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Technical Note

A geometrical acoustic simulation of the effect of occupancy and source position in historical churches

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ABSTRACT

Historical churches represent an important cultural heritage that nowadays is often used in different ways compared to the original design. In fact, both the "new style" of the celebration (introduced after the Second Vatican Council) and the frequent use as multifunctional spaces ask for different acoustic conditions, also changing the nature and the position of the sound sources compared with the original usage. Most of the available measurement campaigns were carried out using conventional sound positions and unoccupied conditions. However, due to the widespread use of scarcely sound absorbing surfaces, the presence of congregation may change dramatically the acoustical conditions inside the churches, and further variations can be introduced by changes in source placement. In order to analyze such effects, acoustic simulations were carried out using a commercial software, and starting from calibrated models of six different churches. The presence of the congregation determined a significant improvement in monaural acoustical parameters, especially in reverberation which was strongly reduced in all cases. Conversely, spatial parameters showed negligible variations. As variations in reverberation time were predicted with good accuracy by Sabine's formula and variations in center time were in agreement with diffuse field theory, a simplified method to estimate occupied parameters from unoccupied values was proposed. Finally, the original acoustic conditions were simulated by placing a source with human talker directivity in front of the altar facing both the congregation and the main altar, and, where available, on the pulpit facing the congregation. When the priest turned his back to the congregation speech intelligibility dropped in all the churches, particularly where the reflecting surfaces of the apse were at greater distance. The pulpit position provided better results, however in most of the cases they were simply due to the shorter source–receiver distance.

1. Introduction

The study of the acoustic characteristics of worship places, and churches in particular, has received considerable attention in the last two decades, with a number of researchers focussing on this topic and its multifaceted aspects. Even though a detailed recap of the research results in these years is beyond the scope of this paper, it is interesting to point out that the large majority of the studies [1–5] starts from on-site measurements aimed at describing the acoustic behavior of the churches. Then, what clearly appears by putting together the different studies is that the complexity and the variety characterizing such buildings often prevents generalizations (apart from very homogeneous groups of churches), and conversely requires detailed analysis taking into account the specific features of each space. Another aspect that can be pointed out is that only a few studies consider the effect of occupancy [6,7], and in most of the cases they refer to relatively small places, mostly because of the difficulty of performing measurements in occupied conditions in large buildings, combined also with the even most difficult task of filling very large churches with a sufficiently large number of persons. In one case [6], despite significant variations in the sample, results are conveniently used to show that audience can affect both reverberation time and intelligibility. Reverberation time variations are large only for the most reverberant churches and the average difference in speech transmission index (STI) is about 0.035 when no PA system was used. However, a regression line is found to correlate the improvement in STI values with the ratio between unoccupied and occupied reverberation time. In the other paper [7], as the occupancy conditions are not homogeneous, results are not discussed directly but used to vali-

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date sound absorption coefficients due to congregation. Anyway, a comparison between unoccupied and occupied data at mid frequencies shows that large variations in reverberation time appear (with an average of about 2 s), particularly in more reverberant churches. Such variations are of the highest importance in churches as the seating area is rarely characterized by upholstered pews or seats, with the consequence that the difference in sound absorption may be significant in spaces with large floor area. Following such increase in absorption, changes in acoustical parameters should be expected with the consequence of improving, in most of the cases, the listening experience of the congregation. In fact, subjective studies have shown [8] that preferred listening conditions for liturgical music are often far from what is experienced in empty reverberant churches. Conversely, the reduced reverberation due to the same congregation might lead to much better conditions. This is obviously true also for speech intelligibility, which would ideally require much drier acoustics, and even though Ref. [2] showed relatively small variations for unamplified signals, they became more evident when a PA system was used. Now, as a detailed acoustic measurement survey in occupied conditions would be very difficult to carry out, the effect of occupancy on acoustical parameters may be investigated by using acoustic simulation software tools. A similar exercise has been carried out for Early Christian churches [9] starting from architectural drawings and literature values for absorption coefficients. However, the availability of many on-site measurements and the consideration that acoustic simulation software tools perform better when properly calibrated and set up starting from measured conditions [10,11], together with the fact that usage of absorption coefficients of congregations has been validated using the same tool [7], led us to propose this investigation.

A selection of six churches (five Italian and one Spanish) of different styles and dimensions was taken into account. After calibrating the acoustic virtual models with reference to the actual measured conditions, standardized occupancy due to the congregation was added. The effect of this addition on the acoustical parameters was discussed by comparison with values in unoccupied conditions. Furthermore, taking advantage of the ability of the software to simulate the directivity of natural sources, the effect of different position of the priest during the celebration was finally discussed.

2. Methodology

2.1. Surveyed churches

In order to analyze the effect of occupancy in worship places, six historical Catholic churches, located in Italy and Spain, which date from different periods (from 12th to 17th century) and vary in style, dimensions, and typology, were selected. A brief description of these churches is given below, while Table 1 summarizes their main geometric data. The range in volumes spans approximately from 9000 to 170,000 m^3, which implies noticeable differences in the values of the reverberation time.

The Abbey of Chiaravalle della Colomba (*ACC*) in Alseno was founded in 1136 but the completion took about 200 years. It is a typical Cistercian church, characterized by a rigorous geometrical scheme, even though its architecture still shows the influence of Romanesque models in the use of rounded arches and a less emphasized verticalism (in fact the nave height is 1.5 times the width, while in other Cistercian churches the ratio was usually about 2). The interior is finished in plaster and facing bricks.

The church of San Fancesco in Lucera (*SFR*) was built from 1300 to 1304 in Agevine-Gothic style for a community of Franciscan monks. It has a simple oblong rectangular plan with side altars and a wooden roof, terminating with a Gothic choir.

The Basilica of San Petronio (*BSP*) in Bologna was built from 1390 to 1659 (when the vaults were completed), its interior layout is clearly Gothic, subdivided into three naves divided by ten cluster columns made of bricks supporting pointed arches and ribbed vaults. Vaults and walls are finished in smooth plaster. The side walls of the aisles are flanked by side chapels. It has a wooden pulpit, located under the third span of the nave, dated 1470, from which famous preachers (like Girolamo da Savonarola) held their speeches.

The church of the Most Holy Name of Jesus (*GES*), better known as the Gesù, in Rome was built between 1568 and 1584 as the specimen of the Counter-Reformation Catholic church. The interior is organized on an elongated central plan, with a large and richly decorated nave flanked by chapels and covered with a barrel vault, followed by a transept with short braces and by the chancel. An outline of the acoustical ideas behind its building can be found in Ref. [12].

The Cathedral of Malaga (*MAL*), located in the south of Spain, was erected on the site where the main mosque of the city had existed during the eight centuries of Muslim dominion. Its construction began in 1528 and lasted until 1782. The church has a rectangular plan, subdivided into 3 naves, and is surrounded by chapels on its entire perimeter. A typical characteristic of Spanish cathedrals is that the choir is placed in the middle of the central nave, dividing the huge interior space in several parts.

The church of Santi Martina and Luca (*SLM*) in Rome was built by Pietro da Cortona between 1635 and 1644 as the church of the Drawing Academy (known as "Accademia di San Luca". The interior is a perfect Greek Cross plan with semi elliptical apses at the end of each brace. The surfaces are finished in plaster and stucco and are richly decorated.

2.2. On site measurements

The on-site acoustic measurements were carried out using different equipment (according to the research team), but in all the cases an omni-directional dodecahedron sound source was used, together with an additional sub-woofer in order to improve the

Table 1
Summary of the main geometric data of each church. S_T is the total surface area, S_F is the total floor area, S_{Pews} is the area covered by pews at the time of the survey, and S_{occ} is meant as the floor surface likely covered by the congregation.

Church ID	Constr. date	Arch. style[a]	Plan typology[b]	Naves	V (m^3)	W/L (m)	S_T (m^2)	S_F (m^2)	S_{Pews} (m^2)	S_{occ} (m^2)
ACC	1136–1300	Ro/G	LC	3	15,000	40/59	7394	1363	75	199
SFR	1300–1304	G	Re	1	9000	12/40	3268	530	158	184
BSP	1390–1659	G	Ba	3	170,000	59/133	40,000	5457	559	579
GES	1568–1584	R	LC	–	40,000	37/68	10,395	1413	480	480
MAL	1528–1782	R	Re	3	120,000	52/98	27,510	3850	323	1133
SLM	1635–1644	B	GC	–	11,000	30/30	4768	475	40	116

[a] Ro = Romanesque, G = Gothic, R = Renaissance, B = Baroque.
[b] Re = Rectangular plan, Ba = Basilican plan, LC = Latin cross plan, GC = Greek cross plan.