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A methodology for the study of the acoustic environment of Catholic cathedrals: Application to the Cathedral of Malaga

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ABSTRACT

Sound propagation in large reverberant religious spaces has remained relatively unexplored within the general context of the acoustics of places of worship. However, complex acoustic physical phenomena can occur in these buildings, where substantial changes in the behaviour of the space can be produced depending on where the sound source is placed. This paper describes the methodology used for the study of the acoustic environment of the Catholic cathedrals of southern Spain, and this is applied to the Cathedral of Malaga. The monaural and binaural impulse responses were determined in the various receivers for five positions of the sound source: major altar, pulpit, choir, organ and retrochoir, which correspond to the positions of use of liturgical, musical, and cultural activities that take place in the temple nowadays. According to the typology of the cathedral, six areas can be established for the location of the congregants and/or the audience. The interdependence of the positions of the source and positions of listeners in the various zones is analysed by processing acoustic parameters related to reverberation, sound strength, clarity, early lateral reflections, and the speech intelligibility. Furthermore, experimental results are compared spectrally with the simulated values obtained from a 3D geometrical-acoustic model created for the space, in which simulation mappings determine the areas of visibility for each sound source position together with the statistical distribution of the values of the acoustic parameters in the areas of influence selected in the cathedral.

1. Introduction

Throughout history, architecture of the Christian church has transformed its layout based on liturgy and activities performed within the worship space. The transition from Romanesque to Gothic, for example, is a change aimed at urban life and the birth of universities and great cathedrals [1]. Not only is the cathedral conceived for liturgical worship, but also as a place of remembrance, celebration and massive representation. The history of architecture is rich in allusions to ephemeral interventions made in the great temples (carpets, drapes, stands, etc…), mainly from the second half of the sixteenth century, reaching its peak in the two Baroque centuries, the seventeenth and the eighteenth centuries, for magna religious, civil, festive and mourning ceremonies. These occasions significantly increased sound absorption in churches and cathedrals, towards which large crowds also contributed. In the absence of a specific architecture for music, large temples were also ceded for music which sponsored, for example, the evolution of monody to polyphony in the history of music [2].

Speech intelligibility in Catholic worship has been an essential objective of its activity only in certain historical periods. In this context, the second half of the sixteenth century can be highlighted as a result of the determinations of the Council of Trent, and the importance that it gave to preaching as a tool of the Counter-Reformation movement. In recent times, the reformation in the liturgy introduced by the Second Vatican Council (ended in 1965) allowed priests to face the congregation, the use of common language instead of Latin in the religious services and masses, and the call for the active participation of the congregation in choral singing. The relevant role of the spoken word in sermons and prayers implied the need for good speech intelligibility. Hence, design of contemporary Catholic churches must ensure both an acceptable standard of acoustics, since original flaws are hard to remedy by using electro-acoustic systems, and refrain from compromising the quality of a good ambience for music [3,4].

From a scientific standpoint, a more in-depth knowledge of room acoustics together with the introduction of digital computers

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as research tools have propitiated great advances. Computers are involved in various purposes: for acoustic measurement to produce impulses and to process impulse responses; to generate synthetic acoustic fields which are addressed to subjective perception investigations; and the most recent, to produce 3D virtual scenarios, related to the past, present or future, for the evaluation and reproduction of optical and sound field conditions of indoor and outdoor designs [5–7]. Since the beginning of this digital age, the main focus has been to quantify the physical parameters that determine the ear response to sound, in order to apply this information to the design process with special emphasis on the architecture for music performances. However, at around the same time, acoustic studies of places of worship were initiated in all faiths [8], following the same metric procedures established and agreed for music venues [9]. Therefore statistical methods to determine the orthogonal acoustic parameters in churches are also used [10,11], and models are formulated to describe the pattern of early reflections in these religious spaces through diffuse sound field hypotheses [12,13], by imposing corrections to theories for concert halls and other proportionate spaces [14]. Given the great variability of ecclesiastical shapes and in order to compare the acoustics between them, a team of three Italian universities has proposed a specific methodology for conducting acoustic measurements in worship spaces [15]. The most recent research considers, through acoustic measurements at various source locations and directions, the effects of the style of liturgy on the acoustic characteristics within churches [16], and several authors propose a synthetic way to summarize the acoustics of churches for both music and speech, by means of the calculation of synthetic indexes [17,18].

In regard to large reverberant worship enclosures, the pieces of work that analyse sound propagation in cathedrals are scarce at the moment, and only studies addressed to partial aspects are currently under development, such as the dependence of the just noticeable differences of certain descriptors of musical sound quality [19] on long reverberation times, and advanced phenomena of acoustic coupling effects in St Paul's Cathedral in London [20], and in St Peter's Basilica in Rome [21].

Despite the large geometric complexity of religious buildings, improvements in computational algorithms have extended the use of ray tracing techniques to also study the spatial sound field in these spaces [21,22].

As a final comment in this section, the quest for in-depth knowledge of the aspects of architectural heritage has led to abundant work in regard to the study and determination of the acoustics of existing spaces, a certain number of which have been rehabilitated and/or renovated for cultural purposes in several countries in the Western environment [23,24]. In this context, the research described in this paper is part of an interdisciplinary research project on the acoustic behaviour of the main cathedrals of Andalusia, which aims to incorporate this behaviour of religious buildings as a scientific part of their cultural legacy and intangible heritage [25]. All cathedrals are organized in the so-called "Spanish style" in which the choir is situated in the centre of the temple.

This paper describes the methodology implemented in the aforementioned research project for the characterization of the sound fields of the Catholic cathedrals of Andalusia and its application to a particular case study, the Cathedral of Malaga (southern Spain), to describe all liturgical and cultural uses of the building for speech and musical events.

2. Methodology

This section describes the procedures followed to measure objectively the room acoustic quality of the Catholic cathedrals by using experimental measurements and simulation techniques. In this analysis, the various usual positions for natural sound sources and the various zones for audience locations are considered and that determine the adopted methodology.

2.1. Experimental measurements

An impulse response (IR), in general, describes the behaviour of a linear time-invariant system in response to a certain external change, as a function of time. Thus, by considering the room as a linear time-invariant system, the room impulse responses (RIR) can be measured at various reception points in order to describe the acoustic behaviour of the cathedrals (see Fig. 1a). Fig. 1b shows a decay energy curve calculated from the RIR by means of backward integration [9] (Schroeder's curve). The reverberation time and other acoustic parameters have been obtained from those impulse responses in accordance with ISO 3382-1 [9].

Measurements were carried out in the unoccupied temples. Environmental conditions were monitored during the measurement period in order to control the sound velocity in air and its absorption in the calibration process of the geometrical models for the simulations. The background noise spectrum was recorded by averaging several minutes of "silence" with a Svantek 958 sound analyser meter. This information is introduced into the simulation setting dialogue in order to obtain the index for the assessment of speech intelligibility.

For the description of the acoustic environment of the cathedrals from RIRs, it is essential to address the various uses of each enclosure. Nowadays, in addition to the liturgical function, with

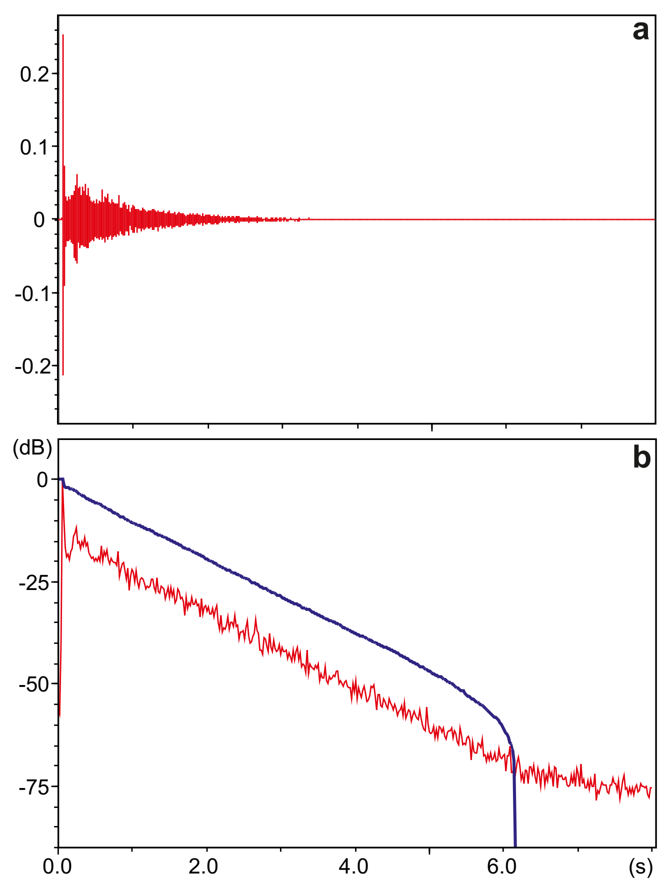

Fig. 1. (a) Room impulse response, RIR; and (b) energy time curve, ETC, with the Schroeder's integral (thick line) calculated with noise compensation. (All measured at the receiver point R3, for source S1, filtered at 1 kHz in the Cathedral of Malaga).