ACOUSTICAL REHABILITATION PROJECT OF THE SANTA MARÍA DE LA MOTA CHURCH, IN MONTORO (CÓRDOBA)

43.55.GX

Suárez, R.; Sendra, J.J.; Navarro, J.
Instituto Universitario de Ciencias de la Construcción (I.U.C.C.) Universidad de Sevilla
Escuela Técnica Superior de Arquitectura. Av. Reina Mercedes, 2. 41012 Sevilla. Spain.
Tel. +34 95 4556595. Fax +34 95 4557024. jsendra@us.es

ABSTRACT

The current importance of cultural heritage is traduced in recuperation programs of historic heritage. One of these working lines is the rehabilitation of churches for their conditioning for cultural uses. Intervention on ecclesiastic spaces should respond to acoustic conditioning.

The aim of this work is to study the acoustic conditions of the Santa María de la Mota Church, in Montoro (Cordoba), starting from values measured in situ and by means of computer simulation. This church, from the XIIIth century, was restored and adapted for cultural uses, but presents acoustic disfunctions. Therefore, architectural solutions to obtain a correct acoustical rehabilitation have been proposed, both for theatral and musical uses.

INTRODUCTION

After the Christian conquest of Andalusia, the first Christian art arises as an improvised architecture, in which both Muslim and Christian elements exist side by side, being these churches an adequate place for that time's liturgy, sacred singing and the teaching of the Christian religion[1]. The Santa María de la Mota Church, built around mid XIIIth century, has a rectangular ground plan following the Mozarabic tradition, with three naves separated by pointed archs, and an apse which was later added and worked as a *side-chapel*. In 1982 it was restored to adapt it to cultural uses. Since then the church combines cultural activities (choral concerts, quartets, conferences, etc.) and being an archeological museum.

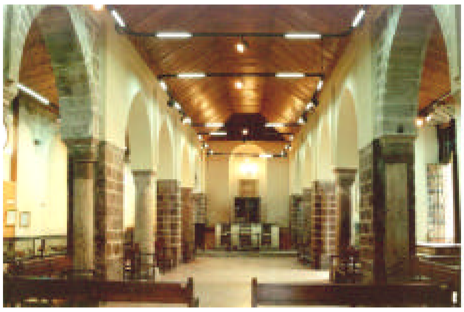


Fig. 1. Church interior after restoration

ACOUSTIC ANALYSYS OF THE CURRENT CONDITIONS

The acoustic measurement was made with the audience area without any kind of furniture. Eight measurement spots were taken, four in the central nave and four in the side aisles, 1.20 m above ground level. The sound source was placed at the end of the main nave's gap, 1.50 m above ground level.

Reverberation time

Denotations were made to record the impulsive response in the source spot, obtaining reverberation time values in the different spots within octave bands. With the help of a computer model, with the CATT-Acoustic program (version 7.2f), a theoretic prediction of the church's reverberation time values was made with spectators sat in the central nave. These values were compared with the optimum theoretic values, both for speech and music, as proposed by Beranek[2].

The reverberation time obtained in the measurement reflects a relevant sound absorption for low frequencies, due to the church's suspended wood ceiling. This suspended ceiling works like an absorbent element of the "membrane" type. For the hypothesis of having the central nave occupied with spectators sitting on chairs, the tonal curve comes closer to the optimum tonal curve for religious music (fig. 4), being high for speech.

Sound distribution

The study of sound distribution was made starting from the sound emission of an omnidirectional sound source. The sound power level was 105 dB. The distribution of the sound level throughout the church is uniform, being relevant the first reflections from side walls and from the wood ceiling[3].

To analyse the sound diffusion degree in the church, the measured sound levels have been shown in accordance to the reference level, with regard to distance, and have been compared with the expected values given by the classical model and Barron's model (fig. 2). The measured sound levels fit into those expected by Barron's model, except for the nearest spots and for the spot at the bottom of the church, in which sound levels fit into those expected the classical model. This is due to the sound concentration given in those areas because of the increase of reflections. The small size of the church, together with low absorption surfaces, favors an homogenous reverberated field, with scarce variation of the sound level, both in the central nave and in the side aisles.

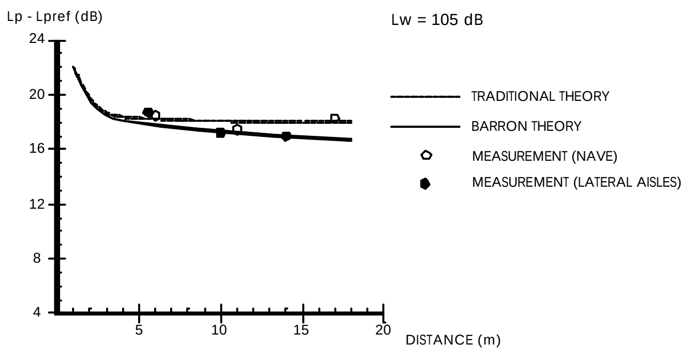


Fig. 2. Performance of the acoustic field of the empty church with regard to distance (measurement). Wide band

Intelligibility

The RASTI values of the measurement, for the different spots, are shown in figure 6, with regard to the distance of each spot to the source. These values (average value: 0.48) allow to qualify the intelligibility of the central nave as "fair", but the values diminish for the spots in the side aisles[4]. The intelligibility of the church with spectators is valuated by means of computer simulation, obtaining a tangible improvement of the RASTI values, keeping the qualification of “fair” (average value: 0.53). The intelligibility offers adequate values for music playing, but shows to be insufficient for speech due to excessive reverberation.

Background noise

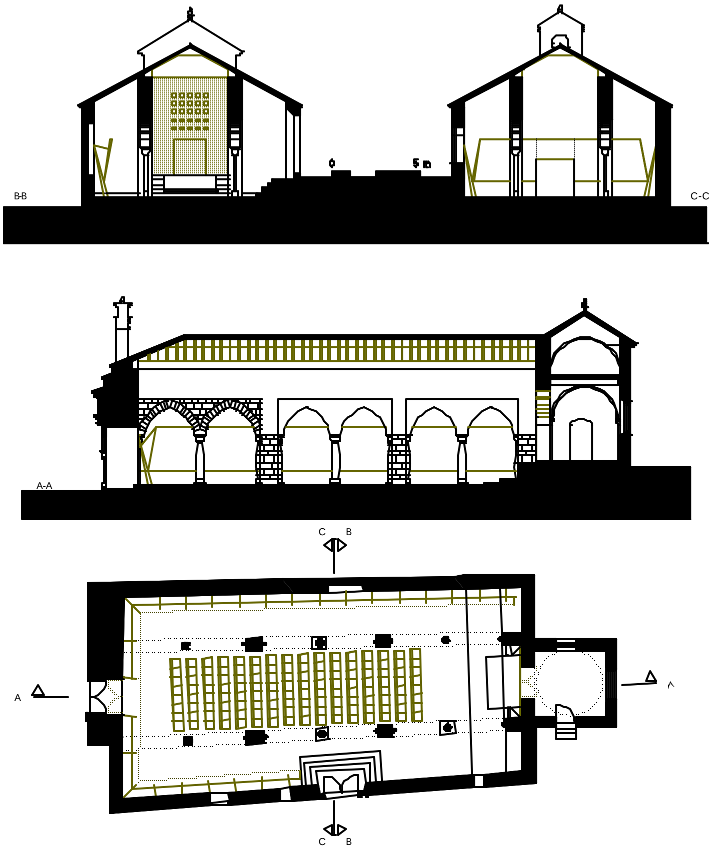
The measurement of background noise level taken in the bottom of the church shows an equivalent continuous sound level L_{eq} = 38.3 dBA. To rate the noise within the church, the spectrum measured and the NR curves have been compared. It has been obtained a NR value of 35, which is within the recommended margin between 25 and 35.

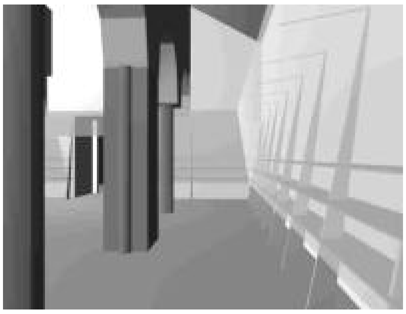
Starting from this data, it is concluded that the acoustic conditions of the church can be considered as acceptable for music but inadequate for speech, mainly due to the lack of sound absorption.

INTERVENTION PROPOSAL

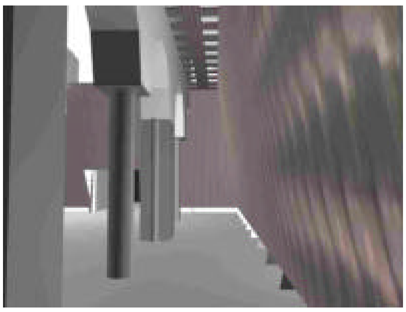
The church currently has a permanent use as archeological museum, as well as a use for cultural activities, like conferences and concerts. This versatility of use makes it necessary to modify the absorption characteristics of interior faces of the church’s walls. The aim is to increase sound absorption in order to decrease reverberation times and increase intelligibility (when the required use is speech) and to modify the tonal curve for musical use, therefore searching an adequate tonal balance, mainly for high frequencies.

The tonal balance needed for musical activities may be achieved by decreasing sound absorption for high frequencies (something difficult to be obtained because absorption mainly is attained from spectators sitting on chairs and from the suspended wood ceiling), or by means of increasing the volume of the church and adequately increasing absorption for mid and low frequencies.





Musical configuration



Theater configuration

Fig. 3. Intervention proposal

It is proposed to recuperate the church's primitive interior volume[5], increasing the roof's height, using timber roof trusses to cover the naves. This operation wil increase the absorption sound at mid and low frequencies while the reverberation time values will decrease for high frequencies.

In the area that separates the side-chapel a wood perforated multi-paneled resonator is planned, assuming the idea of the altar-piece rounding off the church. This closing device consists of a membrane type resonator, a set of 12 mm thick perforated panels with 5 mm diameter perforations summing up 20% of the panel surface and with 20 mm air space stuffed with mineral fiber.

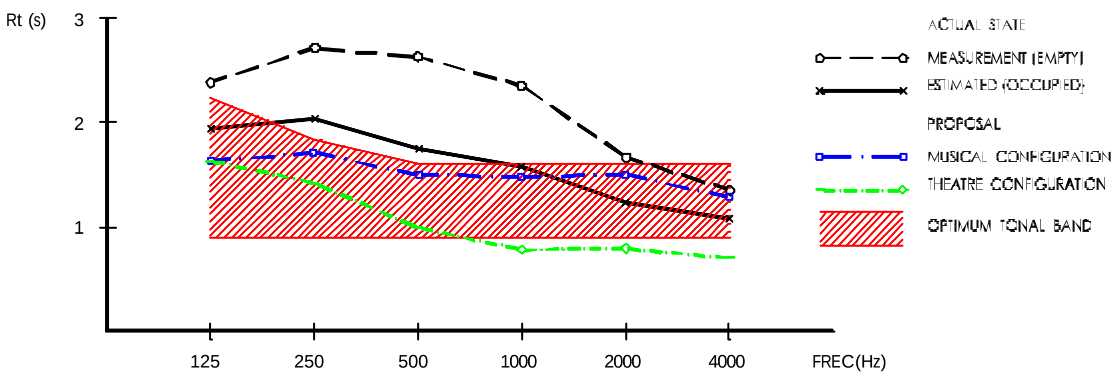
To display the pieces shown in the museum, it is proposed to substitute the present glass cases, in side aisles, for metal shelves protected with oblique glass panels that would favor side reflections therefore increasing sound diffusion in the church since they are vibrating surfaces. Besides, glass panels perform like an elastic material with sound absorption of low frequencies, while for frequencies in which there is almost no absorption, the vibration of panels would have a diffussing effect.

In order to increase sound absorption, needed for activities of the church related with speech (theater configuration), it is proposed a solution that consists of incorporating a porous material with air space by means of a curtain system in side aisles. This system is 14 cm parallel to glass panels, with white furrowed (up to 180%) fabric that goes up to the wooden roof and hides the exhibition panels.

Reverberation time

The increase of the church's space volume compared to its present condition is compensated for the musical configuration. The sound absorption increase due to both the Mudejar wood roof and the membrane resonator (as an altar-piece) implies a decrease of reverberation time. The reverberation times are similar to the optimum values for music, except for low frequencies, due to roof and glass absorption (fig. 4).

The increase of sound absorption made to adapt this space suitable for speech is obtained by means of incorporating furrowed fabric curtains, with which a specially relevant sound absorption is achieved for mid and high frequencies. The resulting tonal curve for the theater configuration is adapted to the optimum tonal curve for speech with regard to mid and high frequencies, being high for low frequencies[6].



	125 Hz	***250 Hz***	***500 Hz***	***1000 Hz***	***2000 Hz***	***4000 Hz***
Empty. Measurement	*2.37*	*2.71*	*2.63*	*2.35*	*1.67*	*1.35*
Occupied. Estimated	*1.94*	*2.04*	*1.74*	*1.57*	*1.24*	*1.08*
Musical configuration. Occupied	*1.63*	*1.71*	*1.50*	*1.48*	*1.50*	*1.28*
Theater configuration. Occupied	*1.63*	*1.42*	*0.99*	*0.78*	*0.79*	*0.70*
Music optimum	*2.24*	*1.84*	*1.60*	*1.60*	*1.60*	*1.60*
Speech optimum	*0.89*	*0.89*	*0.89*	*0.89*	*0.89*	*0.89*

Fig. 4. Estimated, proposed and optimum reverberation times. Spectators sitting on chairs

Sound distribution

Sound pressure *values* levels, obtained for the musical configuration and with regard to distance to the sound source, are slightly inferiors to the values obtained by means of simulation of the current situation with spectators (fig. 5). On the contrary, for the theater configuration, the increase of sound absorption leads to a decrease of the sound pressure level, with a reduction of 6 dB each 10 m, which turns out to be uniform in the last gaps of the church

For each configuration, the global sound pressure levels estimated with regard to the distance to the source have been shown, and they have been compared with the expected values of the classical model and Barron's model (fig. 6) . In both configurations the estimated sound levels fit into those expected by Barron's model. For each configuration, the proportions between the church and an adequate reverberation time favor an adequate sound diffusion.

Intelligibility

With regard to the music configuration, intelligibility values remain within the values obtained previously for simulation of the current situation with spectators, obtaining a qualification of "fair" (RASTI average values: 0.56), while for the theater configuration there is an increase of intelligibility that is qualified as "good" (RASTI average values: 0.70), as it can be observed in figure 6.

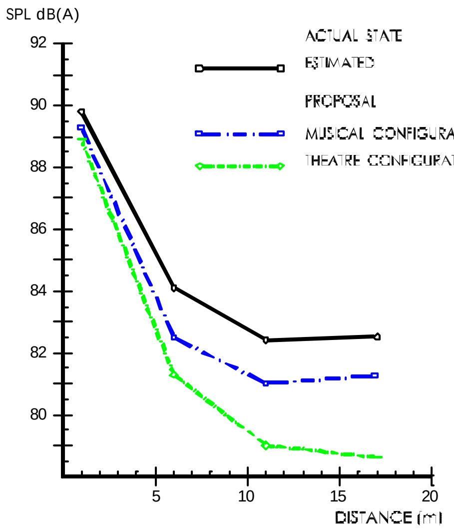


Fig. 5. Sound pressure level with regar to distance. Spectators sitting on chairs.

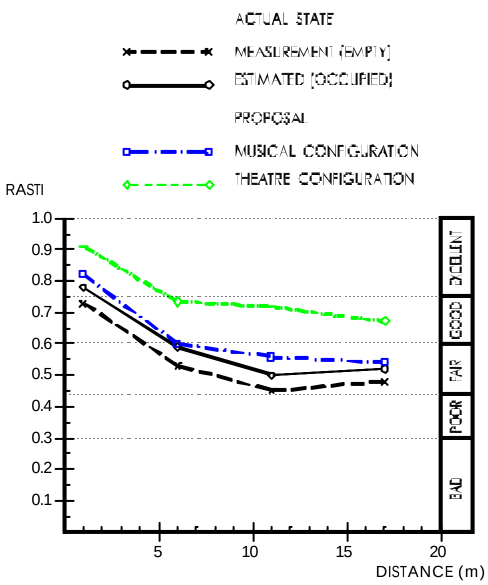


Fig. 6. RASTI values with regard to distance. Estimated, with spectators sitting on chairs

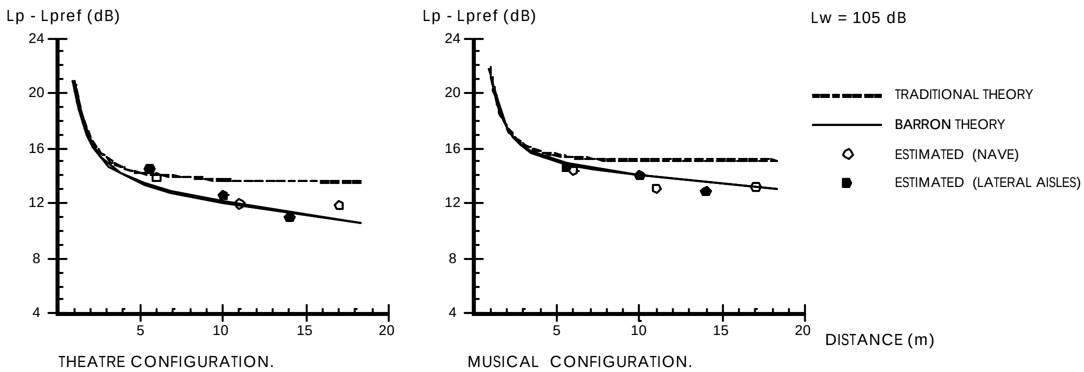


Fig. 7. Estimated performance of the acoustic field with regard to distance to the occupied church. Wide band

MATERIAL	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Ceramic flooring	0.02	0.02	0.03	0.04	0.05	0.07
Spectators on chairs	0.24	0.32	0.51	0.60	0.59	0.56
Lime covering	0.03	0.03	0.03	0.03	0.04	0.07
Stone	0.02	0.02	0.06	0.08	0.04	0.05
Wood	0.16	0.16	0.13	0.10	0.06	0.05
Glass	0.17	0.07	0.04	0.03	0.03	0.02
Wood suspended ceiling	0.16	0.16	0.13	0.10	0.06	0.05
Wood roof	0.30	0.25	0.20	0.17	0.13	0.10
Membrane resonator	0.20	0.40	0.80	0.70	0.40	0.05
Curtain	0.03	0.03	0.25	0.95	0.95	0.99
Curtain in front of glass	0.17	0.32	0.62	0.60	0.60	0.67
Air (m^3)					0.008	0.021

Table 1. Absorption characteristics of different materials

CONCLUSIONS

The church has an adequate reverberation time not only for music playing but also for speech hearing. Tonal curves are adapted to the optimum curves for the aforementioned uses. Sound distribution is homogenous throughout the church, with a bigger fall of sound intensity level for theater configuration due to a higher sound absorption. There are no sound concentration areas. RASTI values allow to qualify intelligibility as “good” for theater configuration, while for musical configuration it may be considered as “fair”.

As a consequence, after the intervention proposal, the church show favorable acoustic conditions, for both musical use and speech and for each configuration. These favorable acoustic conditions, together with its small size involve that, with regard to musical aspects, this space would be appropiate for chamber music playing, both instrumental and lyrical interpretation.

REFERENCES:

1 “Melodies share their monodic character, their liturgical function and the use of the latin language; besides, music should have a teaching function”. VICENTE, A. *Música Sacra, Tomo I*. Ediciones Altaya, Barcelona 1999, p. 8.

2 Reverberation time values for 500 Hz frequency:
Religious music : $Tr = 0.55 \log V - 0.14$
Speech : $Tr = 0.33 \log V - 0.15$
Corrections for religious music, with regard to frequency, es 1.40 for 125 Hz and 1.15 for 250 Hz. BERANEK, L., *Acoustics*. Acoustical Society of America, Nueva York 1993, pp. 425-426.

3 This apreciation has been done after studying the ecograms. However, there is a loss of sound quality due to the excess of sonority. Taking into account that sound attenuation with regard to distance of the reverberated sound adjusts to Barron’s model proposal, and background noise is adequate and intelligibility is correct, we understand that these sonority values are due to an excess of energy related to initial reflections.

4 A measurement with the transmitter’s level adjusted to its reference level was made, and another one increasing the emission level in 10 dB. It was observed that a very slight variation of the RASTI values did happen, even in certain spots it did decrease due to the high reverberation produced within the church. Therefore, an increase of the sound level does not imply an increase of intelligibility in this space.

5 The original volume was 1500 m^3. In 1982, after restoration, it was reduced down to 1225 m^3. The proposal plans to increase the volumen up to 1469 m^3.

6 “The intelligibility of speech is closely related to a correct perception of high frequencies” CARRIÓN ISBERT, A. *Diseño acústico de espacios arquitectónicos,* Edicions UPC, Barcelona 1998, p. 45.