Acoustic design of a modular studio box for use as control and mixing room for immersive audio

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This article presents a detailed analysis of the acoustic design process of a soundproofed box intended for control room and mixing for immersive audio. The main objectives of the project were defined based on the quality criteria required for critical listening environments, particularly for Dolby Atmos rooms. The adopted methodological approach relies on predictive evaluations of key acoustic parameters, supported by studies and calculations conducted using advanced numerical models and software. Key phases of the design process include the optimisation of the box dimensions, the modal analysis for low-frequency response, the design of the listening layout and early reflections, the specification of the internal acoustic treatment. The technical solutions adopted aim to ensure an accessible and cost-effective environment, achieved through optimization in material and space selection while still meeting requirements.
Keywords: studio acoustics, acoustic treatment, immersive audio, numerical modelling

Progettazione acustica di un box modulare adibito a sala regia e mixing per audio immersivo

L'articolo presenta una dettagliata analisi del processo di progettazione acustica di un box insonorizzato destinato alla sala regia e mixing per audio immersivo. Gli obiettivi principali del progetto sono stati definiti in base ai criteri di qualità richiesti per ambienti di ascolto critico e, in particolare, per sale Dolby Atmos. L'approccio metodologico adottato si basa su valutazioni previsionali dei parametri acustici chiave, supportate da studi e calcoli svolti tramite modelli numerici e software avanzati. Le fasi chiave del processo di progettazione includono l'ottimizzazione delle dimensioni del box, l'analisi modale per la risposta a bassa frequenza, l'ottimizzazione del layout di ascolto e delle prime riflessioni, nonché la progettazione del trattamento acustico interno. Le soluzioni tecniche adottate mirano a garantire un ambiente accessibile e a costo ridotto, attraverso l'ottimizzazione nella scelta dei materiali e degli spazi, pur rispettando i requisiti previsti.
Parole chiave: acustica degli studi, trattamento acustico, audio immersivo, modellazione numerica

1 | Introduction

In music and film industry, immersive audio is rapidly emerging as an essential element to deliver engaging and increasingly realistic sound experiences. This trend signifies a revolution in the standards of audio production and reproduction, generating new demands in terms of recording and playback technologies, including the need for acoustically controlled environments to ensure precision and fidelity of sound, especially during the mixing stage.

However, critical listening environments are often set up in small spaces where the effects of room resonances become more obvious at lower frequencies, requiring a challenging acoustic design exercise to avoid them compromising the perceived acoustic quality of the reproduced material.

The literature on the acoustics of small rooms is extensive. The earliest work was carried out on ideal room dimensions ratios and the influence of room geometry on the low-frequency response. With regards to rectangular-shaped rooms, studies have been conducted to determine the ideal ratios between height, length and width [1,2] to prevent modal overlapping and reduce the bandwidths with the absence of resonances. Bonello [3] developed a criterion for which the modal density should always be increasing when going from the one-third-octave band to the next higher one in the spectrum. Further developments were provided by Cox and D'Antonio [4,5] who have proposed numerical optimisation of dimension ratios to maximise the flatness of the room low-frequency response. The work has been extended onto non-cuboid rooms [6,7] employing advanced numerical techniques and considering the effects of boundaries' complex impedance.

Research was also conducted on the perceptual aspects of critical listening in small rooms. Studies based on listen-

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ing tests [8–10] have demonstrated the strong correlation between the perceived improvement in acoustic quality with the reduction of energy decay times at low frequencies. With regards to music stimuli, Fazenda et al. [11] defined the perceptual thresholds for the detection of the room resonances, while Rizzi et al. [12] have refined the characterisation of the transient behaviour of the response at low frequencies and analysed the perceived effects.

In terms of acoustic analysis for small rooms, Rizzi et al. [13] provide a comprehensive work, where a thorough review of the design criteria and the methodology for identification of acoustic defects based on on-field experience is conducted.

In this context, this article aims to examine the stages of the acoustic design of a soundproof cabin designed for use as control room and mixing for immersive audio according to Dolby Atmos criteria, with the intent to propose a structured design workflow to deal with the various aspects of acoustics for the specific type of listening environment, while introducing advanced modelling techniques for low-frequency treatment. The findings of the design exercise are then validated with post-completion measurements, showing good agreement with the defined criteria.

Tab. 1 – Relevant design criteria summary
Prospetto criteri di progettazione scelti

Item	*Description*	*Ref.*
Room Dimensions	• To be chosen to ensure a reasonably uniform distribution of room modes across the LF region	[3,16]
Speaker Layout	• 7.1.4 equidistant layout • Minimum layout height 2.4 m • Minimum layout width 3.0 m • Minimum layout length 3.5 m	[15]
Early Reflections	• Attenuated in the range 1-8 kHz by at least 10 dB relative to the direct sound within the first 15 ms	[16]
Reverberation Time	• Optimum RT at 500 Hz: 0.2 s • Octave-band RT values within provided limits (see Fig. 1)	[15,16]
Operational Room Response Curve	• AESTD1001.1.01-10 tolerance limits (see Fig. 2) • Dolby Atmos Music Curve (see Fig. 3)	[16,17]
LF Modal Decay Times	• < 0.90 s at 32 Hz • < 0.51 s at 63 Hz • < 0.30 s at 125 Hz	[11]

2 | Project overview

The project was commissioned by Clockbeats Srl in Brescia, Italy, a leading Italian company for music production and promotion.

Clockbeats studio facilities include several control rooms and tracking rooms, all built as "soundproof box", consisting in a modular structure made of a wooden panels build-up, to favour flexibility and rapidity in the assembly and disassembly process, integration in existing structures and reduced costs if compared to traditional recording studios, known for their architectural and structural complexity, while maintaining ample space available and high levels of performance.

With regards to the specific project, the aim is to build a new multichannel control room to be acknowledged in the official *Dolby Atmos Music Studio Public Listing* [14], which includes all the studios that have passed a rigorous commissioning test consisting in the verification of several requirements in terms of hardware, speaker layout and acoustics. Hence, the need for specialist acoustic design.

3 | Design criteria

The reference document titled *Dolby Atmos Home Entertainment Studio Technical Guidelines* [15] summarises the relevant design criteria in terms of studio acoustics. Additionally, recommendations from *AESTD1001.1.01-10* [16] as well as other quality metrics were considered in the design process to further improve the room performance. Tab. 1 shows a summary of all the design aspects that were taken into account.

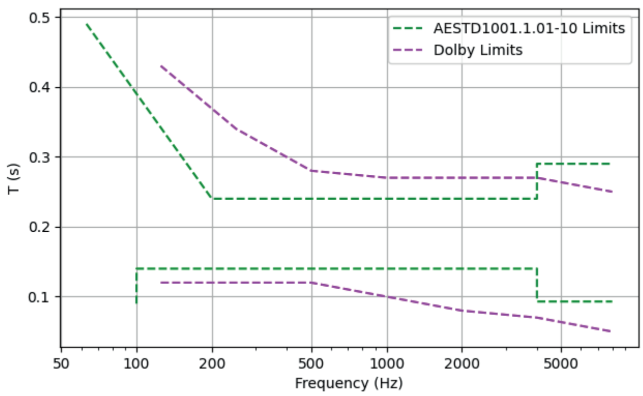

Fig. 1 – Reverberation Time tolerance limits
Limiti di tolleranza per il Tempo di Riverberazione

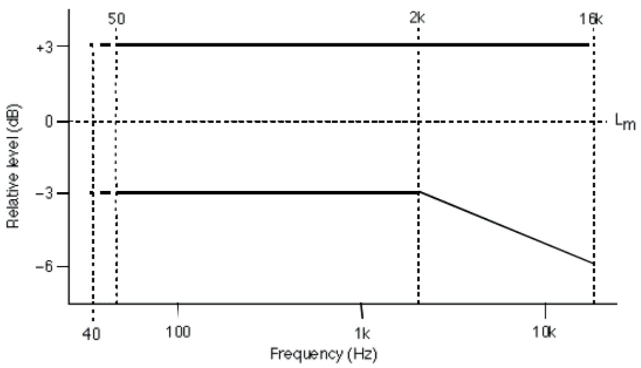

Fig. 2 – Operational Room Response tolerance limits according to AESTD1001.1.01-10 [16]
Limiti di tolleranza per Risposta in Frequenza secondo AESTD1001.1.01-10 [16]

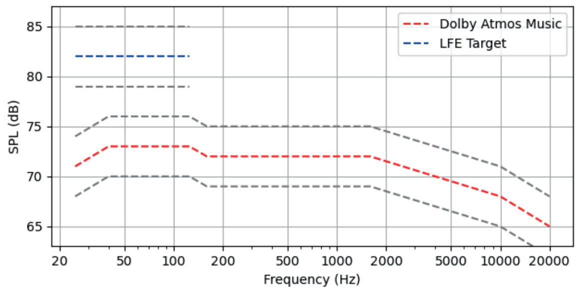

Fig. 3 – Dolby Atmos Music curve [17]
Curva per Dolby Atmos Music [17]

It is noted that sound insulation of the box and noise criteria from the air-conditioning system was beyond the author's scope, hence these aspects are not analysed in the present paper.

4 | Design process

4.1 | Box dimensions

The advantage of a "box" structure is its flexibility in being sized and shaped according to in-situ geometrical constraints, however the implications on the acoustics need to be considered, as the modal behaviour at low frequencies is affected.

Based on the available space on site and the requirements for speaker layout size (see Tab. 1), a trial-and-error process led to the dimensions shown in Tab. 2. It is noted that the proposed height is less than the required minimum in [16], however the chosen dimensions still allow for the minimum speaker layout extents required by Dolby Laboratories (see Tab. 2).

The calculated modal distribution is shown in Fig. 4 together with the number of modes per one-third octave band, demonstrating that the Bonello Criterion is satisfied.

Tab. 2 – Box dimensions
Dimensione del box

Dimension	*Size*	*Ratio to Height*
Length	4.50 m	1.61
Width	3.70 m	1.32
Height	2.80 m	1.00
Volume	46.6 m³	

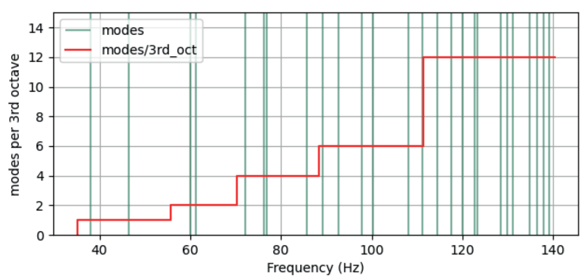

Fig. 4 – Predicted modal distribution, with modal density monotonically increasing over frequency
Distribuzione modale calcolata, con densità modale crescente monotona in frequenza

Fig. 5, instead, shows where the chosen dimensions, represented by a yellow cross, sit in the diagram from [4], together with the Bolt Areas (purple curves): for a 50.0 m³ room (the box is 46.6 m³), the light green patches represent the best and the dark green ones the second-best combinations for room ratios.

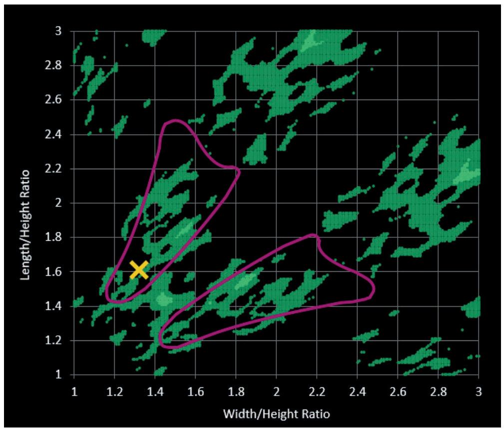

Fig. 5 – Room Dimension Ratio Analysis – screenshot from [18]
Analisi rapporto fra dimensioni della stanza – schermata da [18]

4.2 | Speaker layout

The next step is about placing the listening position along the longitudinal axis of the room and designing the loudspeaker layout, paying attention to constraints in terms of minimum layout dimensions, maximum distance from loudspeakers, maximum and minimum azimuth and elevation angles of loudspeakers, headroom above target SPL [15].

Dolby Laboratories have developed the *Dolby Atmos Room Design Tool Home Entertainment + Music* (from now on referred to as *DARDT*) [18], a Microsoft Excel Macro Tool that helps designing the speaker layout in a parametric way based on working space dimensions, mix position and speaker number and model. The tool automatically generates all the distances from walls to the front baffle of the speakers, providing rapid feedback on potential non-compliances with respect to requirements.

The preferred type of Dolby Atmos layout for mixing music is the "equidistant" one [15], where the distance to each speaker is approximately equal. Loudspeakers are arranged in the most common 7.1.4 configuration (7 speakers in the standard plane, 1 subwoofer, 4 top surround speakers) and the selected models are reported in Tab. 3.

Tab. 3 – List of loudspeakers
Lista altoparlanti

Speaker Position	*Speaker Model*
Screen Speaker (C/L/R)	Genelec 8340A
Side Surround (Ls/Rs)	Genelec 8330A
Rear Surround (Lrs/Rrs)	Genelec 8350A
Top Front (Ltf/Rtf)	Genelec 8330A
Top Rear (Lrf/Rrf)	Genelec 8330A
Subwoofer (LFE)	Genelec 7380A

The main challenge lies in the choice of the optimal mix position, which should be affected the least by the peaks and the dips cause by the modal behaviour of the room at low frequency. The position of speakers is also crucial to avoid pronounced cancellations at specific frequencies caused by Speaker-Boundary Interference (SBIR).

To allow for larger space available inside the box, it was decided to bracket the loudspeakers to the walls and the ceiling of the shell. This, however, sets constraints in terms of distance of speakers from the room boundary, hence some modifications were necessary compared to the standard dimensions and angles proposed by Dolby Laboratories.

The layout shown in Fig. 6 was deemed the best configuration in terms of speaker response.

The mix position was set at 1.78 m from the front wall, corresponding to 0.4 of the box length, to sit in a balanced spot between the peaks and the nulls of the first three axial modes, shown in Fig. 7.

The largest drifts from standard azimuthal were introduced for the following speaker positions:

- **L/R:** 25° from room centre line (recommended 30°, min. 20°, max. 40°), mainly due to minimise a cancellation happening around 90 and 110 Hz, due to the 92 Hz and 100 Hz mode having nulls along the width of the box (see Fig. 8).
- **Lrs/Rrs:** 158° from room centre line (recommended 135°, min. 120°, max 160°), to accommodate low-frequency treatment at the rear corners of the box.

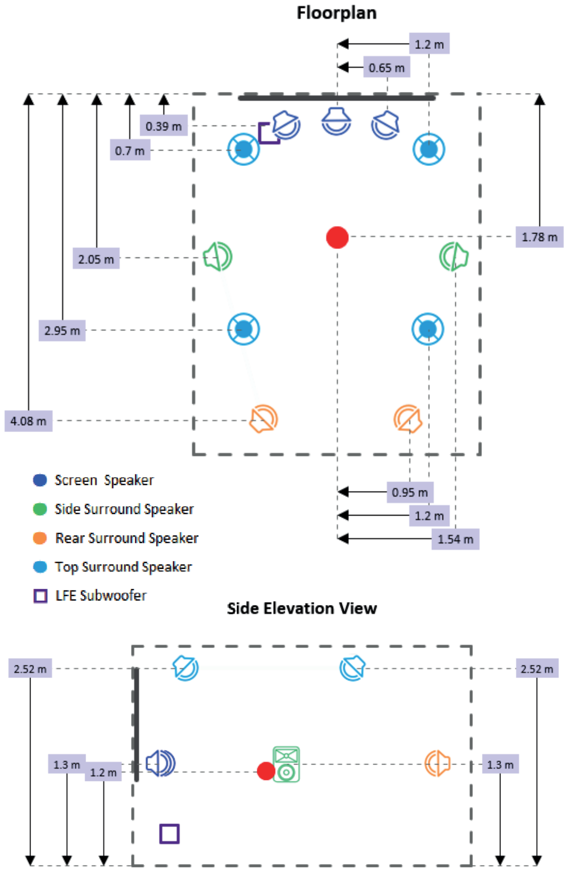

Fig. 6 – Speaker layout – screenshot from [18]

Layout altoparlanti – schermata da [18]

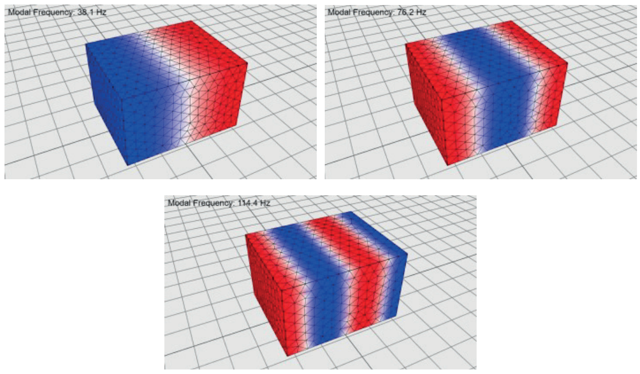

Fig. 7 – First three axial modes along the box length – 38 Hz, 75 Hz and 114 Hz

Primi tre modi assiali lungo la lunghezza del box length – 38 Hz, 75 Hz e 114 Hz

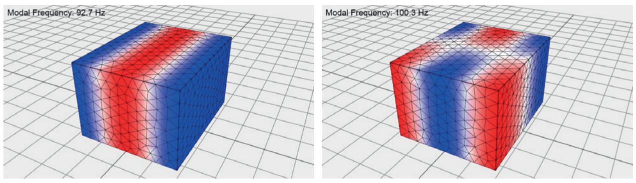

Fig. 8 – 92 Hz and 100 Hz modes

Modi a 92 Hz e 100 Hz

4.3 | Early reflections analysis

Once the layout was approved, the analysis on Early Reflections was conducted in order to locate first-order sound reflections points from all loudspeakers and place acoustic absorption properly. The Image Source Model is employed to estimate the reflections in a geometrical way, using the dedicated module included in CATT-Acoustic v9.1 software [19].

Fig. 9 shows all strong early reflections (more than –15 dB relative to direct sound) in the first 20 ms of the impulse response.

First-reflection points on walls and ceiling can be easily treated with porous absorption to mitigate the strength of reflected sound, preventing alterations in sound source localisation and distortion in the frequency content. One reflection point is also found on the entrance door, for which an absorptive finish was prescribed as well.

The analysis, however, shows reflected paths from the desk and the floor. While the first depend on the final desk shape (outside the author's scope), the latter can represent an issue for sound coming from the Rear Surround and Top Rear speakers. Typically, the use of a thick rug is recommended to attenuate such strong reflections, however the choice depends on the end user's needs, which may go beyond the acoustic aspects.

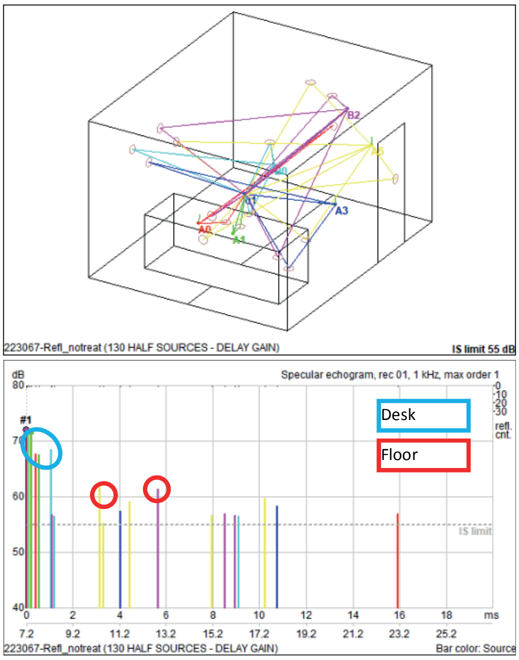

Fig. 9 – Early Reflection analysis (top: direct + reflected paths, bottom: specular echogram for first 20 ms). Different colours correspond to different sources

Analisi Prime Riflessioni (sopra: percorsi diretti + riflessi, sotto: ecogramma speculare per primi 20 ms). Colori diversi corrispondono a sorgenti diverse

actions of people within the room. This is achieved maintaining an open area to absorption greater than 50%.

The thickness of absorption ranges as follows: 35 cm to 47 cm for the front wall; 10 cm to 20 cm for the side walls; 35 cm to 60 cm for the back wall; 16 cm to 30 cm for the ceiling. Assuming a flow resistivity value of 10'000 rayls/m and using Miki model [21], the diffuse incidence absorption coefficients were calculated for the various thicknesses, as shown in Fig. 10. It is noted that the presented curves are valid for treatment with constant thickness, while the proposed treatment features elements with variable thickness.

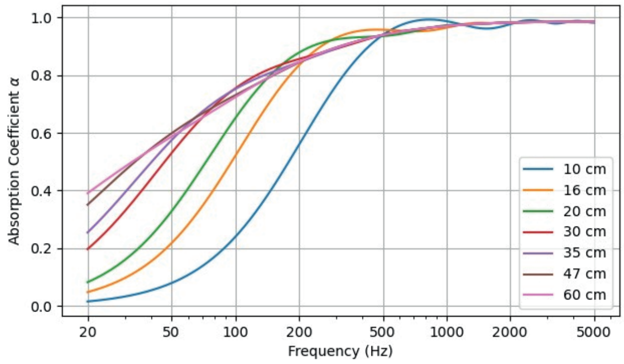

Fig. 10 – Predicted diffuse incidence absorption coefficients for porous treatment

Stima dei coefficienti di assorbimento a incidenza diffusa per il trattamento poroso

4.4 | Acoustic treatment design

The approach to acoustic treatment design was primarily focused on utilising porous absorbers, known for their ability to achieve broad-spectrum absorption across a wide range of frequencies. While it is acknowledged that porous materials exhibit weaker absorption at lower frequencies, they can effectively absorb sound energy throughout the useful spectrum if adequate thickness is considered. This obviates the need for additional solutions like resonators or membranes, which would require more space and tuning efforts. Additionally, porous absorbers offer a more linear absorption profile compared to pressure-based absorbers, making them a practical choice for acoustic treatment projects where efficiency and budget considerations are paramount.

While a *non-environment* room type [20] would be best for immersive audio due to the exceptional level of reduced colouration and consistency in the treatment effectiveness, the reduced area of the box requires the front wall to be made absorbent to increase damping at lower frequencies.

Thus, the design involves all walls and the ceiling to be as absorptive as possible: this is achieved using 40 kg/m^3 rock wool at different thicknesses covered in stretch fabric.

However, the drawback of this type of treatment lies in making the room feel uncomfortably "dead". This issue can be overcome by adding wooden finishes to the corner treatment in a way that it does not affect absorption, except for the high frequencies, in order to provide life to the speech and

While it is obvious that Reverberation Time values at high frequencies are well controlled, a more in-depth study was conducted at lower frequencies to assess whether the proposed treatment is sufficient to mitigate the effects of modal resonances.

A Finite Element Method (FEM) model, developed by the author using Python and the open-source library FEniCSx [22], was set to perform a Frequency Domain study and compute the Operational Room Response curve for both "untreated" and "treated" scenarios. The curves are calculated at the mix position using a monopole source at the chosen subwoofer location.

The geometries were constructed in STEP format and then imported into GMSH [23] to generate the 3D mesh for the model.

The "untreated" case was modelled as a whole cuboid volume with light constant normalised admittance at the boundary, calculated using the simplified formulation provided in [24, p. 351] and assuming an absorption value of 5%, making it as a purely resistive boundary. It is known that this represents an oversimplification on vibrational behaviour of the wooden shell at low frequencies, with a strong reactive component, however, the FEM simulation of the vibroacoustic system would require an important computational effort affected by strong uncertainty on the material properties and mounting constraints, with little or no advantage on the final accuracy of the results.

The "treated" case, instead, required the construction of two solid volumes, corresponding to air and porous absorber respectively, in order to assign different sound propagation properties. The damping provided by the outer wooden shell is still included in the same fashion as the "untreated" scenario. For the proposed treatment, the complex wavenumber for the porous volume to be input in the FEM model was calculated using Miki [21]. Geometries for both models are shown in Fig. 11.

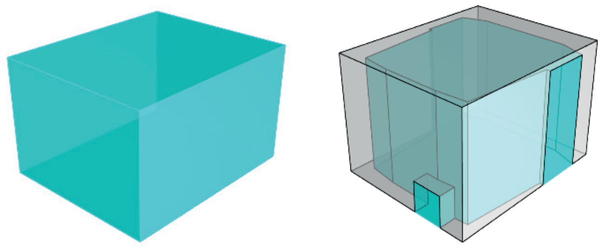

Fig. 11 – 3D geometries for untreated (left) and treated (right) case. Cyan indicates air volume, grey indicates porous volume
Geometrie 3D per i casi non trattato (sinistra) e trattato (destra). Il ciano indica il volume d'aria, il grigio il volume poroso

Simulation results are plotted in Fig. 12, shown both as narrow-band Magnitude Frequency Response (Fig. 12a) and 1/3 octave-band response (Fig. 12b) applied to pink noise, the latter being typically used for verification of compliance with design criteria.

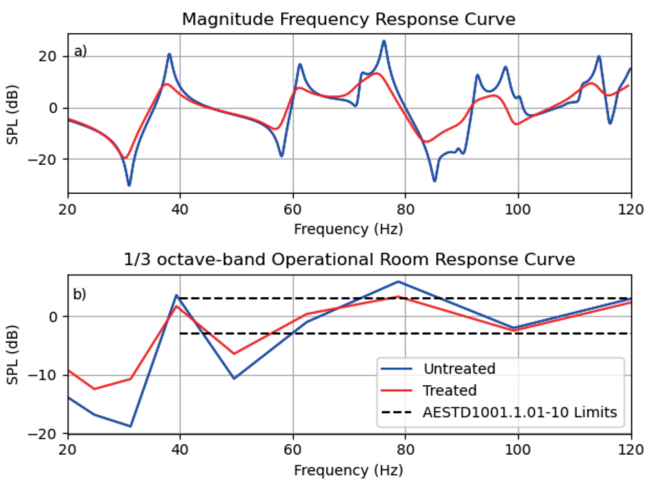

Fig. 12 – Simulation results: a) Magnitude Frequency Response Curve b) 1/3 octave-band Operational Room Response Curve, corrected for Pink Noise
Risultati delle simulazioni: a) Modulo della Funzione di Trasferimento della Curve di risposta in frequenza b) Curva di risposta in 1/3 di bande d'ottava, corretta per rumore rosa

It is noted that, despite the introduction of acoustic treatment significantly improves the flatness of the modal response, some of the peaks and dips caused by the room resonances are still located outside the tolerance limits previously defined. This was expected due to the limited space available for porous treatment to be effective at lower frequencies, requiring the use of equalisation filters on the loudspeakers in a more intensive way than typical fine tuning to adjust the response during the final calibration stage.

Another aspect to consider is the time domain response. Studies based on listening tests [8–11] have demonstrated the strong correlation between the perceived improvement in acoustic quality with the reduction of energy decay times at low frequencies in small rooms, subjectively preferred to the direct "flattening" of the magnitude frequency response.

In order to extract modal decay times (MT_{60}) from the predicted frequency response curves, the indirect method described by Prato et al. [25] was employed, consisting in fitting a Lorentzian function to each detected modal peak and calculating the bandwidth at half maximum. MT_{60} values can then be expressed as follows [26]:

$$MT_{60} = 2.2/\Delta f \, . \qquad (1)$$

These values are then compared to the perceptual thresholds of resonances for music from [11], as shown in Fig. 13. The difference in terms of MT_{60} reduction is significant, demonstrating that adequate control of the modal energy and compliance with the defined criterion can be obtained with porous treatment on an extended low-frequency range.

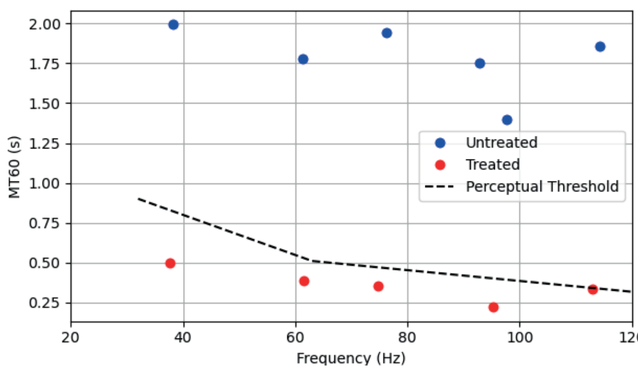

Fig. 13 – Modal Decay Times analysis.
Analisi dei tempi di decadimento modale

5 | Construction and commissioning

The construction phase took place in February 2024, requiring two weeks of work for the complete assembly of the box from scratch.

The wood finishes on all room corners were customised with CNC-milled panels to suit the intended aesthetic of the room, while maintaining the 50% open area to absorption. A custom design desk with the outboard was also fit in the room (see Fig. 15).

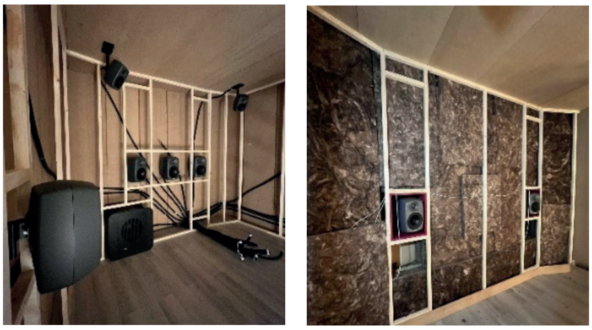

Fig. 14 – Timber structure for acoustic treatment support (left: front wall, right: rear wall)

Struttura in legno per il supporto del trattamento acustico (sinistra: parete frontale, destra: parete posteriore)

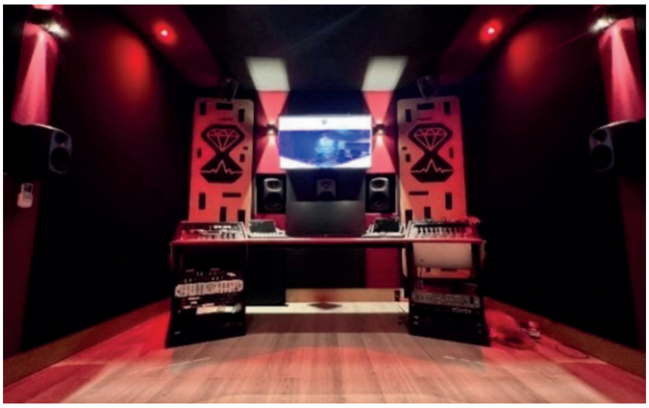

Fig. 15 – End of works – front wall view

Fine lavori – vista parete frontale

Acoustic measurement from the commissioning session were made available for analysis of the results post-completion. It is noted that measurements were performed after the calibration EQ was applied on each loudspeaker channel.

With regards to Operational Room Response, the curves obtained for each channel, as shown in Fig. 16, fall well within the ±3 dB tolerance from the Dolby Atmos Music Curve though, as expected, the requirement of electronic correction with negative gain on modal peaks was confirmed by the commissioning staff.

For the validation of modal decay times MT_{60}, Room Eq Wizard (REW) software [27] was used. The software, by means of the "RT60 Decay" function, allows to assess decay times based on fitting a "decay + noise" model on the on the Short-time Fourier Transform (STFT) of the measured impulse response for the identified modal frequencies. Such procedure, similar to the direct method described in [25], was preferred since the frequency response curves did not present identifiable peaks because of the active EQ correction, making the use of an indirect method not possible. Decays were calculated on the 1/12 octave-band smoothed response measured with the subwoofer only, with 12 points per octave resolution. Then, the decay value corresponding to the closest frequencies to the simulated ones were retrieved.

The obtained MT_{60} values are then compared to the previously defined perceptual threshold limits and the predicted values from FEM (see Tab. 4).

Tab. 4 – Evaluation of measured MT_{60} – Retrieved from LFE response. Values highlighted in green comply with design criteria, yellow ones do not

Valutazione dei MT_{60} misurati – Ricavati dalla risposta LFE. I valori evidenziati in verde verificano i criteri di progetto, in giallo non verificano

Simulated Frequency (Hz)	Simulated MT_{60} (s)	Measured Frequency (Hz)	Measured MT_{60} (s)
37.7	0.50	39.4	0.42
61.5	0.38	62.5	0.28
74.7	0.35	74.3	0.25
95.2	0.22	93.6	0.16
112.9	0.33	111.4	0.40

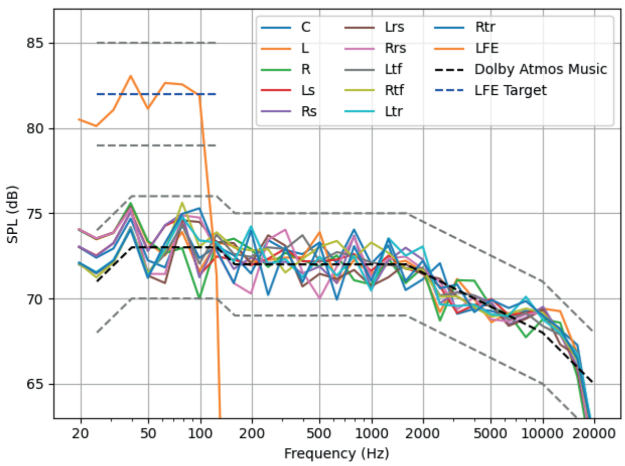

Fig. 16 – Measured frequency response curves – commissioning, 1/3 octave – Active EQ on channels.

Curve di risposta in frequenza misurate in fase di collaudo, 1/3 octave – EQ attiva sui canali

Results show that measured values are close to the design ones and, most importantly, below the perceptual threshold. The measured MT_{60} obtained for 111.4 Hz shows a non-compliance with respect to criteria, to be attributed to the subwoofer being low pass filtered at 90 Hz. This causes a low signal-to-noise ratio at the specific frequency, hence an artifact (overestimation) of the decay rate.

With regards to Reverberation Time, the average curve measured at and around the mix position is shown in Fig. 17, demonstrating a good achievement in terms of decay control. In the range between 250 Hz and 1000 Hz, the curve falls below the recommended Dolby limits (green lines), to be attributed to the oversizing of porous treatment for low-frequency control, while above 2000 Hz the effect of diffusive surfaces at the corners and furniture, and the increased directivity of loudspeakers become more prominent. This, however, it is not of concern in acoustic terms, as it pertains more to the comfort of the individuals working within the space.

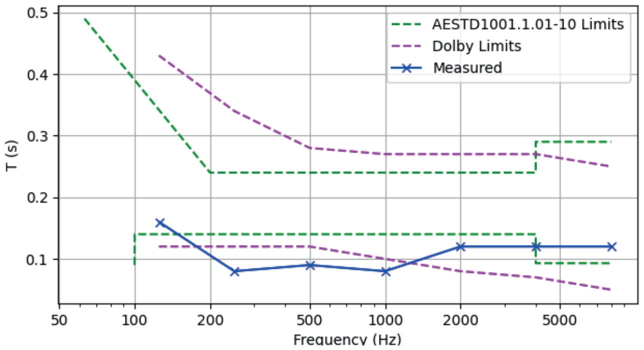

Fig. 17 – Average Reverberation Time curve at mix position
Curva Tempo di Riverberazione medio alla posizione di ascolto

Finally, it is worth noting that the studio has obtained the official *listing* in [14] in May 2024 with no reservations from Dolby Laboratories.

6 | Conclusions

In conclusion, this project aimed to design an acoustically optimized box for immersive audio control room and mixing purposes. The different stages involved in the design workflow have been described, showing the required tasks to ensure that project would successfully achieve its objectives by adhering to stringent design criteria. Advanced techniques for modelling and analysis were employed to minimise uncertainties on the effectiveness of the proposed treatment. Finally, commissioning results demonstrated compliance with designated standards, ensuring optimal sound quality. Moving forward, the intent of this work is to propose a standardized and structured procedure for the design of similar listening environments, facilitating the creation of immersive audio spaces that meet industry quality standards.

Conclusioni

In conclusione, lo scopo del progetto era quello di progettare un box ottimizzato acusticamente per sala regia e mixing per applicazioni in audio immersivo. Le diverse fasi del lavoro di progettazione sono state descritte, mostrando quanto si è reso necessario per garantire che il progetto raggiunga gli obiettivi posti aderendo a requisiti molto rigorosi. Tecniche avanzate di modellazione ed analisi sono state impiegate al fine di minimizzare l'incertezza sull'efficacia del trattamento proposto. Infine, i risultati del commissioning hanno dimostrato la conformità ai criteri di progettazione designati, garantendo una qualità sonora ottimale. L'intento di questo lavoro, dunque, è quello di proporre una procedura standardizzata e strutturata per la progettazione di questa tipologia di ambienti, facilitando la creazione di spazi audio immersivi che soddisfino gli standard di qualità del settore.

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References

[1] R.H. Bolt, Note on Normal Frequency Statistics for Rectangular Rooms, Journal of the Acoustical Society of America 18 (1946) 130-133. https://doi.org/10.1121/1.1916349.
[2] M.M. Louden, Dimension-ratios of rectangular rooms with good distribution of eigentones, Acustica 24 (1971) 101–104.
[3] O.J. Bonello, New Criterion for the Distribution of Normal Room Modes, Journal of Audio Engineering Society 29 (1981) 597-606. www..aes.org/e-lib/browse.cfm?elib=3889.
[4] T.J. Cox, P. D'Antonio, Room optimizer: A computer program to optimize the placement of listener, loudspeakers, acoustical surface treatment and room dimensions in critical listening rooms, 103rd Convention of the Audio Engineering Society (1997).
[5] T.J. Cox, P. D'Antonio, M.R. Avis, Room sizing and optimization at low frequencies, Journal of Audio Engineering Society 52 (2004) 640-651. www..aes.org/e-lib/browse.cfm?elib=13011.
[6] P. D'Antonio, R. Petrolli, J. Storyk, Non-cuboid iterative room optimizer, J Acoust Soc Am 148 (2020) 2798–2798. https://doi.org/10.1121/1.5147791.
[7] M. Cardoso Soares, E. Brandão Carneiro, R. Aizik Tenenbaum, P.H. Mareze, Low-frequency room acoustical simulation of a small room with BEM and complex-valued surface impedances, Applied Acoustics 188 (2022) 108570. https://doi.org/10.1016/j.apacoust.2021.108570.
[8] B.M. Fazenda, L.A. Elmer, M. Wankling, J.A. Hargreaves, J.M. Hirst, Subjective preference of modal control in listening rooms, 129th Audio Engineering Society Convention 2010 1 (2010) 496-507.
[9] S.E. Olive, P.L. Schuck, J.G. Ryan, S.L. Sally, M.E. Bonneville, The detection thresholds of resonances at low frequencies, Journal of the Audio Engineering Society 45 (1997) 116-128.
[10] M.R. Avis, B.M. Fazenda, W.J. Davies, Thresholds of detection for changes to the Q factor of low-frequency modes in listening environments, Journal of Audio Engineering Society 55 (2007) 611-622.
[11] B.M. Fazenda, M. Stephenson, A. Goldberg, Perceptual thresholds for the effects of room modes as a function of modal decay, J Acoust Soc Am 137 (2015) 1088-1098. https://doi.org/10.1121/1.4908217.
[12] L. Rizzi, F. Ascari, G. Ghelfi, M. Ferroni, Perception of Low Frequency Transient Acoustic Phenomena in Small Rooms for Music, in: Audio Engineering Society Convention 140, 2016. www..aes.org/e-lib/browse.cfm?elib=18211.
[13] L. Rizzi, G. Ghelfi, M. Santini, Small-Rooms Dedicated to Music: From Room Response Analysis to Acoustic Design, in: Audio Engineering Society Convention 140, 2016, Paris, 2016.
[14] Dolby Laboratories, Dolby Atmos Music Studios, (n.d.). https://professional.dolby.com/music/dolby-atmos-music-studios (accessed March 27, 2024).

[15] Dolby Laboratories, Dolby Atmos Home Entertainment Studio Technical Guidelines, (2021). https://professionalsupport.dolby.com/s/article/Dolby-Atmos-Home-Entertainment-Studio-Technical-Guidelines?language=en_US.

[16] Audio Engineering Society, Multichannel surround sound systems and operations, 2001. www..aes.org/technical/documents/AESTD1001.pdf (accessed April 27, 2024).

[17] Dolby Laboratories, Dolby Atmos Music Room Configuration, (2021). https://professionalsupport.dolby.com/s/article/Dolby-Atmos-Music-Studio-Best-Practices?language=en_US (accessed March 21, 2024).

[18] Dolby Laboratories, Dolby Atmos Room Design Tool Home Entertainment + Music (DARDT HE+Music), (2023).

[19] B.-I. Dalenbäck, CATT-Acoustic, (2022).

[20] P. Richard. Newell, Recording studio design, 3rd ed., Focal, 2012.

[21] Y. Miki, Acoustical properties of porous materials. Modifications of Delany-Bazley models., Journal of the Acoustical Society of Japan (E) 11 (1990) 19-24. https://doi.org/10.1250/ast.11.19.

[22] C.N.R.M.W. Scroggs J.S. Dokken, G.N. Wells, Construction of arbitrary order finite element degree-of-freedom maps on polygonal and polyhedral cell meshes, 2022.

[23] C. Geuzaine, J.-F. Remacle, Gmsh: A 3-D finite element mesh generator with built-in pre- and post-processing facilities, Int J Numer Methods Eng 79 (2009) 1309-1331. https://doi.org/10.1002/nme.2579.

[24] L. Kinsler, A. Frey, A. Coppens, J. Sanders, Fundamentals of acoustics, 4th ed., Wiley, New York, 2000.

[25] A. Prato, F. Casassa, P. Di Torino, A. Schiavi, A modal approach for reverberation time measurements in non-diffuse sound field, in: Proceedings of the 23rd International Congress on Sound & Vibration, Athens, 2016.

[26] M. Kleiner, J. Tichy, Acoustics of small rooms, CRC Press, Boca Raton, Florida, 2014.

[27] J. Mulcahy, Room Eq Wizard, (2024). www..roomeqwizard.com/index.html (accessed March 23, 2024).