A proposal to improve the acoustics in Fernandina churches. The example of Magdalena Church in Córdoba (Spain)

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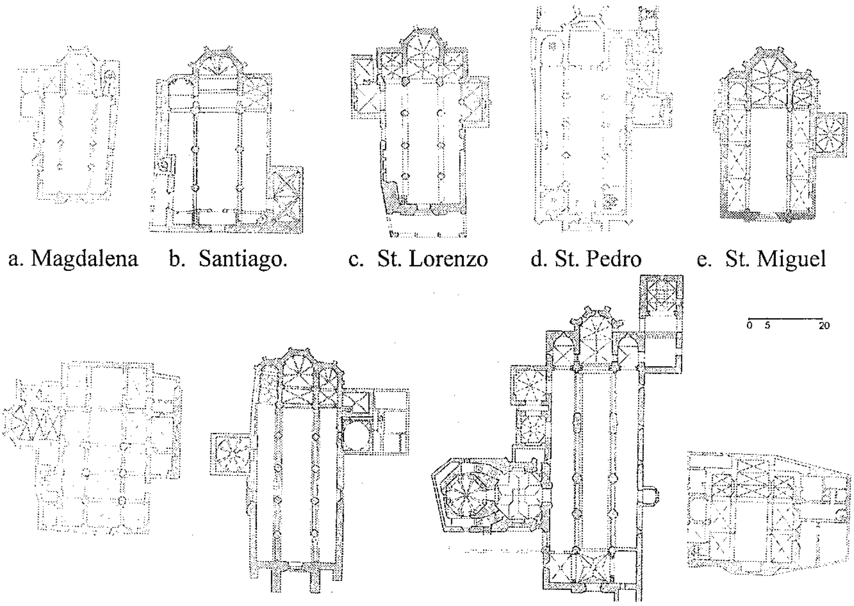
Abstract

After the Christian conquest of Córdoba by Fernando III in 1236, small churches were erected in substitution of Muslim mosques. Thus arises the Fernandina church model which will become a church archetype after the Reconquest. They are simple churches, with three naves covered with wooden roof structures and domed apses that satisfied the needs of liturgy and preach at that time, in which music was enphasized over speech. Nowadays many of those churches combine their liturgical activities with cultural uses.

In this work the acoustic conditions of this church model are studied. An acoustic analysis on one of these type of churches will be applied: Magdalena church, which has been recently restored for cultural uses. From measuring taken in situ together with computer simulation, architectural solutions are proposed to adapt the acoustics of the space to both speech and music use.

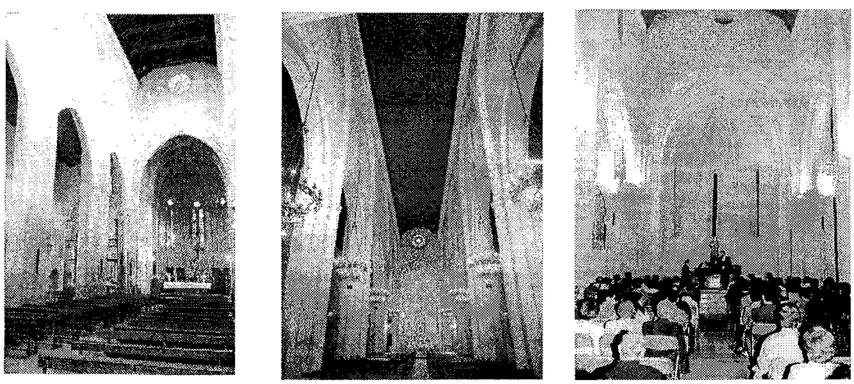
1 Introduction

The need to adapt Córdoba, Muslim capital of the Western world, to the need of Christians, involves the reorganization of the city by means of "collaciones" (districts defined by parish lines), creating parish churches in the city's most important areas. This is the origin of the first temples of Córdoba to be built along the last third of the 13th century.



f. St. Andrés g. St. Marina h. St. Pablo i. St. Nicolás

Figure 1. Plans of Fernandina churches in Córdoba.



St. Marina. St. Pablo. Magdalena.

Figure 2. Interior of Fernandina churches

These small churches, so called Fernandina, are Gothic in their conception, but include elements of the local Hispanic-Muslim art. All churches display a rectangular plan with three naves separated by means of pillars, being the central one wider and higher than the side ones, the far end with domed apses. They lack of transept and are covered with wooden roofs, "de par y nudillo" roof (doublepitched) in the central nave and single-pitched in the side ones. The walls were built up with ashlars following the caliphal tradition. This church model becomes predominant and will be extended throughout Andalusia with slight local variations [1].

All through, these churches undergo a series of interventions and alterations. The most important, from an acoustic approach, was the incorporation of a series of funeral chapels added to side naves which can involve an alteration of the acoustic conditions of these spaces, due to the coupling effect between the main volume and the volumes of the side chapels [2].

Nowadays, nine of the fourteen churches built up in Córdoba remain, being Magdalena church responsible for defining this model of church. Throughout history this church undergoes a series of alterations that end up with the fire that in 1990 destroys the main nave. From this date on, a sequence of interventions begins ending in 1999, when the church is recuperated for cultural use, offering since then an intense cultural programme, including concerts that range from late Middle Ages music or Gregorian chants to chamber concerts.

2 Acoustic analysis of the present state

The acoustic measuring was carried out with the main central nave occupied with plastic chairs placed on carpet, without any kind of decoration in the church. Eleven measuring spots were taken, six in the central nave, four in side naves and one in the chapel. All of them at a height of 1.20 m above floor level. The sound source was placed in the first third of the presbytery, in its central axis, at a height of 1.50 m above floor level.

2.1 Reverberation time

In the spot were the source was placed a sequence of detonations were performed in order to register the impulse response, obtaining the reverberation time values in octave bands for the different spots. With the aid of computer simulation, using CATT-Acoustic software, together with Sabine's formula, a theoretical prediction of reverberation time values of the church with spectators sitting on chairs in the central nave has been carried out.

In the same way and for a better knowledge of the acoustics of this church model, a theoretical estimation of the reverberation time with spectators seated on pews in the main nave, including decoration in the walls of the temple corresponding to typical liturgical furnishings of a Fernandina church (a common display when these churches are used for worship), has been carried out. As a matter of fact, this hypothesis including decoration and furniture can be considered as the *previous state* to restoration.

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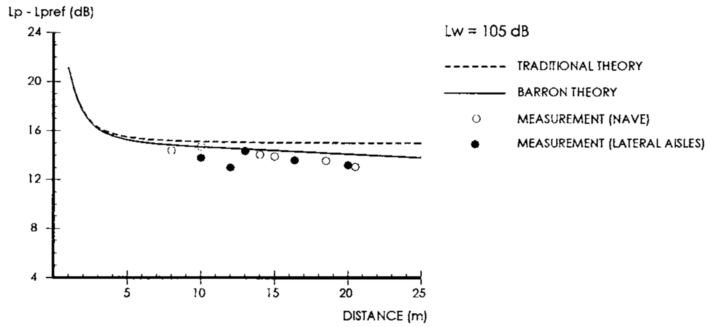

Figure 3. Performance of an acoustic field in relation to distance. Wide band.

Those reverberation time values are compared to theoretical optimum values, both for speech and for music, as proposed by Beranek [3] (Reverberation time values for a 500 Hz frequency are: Tr = 0.55 log V – 0.14 for religious music, Tr = 0.33 log V – 0.15 for speech. Correction for religious music, with regard to frequency, is 1.40 for 125 Hz and 1.15 for 250 Hz.

The reverberation time obtained with the measuring, in the case of the church being unfurnished, shows high values for each octave band, although with a significant sound absorption for low frequencies (125 Hz band), due to the absorption attained with the wooden roof that behaves like a “membrane” type absorber (fig. 6). The bareness shown by this space, after its restoration, is responsible for these reverberation time values being so high. These values decrease when spectators occupy the chairs, although they continue to be high values compared to the optimum values considered.

In the previous state, liturgical furnishings increase the sound absorption. However, even when the church is occupied with the audience seated on pews in the central nave, the tonal curve is slightly superior to the optimum tonal curve for music.

2.2 Sound distribution

Sound distribution measurements have been carried out starting from the emission from an omnidirectional sound source with an emission power adjusted up to 105 dB.

In order to study the diffuse character of the church’s acoustic field, the sound levels measured in relation to the reference level, with regard to distance, and the values expected with both the classical model and Barron’s model [4] are compared (fig. 3). The sound levels measured are kept slightly below compared to those expected by Barron’s model, with a slight variation of the reverberation level in relation to distance. As a consequence, a very homogeneous and uniform sound field is attained, thanks to a very reverberant

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space [5], to which the diffusion created by the wooden roof and the surface occupied with chairs has to be added.

2.3 Intelligibility

RASTI values obtained along the different spots, after the measuring, are shown in figure 9, in relation to the distance from each spot to the source. These values (average value of 0.35) allow to qualify the intelligibility as "poor" throughout the central nave.

When the church is occupied by the audience, the RASTI value obtained by means of computer simulation shows almost no improvement, maintaining the qualification of intelligibility as "poor"; while in the so called previous state, it can be qualified as "fair" for the spots along the central nave.

2.4 Back-ground noise

The back-ground noise level measured in the church indicates an equivalent continuos sound level (L_{eq} = 43.8 dBA) superior to the maximum recommended for churches: 40 dBA. To evaluate the back-ground noise in churches with liturgical use, the measured spectrum and the NR curves have been compared, and thus a NR value of 38 has been assigned, a value superior to the recommended range between 25 and 35. These values are due to the deficient acoustic insulation provided by glazed windows and doors that communicate with the exterior.

2.5 Conclusions of the present state

Starting from these data, it is concluded that the acoustic conditions of the church for its present state are inadequate, both for music and speech uses, mainly due to the lack of sound absorption. The existing high reverberation level makes it inappropriate to use the church for chamber concerts where it is needed to hear the melodic lines played by the orchestra and in which the harmony among the instruments should be audible.

In the previous state, it can be considered the existence of more acceptable acoustic conditions for musical use of the church, with reverberation time values slightly superior to the optimum, being inadequate for speech. The musical expression during the middle-age was very different to the present's, since instrumental sonority was high-pitched, liturgy was in Latin and the purpose of music was to enrich liturgy.

3 Intervention proposal

The restoration project that ends in 1999 intervenes in the church to leave it, apparently, in its original state, with a complete removal of any kind of decoration. This solution, as it has been studied, raises acoustic problems.

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Therefore, the recuperation of the sound absorption that the church had in its previous state, prior to restoration, when it was devoted to worship, is needed. The main acoustic problems detected in the church are high reverberation time values together with an excess of back-ground noise due to an inadequate insulation of window spaces and doors to the exterior.

The reduction of reverberation time can be obtained by means of a reduction of the church volume and an increase of sound absorption, mainly for low and medium frequencies. The use of cavity multiple resonators provides sound absorption mainly for low sounds, which are the most difficult to be attained in these type of spaces. The addition of porous finishings, fabrics or tapestries, provides sound absorption for medium and high frequencies. A greater sound absorption for low frequencies may be attained by means of an air chamber behind the porous material.

All these measures, sometimes contradictory depending on uses [4] [5], are carried out for the acoustic correction of the space. The intervention proposal starts from the respect for the church space avoiding the introduction of elements that could spoil the character of the space. Thus, the concrete proposal consists of (fig. 4 and 5):

- Display of a glass pane closing the side chapel from the main volume. The volume reduction (V=279 m^3) is not important in relation to the total volume (V=3785 m^3).
- Arrangement of small and fragmented surfaces consisting in cavity multiple resonators that mainly provide sound absorption for low frequencies.
- Layout of horizontal bands consisting of rock wool panels, separated from the walls and placed below the windows in the central nave and at the bottom ends of the side naves. Therefore the tradition of Gothic churches and cathedrals is followed, in which it was usual to display tapestries and wool cloths hanging from the walls.
- Arrangement of two windproof doors placed in the central nave door and in the Evangelio door in order to reinforce the acoustic insulation of the doors providing access to the church.

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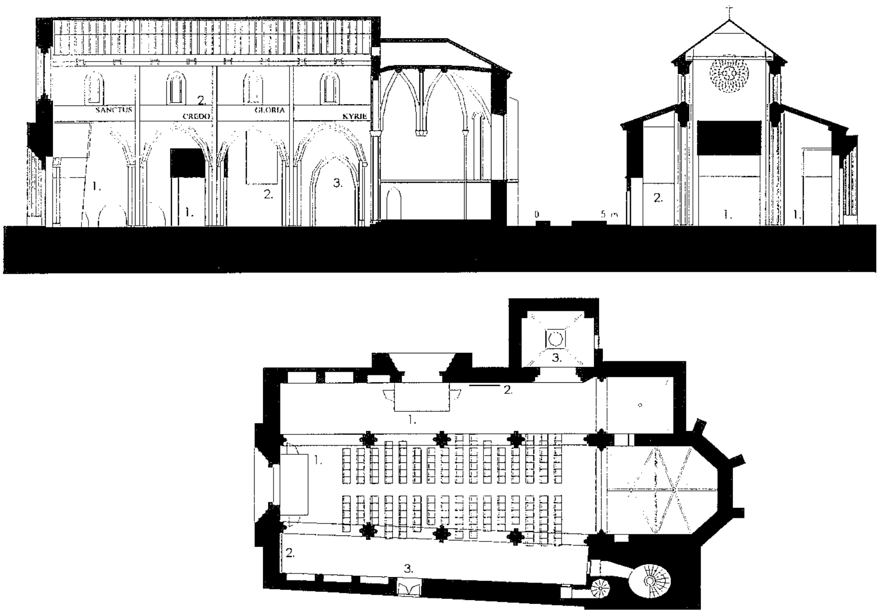

1. Windproof door composed by 4+4 glasses and multiple resonator made with a 17 mm wood panel with diameter 8 mm perforations in 5% of its surface, and a 10 cm air chamber filled with 6 cm wide rock wool.
2. 30 mm wide rock wool panel placed 5 cm from the wall.
3. 10 mm glazing.

Figure 4. Intervention proposal

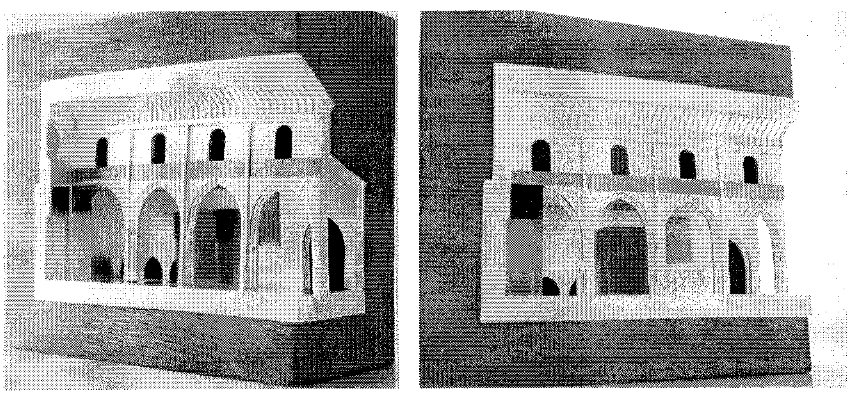

Figure 5. Model of the proposal.

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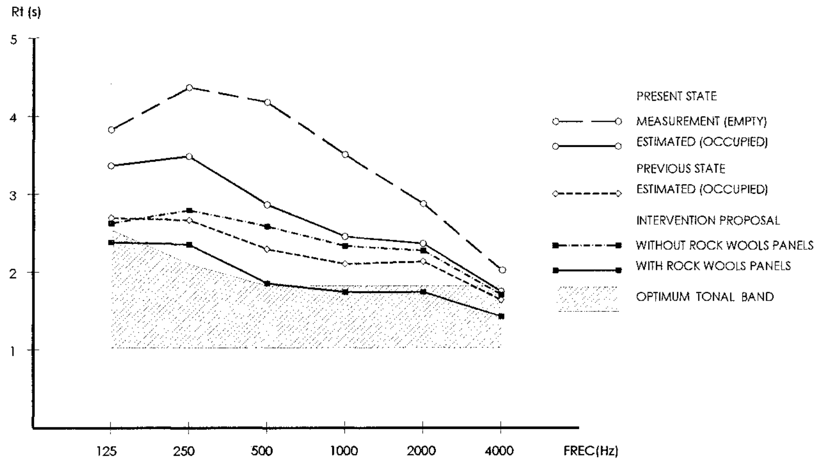

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Measured, empty	3.82	4.36	4.17	3.50	2.87	2.03
Estimated, with audience	3.36	3.45	2.86	2.45	2.36	1.75
Previous, audience on pews	2.69	2.66	2.29	2.10	2.13	1.64
Proposal, with audience. Without rock wool panels	2.62	2.79	2.58	2.33	2.27	1.72
Proposal, with audience With rock wool panels	2.38	2.35	1.85	1.74	1.74	1.40
Music optimum	2.53	2.08	1.81	1.81	1.81	1.81
Speech optimum	1.02	1.02	1.02	1.02	1.02	1.02

Figure 6. Reverberation times. Audience sitting in chairs.

3.1 Reverberation time

The conjunction of all the correction measures would provide adequate reverberation times for all the frequencies needed for musical use. In order to reinforce high pitched sounds, part of the absorbing rock wool panels could be eliminated, taking into account that the kind of musical composition may recommend this option.

3.2 Sound distribution

Sound distribution is similar to the present state, although the increase of sound absorption in the proposal supposes a reduction of the sound pressure level (fig. 7). For the proposal, the estimated global sound pressure levels in relation to the distance to the source have been represented, and they have been compared with the values foreseen by the classical model and Barron's model (fig. 8). In proximity to the source, the estimated sound levels are close to those foreseen by the classical model, due to an effect of sound concentration caused by the increase of reflections from the entrance door and the closing of the side chapel.

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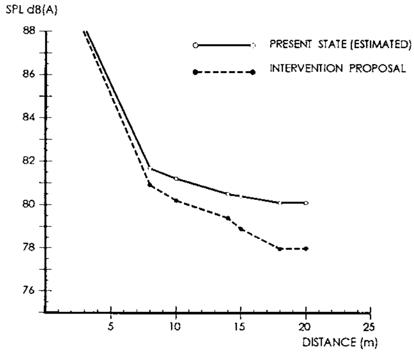

Figure 7. Sound pressure level in relation to distance.

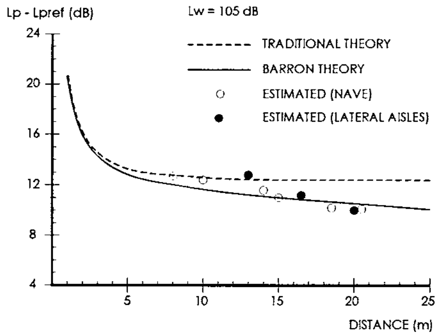

Figure 8. Performance of the acoustic field in relation to distance.

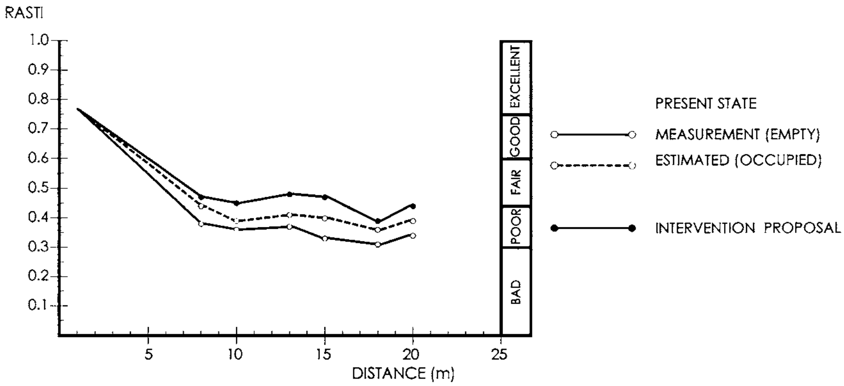

Table 1. Absorption characteristics for different materials.

MATERIAL	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Marble	0.01	0.01	0.01	0.01	0.01	0.01
Empty plastic chairs	0.09	0.09	0.09	0.14	0.27	0.27
Audience on chairs	0.24	0.32	0.51	0.60	0.59	0.56
Empty pews	0.04	0.05	0.06	0.08	0.10	0.10
Occupied pews	0.23	0.31	0.40	0.45	0.45	0.40
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
Wooden roof	0.33	0.28	0.25	0.20	0.20	0.21
Paintings, Altarpieces	0.05	0.12	0.35	0.45	0.38	0.36
Multiple Resonator	0.80	0.94	0.46	0.27	0.13	0.09
Rock wool panel	0.25	0.42	0.95	0.92	0.84	0.84
Air (m^3)					0.008	0.021

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In the remaining spots, the estimated sound levels adjust to those foreseen for Barron's model showing an adequate diffusion of sound.

3.3 Intelligibility

The values obtained allow to qualify intelligibility as "fair", as shown in figure 9. With regard to reverberation time values obtained in the proposal, RASTI values are not appropriate for those activities associated with speech use.

4 Conclusions

The proposal shows a reverberation time adequate for music playing, with a tonal curve adapted to the optimum tonal curve for music. Sound distribution is homogeneous throughout the church, with a slight reduction of sound pressure level at the bottom end of the church, existing no other sound concentration zones. RASTI values allow to qualify intelligibility as "fair" in the proposal. However, in order to use the church with activities associated to the use of speech, it will be necessary the backing of an electroacoustic system.

In consequence, the church shows favourable acoustic conditions for musical use, which, together with its small size, qualify the space for chamber concert playing as well as solo recitals. The variation of sound absorption created by the presence or absence of rock wool panels, together with the different degree of occupation, allows to adapt the acoustics of this space to any kind of musical works. Thus, without the use of panels, the church will display reverberation time values appropriate for the interpretation of Gregorian chants or mediaeval music, musical pieces composed for spaces with a higher reverberation time.

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