Audio Engineering Society

Convention Paper 10569

Presented at the 152nd Convention
2022 May, In-Person and Online

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Acoustic Design Review for the Historical Aula Magna at the University of Parma. Measurement and Simulation Tools to Predict the Amount of Absorption to be in Place.

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ABSTRACT

The Aula Magna (Great Hall) of the University of Parma, historically known as the Hall of the Philosophers, is part of a 16th-century palace located in the core of the city. The Aula Magna hosts official ceremonies and graduations. The geometrical composition of the room, provided with a wagon vault, and the high level of reflections due to the hard finish materials lead to a poor quality of speech intelligibility. This paper deals with an acoustic design review of the current furniture inside the auditorium, with the purpose of adjusting the acoustic parameters to be suitable for the current uses of the room. Acoustic measurements have been undertaken in accordance with the standard requirements outlined by ISO 3382-1, capturing the existing conditions of the hall. A highly accurate digital model of the room was obtained with photogrammetry and modelling, in order to carry out numerical simulations regarding the implementation of the acoustic treatments. The quantity and quality of the proposed absorbing panels improve the listening conditions to a degree of comfort assessed against the criteria set by UNI 11532-2:2020.

1 Introduction

It is very common to adapt rooms in historical buildings to host conferences and official ceremonies. Despite the commonality of this practice, the acoustic corrections to be applied to cultural heritage constructions are sometimes very challenging, due to the constraints of the room geometry and finishing materials. In addition, constraints upon the choice between temporary or fixed acoustic treatments can introduce more complex limits to the design process. This paper suggests some mitigation measures applied to the Aula Magna at the University of Parma. A simulation-driven approach, using the Ramsete 3.02 software, has allowed for constant control over the adaptation design process. The room has been faithfully reproduced, under a geometric perspective, including the absorption coefficients of the finishing materials, that have been calibrated with the measured impulse responses (IRs). The calibrated results have been compared with the simulated values obtained by the introduction of the acoustic treatments in the 3D model. Thereafter, the simulated results have been assessed against the criteria set by UNI 11532:2004 [1].

2 Historical background of the Aula Magna at the University of Parma

The Jesuit order arrived in Parma in 1539 establishing itself in the church of St Rocco [2]. When the Duke Ottavio Farnese officially recognized the presence of the Jesuits in 1564, three other residential properties were assigned to them [3]. The Jesuits collaborated with the University of Parma by teaching specific subjects [2]. During the following decades, the Jesuits collected honours and donations from the kindness of the aristocrats, including the bequeath of the Cusani palace. The Jesuits finally got their own space for teaching and studying, which remained under their control from 1659 to 1730 [4]. The Jesuits were ejected from Parma in 1768 and the palace became the property of the University of Parma [2].

Nowadays, the palace hosts the administrative offices, the lecture rooms of the Department of Law and the Aula Magna, used primarily for graduation celebrations, as shown in Figure 1.

Figure 1. Aula Magna of the University of Parma during a graduation.

3 Architectural features, geometry, and construction of the Aula Magna

The Aula Magna has a rectangular layout having dimensions of 10.3×22.2 (W×L) m, with a maximum height of 12 m at the top of the vault, having a room volume of 2400 m^3 [5]. The ceiling is composed of a barrelled vault running along the longitudinal axis, and it is perpendicularly crossed by pointed-arched vaults of smaller width. This geometry creates space for frescos in the centre of the main vault [5]. The barrel-vaulted ceiling was constructed with a 5.15 m radius arc.

Along one side of the room, eight windows are open to the internal courtyard, designed to be two windows per vault span. Along the walls there are wooden choir seats with carved wooden boards reaching 2.1m of height and featuring bronze cherub heads. Above the choir seats there are bronze sculptures from the mid-20th century, created by Arnaldo Pomodoro, attached to the plastered brick walls. The floor is composed of marble tiles. Along the aisle there are non-upholstered wooden chairs.

4 Acoustic measurements

Acoustic measurements have been undertaken inside the Aula Magna by using the following equipment:

- Equalized omnidirectional loudspeaker (Look Line)
- Omnidirectional microphone (Bruel&Kjaer 4165).

The sound source was installed in front of the presidential desks and in the middle of the hall, at the height of 1.4 m, while the receiver was moved across the audience area and installed at the height of 1.1 m. The excitation signal emitted by the sound source was the Exponential Sine Sweep (ESS) having a duration of 15 s in a uniform sound pressure level for the range comprised between 40 Hz and 20 kHz [6]. The measurements were undertaken in unoccupied conditions.

Figure 2 shows the measurement positions of the equipment placed across the sitting area, according to ISO 3382-1 [7].

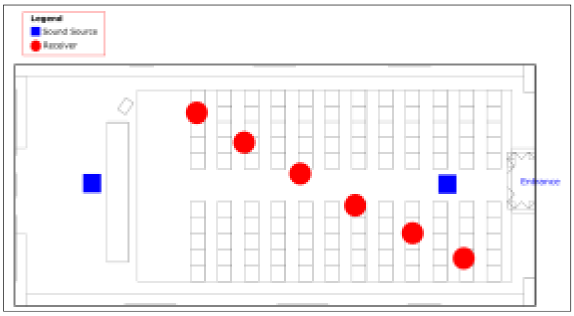

Figure 2. Scheme of the equipment location during the acoustic measurements.

The acoustic parameters extracted from the measured IRs have been averaged for all the receiver positions and shown in Table 1.

Acoustic parameter	Octave Bands – Frequency (Hz)					
	125	250	500	1k	2k	4k
EDT	1.9	3.1	3.8	3.6	3.1	2.3
T20	2.6	3.5	3.7	3.6	3.1	2.4
C50	-1.9	-9.7	-9.7	-8.4	-6.9	-5.8
C80	1.4	-4.6	-4.3	-4.9	-3.8	-2.4
D50	40	9.8	10	14	17	21
JLF	0.1	0.2	0.2	0.3	0.3	0.3

Table 1. Averaged measured results of the acoustic parameters taken inside the Aula Magna.

5 Criteria and Regulations

In Italy the reference guidance for the acoustic criteria of educational buildings is UNI 11532-2:2020. The Aula Magna falls into the A3.2 group, which includes lecture rooms, study group spaces and laboratories, where speech communication is considered the main room function.

In terms of criteria, for room volumes greater than 250 m^3, the speech transmission index (STI) shall be ≥ 0.5 or ≥ 0.6 if it is provided with an amplified audio system.

In terms of speech clarity index (C_{50}), no criterion is applied to rooms having a volume exceeding 250 m^3. Regarding the reverberation time (T_{20}), for rooms having volume size comprised between 30 m^3 and 5000 m^3 the following equation shall be applied.

$$RT = 0.32\, Log(V) - 0.17 \qquad (1)$$

Where V is the volume of the room. Specifically referred to 500 Hz, the graph shown in Figure 3 indicates that the T_{20} value for the Aula Magna shall be near 0.9 s.

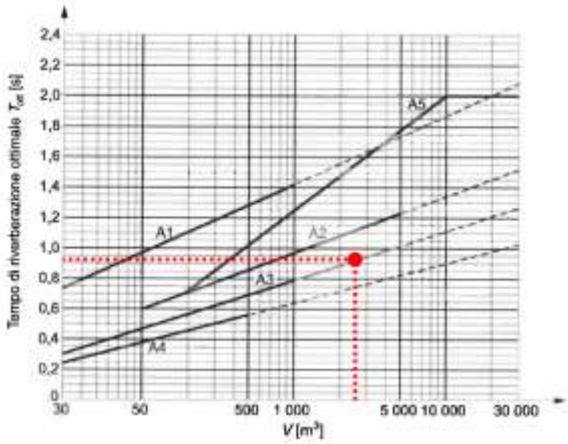

Figure 3. Optimal values of reverberation time at 500 Hz.

6 Digital model

A digital model of the Aula Magna has been realized using AutoCAD. All the elements have been drawn as flat plans, as shown in Figures 4 to 6, and exported in dxf format. The AutoCAD layers have been grouped based on the existing finishing materials and architectural components.

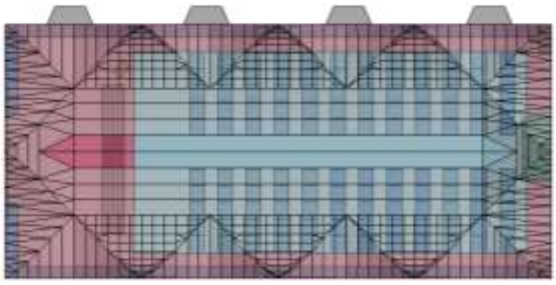

Figure 4. Plan layout of the 3D model.

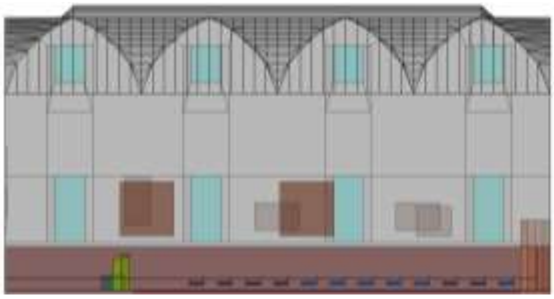

Figure 5. Long side elevation of the 3D model.

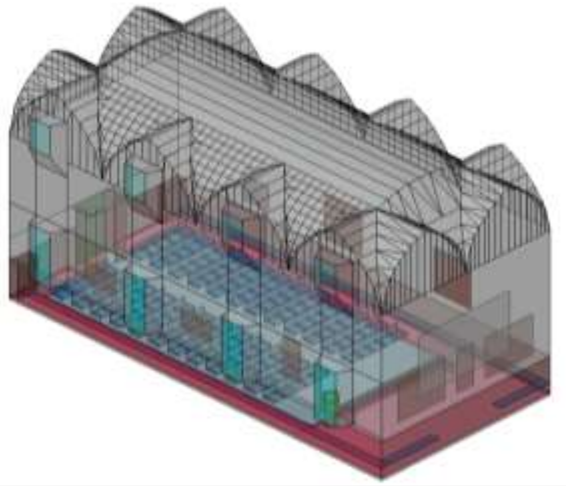

Figure 6. Axonometric view of the 3D model.

In addition, a photogrammetric model was captured using a DJI Mavic Mini drone, a Qoocam 8K 360° camera along with some wide-angle photos taken from a smartphone. After reprojecting the 360° images, a selection of 250 pictures has been elaborated with Polycam Web, which produced the model shown in Figures 7 and 8. This model can be exported in several formats, including OBJ, and can be utilized for visual rendering on desktop, web, and even virtual reality (VR).

Figure 7. Photo rendering of the Aula Magna, first view.

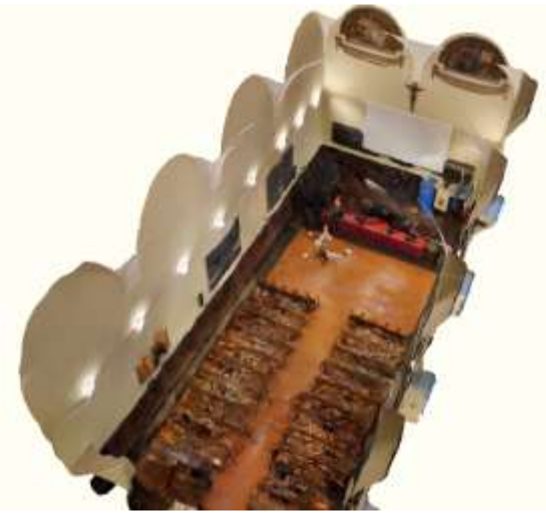

Figure 8. Photo rendering of the Aula Magna, second view.

Once the model has been completed, it was ready for the acoustic calibration and to be imported in Ramsete 3.02 [8], a software that computes reflections by calculating a triangular-base pyramidal spreading. Table 2 reports the absorption coefficients of the materials applied to the model for the acoustic calibration [9]. The absorption coefficients are obtained from the literature and are also the results of the calibration process [10].

Material	Abs. Coeff. @ Octave Frequency (Hz)					
	125	250	500	1k	2k	4k
Furniture	0.28	0.14	0.09	0.18	0.16	0.30
Wooden Basement Wall	0.25	0.13	0.11	0.18	0.13	0.15
Desks	0.18	0.08	0.11	0.15	0.20	0.25
Wall Decorations	0.01	0.01	0.02	0.03	0.03	0.04
Windows	0.35	0.10	0.05	0.12	0.07	0.04
Floor	0.01	0.01	0.08	0.03	0.03	0.04
Plastered Walls	0.02	0.09	0.08	0.04	0.1	0.1
Audience Chairs	0.31	0.10	0.09	0.18	0.09	0.11
Doors	0.28	0.10	0.10	0.16	0.2	0.25
Screen	0.50	0.20	0.10	0.19	0.13	0.19

Material	Abs. Coeff. @ Octave Frequency (Hz)					
	125	250	500	1k	2k	4k
Stage	0.29	0.11	0.10	0.16	0.08	0.10
Curtains	0.45	0.20	0.10	0.24	0.10	0.30

Table 2. Absorption coefficients of the materials applied to the existing conditions of the 3D model.

5.1. Model Calibration

The calibration process of a digital model consists of an iterative procedure of repeated room acoustic modelling to increase the accuracy of the simulated results [11]. A total of 13 calibrations have been undertaken before matching the required values. The difference between measured and calculated values of T_{20} have been minimized across all the octaves [12]. Figures 9 and 10 show the calibrated values of T_{20} and C_{50}, respectively.

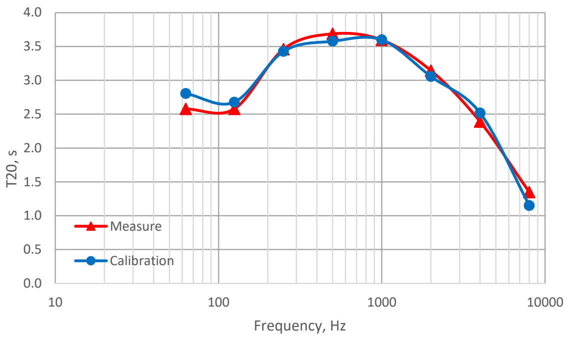

Figure 9. Comparison between measured and calibrated reverberation time (T_{20}) values.

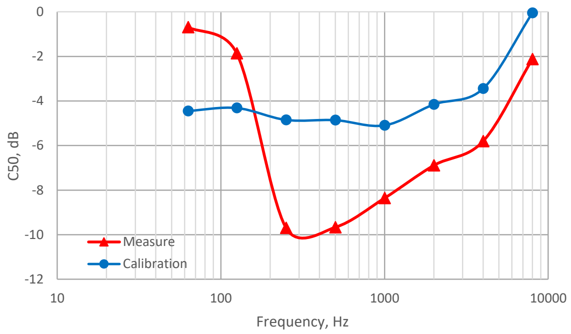

Figure 10. Comparison between measured and calibrated speech clarity (C_{50}) values.

Despite the absence of a norm for C_{50}, the authors preferred to also consider this acoustical parameter, even if the calibration has been focused mainly on the T_{20}.

Figure 9 shows the measured values of reverberation time to be around 3.5s at mid frequency bands, which is outside the optimal range as identified by the standard requirements. These outcomes are not beneficial for a good speech understanding [13,14], also due to the diffuse nature of the room [15]. This detrimental condition is also noticeable in terms of C_{50}, which is found to be around -10 dB at 250 Hz, as shown in Figure 10.

The calibration of the speech clarity index, as indicated in Figure 10, shows a discrepancy outside of the allowable Just Noticeable Difference (JND) range, which is equal to 1dB. Given that C_{50} is a parameter dependent on the ratio between early and late energy, its calibration is very difficult to achieve, as it varies between source and receiver position combinations. On this basis, the calibrated results of speech clarity shall be considered more optimistic than the existing conditions.

7 Acoustic design project

The measures adopted to lower the acoustic parameters to meet the standard requirements consist of the substitution of the existing metal decorations hung to the walls with paintings on canvas, along with the addition of rectangular absorbing panels having dimensions of 1.49 × 1.19 m (L×H). In addition, a carpet covering the central corridor and the areas close to the presidential desks has been proposed. The absorption coefficients of the proposed new materials are indicated in Table 3.

Material	Abs. Coeff. @ Octave Frequency (Hz)					
	125	250	500	1k	2k	4k
Abs. Panels	0.22	0.60	1.00	1.00	1.00	1.10
Canvas	0.35	0.38	0.40	0.40	0.46	0.50
Carpet	0.01	0.05	0.10	0.20	0.45	0.65

Table 3. Absorption coefficients of the new materials [16,17] introduced by the design project.

Figure 11 highlights the application of the acoustic solutions proposed to mitigate the impact for the excess of reverberation [18].

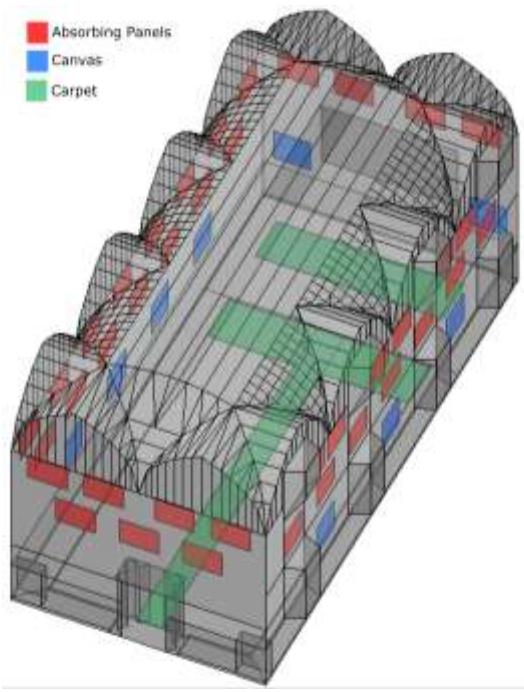

Figure 11. Application of acoustic measures in the model.

An omnidirectional sound source has been installed at the location of the presidential desks while a total of 32 virtual microphones have been installed inside the model, homogenously distributed across the audience area. The acoustic simulations have been carried out without and with the audience at 100% occupancy [19].

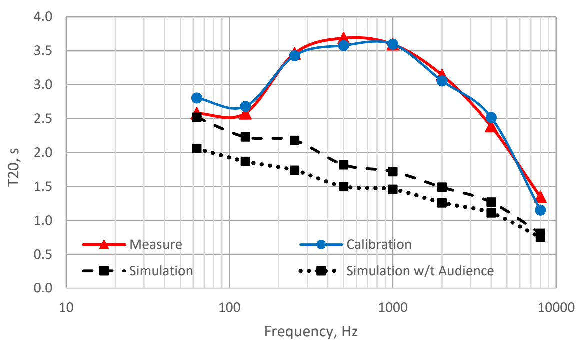

Figure 12. Measured and simulated values of T_{20}.

Figures 12 to 14 show the comparison between measured and simulated values of T_{20}, C_{50}, and STI, with and without audience, considered the averaged of all receivers' positions.

The installation of the absorbing panels lowers the T_{20} values significantly, especially at mid frequencies, as indicated in Figure 12. The simulated outcomes in the central frequency bands are more suitable for a conference hall, having values fluctuating around 1.8 s and 1.5 s, without and with an audience, respectively [20]. At 63 Hz and 8 kHz the simulated values without audience are comparable with the measured results, while the simulated value at 500 Hz is meeting the target expressed by the regulation, around 0.9 s.

Figure 13 shows the improvement of the speech clarity index, found to be more than 0 dB at high frequencies only, with a shortfall of up to – 4 dB at low frequencies.

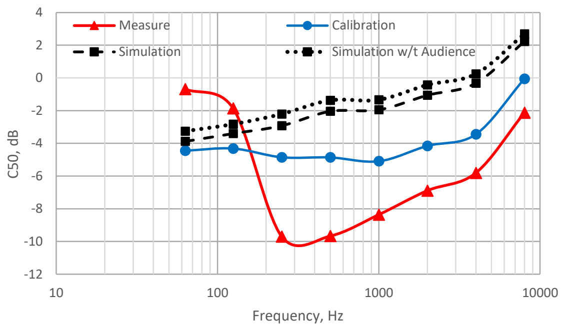

Figure 13. Measured and simulated values of C_{50}.

To complete the acoustic analysis the STI has been assessed in a similar way. Note that this acoustic parameter indicates the degree of amplitude modulation in a speech signal, including any distortion caused by reverberation and/or background noise [21,22].

On this basis, the measured STI values across the spectrum fall into the "fair" category, as defined by the intelligibility rating according to ISO 9921 [23]. With the insertion of the acoustic interventions into the 3D model, the STI values are improved, to be within the "good" range, comprised between 0.6 and 0.8, especially if compared to the background noise level that was found to be equal to L_{eq} 41 dB over a 30-minutes measurement. Note that the ambient noise was taken without any mechanical ventilation in operation. On this basis, the STI obtained with simulations meets the criteria. Figure 14 shows the comparison of calibrated and simulated STI results, considered as the average of all the receivers' positions.

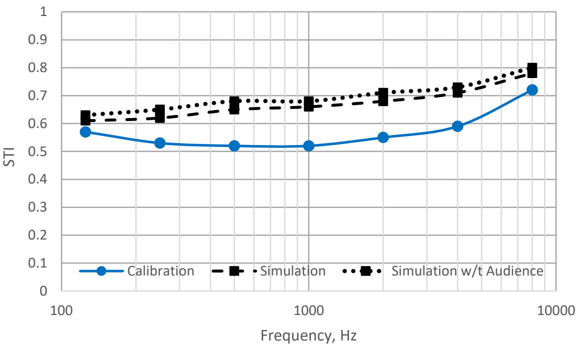

Figure 14. Calibrated and simulated STI values.

Further analysis can be carried out by considering the spatial distribution of T_{20}. Figure 15 indicates the reverberation time spatial distribution of the Aula Magna with the acoustic interventions applied, as per the acoustic simulations. The acoustic map highlights a concentration of sound energy at the quarter back of the room.

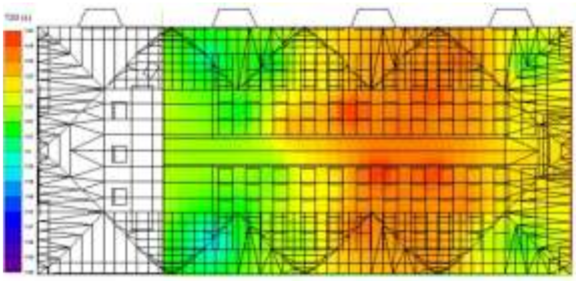

Figure 15. Spatial distribution of T_{20} values at 500 Hz. Simulation without audience.

This is due to the geometrical configuration of the vault, reflecting the soundwaves to the middle rows of seats, while the seats closer to the presidential desks record a lower reverberation time [24].

8 Conclusions

The acoustic quality of the Aula Magna at the University of Parma improved considerably in terms of speech understanding. The measurements have been used to calibrate a digital model that has been used for the acoustic simulations. The interventions adopted in this project involved the installation of acoustic absorbing panels uniformly distributed on the walls and the placement of a carpet in the walking ways. The substitution of bronze sculptures with canvases has been undertaken at the level of the lower windows, that are approximately 3.5 m high.

The overall result meets the criteria set by UNI 11532 in terms of reverberation time, which was lowered by almost 2 s at 500 Hz. Similarly, the speech clarity improved by about 8 dB at 500 Hz, only reaching 0 dB at high frequencies.

The application of the acoustic interventions improved the STI parameter, by passing from a "fair" to a "good" condition, fluctuating between 0.6 and 0.8 as per the reference standard.

Further research studies will be focused on the acoustic measurements to be carried out after the implementation of the outlined design project, in order to assess the accuracy of the simulated results.

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