mid-frequencies the reverberation time was about 4.5 seconds and therefore not adequate to the required needs. To obtain optimal listening conditions, it was necessary to reduce the sound tail by inserting panels of sound-absorbing material.

The evaluation of the appropriate acoustic correction was carried out with the help of the "*Odeon*" architectural acoustics software. The virtual model was first analysed in the initial configuration (reflecting walls) and then with the insertion, on the side walls and under the vault, of sound-absorbing panels. In the room afterwards, acoustic correction work was carried out by inserting the sound-absorbing panels on the side walls and under the vault in order to reduce the effects of acoustic focusing due to the particular geometry. The acoustic characteristics were then measured again so as to evaluate the effects of the acoustic correction. The main goal of the acoustic correction is the decreasing of the negative effects of an excessive (sound tail) and to improve the conditions of listening. The hall should be used for meetings and cultural organizations

Figure 1: Interior at the end of restoration work

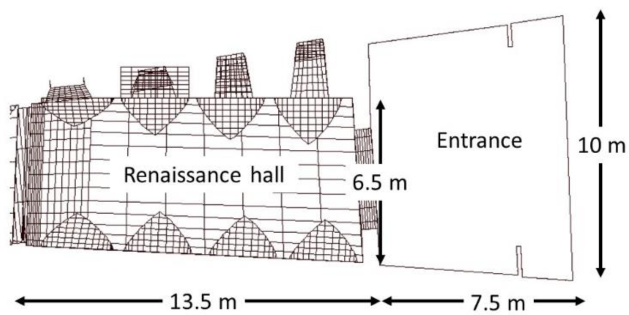

Figure 2: Plan with the most significant geometric dimensions**.**

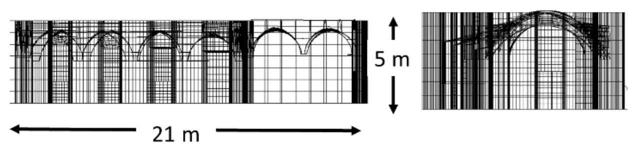

Figure 3: Section with the most significant geometric dimensions

2 Acoustic measurements at the end of the restoration works

In order to analyse the acoustic characteristics of the room, upon conclusion of the restoration works, acoustic measurements were carried out using an impulsive sound source. Acoustic measurements were taken using small firecrackers as the impulsive sound source. The acoustic measurements were carried out in accordance to ISO 3382-1 [7]. The acoustic measurements were taken in the absence of wind and precipitation, with an average temperature of about 20°C and relative humidity of 50%. A BRAHMA microphone was used to record the impulse responses in different receiver points.

The acoustic measurements were taken in empty conditions, without any spectators and there were no noisy activities in proximity and the traffic noise was negligible. During the acoustic measurements the background noise was lower than 30 dBA. The recorded impulse responses were elaborated with the software Dirac 4.0, analysing the acoustic parameters defined in the ISO 3382-1, such as reverberation time (T_{30}), early delay time (EDT), clarity (C_{80}), definition (D_{50}) and sound transmission index for speech intelligibility (STI) [8, 9]. The impulsive sound source was placed at a height of 1.50 metres from the floor, in the position of the speaker (the position in which the speaker sits during the conference), and the sound impulse was detected with a microphone placed at a height of 1.50 meters. The receivers were placed at various points in the hall, in 13 different locations equally distributed. The points where the sound source and the measuring microphone were located are shown in Figure 4.

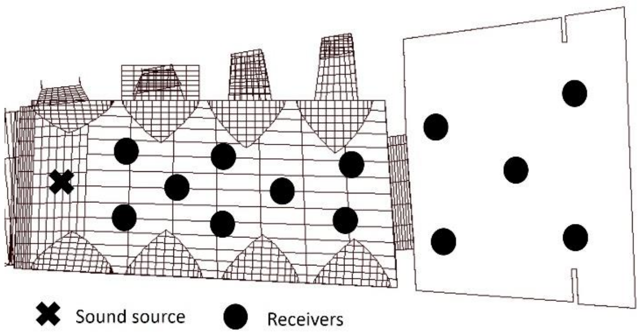

Figure 4: Room with indication of measurement points.

Current architectural acoustics literature shows tables and diagrams in which the optimal acoustic parameters are defined according to the intended use of the room in question. Thus, a room must respect the values of the acoustic parameters shown in Table 1. Figures 5, 6, 7 and 8 show, respectively, the average values and relative standard deviations of the acoustic parameters measured (EDT, T_{30}, C_{80} and D_{50}) at the end of the restoration work.

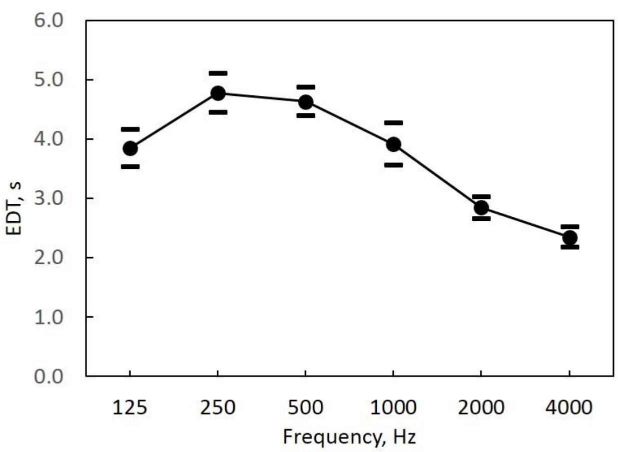

Figure 5: Average measured values of EDT and relative standard deviations.

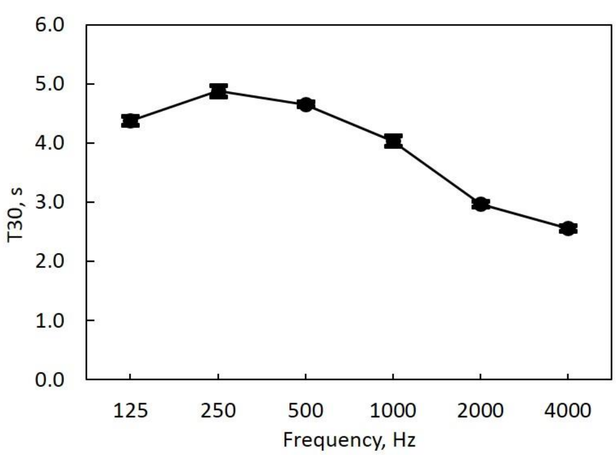

Figure 6: Average measured values of T_{30} and relative standard deviations

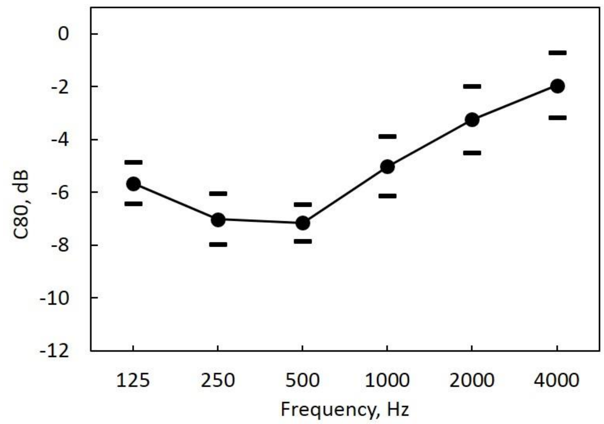

Figure 7: Average measured values of C_{80} and relative standard deviations

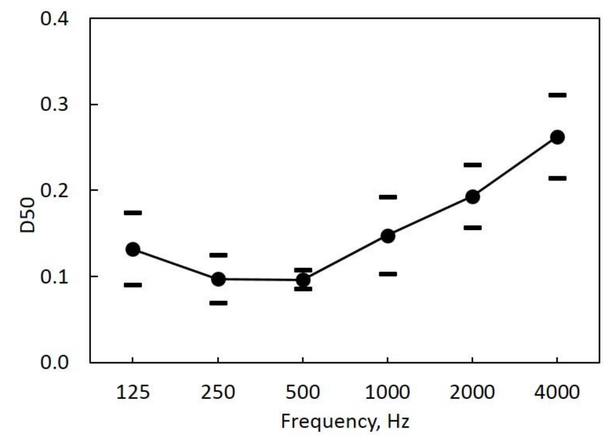

Figure 8: Average measured values of D_{50} and relative standard deviations

The analysis of the measured data showed an excessive reverberation time, at frequencies between 250 Hz and 500 Hz, whose value was about 5.0 seconds, while at the frequency of 1.0 kHz, both the EDT and T_{30} were equal to 4.0 seconds. The reverberation time pattern was a bell, due to the vaulted geometry of the room that focuses the sound in the centre of the room. At the frequency of 125 Hz, the reverberation time decreased respect to that of the successive octave bands (250 Hz and 500 Hz) due to the presence of large glazed surfaces placed laterally to the hall and the back wall made of plasterboard used for film projections. The glazed surfaces and the plasterboard in the low frequency domain behave like extended absorbers. The C_{80} clarity value averaged was about -5.0 dB, while the D_{50} definition averaged value was no greater than 0.3.

A comparison of the average values measured with those of Table 1 showed how the room had not optimal conditions for listening to music or speech. STI is the parameter for the evaluation of the goodness of the speech comprehension in a room, in this condition STI was equal to 0.30 (+/- 0.01). The values of this parameter correspond to a condition of poor intelligibility. In the room there was a poor understanding of speech due to the unsuitable measured acoustic conditions for understanding speech.

Table 1: Optimal acoustic parameter values for the different listening conditions [11].

Parameters	EDT, s	T_{30}, s	C_{80}, dB	D_{50}
Values for musical performances	1.8 < EDT < 2.6	$1.6 < T_{30} < 2.2$	$-2 < C_{80} < 2$	< 0.5
Values for speech performances	1.0	$0.8 < T_{30} < 1.2$	> 2	> 0.5

3 Acoustic properties of the absorbent material

There is no information about the value of the sound absorption coefficient of the material chosen for the acoustic correction. So the authors carried out acoustic measurements to obtain a value of the absorption coefficient which should be used in the numerical model.

The material chosen for the acoustic correction is polyester with a thickness of 4.0 cm. For aesthetic reasons it is covered with an acoustically transparent coloured cloth. There are differences between the absorption coefficients measured with a reverberation chamber or with an impedance tube at normal incidence. But the authors didn't have a reverberation chamber available, so they chose to take the absorption coefficients values using the impedance tube. To assess the material acoustic properties, the absorption coefficient at normal incidence was measured with an impedance tube (tube of Kundt), in accordance with EN ISO 10534-2 [10]. The tube has an inner diameter of 100 mm and length of 560 mm. The distance between the two measurements microphones was 50 mm, with the absorption coefficient measurement that was in the range frequency 200 Hz - 2.0 kHz; while when the distance between the two measurements microphones is 100 mm, the absorption coefficient measurement is in the range frequency 125 Hz - 1.0 kHz. The sound absorption coefficient is obtained from the combination of the transfer functions measured in the two measurement microphones, placed inside the tube. Table 2 shows the average values of the absorption coefficient measured at normal incidence in the frequency range 125 Hz - 4.0 kHz. This average value is obtained from measurements with four different specimens. The value of the sound absorbent coefficient at the frequency of 4.0 kHz is obtained by the extrapolation of the measured data (for the porous materials the values of absorbent coefficient at the frequency of 4.0 kHz is equal to the value measured at 2.0 kHz). Figure 9 shows the impedance tube (tube of Kundt) used for the sound absorption coefficient measurements.

Table 2: Average absorption coefficient measured at normal incidence of the polyester panel

Frequency, Hz	125	250	500	1 k	2 k	4 k
absorption coefficient	0.15	0.40	0.65	0.85	0.90	0.90

Figure 9. Impedance tube (tube of Kundt) used for the sound absorption coefficient measurements

4 Acoustic virtual model

For the purposes of a suitable acoustic correction, the appropriate amount of sound-absorbing material has to be inserted in the room must be evaluated, using the simulation software for architectural acoustics "Odeon" [12 - 14]. This software is based on the principles of geometric acoustics, in particular on a hybrid technique of ray tracing and image sources. The realization of the three-dimensional model is based on flat surfaces that simulate those of each element of the room. After importing the model into the Odeon software, the omnidirectional sound source was inserted and the 13 receiving points were inserted into the room; the values of the sound absorption coefficients of the walls are then assigned. The calculations were performed by fixing set-up parameters: transition order, TO=2; impulse response length = 5.0 seconds; number of late rays = 50,000; impulse response resolution 3.0 ms; max reflection order = 2,000. For the "Odeon" software settings, the scattering coefficient (s) does not depend on the frequency, but rather on the geometrical surface properties [15]. The area where the seats are positioned was simulated as parallelepipeds with a height of 0.8 m, width of 5.0 m and length of 10 m [16]. The area covered by the seats area was equal to 50 m^2, with the assigned value of the absorption coefficient given in [17 - 19] and a value of the scattering coefficient s = 0.5. The first operation is to calibrate the acoustic virtual model; it consists of setting the absorbent coefficient values for all the model surfaces and setting the scattering coefficients for the audience area. The geometric model of the room was calibrated by choosing realistic parameters necessary for the acoustic absorption coefficient in the octave bands in the 125 Hz - 4.0 kHz range, in order to minimize the differences between the measured and calculated mean values of T_{30}. The reverberation time (T_{30}) was chosen as a reference parameter. The calibration consists of changing the absorption coefficient values of the walls so that the reverberation time measured coincides with the simulated one. The calibration was stopped when the difference between the time measured and the time calculated is less than the 5% of all the octave bands calculated between the range 125 Hz – 4.0 kHz. Table

3 shows the absorption coefficient values of the surfaces used for the calibration of the virtual model [20-22].

Table 3: Sound absorption coefficient values of the materials used in the numerical simulation

Frequency, Hz	125	250	500	1 k	2 k	4 k
walls / ceiling	0.03	0.03	0.03	0.03	0.04	0.04
plasterboard	0.25	0.15	0.10	0.09	0.08	0.07
glass	0.20	0.15	0.10	0.10	0.05	0.05

The acoustic measurements carried out, inside the room, after the restoration works and theoretical analysis carried out with the software, showed the presence of an excessive reverberation and non-optimal speech listening conditions. To improve the acoustic performances of the room, it is necessary to reduce the reverberation time by inserting soundproof panels. To improve the acoustics of the room, in the project hypothesis the panels are inserted on the side of the wall in which there are no windows and under the vault to reduce the effects of acoustic focusing, with the absorption coefficient values assigned in the numerical model being reported in Table 2. The theoretical acoustic correction was obtained by inserting in the virtual 34 m^2 surface model of sound-absorbing panels. The numerical results show a reduction in reverberation time and an increase of C_{80} as well as of the STI. After the calibration, the absorption coefficient values of the audience in the room were considered. In fact, the third step of this procedure was to evaluate the effects of the presence of the audience on the acoustic characteristics of the room. In the virtual model, the sound absorption coefficients values of the audience were assigned to the sound coefficients values of box surfaces when the seats were empty. The absorption coefficient values of the audience are reported in current literature. Table 4 shows the audience absorption coefficient used in the virtual model [16, 17, 18]. Figures 10, 11, 12 and 13 show the comparison between the average acoustic parameter values (EDT, T_{30}, C_{80} and D_{50}) obtained through the numerical simulation of the empty room with the acoustic correction and the room when the seats are occupied with the presence of the audience.

Table 4: Sound absorption coefficient values of the audience used in the numerical simulation

Frequency, Hz	125	250	500	1 k	2 k	4 k
absorption coefficient	0.60	0.70	0.80	0.83	0.84	0.85

Figures 10, 11, 12 and 13 do not show the values of the standard deviations because they are the final results of the numerical model elaboration. The values of the acoustic parameters were obtained in an empty room condition, with the presence of the audience there is a reduction in the sound tail and the acoustic parameters improvement.

5 Acoustic measurements after correction interventions

Following the evaluation of the acoustic correction by means of the virtual model, sound-absorbing panels were placed on the walls of the room and under the vault. The absorption coefficients values of the panels were evaluated with the impedance tube. After inserting the sound-absorbing panels, the acoustic measurements in situ were taken again, the sound source and the receivers were put in the same initial positions, both to verify the effectiveness of intervention as provided by the calculated simulation as well as verify the reliability of the predictions implemented by the software for the acoustics architectural "Odeon". The measurements taken following the similar procedures used for the room before correction and by placing the sound source and measuring microphones in the same points. (as shown in Figure 4). The acoustic measurements were taken in the absence of wind and precipitation, with an average temperature of about 25°C and relative humidity of 50%. During the acoustic measurements the background noise was lower than 30 dBA. Figure 14 shows the room in its current state after the installation of the sound-absorbing panels on the side wall and under the vaults.

Figures 15, 16, 17 and 18 show the average measured values of the acoustic parameters EDT, T_{30}, C_{80}, and D_{50}, together with the intervals of the standard deviation. The measured value of the STI is equal 0.53 (these parameters were measured in an empty room, with the presence of the audience these parameters improve).

6 Results

The acoustic measurements were carried out in an empty room in the absence of the audience. In fact, the presence of the audience allows for a reduction of reverberation time and an increase of the clarity and definition values. The insertion of sound-absorbing panels has made possible to obtain good acoustics of the room. The reverberation time values T30, at the frequencies of 500 Hz and 1.0 kHz, which was estimated by experimental measurements after acoustic correction interventions, are about 2.5 seconds and coincides with the prediction implemented by the architectural acoustics software. While EDT values, at the frequencies of 500 Hz and 1.0 kHz, which were estimated by experimental measurements after the acoustic correction interventions, are about 1.5 seconds and coincides with the prediction implemented by the architectural acoustics software. The analysis of the measured data of EDT and T_{30} show the reduction of these parameters, especially at the frequencies between 250 Hz and 500 Hz. Before the acoustic correction at these frequencies the values of EDT were about 5.0 seconds, and the values of T_{30} were about 4.5 seconds. The sound absorbing panels under the vault have reduced the effects of acoustic focusing, improving the characteristics of the room. The parameter D_{50}, which expresses as a percentage the quantity of the phonemes actually understood, after the inclusion of the sound-absorbing panels, gives values close to 0.5, and also confirms the prediction made by the architectural acoustics software.

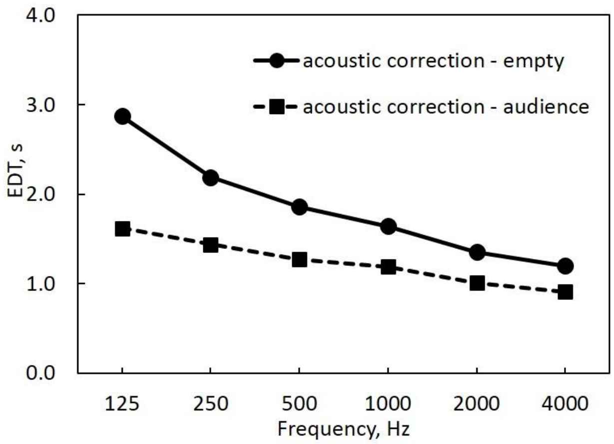

Figure 10: Average calculated values of EDT.

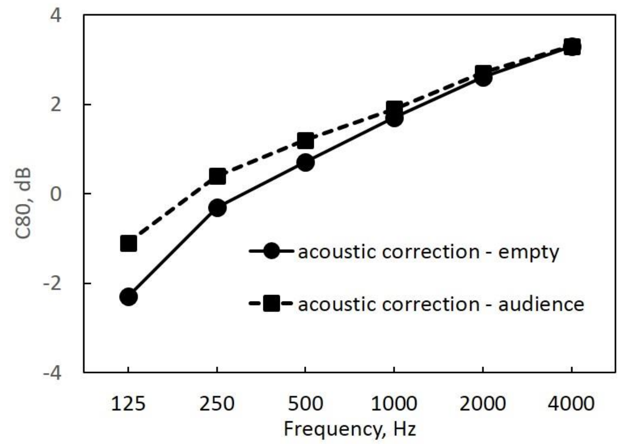

Figure 12: Average calculated values of C_{80}.

The mean values of C_{80}, in the mid-bands, are included between -1 dB and 1 dB after acoustic correction, and is coherent with the parameters T_{30} and EDT. The value of C_{80} experimentally measured, post opera, confirms the prediction made by the software. For both EDT and T_{30}, by inserting sound-absorbing panels (34 m^2) under the vaults at a distance from the vault of 0.5 m, a significant reduction of these parameters is obtained. The trend is linear decreasing with an increase in frequency. The C_{80} clarity values go from - 5 dB to 0 dB on average. When the acoustic parameters measured showed large standard deviation variations, those values change by changing the position of the receivers.

Similarly, definition goes from an initial value of 0.15 to a value after the acoustical correction of the empty room, to 0.4. Finally, the hall was used for conferences and the public that visits the room gave a positive feedback about the intervention performed.

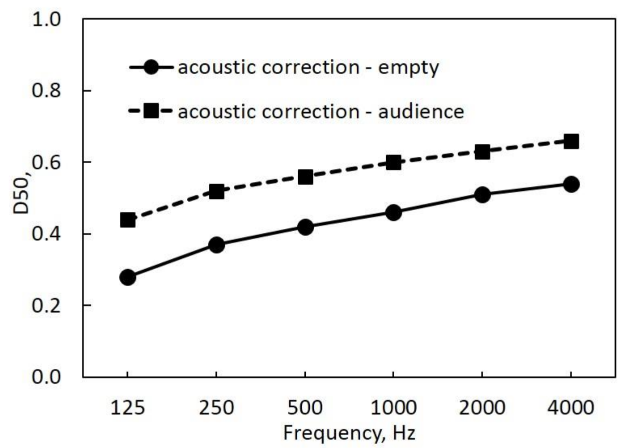

Figure 13: Average calculated values of D_{50}.

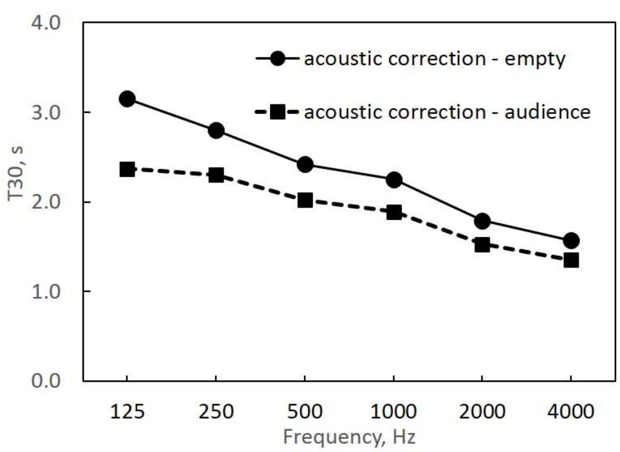

Figure 11: Average calculated values of T_{30}.

Figure 14: Room in its current state after the installation of the sound-absorbing panels on the side wall and under the vaults.

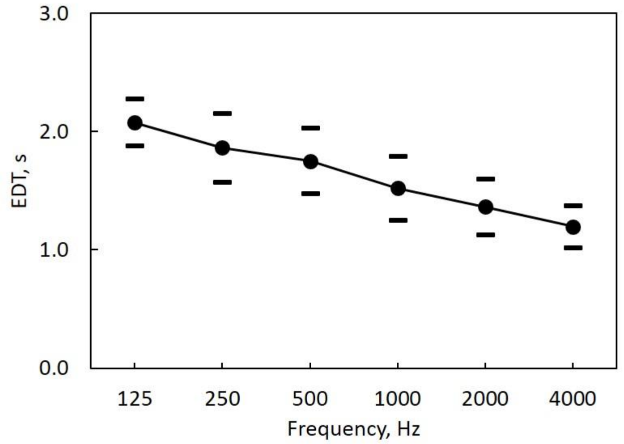

Figure 15: Mean values and relative standard deviations of the measured acoustic parameters of EDT and relative standard deviations.

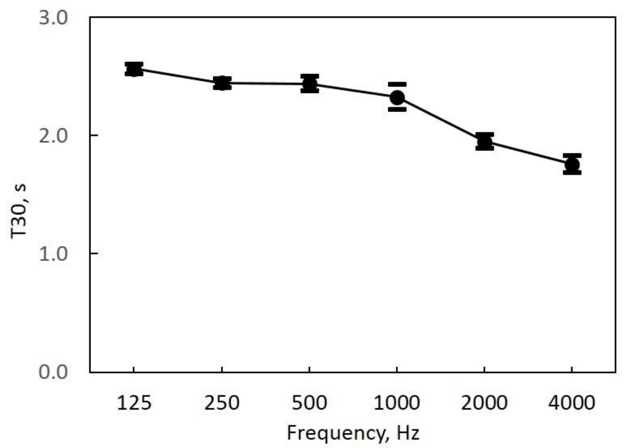

Figure 16: Mean values and relative standard deviations of the measured acoustic parameters of T_{30} and relative standard deviations.

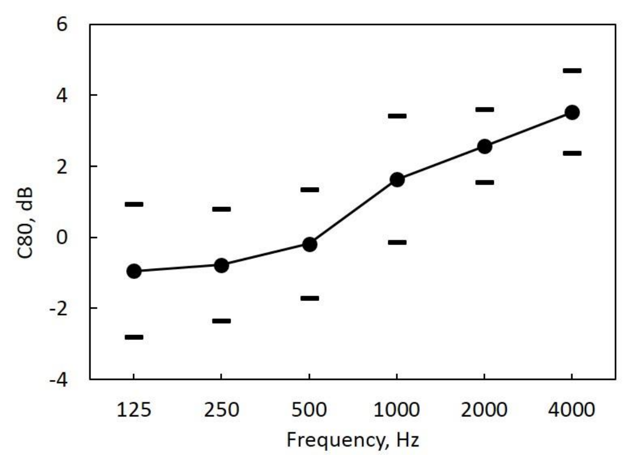

Figure 17: Mean values and relative standard deviations of the measured acoustic parameters of C_{80} and relative standard deviations.

Figure 19 A shows, from a receiver point of view, the progress of the impulse for the hall, before the acoustic correction. It's possible to see that the effects of the acoustic focalization, due to the vaulted ceiling and due to the many sound reflections on the walls, in fact before the reflections, they take much more time to decrease. Figure 19 B shows, from a receiver point of view, the progress of the impulse for the hall, after the acoustic correction. In this configuration the previous reflections tended to decay in a sudden way, due to the acoustic absorption and the effect of acoustic focalization is eased because the soundproofing are collocated under the vaulted ceiling, reducing the unwanted effect

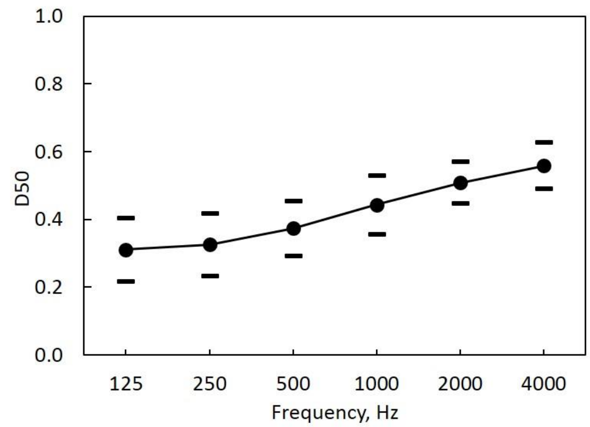

Figure 18: Mean values and relative standard deviations of the measured acoustic parameters of D_{50} and relative standard deviations.

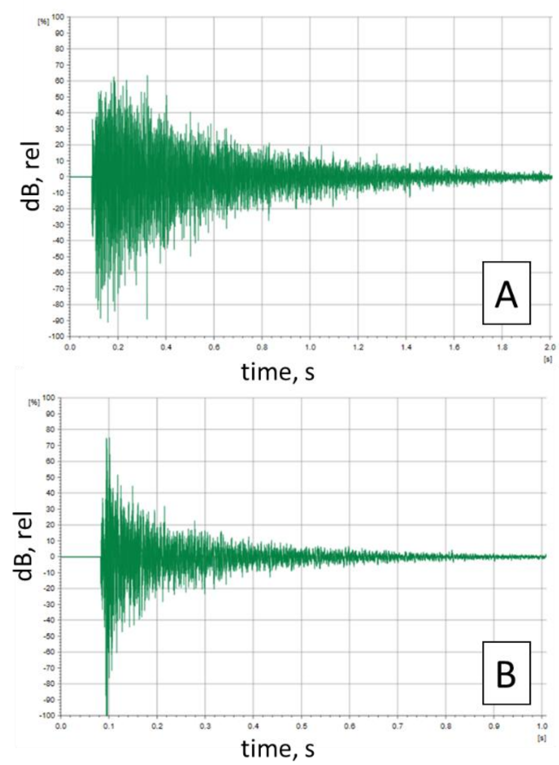

Figure 19: (A) Receiver point, the progress of the impulse for the hall, before the acoustic correction. (B) Receiver point after the acoustic correction

7 Conclusions

This paper discusses the solution for the acoustic correction of a room built during the Renaissance period. The presence of vaulted ceilings and plastered walls caused unsatisfactory acoustics and the audience attending the events was not satisfied due to the excessive sound tail, so it was necessary to carry out appropriate acoustic correction interventions. The hall after the acoustic correction can be used for conferences and film screenings. The acoustic correction was carried out by inserting sound-absorbing panels on the lateral surfaces and under the vaults so as to limit the undesired effects of acoustic focusing. The acoustic measurements carried out in the empty room allowed to verify the initial hypotheses of estimation of the acoustic characteristics of the hall.

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