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ANALYSIS OF ACOUSTIC AND ARCHITECTURAL ELEMENTS TO IMPROVE SOUND CONDITIONS AT AUDITORIUM400, DESIGNED BY JEAN NOUVEL FOR THE MUSEO NACIONAL CENTRO DE ARTE REINA SOFIA

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ABSTRACT.

The Auditorio400, located in the Museo Reina Sofía in Madrid, is the work of French architect Jean Nouvel, and it is dedicated to both, spoken word related events, and concerts of different musical styles.
This paper presents an acoustic analysis of the auditorium associated with the original geometry, and its specific acoustic material, observing the consequences that their design and construction features have in sound propagation: the inappropriate frequency distribution of the reverberation time, and its high value. The introduction of changes in some elements of the auditorium causes fundamental variations in acoustic parameters and their effects will be evaluated.

RESUMEN.

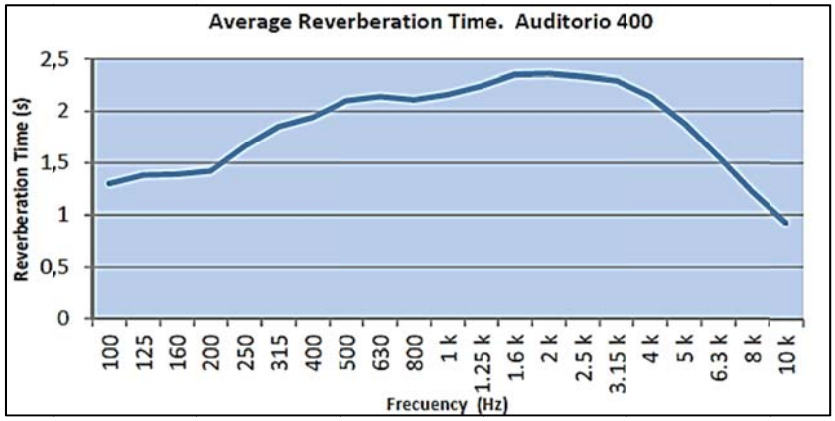
El Auditorio400, localizado en el Museo Reina Sofía de Madrid, es obra del arquitecto francés Jean Nouvel, se dedica tanto a actos relacionados con la palabra como a conciertos de diferentes estilos musicales.
Esta ponencia presenta un análisis acústico del auditorio asociado con su original geometría y materiales acústicos, estudiando las consecuencias que su diseño y construcción característica tienen en la propagación del sonido: la inapropiada distribución en frecuencia del tiempo de reverberación y su elevado valor. También será evaluada la introducción de cambios en algunos elementos del auditorio que pueden provocar modificaciones en sus parámetros acústicos.

1. INTRODUCTION.

The Auditorio 400 is a work of French architect Jean Nouvel, part of the buildings that make up the expansion of the National Museum Reina Sofia Art Center. This hall is dedicated to multipurpose activities, and it is devoted to events associated with both lecture, with voice as sound main signal and concert with music as sound source, the photographs of figure 1 reflects these aspects of the use of the auditorium.

Figure 1. Photographs with different activities in Auditorium 400 [1], [2], [3].

One of the most relevant characteristics of the sound condition of the room is its high reverberation time [4], especially given its multifunctional condition, and its inadequate frequency distribution [5], [6]. The graphic 1,[7], shows that the low frequency sound remains less time in the room that the midrange frequency, this entails a loss of musical warmth in a composition and a reduced intelligibility if the message is only spoken language. It is recommended that the graphical profile was as flat as possible with a slight boost in the lower part of the spectrum.



Graph 1. Average Reverberation Time as frequency function at Auditorio 400 [7].

This paper will propose a change in the absorbent conditions of the room, presenting the most significant tests carried out and showing the results provided by computer simulation, in order to choose the most suitable option when attempting to fit the acoustics of the room to its various uses.

First, it will present a series of changes to the materials that include the boundary surfaces of the enclosure, in order to modify the acoustic characteristics of the auditorium directly associated with the reverberation, like: the graph of the reverberation time as frequency function, the average reverberation time on site (RT), the reverberation time at medium frequencies (RTmid), the brightness (IBrightness) and the warmth (IWarmth).

In order to achieve the right results, for both speech and for music, the software EASE allows choosing the best option. The simulations give the values of different acoustic parameters, in this way; EASE supports and justifies the chosen solution, checking whether the values of the indices correspond to those recommended

2. ABSORTION CHANGES IN BOUNDARY SURFACES AT AUDITORIO 400.

One of the main problems associated with the acoustics of the Auditorio 400, as discussed above, is the high reverberation and inadequate frequency distribution. Below, it is presented a series of tests conducted with the simulation program EASE, [8] in which the original panels of the auditorium has been replaced by some others selected from the EASE database materials. Table 1 specifies: the characteristics of the material introduced, the graph of the absorption coefficient as a function of frequency and the representation in plan and elevation of the auditorium showing the position occupied by the new materials.

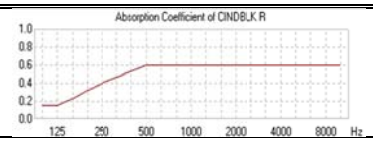
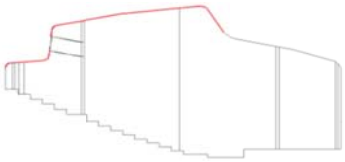
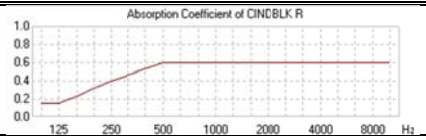
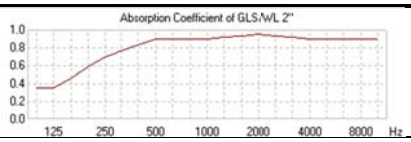
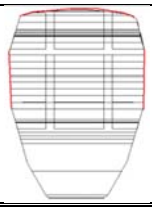
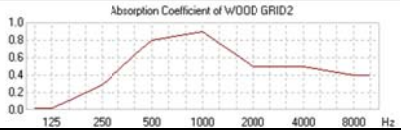
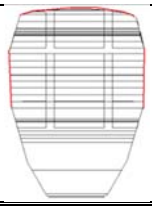
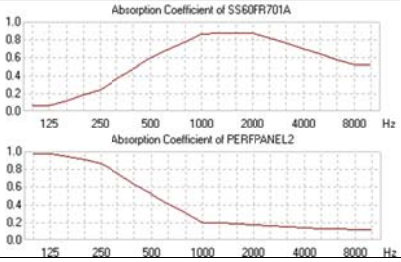
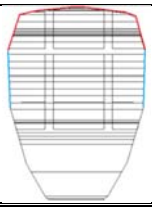
OPTION 1	Type of material	Absorbent material to mid and high frequencies: CINDBLKR. Area occupied with this material: 44,45%.	
	Disposal of materials		
OPTION 2	Type of material	Absorbent material to mid and high frequencies: CINDBLKR. Area occupied with this material: 8%.	
	Disposal of materials		
OPTION 3	Type of material	Highly absorbent material to mid and high frequencies: GLS/WL 2"(fiber glass) Area occupied with this material: 17,75%.	
	Disposal of materials		
OPTION 4	Type of material	Absorbent material to mid frequencies: WOOD GRID 2. Area occupied with this material: 10.7%.	
	Disposal of materials		
OPTION 5	Type of material	* Absorbent material to mid and high frequencies: SS60FR701A (fiber glass). Area occupied with this material: 13%. * Absorbent material to low frequencies: PERFPANEL2 (perforated panel). Area occupied with this material: 7.17%.	
	Disposal of materials		

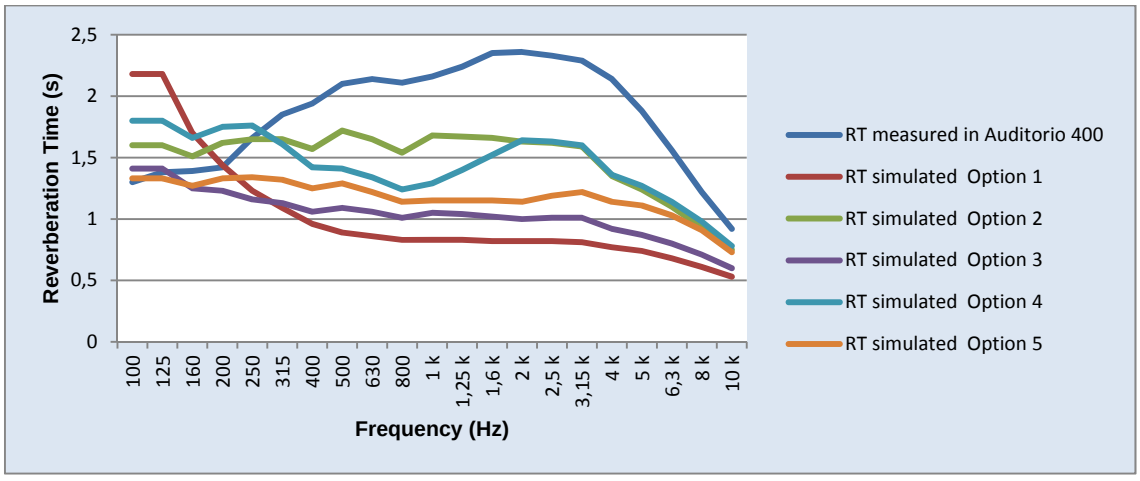
Table 1. Characteristics of the five options for sound absorption change in the Auditorio 400

The different options, indicated above, suggest some comments:

- In the first option, the replacement has been performed on the vertical panels of the audience area and part of the roof. The stage has not changed because the original material is highly reflective, which is ideal for the sound is radiated into the audience.
- In the second option, it has reduced the number of surfaces of replacement material, the surface covered with the new material is just located at the back of the auditorium, the reasons for that site are: first, minimize late reflections which can impair the acoustic quality of the room and second cut down sound pressure level in these areas due to the proximity of different reflective surfaces. The proposal number two can flatten the curve representing the reverberation time as a function of frequency. But the ratio between the values at low and medium frequencies will not be correct.
- The third option proposes a material with higher absorption coefficient in the central and high frequencies region in the audible spectrum. This option improves the ratio between the values at low and medium frequencies of the reverberation.
- The fourth option gives the room a little more liveliness, replacing part of the finishing material of the auditorium, in the vertical walls and ceiling, with another material whose highest absorption is mainly presented in the medium part of the spectrum. The reason for the choice of this material is because the midrange area of frequencies is the section of the audible spectrum which requires greater absorption due to the RT has the maximum value in this part of the spectrum. The faces occupied by this material are located in the back half of the room, combining absorbent and reflective surfaces for better sound distribution.
- The fifth option tries to find a compromised solution, so that although the site does not provide perfect results either for music or speech, this solution could be considered correct, and even "good" for both, improving the sound distribution and the relation D/R, direct sound vs. reverberated sound. In this option, it has been used two types of materials: absorbent material, as fiberglass or mineral wool, and absorbent panels drilled.

3. ANALYSIS OF THE ACOUSTIC PARAMETERS RELATED WITH THE REVERBERATION TIME IN FIVE OPTIONS REVIEWED

The analysis of the acoustic parameters, RT, RTmid, IBrigthess and IWarmth, are presented in a graph and a table in order to evaluate each trial in a clear and intuitive way.
Graph 2 shows the reverberation time as a function of frequency in the Auditorio 400 with the original materials in relations with the simulation obtained from the EASE program taking in consideration the changes in the five options cited above to improve the acoustic of the hall.



Graph 2. Average reverberation time as a function of frequency at Auditorio400, measured and simulated for the five options proposed.

Table 2 shows the values of the acoustic parameters directly associated with the absorption of the enclosure: The average reverberation time (RT), the reverberation time at medium frequencies (RTmid), index of brightness (IBrightness) and index of warmth (IWarmth):

		OPTION 1	OPTION 2	OPTION 3	OPTION 4	OPTION 5
Acoustic Parmeters	RT (s)	1,03	1,49	1,04	1,44	1,18
	RTmid (s)	0,86	1,70	1,07	1,35	1,22
	IBrightness	0,92	0,87	0,89	1,11	0,93
	IWarmth	1,98	0,95	1,20	1,31	1,09

Table 2. Acoustic parameters for the different improvement options.

Comments on this table and its relation to the recommended values for the parameters associated with the reverberation [9], [10], are indicated below:

- The first option, although it would be appropriated to speak signal in terms of RT, RTmid, and IBrightness, nevertheless it would not be adequate for the IWarmth, its value is too high. Another downside of this solution is the profile of the frequency distribution of the reverberation time, in low frequency suffering excessive boost causing move away significantly from the flat profile sought.
- The second option would be focused for musical performance, meeting the objectives for RT, IWarmth and IBrithness but it would not be correct for the RTmid. The frequency distribution of the reverberation time is rather homogenous and flat than in the first enhancement option, nevertheless it is not ideal because high values are obtained at the center frequencies which cause the data RTmid is above the desired.
- The third option would fulfill all the requirements for proper transmission of speech. The frequency distribution of the reverberation time is quite correct, the curve approaches largely the sought flat profile, presenting a slightly increase of RT at low frequency, but perhaps it can be highlight an excessive fall in high frequency. The problem with this result is that being a multipurpose hall for musical performances the room would be a little "dry" or "dead".
- The fourth option would be advisable in case that the site is devoted solely to music events. The frequency distribution of the values of the reverberation time has a profile quite correct but it would be advisable that the reinforcement suffering in time reverberation in bass areas was not as dramatic as the drop in treble areas.
- The option number five would be a compromise solution recommended for the Auditorio 400 as a multipurpose room. This option meets the objectives in terms of brightness and warmth. The average reverberation time and reverberation time at medium frequencies take intermediate values between the numbers recommended for speech and for music. In case it was required more reverberation for music signal, it could be increased with the use of electroacoustic reinforcement.

4. ANLYSIS OF ACOUSTIC PARAMETERS IN A PROPER SPEAKER SETUP FOR SPEECH AND MUSIC DERIVED FROM FIFTH OPTION.

The Auditorio 400 is a multipurpose hall and in addition to improve its acoustic quality in terms of absorbent materials, it was decided that the best option is the fifth one. To complete the acoustic design some electroacoustic reinforcement must be added depending on the action to be performed inside the auditorium: a concert, a lecture, a theater representation, a table round, etc. Previous studies from the authors, have defined two possible arrangements of sound sources suitable for speech and music. [11]

At this point, the paper will present some acoustic simulation using the program EASE performing studies for various acoustic indices: Sound pressure level, SPL, clarity of speech, C50, clarity of music, C80, index of speech intelligibility, STI, loudspeaker overlap with the

provisions of sources, for speech and music, considering that the finishing materials inside Auditorio 400 correspond to the improvement derived from the fifth option. Once the simulation is performed, it can may dictate whether the provision of materials and speaker proposals meet the objectives recommended by the specialized literature in this area, for uniform pressure level, correct values for the clarity of the speech [12], [13], for musical clarity [14], [15], [16], [17], for intelligibility index [18], [19], [20], [21] and a minimum overlap of speakers.

4.1. Speaker setup for speech:

Figure 2 shows the layout plan of the loudspeakers as well as the most significant parameters for evaluating the acoustics of a room:

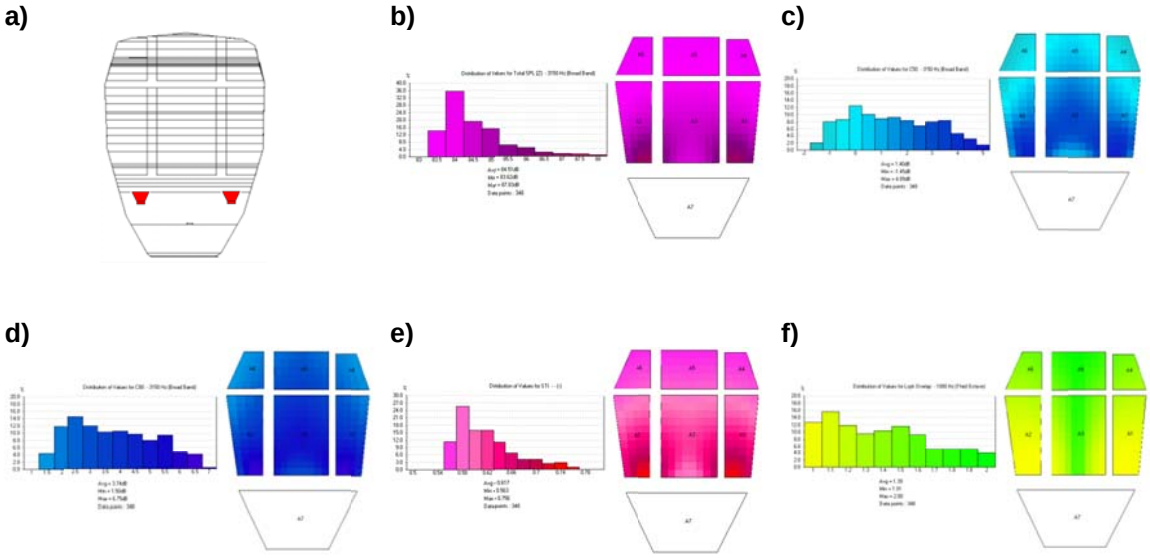


Figure 2. a) Speaker setup for speech. Layout and statistical values of the acoustic parameters: b) Sound pressure level, SPL, c) Clarity of speech, C50, d) Clarity of music, C80, e) Index of speech intelligibility, STI, f) Loudspeaker overlap.

Below, there are some considerations that make a number of remarks on the results obtained in different acoustic parameters, checking whether they meet the values that are recommended by the bibliography:

- The difference between the maximum and minimum values of pressure levels in dB, has increased from the values obtained with the original materials. The reason is the lower contribution of the reverberant field to the total level because the new finishing materials of the room are more absorbent.
- The clarity of the speech index, evaluated from C50, meets the objectives set at every point of the enclosure.
- Respect to music clarity, C80, it should be noted that the average value is within the recommended range. But analyzing the different zones, in the areas near sound sources, the values are too high, because the direct sound level is bigger than the reverberated one.
- The STI index is marked as conforming to the objective to achieve good speech intelligibility in nearly every part of the Auditorio 400.
- The speaker overlap is minimal due to the arrangement in plan and the orientation chosen for speaker setup.

4.2. Speaker setup for music:

The results obtained from a simulation for the different acoustic indices in a suitable speakers configuration for music performing are reflected in figure 3.

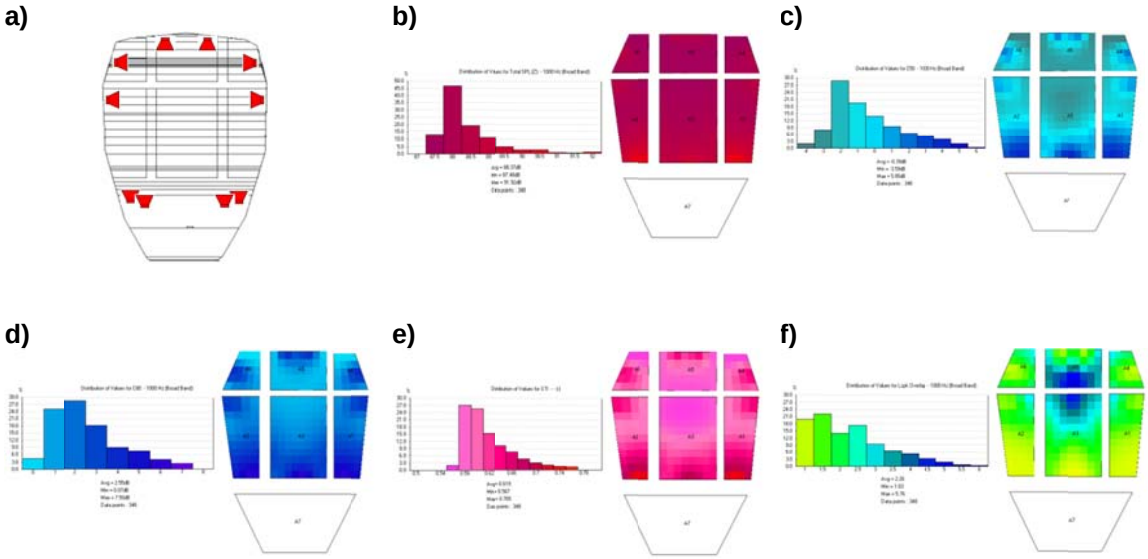


Figure 3. a) Speaker setup for music. Layout and statistical values of the acoustic parameters: b) Sound pressure level, SPL, c) Clarity of speech, C50, d) Clarity of music, C80, e) Index of speech intelligibility, STI, f) Loudspeaker overlap.

With the arrangement of speakers recommended for music, this paper can make the following comments about the results obtained from the simulation:

- The new distribution of materials shows an increase in the range of variation of the pressure level (in dB) at different points sampled over the original materials, the same happened in the case of the speaker arrangement for speech, the reason is due to the increase in the absorption of the enclosure.
- The C50 index values meet the recommended numbers in the vicinity of the sources but they are not adequate in the center of the room where this distribution of loudspeakers and room geometry prevent to achieve the objectives.
- The parameter C80, musical clarity, although it shows an improvement over the distribution obtained for speech, it has some values, near the sound sources that can exceed the values marked as objectives. In order to improve this parameter the room should be more reverberant, which could be obtained by electroacoustic reinforcement.
- The speech intelligibility, assessed with the STI, get very good data, with the new arrangement of speakers. This is an aspect to have into consideration in musical works with recited or sung text.
- The speaker overlap is increased because there are a greater number of activated sound sources, appearing a conflict zone in the first rows of central audience area on the second horizontal corridor.

5. CONCLUSIONS.

The analysis of the different options of change in some panels on the surface of Auditorio 400 which modify the absorption of the room, leads to the conclusion that some of them would optimize the behavior of the hall for voice and another ones will work better for music. But the difficulty in the auditorium acoustical design is to choose an option in accordance with its multifunctional activity; therefore the most suitable proposal would be the fifth option, using only changes of absorption.

Option number 5 provides a compromise solution on site for music and speech, but as described above is not perfect for any of the two applications. In consequence, if the Auditorio 400 must have a very good performance for multiple applications, it should be used architectural elements that allow to achievement variable acoustics in the room, something

which is working and studying at the present moment. Different solutions are being evaluated within the diverse possibilities offered by variable acoustic systems: curtains, movable panels, changes of the volume, etc. It would be chosen the system which would accommodate the Auditorio 400 for different activities taking in consideration the best option in terms of architectural, aesthetic and economic aspects.

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