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An analytical model for evaluating the sound field in Gothic-Mudejar churches

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Abstract

Acoustic correction in churches that are part of our historical and architectural heritage is a subject of great importance and interest today in the field of applied acoustics. This paper deals with a type of church that is often seen in southern Spain: Gothic-Mudejar churches from the thirteenth to fifteenth century period. To be precise, this study of the sound field of these churches is meant to obtain an analytical model that will allow us to quite accurately predict the sound presure levels for different octave bands. Also, this is compared with other analytical models, mainly Barron's model.

1 Introduction

The acoustic rehabilitation of churches in Spain and other countries with a rich architectural heritage is a subject of great importance and interest today in the field of applied acoustics. Many towns and cities and even small villages in these countries have one or more churches of great artistic significance, but lack public buildings that can accommodate cultural activities, especially theatrical, conference hall, and musical activities. This has led to a cultural policy that uses these churches for performances and concerts on a regular basis after renovation or sporadically, alternating these functions with the normal religious and worship functions.

Interior acoustical conditions are not always analysed before making a decision about the compatibility of cultural and liturgical uses or about renovating the church and using it for different purposes. Often, these conditions are very unsatisfactory and no provision is made for an adequate acoustic conditioning of the church. This lack of foresight has been the source of notable functional failures that may lead public institutions to abandon a policy which is effective in helping to safeguard a great deal of historical and artistic heritage.

The historical and architectural values of the interior space, in other words, typological, functional, and formal values, and their impact on its acoustic conditions make it advisable to deal with their acoustic correction more precisely.

This paper focusses on the study of the sound field inside Gothic-Mudejar churches to obtain an analytical model for predicting the sound presure levels in the five octava bands having center frecuencies between 250 y 4000 Hz. It is part of a general acoustic study conducted on this type of church, which is characterized by its good acoustic conditions. The Province of Seville has a representative sample of these churches. Specifically, the acoustic conditions of nine Gothic-Mudejar churches in the city of Seville were studied, all of which have three naves covered with wooden frameworks. The presbytery, on the contrary, is covered with a vault (Figure 1). Angulo[1], the famous specialist, called this type of church the "Seville parish type". Although the date of construction is often variable and imprecise, most of these churches were probably built between the thirteenth and fifteenth centuries. All are used today for worship.

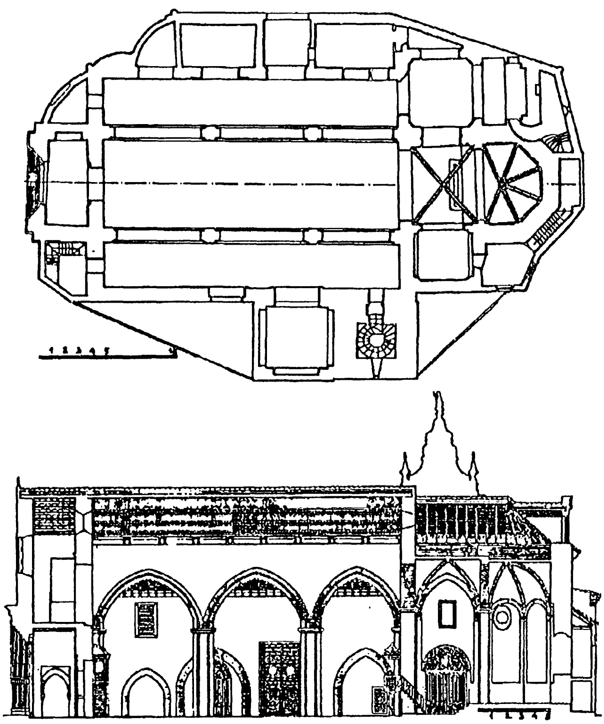

Figure 1: Ground plan and section of St. Catalina.

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2 Acoustical conditions in churches: a brief historical outline

Throughout history, the interior space of churches has never been characterized by good acoustic conditions, although this global assertion must be qualified with a brief historical sketch.

The early church was modelled on the Roman basilica, with a light wooden deck. The wooden ceiling was not very high, was sometimes flat with coffers, and had a larger upper air chamber. Its suitable and harmonious proportions, and the absence of large panels of blind reflective walls meant that their interior acoustic properties were much better than those of their medieval successors, the Romanesque and Gothic churches. The desire for monumentality and permanence had a lot to do with this regression. Durable stone vaults took the place of ephemeral wooden roofs, and the interior space was logically bigger. This resulted in a significant increase in reverberation time -including the formation of echos- and a clear decrease in the intelligibility of speech. The latter must not have caused much worry because by then the people no longer understood Latin, the language used in Mass. On the other hand, the resonance of these churches was very suitable for Gregorian chants.

The transition from these dark Romanesque churches to the luminous Gothic cathedrals only added to the acoustic problems due to the greater height of the main nave and the presence of large reflective wall surfaces. Almost the only significant acoustic absorption was that originated by the public standing during the ceremonies. At that time, there were no seats. Pews and long church services were introduced by the Protestants, and later the Catholic Church adopted them.

The churches in the first Renaissance did not show a substantial improvement in acoustic conditions, although their proportions were more suitable. The substantial change would occur in the second half of the sixteenth century. Both the Protestant Reformation and the Catholic Counter-Reformation thought it essential to recover the intelligibility of speech and of liturgical singing because preaching was considered very important. The Protestants even established the dimensions of their churches according to the range of the human voice (Frankl[2]).

The Anglican Church also took into account this relationship between the size of the church and the interior acoustic conditions. When the Great Fire of 1666 destroyed a large part of London, one objective in the city's reconstruction was, under the guidance of C. Wren, to build fifty-one parish churches. A letter from this architect to Parliament dated in 1708 emphasizes that these churches should be small enough so that all the faithful could see and hear the preacher (Favaro[3]).

The Catholic Church, however, wanting to consolidate symbols of power, soon dropped austerity as a basic objective of the Counter-Reformation. The first Jesuits' preference for the functional and liturgical rather than the formal, which led them to propose flat wooden ceilings for their churches precisely for acoustic reasons (Sendra[4]), would be followed by the great contribution (from the viewpoint of acoustics) of the Baroque: the ornamentation and "dressing" of the interior church space for great celebrations, feasts, and for funeral rites of important people (Oesclin[5], Dávila[6]). This would provide acoustics more closely related with musical acoustics. Many Baroque churches, especially in Italy and Central Europe, are an ideal place to play the music of great Baroque composers: Scarlatti, Vivaldi, Bach, Händel, etc. Jungman[7], the famous liturgical specialist, makes a revealing judgment: "The inside of the church is transformed into a colourful auditorium. We could say that not even the royal boxes and the galleries are lacking. The liturgy is understood as a show to see and hear."

A constant in the following years would be the ephemeral modification of the absorbent characteristics of the surfaces to adapt them to musical interpretation, thus helping extend the false idea that the ecclesial space is appropriate for interpreting classical music, omitting the ornate setups which, at that time, were built for such events.

In the Spanish Middle Ages, in addition to Romanesque and Gothic churches, Mudejar churches were also built using brick instead of stone as construction material because of its greater availability in the peninsula. The presbyteries of these churches were usually covered with vaults, but the naves were covered only with wooden frameworks, following the Morisco style. Smaller proportions and, above all, the use of wooden roofs instead of vaults to cover the naves, are the reason that the acoustic conditions in Mudejar churches are significantly better than those of their Gothic contemporaries (Sendra[8]). The paper we are presenting deals precisely with this type of church.

3 Barron's model

The classical expression for the sound pressure level inside a reverberant enclosure (diffuse field) includes two terms: one for direct sound, which depends on the distance from the source, and another for reflected sound, which is taken to be independent of position:

$$L = L_W + 10 \log\left(\frac{1}{4\pi r^2} + \frac{4}{A}\right) \tag{1}$$

where L is the total sound presure level, L_W is the source sound power level, r is the source-receiver distance, and A is the enclosure's absorption, which should be expressed as a function of the values measured for the reverberation time T ($A=0.161 \cdot V/T$).

It is appropriate to replace the sound power level with the acoustic level produced by an omnidirectional source under free field conditions at a distance of 10 m ($L_0=10 \cdot \log(W/400\pi)$) so that the measured levels are found within a small interval above the reference level. Therefore (1), we can write

$$L - L_0 = 10 \log\left(\frac{100}{r^2} + \frac{31200 \cdot T}{V}\right) \tag{2}$$

In the most common practical situations, it is difficult to assume the diffuse field hypothesis, and with it, the constancy of the reverberant field. Barron and Lee[9] analyse the behaviour of the reverberant field (averaged for medium frequencies: 0.5, 1, and 2 kHz octave bands) in a series of multiuse halls whose behaviour cannot be considered diffuse, mainly because of the concentration of the absorption on the surface of the audience. To predict the total sound pressure levels and the early-to-late sound indices (as clarity, C), they divide the acoustic energy received at each point into three components, all of which depend on r: the direct sound (d), the early reflected sound with a delay time of less than 80 ms (e_r) and the late reflected sound with a delay greater than 80 ms (l). With the previous reference, L_0, the equations they propose for the sound presure levels and the early-to-late index are:

$$L - L_0 = 10\log(d + e_r + l); \qquad C = 10\log\left(\frac{d + e_r}{l}\right) \tag{3}$$

where:

$$d = \frac{100}{r^2}; \quad e_r = \frac{31200T}{V} e^{-\frac{0.04r}{T}}\left(1 - e^{-\frac{1.11}{T}}\right); \quad l = \frac{31200T}{V} e^{-\frac{0.04r}{T}} e^{-\frac{1.11}{T}} \tag{4}$$

which also implies an attenuation of the sound depending on the distance from the source for the reverberant field (e_r+e_l) at an approximate rate of $-1\ dB/10m$.

The in situ measurements we have made suggest that, although the model shown above is suitable for global levels[8], it would need qualifying for use in describing or predicting octave band frequency behaviour for this type of church.

4 Measurement technique

All measurements were taken when the churches were empty, and no corrections for degree of occupation were made. The furniture consisted in wooden pews with low absorption, which may suggest greater attenuation depending on the degree of occupation because of an increase in audience plane absorption.

Reverberation times were measured with Schroeder's integrated impulse method. The impulsive signal was produced by firing a blank cartridge at the place where the source would be located in normal use. At each reception point, the microphone signal was recorded using a Sony PC204 DAT. Each response to the impulse was later processed in the laboratory using a B&K-2133 analyser to find the T values for the bands of interest.

The steady-state sound levels were measured using a reference source (B&K-4205), which was located at the same place where the blank cartridges were fired. For this source we know the octave band sound power spectrum. After calibrating the system, a 30 s recording was made on the DAT and later processed in the

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laboratory with the analyser to obtain the global and the octave bands levels by averaging for 20 s.

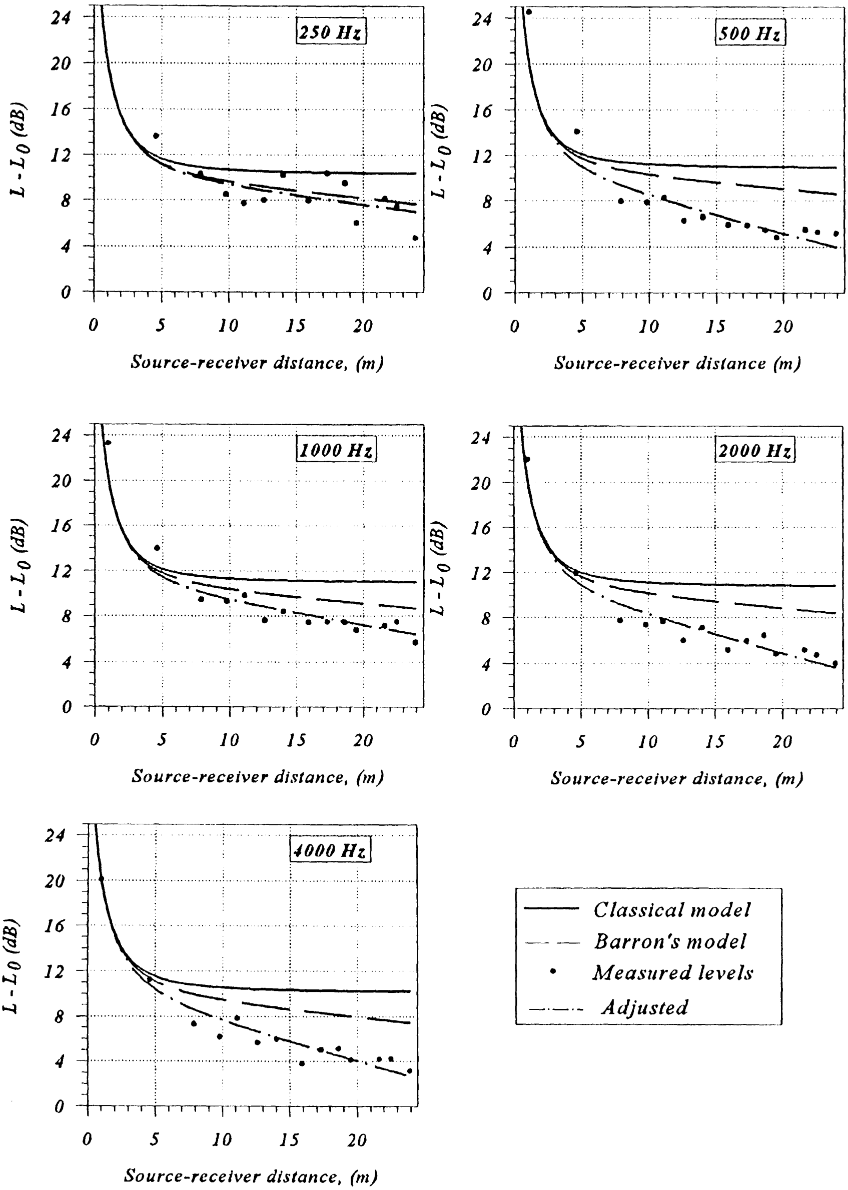

Figure 2: Sound presure levels for the church of Santa Catalina

In all cases, omnidirectional B&K 4165 microphones were used with their respective preamplifiers and polarization sources from the same manufacturer.

The measurement points (between 10 and 16 in each church, with an average of 13) were uniformly distributed in the audience zone, which means that most of them, in the majority of the cases, are located at more than twice the distance of the corresponding reverberation radius.

TABLE I. *Significant data on the Gothic-Mudejar churches studied*

Param.	Santa Marina	San Vicente	San Julián	San Gil	San Pedro	San Marcos	Santa Catalina	San Isidoro	San Sebastián
V (m^3)	8696	6915	6226	6200	6108	4763	4362	3947	3550
S (m^2)	3988	3290	2984	2931	2758	2671	2251	2270	1890
d_{MX} (m)	36	24	27	24	22	29	24	27	25
r_a (m)	2.76	3.87	2.40	3.03	3.46	2.02	3.12	2.50	2.45
α	0.09	0.19	0.09	0.14	0.18	0.07	0.18	0.12	0.14
T_1 (s)	3.62	1.71	3.57	2.49	1.76	4.01	1.50	2.13	1.99
T_2 (s)	3.96	1.81	3.89	2.48	1.98	3.95	1.72	2.21	2.20
T_3 (s)	4.00	1.82	3.81	2.50	1.99	4.01	1.75	2.30	2.20
T_4 (s)	6.57	1.68	3.34	2.35	1.87	3.57	1.67	2.14	2.15
T_5 (s)	2.62	1.40	2.44	1.87	1.56	2.58	1.45	1.76	1.88
β_1	0.05	0.06	0.05	0.07	0.04	0.10	0.05	0.06	0.04
β_2	0.13	0.08	0.11	0.13	0.09	0.14	0.12	0.11	0.09
β_3	0.09	0.07	0.06	0.10	0.07	0.10	0.08	0.08	0.05
β_4	0.13	0.10	0.13	0.14	0.11	0.15	0.12	0.12	0.09
β_5	0.13	0.10	0.13	0.13	0.11	0.20	0.11	0.12	0.10

5 Data analysis

Table I shows significant data for each of the churches studied: the volume (V), the interior surface (S), the maximum source-receiver distance (d_{MX}), the reverberant radius, the mean estimated absorption coefficient (α), the measured reverberation times for the octave bands between 250 (T_1) and 4000 Hz (T_5) and the parameters obtained in the adjustment to which we will refer later on for the same octave bands (β_i).

Taking into account the T_i values and considering that this type of enclosure has no particularly absorbent surfaces, it might be thought that the interior field would better correspond to the diffuse model than the halls analysed by Barron. However, the form, with its large smooth walls and geometrical proportions, are not the most appropriate. In other cases, Barron's model has already been used to evaluate the impact of an intervention in a church using Schroeder diffusers.[10] Our objective is to analyse how the reverberated field varies with distance for the frequency bands being studied.

Figure 2 shows the L - L_0 values obtained from the classical model and from Barron's model for the Church of Santa Catalina. Also, the measured levels are shown after correcting them with respect to reference level L_0. We find this level for each significant octave band based on the known sound power spectrum of the source because the source is omnidirectional and the distances implied are really too short (see Table I) to consider the attenuation of direct sound[11].

As can be seen, the measured values generally differ appreciably from expected levels, although the same tendency suggested by Barron's model for attenuation by distance is observed. This led us to analyse the possibility of adjusting the measured data with an equation similar to that of Barron's model. This equation would use the factor of the exponential of r as an adjustment parameter using the Marquardt-Levenberg iterative algorithm. In other words, for the i octave band, we would have:

$$L - L_0 = 10\log(d + e_r + l) = 10\log\left(\frac{100}{r^2} + \frac{31200\,T_i}{V} e^{-\frac{\beta_i r}{T_i}}\right) \qquad (5)$$

The same procedure was repeated for all the churches and the correspoding adjustment value parameters are listed in the last rows of Table I.

6 Conclusions

The detailed analysis of the reverberant field in the interior of the churches shows that acoustic levels of this field are linearly attenuated depending on the distance from the source, with attenuation indices that vary appreciably according to frequency.

TABLE I I. *Average adjusted β_i parameters*

Frequency (Hz)	250	500	1000	2000	4000
$<\beta_i>$	0.06	0.11	0.08	0.012	0.012

Taking this into account, Barron's Model has been modified for Gothic-Mudejar churches. The modification was carried out seeking the β_i parameter for the best adjustment for each octave band and each church.

The procedure suggests the possibility of adopting this modified model to describe generically the interior field of this type of church, adopting for each

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frequency band the mean values of the exponents found (see Table II) for the 250 to 4000 Hz octave bands. This implies attenuations of *0.9, 1.9, 1.2, 2.1*, and *2.1 dB/10 m* respectively in each band. Taking into account the distances involved (see Table I), this assumes drops of between 2.5 and 6 dB, depending on the band. These drops are significant if we take into account that doubling the source power will mean an increase of 3 dB.

The modified model could be used to predict not only the global levels, but also other early-to-late indices. Therefore, for clarity (C), we would use the expression (3), replacing the value of 0.04 with the average exponents shown before for each band. Although the results measured for C have not been compared in this paper, at present, work is being done in this direction, and similar models are being studied for other typologies.

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