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An investigation of multi-rate sound decay under strongly non-diffuse conditions: The crypt of the Cathedral of Cadiz

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A B S T R A C T

Multi-rate sound decays are often found and studied in complex systems of coupled volumes where diffuse field conditions generally apply, although the openings connecting different sub-spaces are by themselves potential causes of non-diffuse behaviour. However, in presence of spaces in which curved surfaces clearly prevent diffuse field behaviour from being established, things become more complex and require more sophisticated tools (or, better, combinations of them) to be fully understood. As an example of such complexity, the crypt of the Cathedral of Cadiz is a relatively small space characterised by a central vaulted rotunda, with five radial galleries with flat and low ceiling. In addition, the crypt is connected to the main cathedral volume by means of several small openings. Acoustic measurements carried out in the crypt pointed out the existence of at least two decay processes combined, in some points, with flutter echoes. Application of conventional methods of analysis pointed out the existence of significant differences between early decay time and reverberation time, but was inconclusive in explaining the origin of the observed phenomena. The use of more robust Bayesian analysis permitted the conclusion that the late decay appearing in the crypt had a different rate than that observed in the cathedral, thus excluding the explanation based on acoustic coupling of different volumes. Finally, processing impulse responses collected by means of a B-format microphone to obtain directional intensity maps demonstrated that the late decay was originated from the rotunda where a repetitive reflection pattern appeared between the floor and the dome causing both flutter echoes and a longer reverberation time.

1. Introduction

Multi-rate sound decays, that are typically observed in presence of coupled volume geometries, have received considerable attention in recent decades for acoustic design of modern performance venues [1–3]. In fact, non-exponential sound-energy decays can contribute to control reverberation and clarity of the hall [4].

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The interest in coupled volume acoustics dates back to the 1950s [5] and has subsequently received several theoretical developments based on the use of statistical acoustics (SA) theory [6–8]. Recently, such theoretical approaches have been further refined and generalised [9] to address direct sound radiation and non-diffuse transfer of energy between sub-rooms. Other revisions to the improved statistical-acoustics model have later been published by the same authors [10,11]. Applications of the diffusion equation [12] as well as of geometric acoustics methods [13,14] to model coupled-room phenomena can be accounted.

In parallel to the above studies, several research efforts investigated both subjective effects [15,16] and methods to identify and quantify the different components in multi-rate decays. Several measures of double slope effect or ratios between different portions of decay were used in the literature [17–19] to describe the slope variation as a function of time. However, only the application of Bayesian methods to multi-rate decay time evaluation provided the most rigorous instrument for analysing acoustically coupled spaces [20–23].

The above mentioned models and methods of analysis successfully contributed to explain the experimental results of various acoustic parameters measured in large, and complex, spaces. Anderson and Bratos–Anderson [24] extended the original SA two-room model to a larger number of sub-rooms and applied this method to St Paul's Cathedral, London. Similarly, Martellotta used Bayesian analysis [20] and SA models [9] to explain and model the acoustics of St. Peter's Basilica [25], and of a larger set of Papal Basilicas [26] in Rome, within the framework of coupled volumes. Chu and Mak [27] and Martellotta [28] proposed the use of multi-rate decays to predict the early sound energy decay performance in churches. All the previous analyses involved spaces where, despite their complexity, sound propagation complied with diffuse field specifications, otherwise SA model would not have been valid nor accurate. However, multiple-rate decays may also appear under different circumstances, such as in long enclosures [29], in spaces with non-uniform sound absorption distribution [30], and in presence of curved and focussing surfaces [31]. In all of these cases the sound field can hardly be considered diffuse, and together with multiple-rate decays, strong non-uniform sound pressure level distribution, and odd phenomena like coloration and “flutter echoes” may appear. With particular reference to the effect of curved surfaces there are some theoretical studies [32,33], but limited measured data can be found [31] and analyses are carried out only by means of conventional methods.

In the present paper, the case of the crypt of the cathedral of Cadiz in southern Spain, is investigated. Due to its shape, a circular rotunda covered with a low dome, connected to radial galleries, this space presents almost unique acoustic features, including non-linear decays and flutter echoes, which would be difficult to analyse and explain using conventional methods. Consequently, non-linear decays were first investigated by means of Bayesian analysis to identify the different components. As this space is directly connected to the cathedral, the origin of the multi-rate decay was investigated either by comparing decay rates pertaining to different sub-volumes and by taking advantage of visualization techniques based on the use of B-format impulse responses [34]. The latter technique also allowed to clearly explain the origin of the flutter echoes. Results are discussed below and proved that only the use of both Bayesian methods and intensity maps allowed the correct interpretation of the phenomena which, using conventional approaches might have been explained in a different, and probably incorrect, way.

2. Methods

2.1. The case study

The cathedral of Cadiz, located in the historical center of the southernmost city of Spain, is one of the cathedrals more recently built in the country. The long duration of its construction process, which began in 1722, involved seven master architects, a fact that resulted in a combination of different architectural styles: Baroque and Rococo in the interior, and Neoclassicism in the façade and the two towers. The main space of the cathedral has a Latin cross plan surrounded along its entire perimeter by lateral chapels and organised in three naves, creating an interior volume of about 70,000 m^3. Its structure is made up of Corinthian marble columns, from which a second body of limestone pillars emerges, concluded by very lightly decorated vaults. The choir is characterised by stalls made of cedar and mahogany and is one of the key elements of the building, being located in the central nave and subdividing the space. The southern part of the church includes an ambulatory and the presbytery covered with a dome. A gilded bronze pulpit is located on each side of the altar (Fig. 1a). The crypt is located right under the main altar, below sea level. The crypt, which was built by Vicente de Acero in 1730, is almost entirely finished in oyster stone, a brown porous stone typical of the region. The space, having a volume of approximately 3000 m^3, is formed by a central vaulted rotunda, which reaches a height of 5 m in its highest point (Fig. 1b), and five axial galleries with a flat low ceiling (Fig. 2). The crypt is connected to the cathedral by means of stairs arranged symmetrically on both sides of the main altar and also by means of several small openings around the rotunda (Fig. 1b).

2.2. Measurement technique

The measurement methodology applied to record and analyse the room impulse responses followed the recommendations listed in the ISO 3382–1:2009 standard [35] and the specific guidelines published for this type of buildings [36,37]. Such methodology has been applied in order to analyse the current acoustic environment of several Spanish cathedrals of the same typology [38]. Considering the various liturgical and cultural uses of the churches, different sound-source positions were set.