Virtual reconstruction of indoor acoustics in cathedrals: the case of the cathedral of Granada

Alicia Alonso*, Rafael Suárez y Juan J. Sendra

Instituto Universitario de Arquitectura y Ciencias de la Construcción, Universidad de Sevilla, Seville, Spain.

Escuela Técnica Superior de Arquitectura, Av. Reina Mercedes, 2, 41012 Seville, Spain. Tel.: +34 954 55 16 30. E-mail addresses: aliciaalonso@us.es (A. Alonso), rsuarez@us.es (R. Suárez), jsendra@us.es (J.J. Sendra).

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Virtual acoustics provides a highly useful tool for the investigation into the influence that spatial transformations may exert on indoor acoustics of cathedrals, which are remarkable spaces due to their heritage value, complexity and multifunctional character. The spatial organization of cathedrals is primarily governed by the location of the choir, which represents the main musical expression. Following various reforms, certain European cathedrals undertook a relocation of the choir stalls from their original position. The Cathedral of Granada is a highly significant case. Since its original construction, three major changes have occurred due to the relocation of the choir. In this article, simulation of indoor acoustics is employed to recover the soundfield in each of these three configurations. An extensive analysis compares the results of the main acoustic parameters in each of the virtual reconstruction models. Consequently, acoustic models are created and then calibrated based on a campaign of onsite measurements.

Keywords: virtual modeling; acoustic environment; acoustic simulation; cultural heritage

1. Introduction

Analysis of the acoustics of churches and cathedrals has become an object of study in several research studies. Over the last decade, liturgical practices, religious chants, and other activities aimed at preaching provide the focus of this research, which investigates the suitability of worship spaces for these purposes. This new approach requires the application of new technologies to introduce an innovative approach that will expand knowledge in this area.

Acoustic simulation tools allow the virtual recreation of the acoustics of various past and future scenarios to be designed (Lu et al. 2016) and predict the acoustic impact of numerous spatial transformations in different worship spaces of various religions (Kosala and Engel 2013; Soeta et al. 2012; Queiroz-de Sant'Ana and Trombetta-Zannin 2011; Abdou 2003). Several investigations have focused on the assessment of current acoustic conditions of cathedrals (Álvarez-Morales et al. 2016; Segura, Giménez, Romero and Cibrián 2011), and an individualized study for each liturgical use has been attained (Pedrero et al. 2014). Other research has assessed the impact of certain ephemeral decorative elements on the acoustic behaviour of cathedrals that involve speech Álvarez-Morales et al. 2014) or music (Alonso et al. 2014), or spatial past configurations have been acoustically analysed (Suárez, Alonso and Sendra 2016; Martellotta et al. 2008). All this has been carried out through the use of simulation tools that allow the acoustics of the cathedral indoor space to be virtually recreated. Certain studies remain of note for their acoustic assessment of places of worship since they focus on the exploration of the acoustic characteristics and on the influence of textile materials arranged in the acoustic sound field (Alonso and Martellotta 2015; Benedetto and Spagnolo 1984). However, there are hardly any studies into the effect of spatial transformations following reforms experienced in the past (Díaz-Chyla, Pedrero and Díaz-Sanchidrián 2013).

Within religious architecture, cathedrals command a special role. These are functionally complex spaces whose identity and spatial organization are primarily defined by the liturgical function that is developed within. These multifunctional religious spaces are mainly used for worship and prayer, occasionally combining this with major ceremonies, such as religious festivities and concerts, organized for a large audience.

From the architectural point of view, the choir plays a role of the first magnitude in the cathedral space. On occasions, its size and location generate major changes in the spatial configuration. In Spain, the choir is usually placed in the middle of the nave, responding to the old tradition of monasteries, and, these, in turn to the *schola cantorum* of the early Christian basilicas (Navascués 2004; Suárez, Sendra and Alonso 2013). Thus, the chancel and the choir, closely united, constituted a church for the clergy within the cathedral itself, where the congregation was excluded. In accordance with major reforms enacted in both the Council of Trent (16th century) and the Second Vatican Council (20th century), decisive actions affecting the interior space and the liturgy of the cathedral were carried out. For this reason, renovation work based mainly on the transfer of choral space was promoted in certain European cathedrals, in order to strengthen this estranged relationship between the clergy and the faithful.

In this article, an acoustical evaluation is performed on the Cathedral of Granada, which presents one of the most significant examples of the role that such interventions play in special and liturgical changes in cathedrals. In this place of worship, the choir is transferred to three different positions. In order to recover the sound space of the cathedral and to establish a comparative analysis between the current and past indoor acoustic environments. The process involves experimental measurements and virtual modelling, for which simulation software based on geometrical acoustic prediction methods is used. In addition, methods for the acquisition of the input information and the level of geometrical detail of the room are also discussed. The results are analysed in terms of a frequency analysis of the main acoustic parameters. The virtual models of the cathedral recover the acoustic behaviour for choral or instrumental music by means of a spatial-functional form of identification.

2. Spatial and functional analysis of the cathedral of Granada

2.1 Architectural description of the Cathedral

The cathedral of Granada is considered as one of the most important religious spaces in southern Europe. Diego de Siloé was the architect who defined an ambitious project of a renaissance church with a basilica floor plan, divided into five vaulted naves, a transept that sections the naves transversally, a polygonal ambulatory, and chapels along the perimeter.

This approach was innovative in that it sought to move away from the conventional basilican solution, by incorporating the centrality concept at the head of the temple (Navascués 2004). However, the solution finally adopted in the cathedral responded to the so-called “Spanish type”, where the choir is placed in the middle of the space. The central nave was divided into two differentiated areas (Figure 1a).

The temple was conceived with a main transept and a second transept that occupies three naves, thereby providing independent light to these two areas: the solemn liturgy (main transept), and the ordinary liturgy (secondary transept). The chancel, located at the head of the temple, is composed of a series of Corinthian columns, which supports the great dome that rises to 47 metres high.

The main dimensions of the cathedral are that it is 106 m long and 63 m wide. The nave and transept reach a height of 32 m, higher than the rest of the temple; aisles have a height of 25 m. These naves are divided by 28 stoneclad columns, supporting 37 stone ribbed vaults. The enormous volume measures approximately 160500 m^3. The main structure of the building and most surfaces are coated with plaster, with a variety of finishes.

2.2 Spatial transformations of the Cathedral space: the relocation of the choir

Over time, the relationship between the clergy and the faithful has generally become closer in Catholic churches. Existing physical barriers between these two parties have been disappearing in order to enable the participation of the congregation in the church services. This is clearly illustrated in the Cathedral of Granada, mainly through the transformation of the choir stalls, a singular space for the performance of music. The evolution of the location of choral space, with three main positions, brought about major spatial transformations in the cathedral:

- Configuration M1 (Fig. 1a). Originally the choir space was placed in the middle of the central nave, which is divided into two large differentiated areas. The choir space was designed as a fundamental part of the cathedral of Granada due to its influence on the indoor space of the church and the location of the faithful. Its presence constituted a physical obstacle to the congregation's view of the high altar. This private space was mainly used for the performance of instrumental music and chant.
- Configuration M2 (Fig. 1b). An intervention was proposed in the early 20th century that removed the choir from the central nave and installed it in the main chapel, thereby providing an optimal spatial-functional relationship. However, this modification meant that the two organs, remained suspended on the walls of the old choir. In addition, the inclusion of the choir in the presbytery, previously conceived as an open space visible from the ambulatory, would eliminate the concept of centrality. One of the main disadvantages generated by the

centralized location of the choir was the creation of physical obstacles that obstructed forging a closer relationship with the congregation.

- Configuration M3 (Fig. 1c). The latest intervention was carried out in the late 20th century. The choir area was eliminated from the chancel and the openings that connected this space with the ambulatory were reopened, thereby allowing a connection with the congregation. A number of the choir seats were moved to the embouchure of the chancel. The result of this process of functional evolution is an open floor plan that is completely interconnected in all areas. The new location for orchestras and choral groups is established in the transept area and is studied in detail in this paper. However, in this reform, the two organs would also remain suspended over the walls of the old choir.

3. Methods

The procedure followed for the comparative study of the main spatial transformations in the Cathedral of Granada is now described. A campaign of experimental measurements was conducted that characterized the voluminous indoor acoustic enclosure, based on the guidelines given by the standard ISO 3382-1 (2009). In order to carry out the research into the acoustical influence of different choir positions, simulation was required of diverse models that virtually represent the space at different historical moments. Acoustic measurements enabled the calibration of the model that reproduces the cathedral in its current state, in order to faithfully represent the indoor acoustic environment. The remaining models that are intended to virtually reproduce the acoustic soundfield of the cathedral in the past, were built later, by assigning absorption and scattering properties to each surface.

The predicted values were provided using the calculation engine TUCT v1.1a (The Universal Cone Tracer), included in the software Catt-Acoustics v9.0c (Dalenbäck 2011), based on geometrical acoustics (GA) theory (Vorländer 2008). Both commercial packages are supported by modelling techniques that can be used to simulate sound propagation inside 3D spaces to produce echograms and synthesized room impulse responses (RIRs). These GA techniques consist of energy-based octave-band echograms calculated in the usual way for ray-tracing techniques (E algorithm), and pressure-based methods suitable for binaural impulse responses (h algorithm).

Diffraction presents another major phenomenon associated with the propagation of sound, which occurs when the waves radiated from the sound source reach an obstacle and then divert around it. The effects of this phenomenon are generally more pronounced for waves whose wavelength is similar to the object dimensions. This option has been chosen since the prediction software includes the ability to add the comprehensive treatment of early diffraction by using a secondary edge-source method, based on a discrete Huygens interpretation of Biot-Tolstoy. Regarding this aspect, it is worth noting the existence of new methods and simulation techniques that have been developed during the last years and which are characterized by their high degree of reliability and speed of computation. In this sense, there are reliable methods developed for edge orientation and are based on the Biot-Tolstoy-Medwin (BTM) formulation, available as a Matlab toolbox (Svensson 2009). The integration of these tools in this type of research of spaces of worship becomes a future objective to be developed.

Sound space reconstruction was recreated virtually and the main acoustic parameters together with diverse audience mappings were estimated to determine the comparison between the acoustic environments of the three stages. Moreover, a study of early reflections and an analysis of the relationship between subjective qualities and the measured acoustic parameters were also carried out.

3.1 Acoustic measurements

The campaign of onsite measurements to obtain RIRs was performed, at night on the unoccupied temple while following the guidelines established by ISO 3382-1 (2009). Temperature values and relative humidity were monitored, and values between 11.7-12.5 ° C and 36-43%, respectively, were obtained. The measurement process was based primarily on the excitation response of the cathedral space by issuing sine swept signals by means of an omnidirectional dodecahedron sound source (AVM do-12), with a loudspeaker on each face, with frequency increasing exponentially with time. The duration of the sweep was set to 20 s and covered the octave bands from 63 to 16000 Hz with a power amplifier (B&K 2734). Following the standard requirements, sources were raised up to 1.5 m from the floor or support surface. The signal generation was conducted using the WinMLS2004 commercial software together with an audio interface (EDIROL UA-101). Consequently, RIRs were acquired using a multi-pattern microphone (Audio-Technica AT4050/CM5), whose directivity switched from omnidirectional to bidirectional in a figure of eight. The microphone was placed at a height of 1.2 m from the floor at each of the reception points throughout the audience area.

Signal processing based on advanced convolution techniques was applied to calculate all the acoustic parameter results. High INR values determine the suitable quality of the signal recorded, which leads to a reliable calculation for the remaining acoustic parameters (Hak, Wenmaekers and van Luxemburg 2012). Since the measurements were obtained at night, the background noise was much lower than usual, which made it easy to obtain INR values over 45 dB in each frequency band by adjusting the level and duration of the measured signal.

3.2 Virtual modelling

Acoustic simulation is a highly useful tool either to predict the acoustic environment of a new space in the design stage, or to assess the impact generated by specific interventions on the acoustic behaviour. However, not only does acoustic research focus on future purposes such as the construction of acoustically suitable environments, but it also enables the characterization of ancient acoustic conditions by offering the possibility to listen to the acoustics of the space of another era. In this sense this work is defined, whose main purpose is the prediction of the acoustical environment of different choir locations in their original historical form.

A virtual acoustic model of the Cathedral of Granada was created from the geometry of the interior space in its current state. SketchUp 3D modelling software was used to build the models. These models were then were exported to CATT-Acoustic v9.0c (Dalenbäck 2011, Dalenbäck 1999, Bork 2005) thanks to the use of SU2Catt plugin. The predicted values were provided using the calculation engine TUCT v1.1a, incorporated in the acoustic software. The software application has proved to be robust for the prediction of the values of the acoustic parameters (Berardi 2013). During the creation of the model, the main recommendations of other studies were followed, based on the assumptions given by the methods of geometrical acoustics (Vorländer 2008; Pelzer and Vorländer 2010). It should be stated that not only do CPU-based processors, such as CATT-Acosutic, deal with complex models but also there are other recent work on geometric and numeric methods that also can handle a cathedral model by using capabilities of graphics processors (GPUs). Thanks to an efficient algorithm that solve the acoustic wave equation, a fastest time-domain solver for modeling the room acoustics of large, voluminous models generates accurate results, especially focused on both auralization and visualization (Mehra et al. 2012).

From among the various techniques used by acoustic simulation software, one of the main reflection-path-based GA modeling techniques stands out: the ray-tracing method. Its fundamental principle is based on the release of rays from a sound source to the reflection thereof, following certain routes. Those reflections propagated in any direction are categorized as diffuse. In the model under study, a large percentage of surfaces, such as altarpieces, reliefs and the decoration of the temple itself, generates sound diffusion. Since the simplification of the model requires the removal of such details, the determination of this characteristic is partially estimated by Catt-Acoustics v9.0c through the application of scattering coefficients, categorized in four different scales, depending on the irregularities of each surface (Table 2). However, the "surface + edges" option was also selected for considerations of auto-edge diffusion reflection.

In order to adapt to the behavior of sound waves in different frequency ranges, a level of detail implementation can be considered for room acoustics simulation (Pelzer 2010 and Vorländer 2008). In fact, calculation methods for the automatic reduction of level of detail of some models have also been developed (Siltanen 2008). In this research, diverse simplification considerations are applied during the cathedral virtual model construction. It was proved that these interventions have significantly reduced the computation time. Adjustment tests were conducted to justify that such considerations did not affect the accuracy of the results. This fact was proved in a previous work in which two versions of the virtual model of cathedral of Seville were created; one of them reduced the number of planes with respect to the other (Alonso 2014). The slight adjustment and adaptation of the acoustic properties of the stone material of walls, vaults and columns allowed to confirm the similarity of results, which corroborates the reliability of simplification in this type of models of large ecclesial spaces. Table 1 shows the main descriptive data of the current base model.

3.2.1 Calibration of the current base model

The acoustic characterization of the virtual model of the Cathedral of Granada is mainly performed from the assignment of absorption and scattering coefficients of each surface (Table 2).

Data collection was carried out by categorizing the existing materials in the space after a visual inspection. The values of the coefficients that belong to previously tested materials were largely extracted from the scientific literature. In the case of the remaining "unknown" surfaces, an estimation by a calibration process was required. In order to define the coefficients of stone, which constituted the most significant model material due to the large percentage of surface that it conserved, it was necessary to investigate the main characteristics that were defined in other studies. The previous calibration of other Andalusian cathedrals, however, facilitated the work by establishing baseline values (Álvarez- Morales et al. 2014; Alonso et al. 2014).

Regarding the boundary conditions, the number of rays used in the calculations was established according to the size of the space, and more rays were required, the more the volume increases. Based on a recommendation of the software, a ratio of 1.5 times the amount of rays was considered, having tested that this number converges. The length of the room impulse response was set individually, since it was longer than the measured reverberation time. The selected calculation algorithm was type 1, split 0.

The calibration process is essentially based on the application of an iterative algorithm from the variation of estimated absorption coefficients. Differences in the threshold of perception between measured and simulated values of the main acoustic parameters were determined, especially those related to reverberation time (T30). The adjustment was completed after the analysis of other acoustic parameters such as C80 and Ts. The measure used to justify these differences in values is the JND, which is defined as the minimum perceptible subjective variation, widely used in these types of investigations (Bork 2005). Conventionally, completion of the calibration process and subsequent acceptance of the model are established when the JND differences are lower than 1 for T30 (5%), and less than 2 for evaluating other parameters. However, the estimated consideration for widely reverberant spaces must remain flexible, since the threshold of subjective perception differs, as is justified in the work of (Martellotta 2010). Therefore, due to the peculiarity and the scale of the space under study, the reliability of the model can be justified with higher values, mainly at low frequencies.

Figure 2-a)-d) depicts a representation of the spectral result of the model-tuning process of certain acoustic parameters (T30, C80, D50, and Ts). A comparison of spectral behaviour in octave bands between the measured spatially averaged parameters and the simulated parameters is shown. Figure 2-e) shows JND differences for each of the receivers discussed in the adjustment process, that is to say, a total of 14 points located at a distance closer than 35 m from the sound source.

The scope of a suitable adjustment between measured and simulated spectral values can be confirmed, since none of receivers exceeds 1 JND in terms of reverberation time (T30). Differences of perceived definition (D50) are no greater than 1 JND, except for low-frequency spectral values 125 and 250 Hz, where the most significant differences slightly exceed 1 JND. Regarding energy parameters C80 and Ts, the adjustment range has been extended to 2 JNDs, by applying the values established by Martellotta for reverberant churches, as indicated above (Martellotta 2010). After reviewing Figure 2, it can be confirmed that differences remain within the range of 2 JND for each of the receivers. The representation of the averaged values per frequency band shows the difficulty of adjusting for the lower frequencies, since occasional discrepancies appear, especially for the parameter Ts. Note that several studies have proven that GA techniques are sufficiently robust and widely used in the prediction of mid-/high- frequency behaviour of rooms (Savioja and Svensson 2015, Vorländer 2015), while Finite Element Methods constitute the best option for modelling low-frequency sound fields.

3.2.2 Acoustic simulation of ancient configurations

Once the base model that reproduces the current state of the cathedral had been calibrated, it could be used as a starting point to incorporate the required changes, and to develop an extensive analysis between the various spatial transformations over time. The creation of new virtual models in which the choir occupies different positions were then developed (Figure 1). Some changes required the construction of masonry walls both the central nave walls (M1) and the delimitation of the chancel (M2). Such interventions will significantly influence the configuration of the space, since the transfer of the choir involves the creation of new spaces or the removal of existing spaces. The recording impulse responses from all source positions enabled the development of a detailed analysis of various spatial transformations. Regarding the absorption properties that were assigned to the choir stalls (not present in the current base model M3), it was necessary to apply the values obtained after calibration of other Andalusian cathedrals, where there are similar types of lavishly carved choir stalls (Álvarez- Morales et al. 2014; Alonso et al. 2014).

3.3 Acoustic parameters

The acoustic assessment of the three space configurations of the cathedral was carried out by evaluating the acoustical quality both in terms of the objective acoustic parameters defined in ISO 3382-1 (2009), and of the four orthogonal parameters related to subjectively perceived sound in terms of temporal design of the sound field (Ando 1998).

On the one hand, within the group of objective parameters that were analysed, the reverberation time (T30), which was the main factor considered in the calibration process, can be determined as the time needed to attain a reduction of 60 dB in the sound pressure level from the moment the sound source that produces sound stops emitting. The Early Decay Time (EDT) can be defined as the subjective reverberance and corresponds to the slope of the decay curve of the response, between the points, to 0dB to -10dB. As indicated in previous sections, the analysis focuses primarily on the musical quality of the enclosure, due to the wide variety of music performed in the cathedral: chants, and instrumental music (orchestral and organ). Hence, this study centres on the values provided by parameters such as clarity (C80), which measures the range of the listening perception for musical use, and centre time (Ts), which is related to the balance between early and late energy reaching the receiver.

On the other hand, subjective parameters that are based on brain activities are also taken into consideration since the existence of links between acoustic parameters and perceptive aspects of human hearing have been discovered. In fact, the model of hearing, defined by Ando (1998), implies that sound-processing capabilities of each cerebral hemisphere in the human brain significantly influence the description of subjective parameters. In this regard, it has been found that temporal data contains information on important musical qualities (Ando 1998). Within the set of the four orthogonal parameters that assess the acoustic quality of the cathedral, two different groups are categorized: temporal factors and spatial factors. The delay of first reflection ($\Delta t1$) and the subsequent reverberation time of the signal after the early reflections (Tsub) are included in the first group. $\Delta t1$ can be determined as the physical time between the direct sound perceived by the listener and the first reflection; its values were analytically obtained in our study by using the image source model (ISM) calculated by the acoustic software. Tsub was calculated according to conventional procedures and coincides with T30. Listening level of sound (LL) and Inter Aural Cross Correlation (IACC) are contained in the second group. LL coincides with SPL (A-weighted): the primary criterion for listening to sound, which describes the spatial distribution inside the church. IACC measures the similarity in sound signals arriving at each ear of the listener.

3.3.1 Optimal values considered for the acoustic parameters

This section determines the optimal values of the parameters considered, in terms of the subjectively preferred sound qualities for the given environment. Several studies have established recommended acoustic values for concert halls and auditoriums, for each of the previously defined parameters. However, the geometric characteristics of a cathedral and its acoustic requirements significantly differ from those required for a concert hall. In fact, certain studies have shown that an acoustic sensation inside an ecclesial space can vary considerably depending on the musical motif performed (Martellotta 2008). Therefore, the unique characteristics and the spatial complexity of a space such as the Cathedral of Granada, hinder the adjustment of optimum values. Due to the lack of literature related to large spaces, values for opera halls proposed by Gade (2007) were considered, while taking into consideration some flexibility on establishing the ideal ranges of sound quality of the cathedral.

In relation to the orthogonal parameters defined by Ando, It is necessary to first define the optimal values in order to calculate the corresponding scale value of preference (Si-value), which establishes how much the parameter value moves away from the preferred listening conditions. The total S-value is the result of the sum of various Si-values related to each parameter, for each source-receiver combination. The calculation is defined in detail in the research conducted by Ando (1998).

It is found that the basis for the definition of most of the preferred conditions is related to the actual duration of the autocorrelation envelope (τe), which is extracted from the auto-correlation function (ACF). It should be noted that τe is largely dependent on the type of sound signal emitted, and therefore different hypotheses, each depending on the music repertoire, are needed in order to state the acoustic quality of the cathedral. The musical performance in a cathedral is widely varied, since this type of enclosure has become one of the venues for the performance of vocal and instrumental concerts. Hence, a value of 26 and 90 ms was used for Gregorian and Alleluia chants, respectively, and 70 and 136 ms depending on the selected piece of orchestral music (Mozart's Overture and Bruckner's Romantic Symphony, respectively). Based on these assumptions, and by considering the approximate relationship for the most preferred delay time and τe:

$$[\Delta t_1]_p = \tau_p \approx (1 - \log_{10} A_1)\, \tau e \qquad (1)$$

where A_1 is the relative pressure amplitude of the first reflection compared to direct sound. In this study, due to the fact that both a weaker direct sound and weaker reflections correspond to receivers at a greater distance, a simplified approach was followed, assuming the most preferred delay time ($\Delta t_1 p$) just equal to τe value resulting from the various music motifs (Martellotta 2008). The most preferred subsequent reverberation time is defined as follows:

$[Tsub]_p = 23\tau e$ (2)

Regarding LLp, it can clearly be observed that this parameter depends on the type of performance and on the number of instruments. It is therefore conventionally evaluated by assuming the level at a specific point of the enclosure as the preferred value: in this case taken approximately at 15 metres from the source. In the case of IACC, the dissimilarity of signals arriving at the two listener's ears is preferred, and, the most preferred value is assumed to be 0. However, research that is currently under development shows that this fact is not emphasized when the listener perceives the sound in such a reverberant space. In this way, it was possible to check the acoustic suitability of each configuration of the cathedral.

4. Analysis of results

In this paper, the acoustic evaluation is described of the different historical configurations that arose after the transfer of the choir to different positions (Figure 1). Sound-field analysis was performed at various stages, focused on assessing the musical quality of the enclosure. Similarly, a comparative study between the acoustic environments of the three scenarios is developed, whereby both the position of the sound source and the performance of different musical motifs are varied.

The stages in which study are organized as follows: firstly, sound sources linked with these historical configurations are considered in order to study the acoustic suitability of each model according to the main purpose associated with each historical moment; secondly, each model is assessed by considering the same position of sound source, located on the edge between the chancel and the transept, where cantors and orchestra are placed during the performance of musical concerts; likewise, a comparative analysis is made considering multiple sound sources; finally, the musical performance is also assessed in terms of subjective preference by carrying out a discussion of results under a temporal design approach.

4.1 Acoustic analysis of the three configurations

In order to achieve a better approach when developing this analysis, the indoor space of the cathedral was categorized into three areas: chancel (R1, R2, R3), transept (R4, R5, R6 and R7), and central nave (R8, R9, R10). This classification enables the influence of the choir position to be ascertained in each of the areas considered. All models were simulated under both unoccupied (M1_e, M2_e, M3_e) and occupied conditions (M1_o, M2_o, M3_o), in order to estimate the acoustic impact of the congregation. Since the location of the choral space influences the overall configuration of indoor space, it is clear that a density variation of occupation exerts a significant impact on the results.

4.1.1 Sound source position associated with each model configuration

Figure 1 shows that source locations in M1, M2 and M3 configurations vary depending on the historical moment, and correspond to the situation of the choir. Receiver points are located within occupied zones. Figure 4 depicts the spectral behaviour of the perceived reverberation (EDT), clarity (C80), and centre time (Ts) in the three models, both in empty and occupied conditions. Table 4 shows the values of the various acoustic parameters considered in this study for the three models, spectrally and spatially averaged both individually by zone and overall.

Regarding the reverberation time, the high values obtained can be observed, which are widely distant from the optimal values for any musical activity. The immense volume, which exceeds 160000 m3, and the arrangement of reflective materials (marble and plaster) in a large percentage of the surfaces of the temple, constitute the principal facts that have significantly influenced these results.

If results categorized into areas are observed (Table 4), T30 values varied less than 1 JND between each area, except in the presbytery where the choir is located in M2. However, EDT significantly differs between each zone, depending on the position of the sound source, reaching the lowest values in the vicinity of choir, due to the presence of the wooden stalls. This means that the initial slope of the decay curves is more pronounced, which in turn is associated with a relatively low density of early reflections: a factor closely related to EDT. In this case, the perceived reverberation varies up to 4 seconds in the presbytery, between M1 and M2, due to the incorporation of the choir in M2, which involves the closure of the ambulatory. The same effect is observed when analyzing the results of the central nave, where the presence of choir walls drastically reduces the reverberant sensation. However, the spatial average of all receivers reduces the EDT variation between the three models, oscillating around 0.80 s (2 JNDs). Logically, the impact generated in this parameter by the occupation is significantly higher for M2 and M3, since the absence of the choir in the central nave allows a larger congregation to be accommodated. For that reason, a significant variation between the two hypotheses of about 3 JNDs is obtained in M2 and M3, whereas the difference is below 2 JNDs in M1 (Figure 4).

Figure 5 shows simulation mappings of the C80 parameter for the 1 kHz octave band, which allow the influence of the sound-source position to be taken into consideration in the values of the parameter. The presence of columns together with the increase of the source-receiver distance generates a significant variation in the results. Finally, Figure 6 provides the relationship between the spectrally averaged parameters versus source-receiver distance. The expected behaviour for the C80 and Ts parameters from the proposed model of Barron and Lee and Barron (1988) is also incorporated (Figure 5).

It can be observed that the overall C80 values are clearly more unfavourable in the M2 model, since the audience is farther than 20 metres from the sound source. The presbytery is a space for the clergy, with optimal acoustic conditions to attend any performance; however, clarity C80 values decrease when crossing the boundary of the area of the presbytery (Fig. 4 and Table 4). There is a similar occurance in M1, where the choir space located in the central nave behaves as a private area, due to the lack of visibility and worsening acoustic conditions in most of the occupied areas. There is a difference of almost 3 JNDs in this area, between the spectral and spatial average of M2 and M3, as seen in Table 4 for C80. A variation of up to 2 JNDs occurs with respect to the value proposed by Gade (2007). The acoustic behaviour corresponds acceptably with respect to that proposed by Barron and Lee, as shown in Figure 5, although the differences between the hypotheses of occupied and empty space individualized for each receiver increase proportionally to the S-R distance. Finally, regarding the Ts values, it should be noted that the behaviour in the three models corresponds to that previously described for C80. Similar values are obtained both in M2_o and M3_e (Figure 4). The threshold of subjective perception is adapted to the conditions of such enclosures, and reflect significantly different results in the same area of up to 8 JNDs, depending on the model considered (Table 4). Hence, the presence of the choir is relevant, since the arrival of early reflections is significantly reduced outside the enclosure, and greatly affects the ratio obtained between the early and late energy that reaches the listener. The acoustic behaviour does not faithfully correspond to that proposed by Barron and Lee, with disparities from a S-R distance of 15 m (Figure 6).

4.1.2 Source position independent of model configuration

The analysis of the historical transformations when considering the same sound source location allows us to make a comparison that focuses directly on the each model configuration. Receivers selected for the study are visible from the source (S3) and hence enjoy direct sound. Acoustics analysis has diversified into two stages: firstly, a number of the acoustic parameters referred to in the ISO 3382-1 (2009); were taken into account; and secondly, a subjective analysis is conducted which considers the temporal and spatial factors investigated by Ando.

- From the ISO parameter approach:

Table 5 shows the values of the various parameters, spectrally and spatially averaged both individually by zone and in general, in all historical configurations. Figure 7 shows the spectral behaviour of the perceived reverberation (EDT), clarity (C80), and centre time (Ts) in the three models, both under empty and occupied conditions. Figure 8 provides the relationship between spectrally averaged parameters and the S-R distance. The curve that reproduces the behaviour of the model proposed by Barron and Lee (1988) is included.

In relation to T30, the effect of air absorption significantly reduces the EDT at mid and high frequencies. In contrast to the assumptions stated in previous sections, the perceived reverberation is practically the same in empty conditions in the three models, and varied less than 1 JND. M3 is set as the optimum organization of space due to the absence of visual obstacles, which favours the use of the cathedral, for massive attendance events. However, decreasing early reflections in a large open space has repercussions on acoustic conditions with respect to the other two models. Finally, if the results of the unoccupied and occupied hypotheses are compared, then a decrease of EDT of at least 2 JNDs in all the models (M1, M2, M3) is observed.

In relation to C80 and Ts, the detriment of the acoustic sound-field of M3 increase slightly and move away from the values obtained in M1 and M2 (Table 5 and Figure 8). Nevertheless, the minimum threshold of perception is exceeded in only those areas close to the choir (chancel in M2 and central nave in M1), where clarity increases significantly for each model. The proximity of mean C80 values, should be borne in mind, since they resemble the suitable conditions determined by Gade (2007).

The same range of variations is maintained when Ts is considered; however, the relationship between the acoustic sound-field and that proposed by Barron and Lee is lost, except for M3: the configuration with the most open space, characterized by the absence of the choir (Figure 7).

- From the temporal and spatial factors approach:

Figure 9 depicts differences for each receiver point in each model. Gregorian chant was considered as a musical motif performed in S3 source in this comparative analysis due to the importance of ecclesiastic chant at the liturgy, and because of the significant role played by choirs in cathedrals. Parameter values were obtained following the acoustic simulation of various configurations. Consequently, it was possible to observe which model was acoustically more suitable by analyzing how these parameters influence the linear scale value.

On the one hand, the same τe was selected in the obtainment of the parameters in attaining three models (Table 3). However, varying the position of the choir has a strong effect on the arrival of the early reflections at certain points. In relation to S3, an increase of the negative effect on the delay of the first reflections is perceived at points farther away from the source. The obtained Δt values differ significantly from the preferred values in Gregorian chant (τp≈91 ms). When evaluating the results generated by other temporal factors (Tsub), a preference for relatively close reverberation at 2 s is observed, which differs widely regarding the reverberation time obtained in the cathedral. This fact impacts negatively in the scale value (Figure 9). It should be noted that the sum of Si-values in R4 and R5 attain a result lower than 2 in the total scale value, since its strategic position between two pillars, generated a positive effect on the results. In the light of the results, it could be stated that, as for ISO parameters, the M2 configuration provides the best acoustical quality, and obtains the lowest scale value, by assuming the best results are found at points located in estimated occupancy areas.

Moreover, in relation to spatial factors, it should be noted that IACC is the parameter with the greatest negative influence on the subjective preference (except for R6 and R7) since it approaches the scale value -1 at almost all points considered. Consequently, this fact means that signals in the cathedral coming from the two sides are largely equal. This equality occurs by means of the approach of the binaural sensation as monophonic behaviour in the cathedral, since IACC values were close to 1 (Table 6). Except for those points located in the historical choir areas, in general no significant influence on the type of configuration is contemplated. Finally, regarding LL, a negative effect on those points closest to the sound source (R6 and R7) is highlighted in all models; this effect is less noticeable in M1 due to its more uniform distribution generated by the central location of the choir. Therefore, high values of LL are recorded at the excessively close points and these differ from the reference value (LLp) by almost 8 dB (Table 6), conventionally considered at 15m from the source.

4.1.3 Multiple sound sources

Multiple sound sources, located so as to represent the situation of an orchestra or choral group, were considered in this analysis. In this work, simultaneous playback from various sources was calculated using TUCT engine. However, it should be noted that exist other approaches that generate plausible acoustic effects at interactive rates in large environments containing many sound sources. In fact, a hybrid convolution-based audio rendering technique that can process thousand of sound paths at interative rates is performed (Schissler and Manocha 2016).

The aim is to determine the impact on the acoustic behaviour of the cathedral. To this end, the configuration that reproduces the current state of the temple (M3), and the actual position of groups of chanters (S3) was selected. Two receiver points located in the central nave (R08 and R09), 15 and 23 metres from the source respectively, were chosen to establish the comparative.

Figure 10 shows differences in terms of JNDs between the hypothesis with one source and that with multiple (5) sources. Table 7 shows the values obtained for each acoustic parameter considered when both scenarios are taken into account. It is noted that, as could be estimated, variations in terms of reverberation are insignificant. However, when considering variations in the energy parameters C80 and Ts, they remain considerably noticeable. An increase of 8 dB SPL generates a difference of values approaching 3 JNDs and this increases with distance in the case of Ts.

4.2 Acoustic analysis of music motifs

In this section, the perception of the sound field is described by showing variations of each orthogonal parameter, depending on the music motif. The same configuration (M3) was considered in this analysis in order to evaluate how the type of music affects one specific model. The selected repertoire was the following: Alleluia and Gregorian chants were selected within the group of vocal music; Bruckner's Romantic Symphony and Mozart's Overture were chosen in the group of instrumental music. A different τe was therefore chosen for each music motif (Table 2). This choice bears strong consequences on the sum of each scale value (Si-value). In fact, since temporal data contains information regarding important musical qualities, the two temporal factors have a significant influence on the variation of S. In this analysis, spatial factors remain constant since the early reflections are the same (M3).

Based on the assumption that the optimum reverberation time value for the Alleluia chant is less than a second (Tsubp ≈0.60 s), it could be stated that Tsub had the strongest negative influence on total scale value (Figure 10). A reverberant cathedral attains much greater values for this parameter. Nevertheless, a positive effect is observed in S2, since it was observed that delay time values do not greatly differ from the optimum values for this activity ($\tau p \approx 20$ ms), thereby obtaining the poorest acoustic quality. The opposite effect occurs when Bruckner's Romantic Symphony is performed, due to a longer preferred τe requirement for this type of music, characterized by slow-tempo passages and bass tones. In this case, the preferred subsequent reverberation time (Tsubp) was longer, and attained better optimum design objectives in the cathedral. However, except at certain points located at specific positions, general early reflections usually arrived within 20-30 ms, a value that differs greatly from the τp, which was the largest of all the parameters in the selected repertoire, resulting in a severely worse behaviour. Figure 11 shows the influence of music motifs, and it is verified that the effect generated by reverberation is more perceptible. Thus, when optimum reverberation values are longer, they are better suited to the acoustic behaviour of the cathedral. However, it can be observed that there is a balance between the negative effects of S2 and S3 when τp exceeds 70 ms, and therefore the optimum reverberation reaches 2s.

5. Conclusions

This article aims to recreate the indoor acoustics of a cathedral by means of the development of a comparative analysis of the acoustic behaviour of the various configurations associated with spatial transformations that have occurred since its original construction. The procedure carried out involves onsite measurements and virtual modelling in order to create a solid base for the prediction of the acoustic environment of the cathedral. The methodology is applied to the case study of the Cathedral of Granada, which was undergone three spatial transformations throughout its history, following the transfer of the location of the choir: in the middle of the central nave (M1); in the chancel (M2); and the suppression of the choir enclosure (M3).

Music has always been a major aspect for consideration in places of worship, and was recognized as presenting specific features when composed for a given church. An analysis of the three space configurations of the cathedral was carried out by evaluating the musical quality of indoor acoustics both in terms of acoustic parameters relating to reverberation, early-to-late arriving sound energy ratio and temporal design. Various hypotheses were considered related to the position and the number of the sound sources together with occupation. Furthermore, the perception of the sound-field was also described by analysing the subjective preference depending on the music motif.

In the study of indoor acoustics reconstruction, the importance of the choir position, understood as a distinct space inside the cathedral, is provides the focus of this work. The structure that delimitates the choir enclosure generates, in the same model, diverse acoustic environments with greatly varying characteristics depending on the source position, the configuration of the space, the occupancy rate, the number of sound sources, and the musical motif.

- Sound source position linked to each model configuration: The best acoustic assessment occurs when the sound source is associated to its choir configuration (S1 inn M1, S2 in M2 y S3 in M3). These source positions do not determine the reverberation time, but the perception of the reverberation time, with smaller EDT values in areas close to the choir. In the environments of close proximity, spatial averages of the energy parameters at receiver points where the choir is delimited (M1 and M2) reflect better acoustic conditions when these obstacles are removed (M3). However, when globally assessing these parameters at the remaining points occupied by the congregation, better results are obtained with the M3 configuration. The influence of occupation on EDT can vary by 3 JNDs, both in M2 and M3; in the case of the Ts parameter the difference can even reach 8 JNDs.
- Source position independent of model configuration: If S3 sound source is adopted as the sole position in the three models (M1, M2, and M3), conclusions can be drawn on indoor acoustic assessment of the cathedral depending on the configuration. The absence of visual obstacles in M3 is highly favourable for achieving an open space that allows its use for massive attendance events. However, a decreas of early reflections worsens the subjective acoustic conditions with respect to M1 and M2. The results obtained in these two models indicate that the presence of the choir plays a representative role. Outside these walls, the lack of early reflections becomes more acute, greatly affects the ratio obtained in the energy parameters C_{80} and Ts. It was possible to verify that the M2 configuration also provides the best acoustical suitability, in terms of

temporal design, by obtaining the lowest scale value, on assuming the best results are found at points located in estimated occupancy areas

- Multiple sound sources: variations in terms of reverberation remain insignificant, while variations in the parameters C80 and Ts are considerably noticeable. These differences are emphasized when S-R distance is increased. An increase of 8 dB in the SPL, generated by placing several sources, causes an improvement of up to 3 JNDs in the results of those energy parameters results.
- From the temporal and spatial factors approach: Different music motif: The various optimal conditions of reverberation associated with each musical motif exert great influence on the subjective perception. The high reverberation of the cathedral, of close to 10 s, has a negative influence for any musical style. Nevertheless, a subjective preference for certain passages of instrumental pieces rather than for chants should be noted, since long reverberation generates a positive effect on those slow tempo and bass passages performed by wind or string instruments. In the light of the results, it can be confirmed that the cathedral is acoustically more suitable when optimum reverberation values are longer, due to the relative insignificance of the negative effect generated by the early reflections.

References

Abdou, A.A. 2003, “Measurement of acoustical characteristics of mosques in Saudi Arabia”. *Journal of the Acoustical Society of America* 113: 1505–1517.

Alonso, A., J.J. Sendra, R. Suárez and T. Zamarreño. 2014. “Acoustic evaluation of the cathedral of Seville as a concert hall and proposals for improving the acoustic quality perceived by listeners”. *Journal of Building Performance Simulation* 7 (5): 360-378.

Alonso, A. and F. Martellotta. 2015. “Room acoustic modeling of textile materials hung freely in space: from the reverberation chamber to ancient churches”. *Journal of Building Performance Simulation*. Published online, Article in press.

Álvarez-Morales, L., S. Girón, M. Galindo and T. Zamarreño 2016. “Acoustic environment of Andalusian cathedrals”. *Building and Environment* 103: 182-192.

Álvarez-Morales, L., T. Zamarreño, S. Girón and M. Galindo. 2014. “A methodology for the study of the acoustic environment of Catholic cathedrals: application to the Cathedral of Malaga”. *Building and Environment* 72: 102-115.

Ando, Y. 1998. “Subjective Preference as an Overall Impression of the Sound Field.” Chap. 4 in *Architectural Acoustics: Blending Sound Sources, Sound Fields, and Listeners* Springer-Verlag: New York.

Barron, M. and L.J. Lee. 1988. 2Energy Relations in Concert Auditoriums” *Journal of the Acoustical Society of America*. 84 (2): 618–628.

Benedetto G. and R. Spagnolo. 1984. “Evaluation of sound absorbing coeffcients in a reverberant room by computer-ray simulation", *Applied Acoustics* 17: 365 – 378.

Berardi, U. 2013. “Simulation of Acoustical Parameters in Rectangular Churches.” *Journal of Building Performance Simulation* 7 (1):1-16.

Bork, I. 2005. “Report on the Third Round Robin on Room Acoustical Computer Simulation –Part II: Calculations.” *Acta Acustica united with Acustica*. 91 (4): 740–752.

Carvalho, A., M. Lencastre, M. and V. Desarnaulds. 2002. “Sound absorption of 18th-century baroque woodcarving in churches”, Paper presented at the Inter-Noise, Michigan, USA, August 19-21.

Dalenbäck, B.I.L. 1999. “Verification of prediction based on randomized tail-corrected cone-tracing and array modeling”. *Journal of the Acoustical Society of America*. 105, 1173.

Dalenbäck, B.I.L. 2011. “CATT-Acoustic v9 Powered by TUCT User’s Manual”. Gothenburg: CATT.

Díaz-Chyla, A., A. Pedrero, C. Díaz-Sanchidrián. 2013. “Influencia en los parámetros acústicos de las posiciones conocidas del coro catedralicio de León y sus revestimientos históricos” Proceedings of 44 th Tecniacustica and EAA European Symposium, Valladolid, Spain, October 2-4.

Gade, A. C. 2007. “Acoustics in Halls for Speech and Music”. In *Springer Handbook of Acoustics,* edited by T. D. Rossing, 301–350. New York: Springer.

Hak, C. C. J., R. H. C. Wenmaekers, L. C. J. van Luxemburg, 2012. “Measuring Room Impulse Responses: Impact of the Decay Range on Derived Room Acoustic Parameters”, *Acta Acustica united with Acustica*. 98 (6): 907–915.

ISO 3382-1. 2009. *Acoustics-Measurement of Room Acoustic Parameters. Part1: Performance Rooms*. Geneva: International Organization for Standardization.

Kosała, K., and Z. W. Engel 2013. “Assessing the acoustic properties of Roman Catholic churches: A new approach”. *Applied Acoustics*. 74: 1144-1152.

Lu, S., X. Yan, W. Xu, Y. Chen and J. Liu. (2016). “Improving auditorium designs with rapid feedback by integrating parametric models and acoustic simulation”. *Building Simulation* 9 (3): 235-250.

Martellotta, F., E. Cirillo, M. D'Alba, E. Gasparini, D. Preziuso. 2008. "Acoustical reconstruction of San Petronio Basilica in Bologna during the Baroque Period: The Effect of Festive Decorations." Paper presented at the Acoustics08, Paris, July 29– 4.

Martellotta, F. 2008. "Subjective study of preferred listening conditions in Italian Catholic churches", *Journal of Sound and Vibration*. 317: 378-399.

Martellotta, F. 2010. "The Just Noticeable Difference of Center Time and Clarity Index in Large Reverberant Spaces" *Journal of the Acoustical Society of America* 128 (2): 654–663.

Mehra, R., Raghuvanshi, N., Savioja, L. Lin, M.C., Manocha, D. 2012. "An efficient GPU-based time domain solver for the acoustic wave equation". *Applied Acoustics* 73: 83-94.

Navascués, P. 2004. La Catedral en España. Arquitectura y liturgia, Lunwerg editor, Barcelona.

Pedrero, A., R. Ruiz, A. Díaz-Chyla and C. Díaz. 2014. "Acoustical study of Toledo Cathedral according to its liturgical uses". *Applied Acoustics* 87: 23-33.

Pelzer, S. and M. Vorländer. 2010. "Frequency and Time dependent Geometry for Real-time Auralizations". In Proceedings 20th International Congress on Acoustics (ICA 2010), Sydney, Australia, August 23-27.

Physikalisch-Technische Bundesanstalt (PTB) database. Braunschweig (Germany).

Queiroz-de Sant'Ana, D. and P. H. Trombetta-Zannin. 2011. "Acoustic evaluation of a contemporary church based on in situ measurements of reverberation time, definition, and computer-predicted speech transmission index". *Building and Environment*. 46: 511–517.

Savioja, L. and U. P. Svensson. 2015. Overview of geometrical room acoustic modelling techniques. *Journal of the Acoustical Society of America* 138 (2): 708-730.

Schissler, C. and Manocha, D. 2016. “Interactive Sound Propagation and Rendering for Large Multi-Source Scenes”. *ACM Transactions on Graphics* 36 (1) Article 2:1-12

Segura García, J., A. Giménez Pérez, J. Romero Faus and R. Cibrián Ortiz de Anda. 2011. “A comparison of different techniques for simulating and measuring acoustic parameters in a place of worship: Sant Jaume Basilica in Valencia, Spain”. *Acta Acustica united with Acustica*. 97: 155-170.

Siltanen, S.; Lokki, T.; Savioja, L.; Christensen, C.L. 2008. Geometry Reduction in Room Acoustics Modeling. *Acta Acustica united with Acustica* 94:410–418.

Soeta, Y.,K. Ito, R. Shimokura, S. Sato, T. Ohsawa and Y. Ando. 2012. “Effects of sound source location and direction on acoustic parameters in Japanese churches”. *Journal of the Acoustical Society of America*. 131: 1206–1220.

Suárez, R., J. J. Sendra and A. Alonso. 2013. “Acoustics liturgy and architecture in the Early Christian Church. From the Domus ecclesiae to the Basiliaca”. *Acta Acustica united with Acustica* 99: 292-301

Suárez, R., A. Alonso and J. J. Sendra. 2016, “Archaeoacoustics of intangible cultural heritage: The sound of the Maior Ecclesia of Cluny” *Journal of Cultural Heritage* 19: 567-572.

Svensson, U.P., Calamia, P., Nakanishi, S. 2009. "Frequency-domain edge diffraction for finite and infinite edges," Acta Acustica united with Acustica 95:568-572.

Vorländer, M. 2008. *Auralization*, Springer-Verlag: Berlin.

Vorländer M., D. Schrödera, S. Pelzera and F. Wefersa. “Virtual Reality for Architectural Acoustics”. *Journal of Building Performance Simulation* 8 (1); 15-25.

Figure captions

Figure 1. Floor plans of the Cathedral of Granada: a) 1619-1929 period; b) 1929-1992 period; c) Current status, since 1992, with representation of furniture. Sound source (S) and receiver (R) positions.

Figure 2. Spectral behaviour of spatially averaged acoustic parameters: a) T_{30}; b) C_{80}; c) D_{50}; d) Ts; e) differences in JND between measured in-situ and simulated values.

Figure 3. Representation of the process of creating virtual models.

Figure 4. Spectral behaviour of spatially averaged acoustic parameters: a) EDT; b) C80; c) Ts.

Figure 5. Simulation mappings of C80 parameter at 1kHz: a) M0; b) M1; c) M2.

Figure 6. Average values of acoustic parameters C80 (a) and Ts (b) with respect to S-R distance for M1, M2 and M3, in empty and occupied conditions. Correspondence with Barron model.

Figure 7. Spectral behaviour of spatially averaged acoustic parameters: a) T30; b) C80; c) Ts.

Figure 8. Average values of acoustic parameters C80 (a) and Ts (b) with respect to S-R distance for M1, M2 and M3, in empty and occupied conditions. Correspondence with Barron model.

Figure 9. Influence of various configurations of the cathedral in the orthogonal parameters considered on the linear scale value of each receiver, from the same sound source (S3).

Figure 10. Differences in JND when multiple sound sources are considered.

Figure 11. Influence of four separate music motifs on the orthogonal parameters considered on the linear scale value of each receiver. Configuration M3 and sound source S3.