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Virtual acoustic environment reconstruction of the hypostyle mosque of Cordoba

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ABSTRACT

Current simulation tools and virtual-reality technologies enable the reconstruction of the historical sound inside heritage buildings, and have become powerful tools in Archaeoacoustics. The sound generated within the current state of a heritage building can be used to characterize the sound of the past inside that building by using virtual sound reconstruction. In this work, this methodology is applied to one of the emblematic Islamic temples of the West: the Aljama Mosque of Cordoba. Based on the onsite acoustic measurements carried out in its current state as Mosque-Cathedral, the original state of the Mosque has been reconstructed in the different spatial configurations throughout its history from the 8th to the 10th century. By means of the acoustic simulation of the different models generated from these spatial configurations, it has been possible to reconstruct the sound of the Islamic past of this monumental building. Although the successive enlargements of the mosque managed to maintain visual unity in its interior space, its sound perception has become divided. The values of the main acoustic parameters that characterize this acoustic perception support the hypothesis that spatial division occurs from the point of view of sound.

1. Introduction

The importance of intangible heritage is recognized in the Convention for the Safeguarding of the Intangible Cultural Heritage [1]. From this convention, a new scientific approach to cultural heritage emerges [2], with new methodologies that include the application of diverse computer technologies, initially focused on the visual aspect, thanks to the potential of immersive visualization and 3D reconstruction of archaeological sites [3]. Other studies took into consideration the incorporation of simulation tools by focusing on sensory features, such as acoustics and lighting [4]. In this regard, the combination of different techniques can be considered as a useful and interesting resource, since the recreation of virtual reality allows the sensory experience to be extended. In this way, the addition of a subjective component that incorporates realistic rendering techniques facilitates the virtual reconstruction of sound, understood as an intangible cultural heritage [5]. Through Archaeoacoustics, and thanks to the virtual acoustic simulation tools developed in recent decades, it is possible to study the acoustic environment of ancient sites and monuments [6], and to recover the sound of heritage spaces that have disappeared or have since undergone major transformation [7].

The recovery of the sound of the past has been applied to various types of approaches ranging from the conception of soundscapes of the past [8], to the expansion of the concept to different ages and cultural contexts [9,10], as well as several building typologies, and with various objectives [11–14]. These applications include: prehistoric constructions, such as Stonehenge [15], which are rebuilt in their original state; Greek and Roman theatres, as have been carried out in the ERATO Project [16], the Syracuse Charter [17], and by Berardi et al. [18], reconstructed from onsite measurements; ecclesial spaces in the West that have since disappeared [19], thereby linking the liturgy and its spatial configuration [20] by modifying the position of the choir space [21], and analysing the functional use of these spaces for cultural purposes [22]; and ecclesial spaces in the East, such as Sinan's Mosques and the Byzantine Churches, which are reconstructed acoustically as a form of identification, revival and conservation (CAHRISMA) [23].

There is extensive scientific literature on acoustics of worship spaces, with several significant examples throughout history [24], grouped by architectural styles [25], with different measurement techniques [26,27] and simulation techniques [28], that analyse the acoustics [29], or consider the methodology to be applied in large cathedral spaces [30]. However, acoustic studies on mosques remain scarce. Of these studies, the first work carried out by Hammad [31] stands out, as are those studies that characterize the acoustics of

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contemporary mosques by means of onsite measurements, through objective indicators of Reverberation Time (T_{30}), clarity index (C_{50}), and Speech Transmission Index (STI) [32], or by Reverberation and Strength (G) [33], or by analysing the degree of intelligibility, both measured and simulated [29]. Furthermore, studies that focus on subjective aspects of Ottoman mosques through subjective surveys [34] are also worthy of note.

The main aim of this work is to reconstruct the sound of the Islamic rite throughout the enlargement process of the Mosque of Cordoba, from its initial creation to the erection of one of the biggest mosques of the time, and to recover the sound of the hypostyle typology of mosques, considered as a prayer space, through the application of acoustic simulation technologies. A second objective involves both the determination of the acoustic quality of the Muslim space, according to the current evaluation criteria applied in room acoustics, and the evaluation of the differences in the acoustic behaviour of each spatial configuration associated to its liturgical function. Therefore, a paradigmatic example of this typology has been chosen, the Aljama Mosque of Cordoba, whose interior space has undergone continual transformations since the 8th century, with three enlargements as a mosque until its transformation into the current space configuration as a Mosque-Cathedral. The main parameters that determine the acoustic behaviour of this Muslim space in each of its configurations throughout history are obtained by carrying out virtual sound reconstruction.

2. The mosque of cordoba

The Mosque of Cordoba was the largest in the western Muslim world and it consolidated the typology of hypostyle rooms. Its preservation, after more than 1200 years, has been possible thanks to its transformation into a Christian cathedral. At present, it can be contemplated as a construction of enigmatic beauty in which the Muslim space fuses with the Christian space, thereby establishing a unit of space that was declared Patrimony of Humanity by UNESCO in 1984.

The typology of a hypostyle mosque responds to the needs of the Islamic rite: it is associated to the principle of maximum simplicity and accommodates a massive congregation. It presents a series of basic elements:

– A covered prayer room divided into aisles, *haram*, preceded by a courtyard, *sahn*.
– A wall facing Mecca, *qibla*, which marks the direction of the prayer, where a small empty niche opens, the *mihrab*.
– A raised platform to the right of the *mihrab*, the *minbar*, from which the Friday sermon, *jutba*, is proclaimed in the aljamas mosques.

The ceremony of Islamic worship that takes place in the mosque establishes a relationship between the faithful and God through two rites:

– Rite of prayer, in which the imam, facing the *mihrab*, directs the collective ritual prayer, consisting of verbal sentences and gestures. The preceptive prayer is shaped by a series of cycles, *rakat*, which accompanies the prayer with repetitive movements of the faithful who are standing, sitting, or prostrated.
– Rite of the sermon, in which the *jatib* or preacher, from the *minbar*, directs the prayers, reads the Quran, and delivers the *jutba* or sermon, which is heard by the seated faithful.

The aljama Mosque of Cordoba was erected in 788 by Abd al-Rahman I, who adopted a typology of hypostyle hall that would become the pattern of the mosques of the West. This mosque is formalized by a square enclosure, where the *sahn* courtyard is located in the northern half and the rest, supported by the south wall that serves as the *qibla*, is a hypostyle space for prayer. The great prayer room, of 74 × 37 m, presents eleven aisles arranged perpendicular to the wall of the *qibla* (Fig. 1.a). The need to design the prayer room with a height of more than 9 m implies the idea of an intelligent constructive solution, with a system of double arches superimposed onto slender columns of small diameter (Fig. 2). This solution generates a diaphanous space that allows its expansion in any direction, of greater breadth than depth, and liberates the maximum surface of the floor for a large number of the faithful, while also enabling a greater visibility of the *imam*.

Faced with a demographic increase in Cordoba, Abd al-Rahman II extended the prayer space in the year 848. The enlargement increased the depth of the prayer hall, breaking through the *qibla* wall and built eight new arcades to the south, and hence the original formal structure was repeated, resulting in a practically square prayer room (Fig. 1.b).

In 966, Al-Hakam II built the most important expansion of the mosque following the same approach put forward in the enlargement by Abd al-Rahman II. The wall of the *quibla* was again broken through and the building extended to the south with twelve new arches, resulting in a prayer room where the depth clearly predominates (Fig. 1.c). The formal mechanisms of the first mosque were repeated by incorporating four skylights with ribbed vaults that introduce natural daylight into the prayer room.

The large population of Cordoba in the late X century led Al-Mansur to build the last expansion of the mosque. Faced with the impossibility of further expansion towards the south, the new enlargement was carried out to the east, whereby eight naves were added to the prayer hall throughout its length, by repeating the original formal schema. This enlargement undermines the formal unity, since it widens the building by decentring the *mihrab*, from Al-Hakam II, which is preserved. The result is a large, abstract, and nearly isotropic enclosure, with a length of 79 m and a width of 128 m (Fig. 1.d).

Regarding the spatial division that includes all the enlargements of the Mosque, the “sea” of columns, arches and aisles that form the temple should be borne in mind, since it holds an extremely important role for visual unity and plays a significant part in the indoor acoustics.

3. Methodology

The applied methodology aims to identify and acoustically evaluate each spatial configuration, resulting from the different enlargements previously indicated, and also to create a virtual sound environment.

This work is based on the experimental results obtained from the onsite acoustic measurements of the *mihrab* area of the current state of Mosque-Cathedral. Subsequently, based on the results obtained from the experimental technique, the created model has been calibrated in the same unoccupied conditions. The original interior space of the mosque is then reconstructed in each of its spatial configurations [35], with the presence of the audience taken into consideration. Since none of the models, that of the founding mosque and those of any of its extensions, remains available, the creation process has been carried out in an inverse way in order to achieve a proper validation of the acoustic models, that is, starting from the current model until the foundational model is attained.

From the simulations of the acoustic models, the impulse response (IR) is obtained at each of the receiver points, and the most relevant acoustic parameters of each spatial configuration are deduced. Simultaneously, the generated audio signals are used in subjective evaluations and auralizations.

The acoustic simulations were performed with the CATT-Acoustic v9 program [36] with the TUCT v1.0 h (The Universal Cone Tracer) version 1.0 h, using the algorithm 1, developed by CATT for the acoustic simulation and auralization of enclosures. This software is based on geometrical acoustics (GA) theory [37], which consists of energy-based octave-band echograms. These echograms are calculated in the usual way via pressure-based methods and ray-tracing techniques. These ray-racing techniques involve a ray-tracing algorithm, according to the image source method, a diffuse reflection algorithm by studying the late decay of the sound [38].