CHURCH ACOUSTICS

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ABSTRACT

Church acoustics has not been studied well enough in its historic evolution. Despite these premises are mainly used for speech, a musical environment (organ) as good as possible has to be guaranteed without intelligibility loss.
Comparing the reverberation times experimentally measured in these premises with their optimum times, it leads that almost all the churches should need a treatment for speech. Therefore, a deeper study of acoustics determinant factors is recommended.
Through the cross-study done about experimental reverberation times of the 14 available churches, some empiric expressions have been deduced for the prediction of reverberation time, depending on the volume and the architectural style of the church.

INTRODUCTION

Historically, in a first time, church acoustics had to provide a good speech intelligibility for the faithful to get sermon message, but as people's language was becoming less similar to Latin, speech intelligibility was less important too in front of sacred music, which raised to its maximum together with the huge gothic cathedrals. Being the church a see that should spread its message and maintain the worship, it may seem a bit strange that acoustics have never been taken into account. This contradiction grew up to a point that small reverberation time was required for speech intelligibility, but high time for religious music.

Despite we know that reverberation time is not the unique factor to characterize the acoustics of a room, it is, in fact, one of the most important and significant, and hence, we will focus on that parameter in church acoustics analysis from experimental measurements of reverberation, sound pressure and noise. Starting from these data, a set of objective parameters are calculated showing acoustics characteristics through a computer application. With the obtained results, we will try to find acoustic behaviour patterns for these buildings and some empirical expressions to predict its reverberation time. As a help to accomplish these aims a software application has been designed to automate the process.

Throughout this research, theoretical bases for church acoustics will be indicated. The measurement process will be pointed out, and the program will be presented. Lastly, comparative results will be showed.

CHURCH ACOUSTICS

Church acoustics is based on architectural acoustics, but with some particularities that make worthwhile a revision of theory and historic evolution in order to act properly in a church fitting-out.

Historic Revision

Initially, a church is a building destined to worship. A good speech intelligibility is necessary for understanding sermon's oral message, but as music is also played at churches, an adequate reverberation is desirable. Then, a compromise has to be established so that the best musical ambient could be granted whereas it does not interfere with speech intelligibility.

Church architecture is a leading factor involved in its acoustics, and it has almost never been taken into account at a design phase. Paleochristian churches had a structure of harmonic proportions with cross-shaped plan, brick walls, low plane wooden ceilings without vaults, what in fact helped to a good acoustics. In the Romanesque, plain stone-masonry and barrel vaults were the common elements that built-up a cave acoustics given by such high reverberation times that intelligibility was reduced and focalizations were produced.

Huge dimension churches and cathedrals were the beginning of the Gothic, where the vaults' excessive height and the great reflective parallel walls brought large reverberation and echoes. However, other elements arose to fix the acoustics slightly, such as big stained glass windows that reinforced bass sound absorption, or the deep side chapels that acted as bass diffusors.

Renaissance went back to plane wood ceilings and harmonic proportions with non cross-shaped plans. In addition, it used a rich ornamentation to diffuse treble and side chapels to diffuse bass. Baroque introduced dense decoration, more side chapels, plasterworks, tapestries, carpets, and alternation of concave and convex shapes to reduce focalization and spread bass and mids; but in the other hand, it kept using circular plans. As a crosscurrent, Neoclassicism took back Renaissance essence and abandoned circular plans. Nowadays, acoustics is finally involved in church design, so modern churches are not excessively overelaborated; instead, plain brick walls are used and paneled diffusors or adequate ceiling shapes are included as well.

Acoustic Characterization

From a technical point of view, the best, but not unique, parameter that describes the acoustics of a church is the reverberation time and its comparison with the optimum reverberation time. Optimum reverberation time is obtained by experimental ways that vary depending on the author. So, there are given experimental curves showing the reverberation margin allowed depending on the volume, or empiric formulae of reverberation time prediction with the volume too; as the classical expressions recommended by Mayer-Thiele for music, by Knudsen for speech, by Lifshits for speech and music, or by Pérez-Miñana, that is the only especially adapted for churches, depending on frequency, utilization, and sound reinforcing help parameters. Despite reverberation time is not the only determinant factor, it can be affirmed that if this value is very high, measurements will have to be taken; hence, an acting criterion can be established: if the relative difference between reverberation time and its optimum is more than 10%, building acoustic fitting-out will be necessary.

Intelligibility is essential in churches, and it may decay due to the high reverberation times involved. ALCONS index is one of the easiest to be predicted because reverberation time (if SNR>25 dB) is the only necessary for its calculation, giving a subjective scale resumed as: 0-1.5% excellent, 1.5-5% good, 5-10% acceptable, 10-25% poor, >25% bad. More subjective values of room acoustics are liveness, warmness (bass-ratio) and brightness. Liveness means the perceived degree of reverberation in the room and is given by average reverberation time measurement in mid-frequency. Warmness, or timbre, shows room response in low frequency, representing bass sound richness and music softness. Brightness indicates clarity and harmonic richness of sound.

Noise control inside churches is also one of the key factors in acoustics. Interfering noise sources may be reverberation, conversations, footsteps, installations, wheeled traffic, and external commerce activities. Assessment is done through curves relating subjective response to background noise, such as NR, NC, and PNC. The maximum recommended levels for a church are: NR-35, NC-30, PNC-35, LN= 40 dB / 45 dBA.

From the mentioned aspects, a church acoustics can be determined, except for isolation, and serve as the base point to decide the actions to be followed.

DATA BASE FOR CHURCH ACOUSTICS

For the acoustic study of churches a data base has been created to keep the empirical measurements taken, so that the process is as systematic and automatic as possible. Therefore, one can conclude that for an initial acoustical characterization, without isolation, it is enough with reverberation time, sound pressure and noise measurements depending on the frequency, a part from the knowledge of dimensions, surface, volume, and architectural style.

Measurements have been taken with the digital acquisition platform SYMPHONIE by 01dB improved with dBBATI32 module of architectural acoustics and following procedures of the ISO-3382 standard for reverberation time measurement. Obtained data, conveniently formatted, of the more than 15 churches tested, have feed a data base designed for MS-Access2000 that has been built-up from an interrelation 1:1 of basic and global data of each church to its measurements.

From the basic information held, the data base calculates a wide set of derived parameters, table 1, that permits to conclude about the acoustical characterization of a particular church. This is possible thanks to the results window, whose numerical part is showed in figure 1, and that is organized into three sections: the first displays user given data, including photographs, plans, recordings and spectra; second section shows numerical calculated parameters, such as absorption, optimum reverberation times according to different authors, fitting-out criterion...; and the third part presents graphically the spectra, together with the ALCONS and the comparison among noise spectrum and maximum permitted indexes.

COMPARATIVE RESULTS

Thanks to the created data base, the comparison among several churches is very easy. So, it seems that there exist some patterns defined for the acoustical characterization of each architectural style, that remain even after long time and many modifications of the original temple.

Baroque churches present high reverberation times together with very loud pressure and noise levels. In addition, absorption is extremely low, especially compared to other styles, as absorption coefficient and room constant show. Excessive ornamentation fulfills its role with treble, and side chapels do the same with bass, while vaults and circular plans rise reverberation; therefore, the typical reverberation time spectrum shape for baroque presents increasing levels at low frequencies to a maximum around 500 Hz, and after that a fast lineal (in dB) decreasing , as can be seen in figure 2. Comparison with optimum times is very uneven, then, fitting-out is highly recommendable for these churches. Furthermore, the maximum distance for which ALCONS still considers the church as good (<10%) is only 4 to 8 m, that is very small compared to other styles. Subjective parameters show a large liveness, and a poor warmness, less than 1 in some cases, what means there is a great discompensation between low and mid frequency, that joined to a high brightness produce a confusing and unclear sound.

Gothic churches present reverberation times rather close to the optimum ones, with high absorption as its related parameters reveal. Liveness and warmness is also quite appropriate, including as well a wide area qualified as good by ALCONS; but the area qualified as bad is also wide due to the huge dimensions of these churches. So, acoustics is proper in the small area where parishioners stay. Typical reverberation time spectrum is totally decreasing from the beginning; see figure 3.

Field name	Used formula	Particularities
Mean absorption (metric sabin)	$A = 0'161 \cdot \frac{V}{T_R}$	From the mean reverberation time
Mean absorption coefficient	$\overline{\alpha} = \frac{A}{S}$ $\quad \overline{\alpha} = 1 - e^{-\frac{A}{S}}$	Sabine and Eyring calculations respectively.
Decreasing index (s^{-1})	$\delta = \frac{13'8}{T_R}$	Sound decay speed.
Mean free path (m)	$l_m = \frac{4V}{S}$ $\quad l_m = 0'62 \cdot \sqrt[3]{V}$	6:3:2 dimension relationship supposed.
Average reverberation time (s)	$T_{mid} = \frac{T_{500} + T_{1000}}{2}$	Also named as Liveness.
Acoustic warmness	$BR = \frac{T_{125} + T_{250}}{T_{500} + T_{1000}}$	Timbre, bass richness, softness and melody of music. Bigger than 1.
Acoustic brightness	$BR = \frac{T_{2000} + T_{4000}}{T_{500} + T_{1000}}$	Harmonic richness, clarity. Less than 1.
Room's contant.	$R = \frac{S \cdot \overline{\alpha}}{1 - \overline{\alpha}}$	Indicator of total room's absorption.
Critical distance (m)	$D_c = 0'223 \cdot \sqrt{R}$	Q= 2'5 for an unique speaker without sound reinforcement.
Limit distance (m)	$D_l = 3'16 \cdot D_c$	Intelligibility variation limit.
AL_{CONS} (%)	$\begin{cases} \frac{80 r^2 T_R^2}{V} & \text{si r} \le \text{D}_1 \\ 9 \cdot T_R & \text{si r} > \text{D}_1 \end{cases}$	S/N>35 dB & Q= 2'5 supposed. Taken at T_R a 2 kHz. Given value is for limit distance.
Normal vibration modes (Hz)	$171'5 \cdot \sqrt{\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2}$	c= 343 m/s at 20ºC supposed. Calculation from mode 100 to 555.
Optimum reverberation time (s)	$T_{opt} = 0'09 \cdot \sqrt[3]{V}$ $T_{opt} = 0'4 \log V - 0'15$ $T_{opt} = 0'11 \cdot \sqrt[3]{V}$ $T_{opt} = 0'32 + 0'17 \log V$ $T_{opt} = 0'3 \log V - 0'05$ $T_{opt} = 0'08 \cdot \sqrt[3]{V}$	Empiric relations. First by Mayer for music, second by Lifshits for music, third by Pérez-Miñana for music at churches, fourth by Knudsen for speech, fifth by Lifshits for speech, and sixth by Pérez-Miñana for speech at churches.
Fitting-out?	$\frac{T_R - T_{OPT}}{T_{OPT}} > 10\%$	Shows 'Yes' if the condition is accomplished, and 'No' otherwise.
S/N (dB)	$L_p(dB) - L_n(dB)$	Total mean levels of signal and noise.
Spectrum of Trev, L_p y L_n		Semilog graphic of each spectrum.
ALCONS		Graphic of AL_{CONS} vs. distance.
Noise indexes		Graphics of noise vs. indexes NR35, NC30 & PNC35, specific for churches.

Table 1

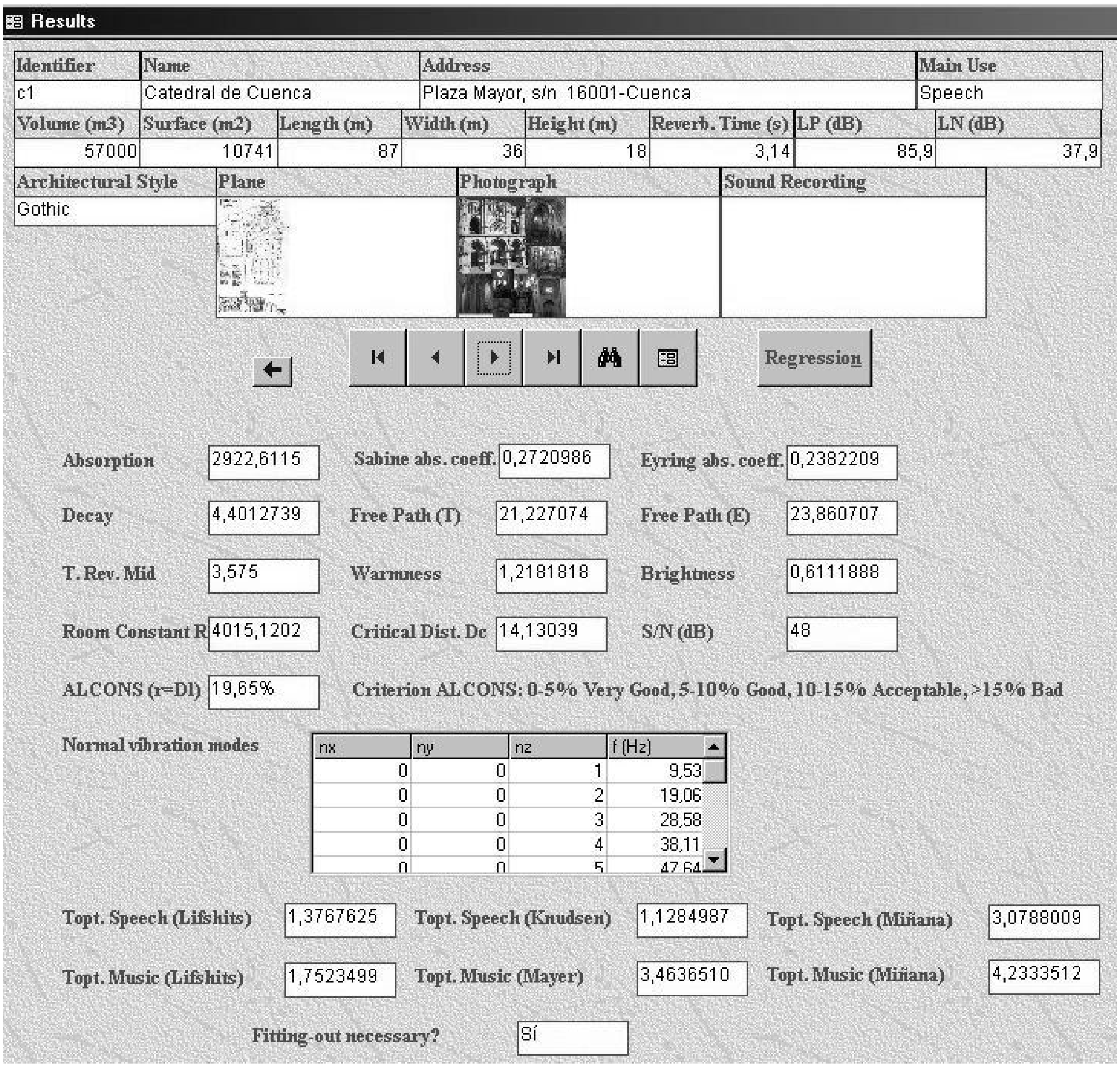


Figure 1

Neoclassical churches are characterized by high reverberation times, rather far from its optimum ones, so fitting-out is recommended in general. Absorption is medium, and warmness is adequate; but due to an excessive reverberation, the good area, according to ALCONS, is medium size, around 10 m. Reverberation time pattern is plain at low frequencies, to commute to another plain stage at mid frequencies, and beginning a monotonically decreasing for high frequency; see figure 4.

There are not enough data of the other styles to establish such a pattern, but we are working on obtaining more data to improve this.

From the previous analysis, and given that patterns exist for each architectural style, we pass then to the cross-study of reverberation times depending on the volume and architectural style. For that case, the data base has the 'regression' option that allows to show graphically the empirical reverberation times depending on the volume for a concrete style selected; calculating as well five regression curves that try to adjust a prediction expression. With the available data, this expression seems feasible for baroque and neoclassical styles with a little margin of error; despite it is also true that more data should be necessary to give more reliability to the expressions obtained. Figure 5 shows predictive results for the baroque, where the most adequate formula is, by now, (1), that has an adjustment parameter of 1, that is the maximum possible.

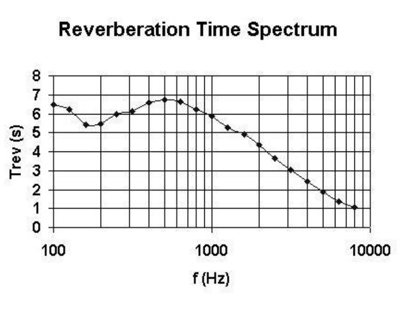
$$Trev = 3\cdot10^{-12}\cdot V^3 - 3\cdot10^{-7}\cdot V^2 + 6.5\cdot10^{-3}\cdot V - 39.022 \qquad (1)$$

CONCLUSIONS

In this research, determinant factors of church acoustics have been reviewed, and the designed program has been explained. The program not only calculates several relevant factors related to church acoustics characterization, but also includes church's planes, photographs and sound recordings. Through the designed data base, acoustical characterization of a church is eased, as well as the comparative and cross-parameters studies.

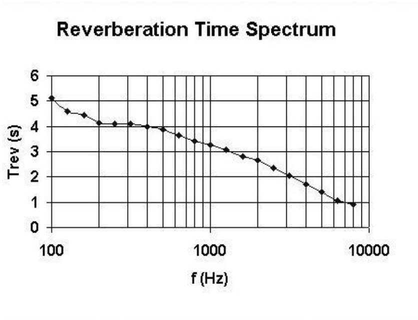
Acoustical patterns for some architectural styles have been deduced, and the possibility of finding out empirical formulae to predict reverberation times depending on the volume and style has been proven.

As future lines we are working on, there are the measurement of more churches to feed the data base to obtain better quality cross-studies, the inclusion of the fields necessary to determine church isolation, and the addition of a software module to print the church acoustics reports.



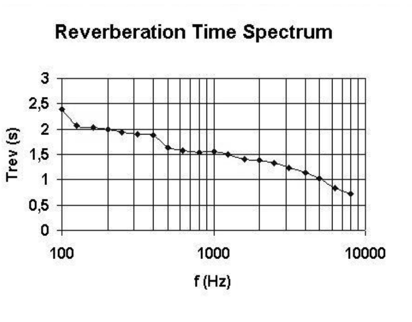
f (Hz)	Trev (s)
100	6,47
125	6,21
160	5,42
200	5,45
250	5,99
315	6,14
400	6,57
500	6,75
630	6,63
800	6,21
1000	5,87
1250	5,27
1600	4,9
2000	4,34
2500	3,63
3150	3,03
4000	2,45
5000	1,89
6300	1,37
8000	1,08

Figure2



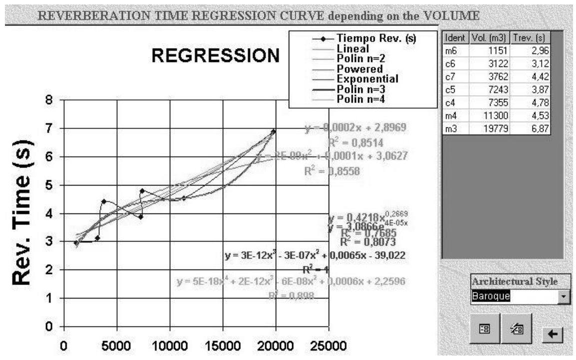
f (Hz)	Trev (s)
100	5,11
125	4,6
160	4,45
200	4,15
250	4,11
315	4,11
400	3,97
500	3,87
630	3,64
800	3,43
1000	3,28
1250	3,06
1600	2,82
2000	2,65
2500	2,34
3150	2,06
4000	1,72
5000	1,41
6300	1,08
8000	0,9

Figure 3



f (Hz)	Trev (s)
100	2,4
125	2,07
160	2,04
200	1,99
250	1,94
315	1,9
400	1,88
500	1,64
630	1,58
800	1,54
1000	1,55
1250	1,5
1600	1,41
2000	1,38
2500	1,33
3150	1,23
4000	1,14
5000	1,02
6300	0,83
8000	0,72

Figure 4



Ident	Vol. (m3)	Trev. (s)
m6	1151	2,96
c6	3122	3,12
c7	3762	4,42
c5	7243	3,87
c4	7355	4,78
m4	11300	4,53
m3	19779	6,87

Figure 5

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