VIII Congresso Ibero-americano de Acústica
1-3 outubro
Évora - Portugal
acústica 2012

STUDY AND ADEQUATION OF NOUVEL´S AUDITORIO 400 AT MUSEUM REINA SOFIA IN MADRID

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Abstract

This paper presents an acoustic study of the Auditorio 400, placed in the National Museum and Center of Art Reina Sofia, in Madrid, realized by the architect Jean Nouvel. This hall was thought for multiple uses and, in this moment, is used both for concerts of classical music, (contemporary and avant-garde music) and for lectures seminars and conferences.
In this study, two of the most relevant parameters in the world of acoustics architectural, SPL and time of reverberation have been analyzed. These measures allow us to value zones of acceptable listening, as well as they provide to us information about the troubled zones of the room. To solve these deficiencies the authors have chosen to adapt the sound reinforcement system of the hall existing in the room changing position, and quality of the system. This solution was chosen because the Auditorio 400 is an architectural work with special value that was designed by an architect of recognized reputation throughout the world, and its possible structural transformation is very complicated.

Keywords: Acoustics, Nouvel, Auditorio 400, RT, SPL.

PACS no. 43.55.Fw, 43.55.Gx

1 Introduction

The Auditorio 400 is a unique room located on the extension of the Reina Sofia Museum in Madrid. It is a creation of the well known French architect Jean Nouvel, Priztker Prize in 2008. It could be classified within the group of multi-purpose auditorium, sometimes it is used as a lecture hall and other times as a concert hall. This means that the acoustic requirements demanded of the room are different when the hall is used for voice or it is intended to music.

This document makes an assessment of the acoustics quality, in order to study the problems and to think about where and how the problems can be found, and, in this way, try to choose the best solutions. Among the magnitudes and most relevant rates to assess the sound quality of a room are the following: RT, SPL, C50, C80, STI, ALcons, ITD Gap, G, etc. The authors analyzed the room, and in a first approximation, the parameters that they studied, from measurements “in situ”, were RT and SPL.

Figure 1- Auditorio 400 Reina Sofía Museum Extension. Photography: José Luis Municio

2 Study / Analysis of reverberation time

The reverberation time is considered one of the most important factors in an acoustic studio. During the last decades of twentieth century, it was thought that the reverberation time was not critical to make an assessment of the sound quality of a hall. However, in recent years, the reverberation time has again become relevant and is considered one of the most important factors in acoustics room assessing [1].

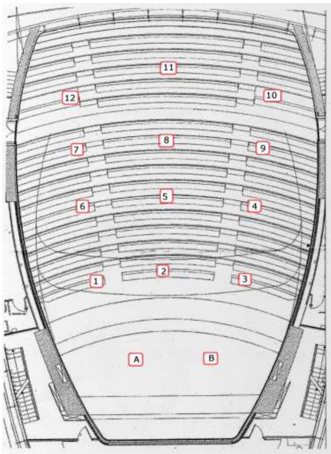

Figure 2 - Location of measurement points of the RT. Auditorium 400. Plant image courtesy LIEM

2.1 Results of measurements of reverberation time.

Measurements on site have been made according to ISO 3382-1/2009 [2]. The distribution and the choice of measurement points, Figure 2, were selected in accordance with this standard. Table 1 shows the results of these measurements.

Table 1 - Reverberation time in different measuring points and valued medium.

F(Hz)	RT (s) Pto.A	RT (s) Pto B	RT (s) Pto.1	RT (s) Pto.2	RT (s) Pto.3	RT (s) Pto.4	RT (s) Pto.5	RT (s) Pto.6	RT (s) Pto.7	RT (s) Pto.8	RT (s) Pto.9	RT (s) Pto.10	RT (s) Pto.11	RT (s) Pto.12	RTmedium (s)
100	1.33	1.05	1.35	1.48	1.31	1.39	0.70	1.17	1.18	1.35	1.33	1.82	1.38	1.62	1.30
125	1.33	1.07	1.52	1.64	1.59	1.31	1.76	1.26	1.82	1.55	1.50	1.18	1.44	1.25	1.38
160	1.19	1.13	1.58	1.17	1.35	1.19	1.20	1.63	1.23	1.34	1.63	1.40	1.33	1.53	1.39
200	1.29	1.36	1.39	1.29	1.50	1.59	1.59	1.50	1.52	1.86	1.49	1.69	1.49	1.37	1.42
250	1.88	1.71	1.76	1.95	1.46	1.66	1.87	2.01	2.07	1.64	1.79	2.06	1.77	2.09	1.66
315	1.91	1.83	2.02	2.12	1.98	1.63	1.78	1.76	2.06	1.81	1.69	2.03	1.89	1.61	1.85
400	1.89	1.89	2.02	2.22	2.11	1.80	2.26	2.01	1.98	2.19	2.01	2.04	1.97	1.87	1.94
500	2.14	2.19	2.11	2.03	2.12	2.02	2.11	2.38	2.37	2.09	2.25	2.20	2.28	2.25	2.10
630	2.05	1.97	1.93	2.05	2.03	2.16	2.08	2.30	2.12	2.04	2.25	2.01	2.20	2.15	2.14
800	2.14	2.20	2.20	2.33	2.16	2.13	2.18	1.99	1.98	2.14	2.18	2.05	2.21	1.96	2.11
1 k	2.07	2.20	2.27	2.12	2.18	2.15	2.25	2.46	2.26	2.11	2.13	1.96	2.25	2.22	2.16
1.25 k	2.17	2.28	2.29	2.30	2.30	2.36	2.31	2.34	2.26	2.31	2.32	2.36	2.39	2.28	2.24
1.6 k	2.40	2.37	2.45	2.42	2.44	2.40	2.47	2.44	2.31	2.37	2.34	2.42	2.21	2.43	2.35
2 k	2.24	2.30	2.32	2.28	2.34	2.30	2.48	2.36	2.32	2.40	2.28	2.30	2.38	2.32	2.36
2.5 k	2.25	2.24	2.35	2.35	2.37	2.29	2.29	2.33	2.39	2.39	2.32	2.37	2.41	2.32	2.33
3.15 k	2.21	2.27	2.29	2.24	2.22	2.24	2.30	2.25	2.22	2.19	2.25	2.27	2.21	2.26	2.29
4 k	1.97	2.07	2.08	2.03	2.02	2.02	2.06	2.03	1.99	2.03	2.01	2.00	2.13	2.11	2.14
5 k	1.70	1.73	1.71	1.73	1.78	1.71	1.75	1.68	1.70	1.77	1.76	1.66	1.74	1.75	1.88
6.3 k	1.40	1.38	1.40	1.37	1.42	1.43	1.41	1.47	1.38	1.37	1.39	1.42	1.39	1.34	1.56
8 k	1.04	1.02	1.05	1.09	1.10	1.05	1.10	1.07	1.06	1.05	1.10	1.00	1.02	1.04	1.22
10 k	0.79	0.77	0.78	0.80	0.83	0.81	0.81	0.78	0.80	0.80	0.81	0.78	0.75	0.77	0.92

The table 1 shows, for each position, different colours to assess intuitively the margins of variation of the reverberation time

RT≥ 2s pink 1.5 s ≤ RT ≤ 2s blue 1s ≤ RT <1.5s green RT < 1s orange

The color consistency and chromatic uniformity to the different frequencies can assert that the reverberation time values at different points have great similarity. In consequence, it is fairly consistent, to work with the average of the reverberation time like a function of frequency. This average includes all points of measurement. Figure 3 shows such a representation, which displays a significant enhancement in the RT at midrange area. The mean of all frequencies gives the RT at Auditorio 400. This value is: RT = 1.84 s. This data is necessary to compare the compound under study with others similar in size and application.

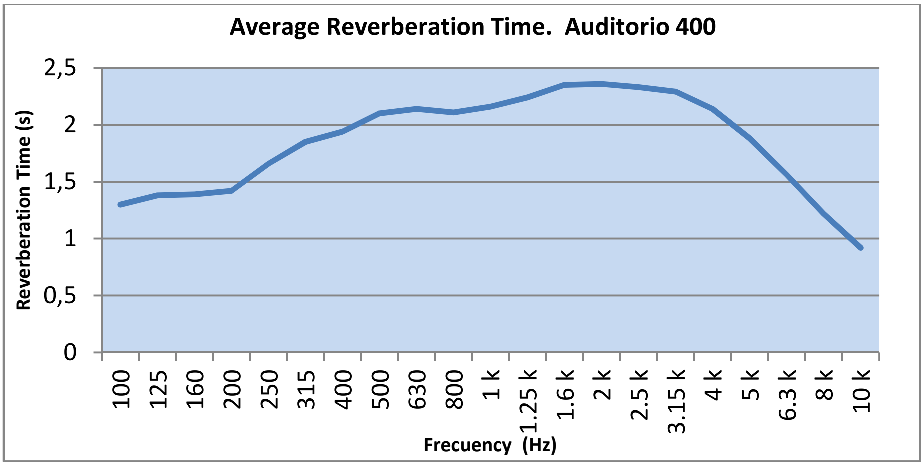

Figure 3-Average reverberation time as a function of frequency

2.2 Evaluation of the reverberation time.

The reverberation time in the Auditorio 400 is quite high compared to other concert halls with great prestige in the world of classical music, according to the studies realised by Shiokawa, H. and Rindel, J.H. [3]. Its order of magnitude is similar to these halls, but the volume of Auditorio 400(4000m3) is significantly lower. Therefore, with these measurements, the first conclusion reached is that the reverberation of the room is slightly higher for certain types of music (especially for chamber music and electroacoustic music), and significantly higher for the use of voice.

Regarding the frequency profile of the reverberation time, it must be comment that does not follow the usual chart form of RT vs. frequency at recognized concert halls [4], [6]. It is advisable that the related graphic at Auditorio 400 would be as flat as possible with a slight bass boost. This curve leads to that the parameters associated with the reverberation time as a function of frequency do not meet the recommended values. These indexes are: reverberation time at medium frequencies (Tmid.), Brightness (IBrightness) and Warmth (IWarmth).

The reverberation time at medium frequencies in the Auditorio 400 reaches the value, Tmid = 2.13 s.

If we take as a model the criteria established by Arau, H. based on usage and size of the enclosure [6], this number is significantly high and the room would be too “alive” for the audience. Arau, H. proposes that if the main use is for music, Tmid should be in the range 1.5s to 1.8s and between 0.84s and 1. 29s if the use is for voice.

Brightness gives an insight into the behavior of the room at high frequency. It is associated with clarity and harmonic richness and depends directly on the relationship between the amount of reverberation time at high frequency (2 and 4 kHz) and midrange (500Hz and 1 kHz). In the auditorium studio reaches a value of IBrightness = 1.05. The collected data meets the specifications given by different authors [4] [6], because it is higher than 0.8. It is recommended that this parameter would be as high as possible. Nevertheless, it is rare that it reach the value of 1 and even that it surpasses these values due to the air absorption becomes considerably significant in the upper audio spectrum area. In Auditorio 400, IBrightness exceeds the limit set by the value 1 due to “singular” evolution of reverberation time with frequency. Like it was explained before and it is reflected in Figure 3, RT displays high values in the frequency range from 2 to 4 kHz. In consequence, this leads that IBrightness reaches a value that is hardly matched by other auditoriums.

Warmth is related to the behaviour of the room in bass frequencies. It is said that a room has “acoustic warmth” if it has good response in the lower audio spectrum. The bass sound has an energy that provides greater depth and strength to the music. The numerical value of the warmth is obtained as the ratio between the sum of the reverberation time for frequencies of 125Hz and 250Hz and the sum of the reverberation time at 500Hz and 1 kHz. The recommended value is usually about 1.2 [6]. In the Auditorio 400 the information that reaches this parameter is: IWarmth = 0.71. The number is significantly lower than the advisable, and in consequence, the bass response in the room is not recommended.

3 Study / Analysis of pressure levels.

The sound pressure level is an objective measure. It parts of a clearly defined physical quantity, making it one of the parameters that may reflect more closely what happens from the standpoint of sound in the Auditorio 400. Studies carried out by Ando, Y. [7] and Fujii, K. [8] confirm this opinion. The mentioned authors have made the acoustic study of prestigious concert halls focusing their analysis on the spatial distribution of pressure levels on the wards.

In order to analyze the behavior of the room, the results obtained will be present with two different configurations of speakers: the first one with only sound sources on stage and the second one with sound sources around the perimeter of the audience, this configuration is known as “crown”. In both cases, the source signal used is pink noise, to analysis the influence of the room at different frequencies.

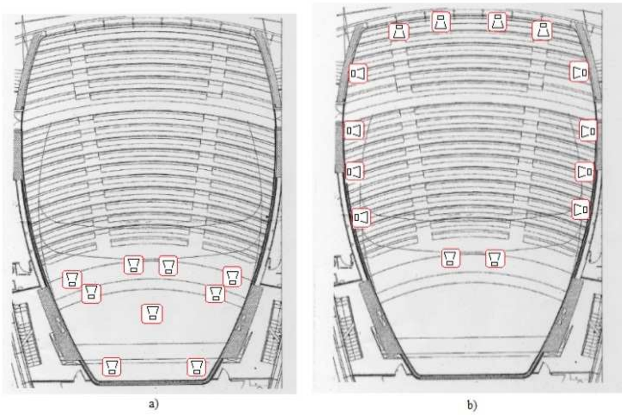

Figure 4 - Location of the speakers at the two measurement situations.
a) Sources on stage. b) Sound sources around the audience.

3.1 Sources sound on stage.

In this situation, the sources activated were located only on stage, trying to simulate the conditions of issue / radiation from a live orchestra.

3.1.1 Results of measurements of the pressure of sound sources on stage.

The Figure 4 shows how the pressure level in the Auditorio 400 is falling with increasing frequency

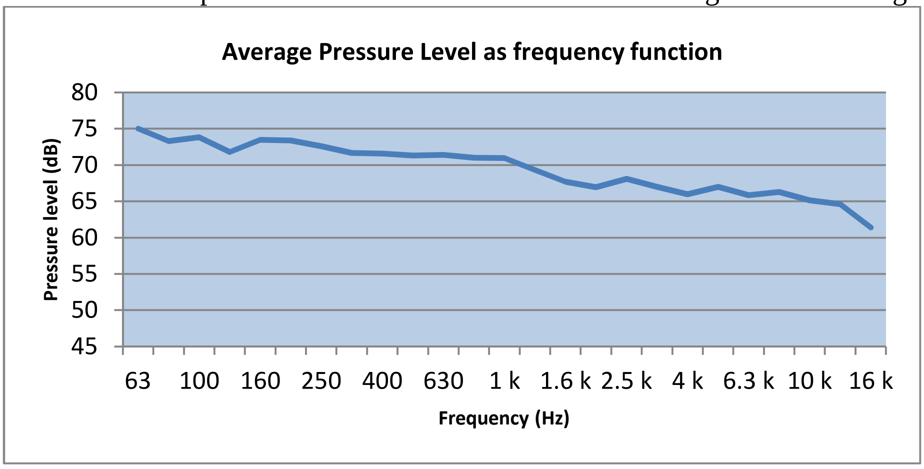

Figure 4- SPL as frequency function with sound sources only at the stage

A more exhaustive analysis is presented in Figure 5. It shows the distribution of pressure levels in different parts of the auditorium, through a plan representation of the pressure level across the entire band and the most significant one-third octave for both, voice and music. In order to have a better valuation for each area in the hall, it has been assigned a colour to the different dB thresholds.
The one-third octave selected was chosen with the following criteria:

- 100Hz: Fundamental frequency of the male voice
- 200Hz: Fundamental frequency of the female voice.
- 400Hz: Frequency key for musical reference (diapason).

- 1000Hz: Frequency key to the room acoustics (test tone).
- 3150Hz: Frequency key to evaluating the "musical presence".
- 10000 Hz: Frequency where we find lots of harmonics.

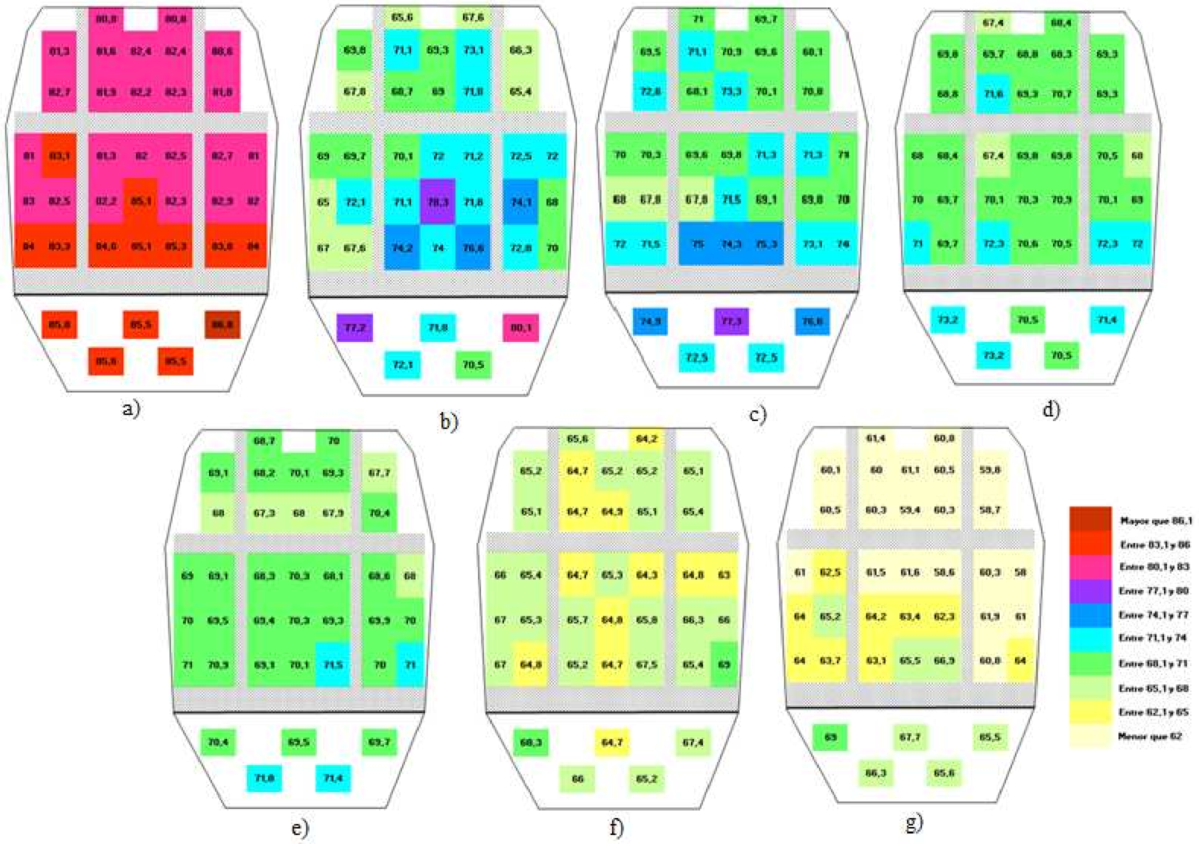

Figure 5 - Distribution plant pressure levels in dB in the Auditorium 400 in the whole band and in the one-third octave more significant: a) the entire band, b) 100Hz c) 200Hz d) 400Hz, and) 1kHz, f) 3.13 kHz, g) 10kHz when the sources are located only on the stage.

3.1.2 Evaluation of the pressure level of sound sources on stage

The figure 4 displays the curve of the average pressure level versus frequency. It shows a fall fairly uniform. The reasons for this result can be found in the presence of subwoofer loudspeakers, which reinforce the signal at the low end, the absorption of elements of the room, although it is not very high and air absorption mainly located in middle and high frequencies.

The figure 5 presents colour representation of sound pressure level at different frequencies. About this display, it can be made the following comments:

- The highest levels in the audience are in the front rows and in the central area. This is logical because they are the closest to the stage and the direction of maximum radiation from the speakers is focused toward the centre of Auditorium 400. The lowest level is 80.8 dB in the last row and the highest in the first row 85.3 dB. The difference is 4.5 dB, meaning a clearly noticeable difference. This difference reaches to a concept that in statistics is called JND (Just Noticeable Difference) [9]. The variation of the values of pressure levels is higher in the row direction than from the center towards walls.

- The pressure level on stage is higher than the rest of the room because all the sound sources are located there. The distribution is fairly uniform. The difference between the maximum and the minimum is only 1.3 dB.
- At a frequency of 100Hz, there are SPL significantly high on the stage. The reason is that these measurements were made close to the subwoofers.
- The sound pressure at different areas in the hall presents a greater irregularity at 100Hz and 200Hz than in high frequencies. The reason is that the smaller the frequency is the higher the influence of the maximum and the minimum of pressure because of the geometry and dimensions of the auditorium.
- The consistency of the SPL levels at midrange is due to the speakers, in this frequency region, have a fairly flat frequency response and high sensitivity settings.
- The values of the pressure levels at 10kHz are lower than the SPL of frequencies discussed above. The reasons may be due to the radiation efficiency of the speakers is lower in this frequencies range, the maximum radiation beam is reduced, the sound sources are more directive and local absorption is higher.

3.2 Sources surround sound to the audience.

In this case, the sources were located around public with the aim of evaluating the effect of electro-acoustic sound reinforcement system.

3.2.1 Results of Pressure Measurements of the sound sources surrounding the audience

As in the previously analyzed speaker arrangement it will be presented the results obtained for the average pressure level versus frequency, Figure 6, as well as its study in frequency.

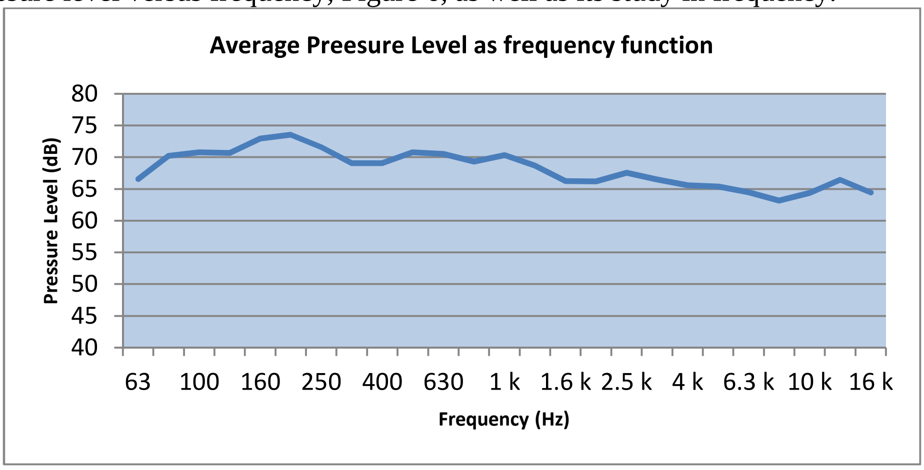

Figure 6 - Pressure Levels Depending on the frequency of sound sources surrounding the audience area

The figure 7 displays the study in frequency. It gives special attention to the degree of homogeneity in the level of pressure throughout the audience area. This representation assigns a color to decibel margin. The degree of color uniformity indicates the degree of uniformity of the pressure level.

Figure 7 - Distribution plant pressure levels in dB in the Auditorium 400 in the whole band and in the one-third octave more significant: a) the entire band, b) 100Hz c) 200Hz d) 400Hz, and) 1kHz, f) 3.15 kHz, g) 10kHz when the sources are located around the audience area.

3.2.2 Evaluation of the pressure level of sound sources surrounding the audience.

The evolution of the pressure level with frequency, Figure 6, shows that the profile of the chart is more irregular than in the case of the sound sources in the stage, and it does not occur a falling graphic so uniform as in the previous case. Nevertheless the overall appearance of the graph is a fall of SPL in the high frequency area. The representation of higher sound pressure level does not correspond to the lower frequencies. The reason may be the absence of subwoofers. The graphic shows an answer more irregular, because of the arrangement of speakers facing one to one, and this disposition may cause constructive and destructive interference arising in reinforcements and attenuation of the signal emitted by the sound sources.

The figure 7 displays a plan representation of pressure levels, from which it could be said:

- In this situation, no measurement was performed in the stage area, and no data was collected.
- The layout of the pressure levels throughout the audible band expressed in dB, shows the highest value in the vicinity of the speakers, especially in the last rows of the Auditorio 400, where sound sources are very close to the public and the roof is significantly lower than in the rest of the room, which implies greater contribution of the reflected sound.
- The analysis at low frequencies shows a greater disparity in colors than the previous configuration. The reason is the speakers facing one to one.
- In the ones-third octave centered 1 kHz and 3.15 kHz, speakers radiation is more evenly than in the remaining frequencies, therefore pressure levels are more homogeneous.

- In the last one-third octave analysis, 10 kHz, it is noteworthy in the central area of auditorium, the level is lower than in others places of the hall. The reason is the speakers power at high frequency is lower than the power al medium and low frequencies.

4 Adequation of the Auditorio 400

The task to improve acoustic characteristics at the Auditorium 400 is especially complex for several reasons. **First**, it is a multipurpose hall, and it can be impossible to find a solution for both, intelligibility of voice and music perception. **Second**, the auditorium has a volume of 4000 m^3 and a capacity of 400 persons. These properties make that the hall is very big for speech lectures, and a little small for symphonic music. The size of the auditorium indicates an ideal use as chamber music recital hall, but in this case the reverberation time has a high value. **Third**, the design of the space is based on big flat surfaces and that mean a big problem in order to an adequate dispersion of the sound, and **fourth**, we need to make mention that the auditorium is an emblematic building in Madrid. It was designed by an important architect, Jean Nouvel. Any change in the building would be specially complicated and very limited.

The plan to change the characteristics of the auditorium was established as: **a)** choose the adequate values recommended for several acoustic parameters, **b)** establish the different available options that we use to improve acoustics characteristics in the hall: Electroacoustic, absorption, and variable acoustic, **c)** select the most valuable option.

In this paper, we speak only about the electroacoustic solution. This option is the best option under two aspects: economic and esthetic, although it must be said that there are several parameters that cannot be improved with only the modifications of speakers settings in the hall. For example the reverberation time cannot be reduced with the introduction and localization of speakers inside the auditorium.

The fundaments of electroacoustic solution are based on the work with speakers. This work implies the change of some characteristic: type, position, elevation, phase and delay, level of excitation, etc.

It would be necessary to realized several changes from the original disposition of the speakers. These changes are based on several rules that we believe are basic for the adaptation of the hall

- The sound beam or beams should be limited to the area occupied by the audience. This situation reduces the number of speakers to be installed, allowing higher-level radiation and reducing sound reflections at the boundary of the site.
- It is necessary to avoid large differences in sound level at the listening area, differences above 6dB among various points of reception are considered inadmissible.
- The speakers must maintain a constant distance between them. This reduces the sound level differences from one area to another.
- It must be avoid, as far as possible, that the sound beams of different speakers are overlapped. This situation increases the clarity of spoken messages.

Keeping these principles of design, there have been made a series of tests to know the most suitable speaker configuration depending on the use of the Auditorio400.

Figure 8 illustrates the location of sound sources for each proposal:

1) Two unique speakers on stage (1 and 2) arranged symmetrically about the axis of the enclosure.
2) Two speakers on stage (1 and 2) plus two speakers in the center of the stage (3 and 4).
3) Four speakers on stage (1, 2, 3 and 4), plus four speakers in the back of the auditorium, which are part of “the crown” (5, 6, 7 and 8).
4) Four speakers on stage (1, 2, 3 and 4), four speakers in the back of the auditorium (5, 6, 7 and 8), and another speaker suspended in front of the roof toward the center of audience area (9).

5) Four speakers on stage (1, 2, 3 and 4), four speakers in the back of the auditorium (5, 6, 7 and 8), plus two speakers suspended in the center of the ceiling directed towards the center and back of the room (10 and 11).
6) Introduction of two subwoofer speakers on stage next to the walls (12 and 13).

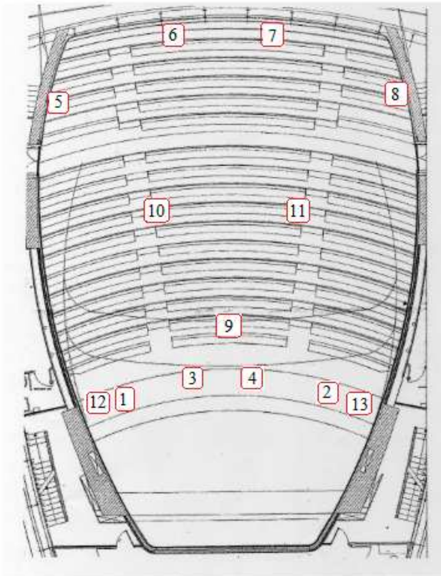

Figure 9 - Layout of the speakers during testing to make electroacoustic improvements.

The tests show that there are some configurations recommended for the transmission of voice and others for music production. In addition, in the case of music, there are different solutions according to the type of music. As illustration, we can say that in the case of the voice the first proposal is the best. Because reducing the number of speakers at minimum decreases the overlap and increases the clarity of the voice (C50). In contraposition, the difference in levels between the front rows of audience and the last one will be more evident than in the third option. For music, it should be used option 4 or 5. More sound sources increase C80 (musical clarity), and provide more effects and richness in musical interpretation. The inclusion of the subwoofer does not change very significantly the acoustic quality of the room. This subwoofer speaker increases the pressure level in the lower spectrum which is highly valuable in some musical compositions. For voice, working with few sound sources, including subwoofer, improves the clarity of the voice (C50) at 100Hz. While the introduction of subwoofers, what means more speakers, implies that C50 becomes worth in the analysis the whole frequency band. Therefore, if the improved treatment of Auditorio 400 is only electroacoustic, to get a good sound depends on the different compositions performed or reproduced. The sound engineer and the interpreter must decide, in each case, which is or are the most recommended options based on the effects that they want to achieve.

5 Conclusions

The Auditorium 400 is an enclosure that presents many difficulties to achieve good acoustics, because of its versatility. According to the results obtained in the reverberation time, it can be said that the Auditorio 400 has associated some problems with this parameter. On the one hand, the high value is a challenge for both, music and speech, especially for the last one. On the other hand, the reverberation

times at medium frequencies presents high values. This causes the “warmth” of the room is poor and the “brightness “unusually high.
From the results obtained in the pressure level in the room for the two situations analyzed, can be said that in the Auditorio 400 due to a number of factors related to its architecture and the arrangement of speakers can presents problems in achieving a homogeneous distribution of the pressure level: **a)** the whole room is made with the same material that is highly reflective on smooth surfaces, this can cause the sound diffusion is not sufficient to achieve diffuse sound field conditions, **b)** the concave surfaces of the roof is likely to give rise to concentrations of the sound rays, **c)** the parallelism of some surfaces of the enclosure and the speaker layout could cause waves that result in modes of vibration producing maximum and minimum pressure that can distort the interpretation or reproduction of the work, **d)** the low ceiling of the back of the room causes large number of reflections that increases the level of pressure in that area
Moreover, look at possible improvements is complicated, as said before, by two aspects, the economic and the aesthetic. Accordingly, the electroacoustic solution is the best one from the point of view of these two aspects, but it is not so good from the acoustic quality criteria. The electroacoustic processing allows slight improvements but not substantial ones. In order to get a valuable acoustics at Auditorio 400 it must be addressed the option of acoustic variable. This will make the hall fits the conditions required for the type of message reproduced or interpreted, word, music or both.
Finally, it must be observed that this work will be supplemented with new studies and the incorporation of new aspects and criteria: analysis of other parameters, simulation of the current situation of the site, comparison with measures “in situ”, simulations proposals for improvements, etc. Some of these new proposals have been already implemented or are being carried out.
This new studies will be presented at future lectures or new articles.

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