ACTA TECHNICA NAPOCENSIS
Electronics and Telecommunications

ACOUSTIC ANALYSIS OF A ROOM

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Abstract: The paper presents the acoustic analysis of a room using both software and hardware tools. First several methods for acoustic parameters estimation were tested. The most accurate measurements were used for building 3D images of the room's impulse response. Next the room was analyzed in realistic conditions and maps of acoustic parameters were plotted. Conclusions regarding the acoustics of the room were drawn.

Keywords: *room acoustics, impulse response, acoustic parameters, plenacoustic function, acoustic sources*

I INTRODUCTION

Nowadays a large number of events take place in closed spaces and so the room acoustics plays an important role in our daily life. As a consequence of the room finite dimensions, a sound meets the walls, ceiling and floor, giving birth to several reflections. If the room is used for a conference, a strong reverberation will lead to noninteligibility of speech, but if the room hosts a concert, than reverberation will add a pleasant effect to the listeners.

The acoustic properties of a room can be objectively measured by parameters, that are defined with the help of the impulse response *h(t)* and the energy decay curve (*EDC*) [1], [2], [3], [4]. *EDC* computes the energy remaining in the impulse response after the time *t*:

$$EDC(t) = \int_{t}^{\infty} h^2(\tau)d\tau \tag{1}$$

The most important acoustic parameters are: the reverberation time *RT60*, the early decay time *EDT*, the center time *Tc*, the clarity *C80* and the definition *D50*. [3], [4]. If the reverberation time is the basic indicator of acoustical behavior, the early decay time is associated with the subjective sensation of reverberation, the center time, clarity and definition are measures of distinctness and clarity of speech and music.

The paper is organized as follows: Section II is devoted to several experiments to estimate the acoustic parameters, Section III builds up the plenacoustic function on a line and Section IV draws the room maps of the acoustic parameters. The last Section draws the conclusions regarding the acoustic evaluation of the room.

II ESTIMATION OF ACOUSTIC PARAMETERS

The acoustic parameters of a room may be computed if the impulse response is measured [5]. To get the impulse response two types of excitations were used in this paper: the impulsive signal obtained using balloons and the software generated sweep sine signal. The measurements were carried out in the room depicted in Figure 1; the room was empty, without chairs. The measurement points were located on 17 rows with 9 points each. The processing of the measurements was made using the Dirac, Winmls or CARACAD software.

The estimation of the acoustic parameters consists of the following two steps:

I. Measure the impulse response of the room with the following equipment:

- two loudspeakers for rendering the excitation; one is for low frequencies and the other for medium and high frequencies;
- a lot of balloons inflated at the same pressure (50 mmHg);
- a portable cardiode microphone (dB VH 210) and an omnidirectional microphone (PCB 130D20). for acquiring the response.

II. Estimation of the acoustic parameters – the measurements processing was done with either the Dirac 3 or Winmls 2004 software.

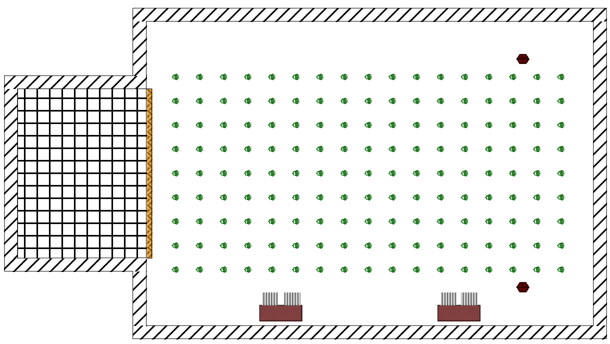


Figure 1. The analyzed room

Manuscript received April 23, 2010; revised June 17, 2010

The reverberation time was estimated both analytically in CARACAD according to the Eyring's and Kuttruff's formulas and experimentally by processing the measurements. The mean values of the *RT60* are depicted in Figure 2. There are not important differences between the values obtained by measurements in the Dirac or Winmls software or for different excitation signals, but significant errors between measurements and simulations at frequencies below 500 Hz. The errors in CARACAD are due to rough approximations in simulations (approximation in the shape of objects, in the absorption coefficient of materials, etc). The values depicted in Figure 2 show that the reverberation time depends neither on the excitation source nor the listener positions nor the room shape. One can observe an increase of the reverberation time at 500Hz, because the absorption is lower at low frequencies than at medium and high ones. The associated subjective sensation of this increase is the "warmth" of musical sounds.

The early decay time was estimated with measurements when applying two types of excitations and processed with two softwares; the obtained mean values are depicted in Figure 3. The early decay time is strongly influenced by early reflections thus depends on the measuring position and the room's geometry. There are larger errors between the values obtained with sweep sine signals than in the case of impulsive signals. Like in the case of the reverberation time, due to lower absorption at low frequencies, the early decay time is maximum at 500 Hz.

The estimation of the mean central time is represented in Figure 4. There are huge differences between the values obtained with different excitations. It is known that the center time is between 70 and 150 ms for music listening and 60 to 80 ms for speech listening. The picture suggests that measurements with one of the sources lead to wrong results.

The mean estimated values of the clarity are depicted in Figure 5. It is known that the typical range of *C80* is from about -5 to +3 dB. Negative values mean reverberant spaces and positive values denote small reverberated spaces. Again the results offered by the measurements with the sweep sine signal are totally different with the ones with impulsive signals. These errors are due to different signal-to-noise ratios (SNR) and measurement equipment.

The definition is a useful descriptor of speech intelligibility and the obtained mean values are represented in Figure 6. The same observations can be made as in the case of clarity: very different results for the two sources and better results are obtained with the impulsive source.

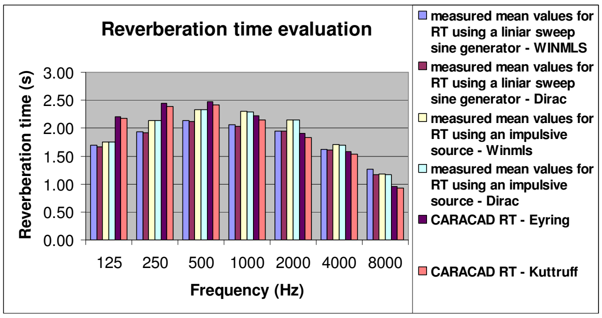


Figure 2. Measured and simulated mean reverberation times

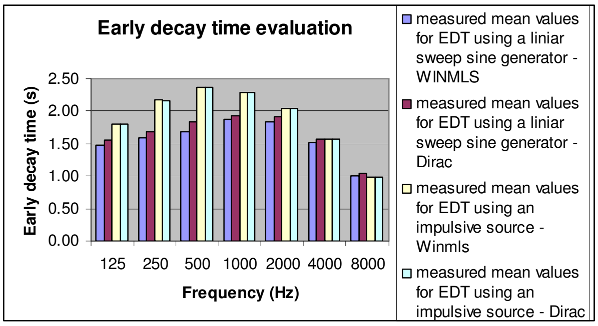


Figure 3. Measured mean early decay times

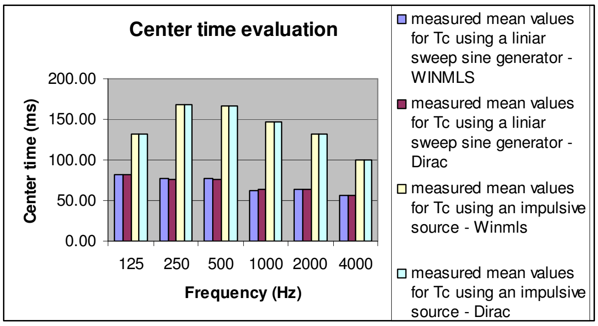


Figura 4. Measured mean central times

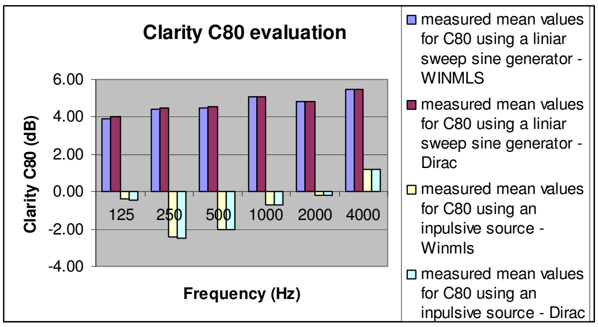


Figure 5. Measured mean clarities

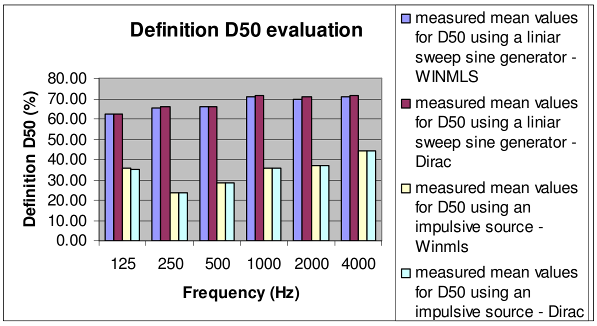


Figure 6. Measured mean definitions

Some general remarks about the estimation of the acoustic parameters can be done:

- the reverberation time do not depend considerably on the excitation source type, room's shape and listener's position;
- the early decay time is more sensitive to the excitation's type, room's shape and listener's position;
- the center time, clarity and definition are very sensitive to the source type; they are not correctly measured for the sweep sine signal, due to the large variations of the SNR. The impulsive source leads to good measurements.
- the center time, clarity and definition are very sensitive to the room's shape and listener's position; maps of these parameters are useful for organizing events;
- as for the processing software, both Winmls and Dirac give similar results.

III THE PLENACOUSTIC FUNCTION OF A ROOM

After concluding that the acoustic measurements should be performed using impulsive sources, the next task was to obtain a 3D image of the impulse response, also called the plenacoustic function. It describes the acoustic field inside a room and is defined as the sound pressure recorded at a location *(x, y, z)* and time *t* given an acoustic event in a room [6]. In this paper we computed the plenacoustic function on a line in the room (Figure 7) and obtained a 3D image of the impulse response in the locations belonging to the considered line.

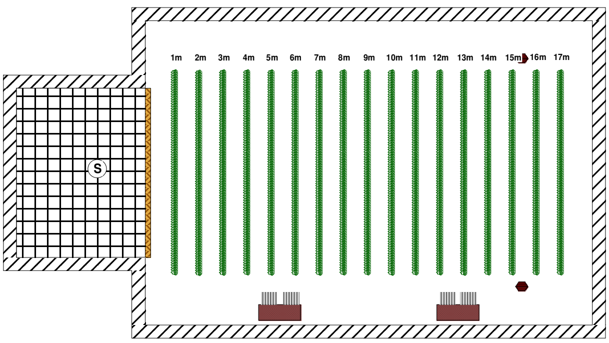


Figure 7. Placement of source and listeners in the room for the plenacoustic function

When the impulse response is known in any location in the room, then the output to any input may be computed by convolution. Because measuring the impulse response in all the locations in the room is not possible, sampling both in time and space had to be achieved. The temporal sampling depends on the desired signal bandwidth. The spatial sampling is done by saving the impulse response in uniformly placed locations.

The temporal frequency f_t (Hz) and the spatial frequency f_d (m^{-1}) are defined as follows:

$$f_t = \frac{1}{\Delta t}; \quad f_d = \frac{1}{\Delta d} \tag{2}$$

where Δt is the sampling period of the impulse response and Δd the sampling interval between successive locations of the measured impulse response. To avoid the alias effect the maximum temporal frequency $f_d\,max$ has to be:

$$f_d \max = \frac{f_t}{c}, \tag{3}$$

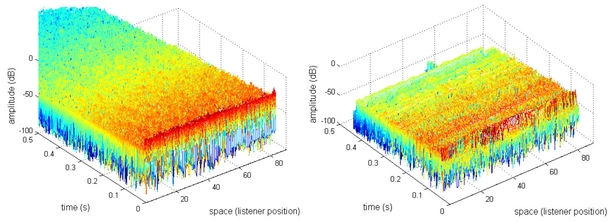
where $c=340\ m/s$ is the sound propagation speed through air. As the temporal frequency increases, the spatial frequency increases too.

To reconstruct the whole audio spectrum, having a sampling frequency of 44100 Hz, so with $f_t = 22\,050$Hz, the maximum spatial frequency is $f_d max = 64{,}85\ m^{-1}$. The spatial sampling frequency has to be the double of this value, that is $f_d = 129{,}70\ m^{-1}$. The sampling period is $T_d = 0{,}0077$ m = 0,77 cm. This means that to reconstruct the maximum temporal frequency of 22050 Hz, we should do measurements from 0,77 to 0,77 cm on a line, that is impossible. If in a room we acquire samples in a room from 10 to 10 cm (T_d = 10cm), then the temporal frequency not affected by alias is ft = 1700Hz.

To build the plenacoustic function of the considered room we traced the lines from Figure 7. On each line 84 samples were acquired in 84 locations of the line. The distance between the listeners' locations is 10 cm and the temporal sampling frequency is 44100 Hz. The source was placed in the front part of the room.

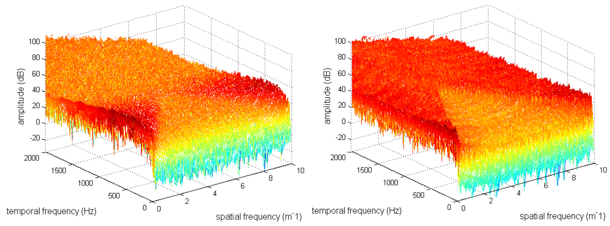
A 3D image of the impulse response was provided for each line in the room. The picture obtained using measurements (Figure 8a) may be compared with the one obtained by CARACAD simulations (Figure 8b); the aspect is similar, the main difference is the fact that using simulations only values until 0.45s are available due to simulation time limitation reasons.

The plenacoustic function was processed with the two-dimensional Fourier transform. The shape of this transform is rather a triangle with its vertex pointing to the maximum frequency nonaffected by aliasing. This frequency has the same value as expected: 1700 Hz (Figure 9). The comparison between the plenacoustic function obtained by measurements and the one by simulations strengthens the idea that the measurements done with the impulsive signal are reliable.



a) b)

Figure 8. The plenacoustic function obtained on the 4th line using: a) measurement; b) CARACAD simulations.



a) b)

Figure 9. The two-dimensional Fourier transform of the plenacoustic function on the 4th line using: a) measurement; b) CARACAD simulations.

IV ACOUSTIC MAPS OF THE ROOM

The next task was to provide an accurate acoustic analysis of the room in realistic conditions. The previous two sections analyzed the acoustic properties of the room without chairs. In real life the room was used with seated listeners, so the measurements were repeated placing the chairs and applying impulsive sources (balloons). The reverberation time was estimated both analytically in CARACAD according to the Eyring's and Kuttruff's formulas and experimentally by making measurements (Figure 10). The processing was made with Winmls 2004, Dirac 3 and Aurora 4.3 software. The results are summarized in Table 1.

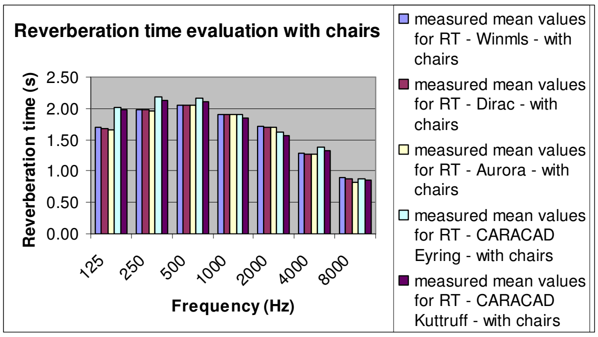


Figure 10. Measured and simulated mean reverberation times int the room with chairs

According to the range of the reverberation time for different rooms indicated in the literature [1], [2], [3], [7], (see Table 2) the considered room is best suited for listening to music (concert hall).

As established in Section II, the central time, the clarity and the definition depend on the position of the listeners, so maps of the acoustic parameters were obtained (Figures 11, 12, 13).

The center time *Tc* is a much more stable acoustic parameter than clarity and definition (Figure 11). If without chairs the center time is between 79.3 and 178 ms, when placing chairs the center time is improved and its range is between 78.66 and 144 ms.

The clarity *C80* (Figure 12) should be higher than -2 dB to avoid the syllable intelligibility decreasing below 80% [9]. If the darker spots in the room without chairs correspond to -3.16 dB, when placing the chairs the situation is greatly improved, the darker spots being of –1.36 dB and of very little surface. Considering that most of the clarity values are between -0.5 dB and 0 dB, the room is suited for symphony.

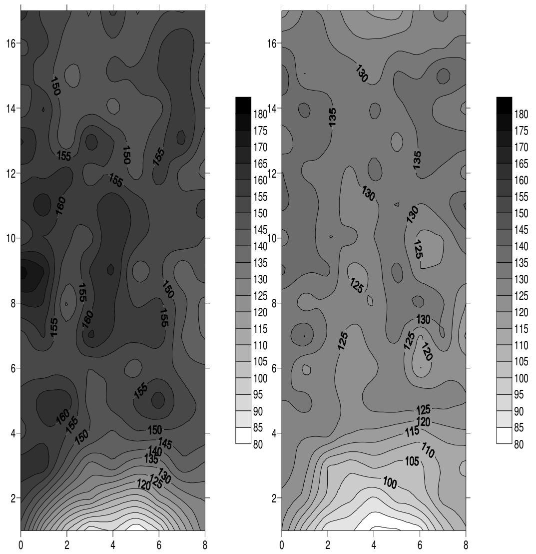
If the definition D < 50%, the room is suitable for music listening (concert hall), else for an auditorium, for speech listening [1], [4], [8]. The definition is comprised in the range 21 to 64.66% for the room without chairs and 27.66 to 62.33 % for the room with chairs (Figure 13), so from this point of view again the room is suited for listening to music (most of definition values are below 50%).

Room type	Reverberation time range
Lecturer rooms, congress halls, theatres	0.5s – 1.2s
Opera houses	1.2s - 1.6s
Churches	1.4s – 2s
Concert halls	1.6s – 2.1s

Table 2 Reverberation time range for different types of rooms

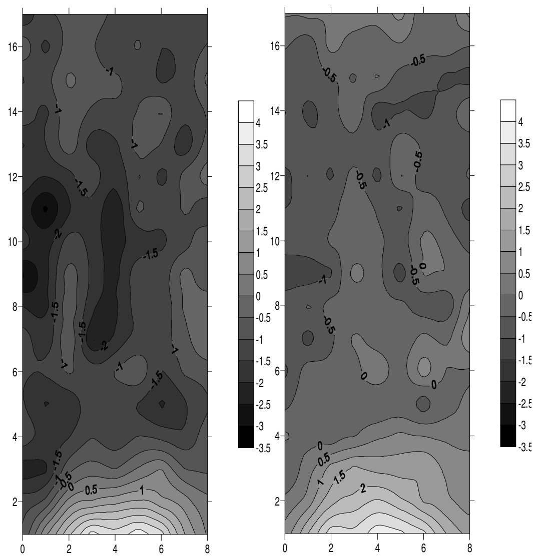
Mean value	Winmls 2004		Dirac 3		Aurora 4.3	
	Without chairs	With chairs	Without chairs	With chairs	Without chairs	With chairs
$RT30_{500Hz,\ 1000Hz}$ (s)	2.31	1.98	2.31	1.98	2.31	1.98
$EDT_{500Hz,\ 1000Hz}$ (s)	2.32	2.02	2.33	2.02	2.33	2.02
$Tc_{500Hz,\ 1000Hz,\ 2000Hz}$ (ms)	148.60	125.10	148.53	125.08	149.56	125.93
$C80_{500Hz,\ 1000Hz,\ 2000Hz}$ (dB)	-0.97	-0.04	-0.97	-0.04	-0.99	-0.06
$D50_{500Hz,\ 1000Hz,\ 2000Hz}$ (%)	33.92	37.92	33.90	37.84	33.77	37.76

Table 1. Mean measured acoustic parameters



a) b)

Figure 11. Maps of the central time a) without chairs; b) with chairs



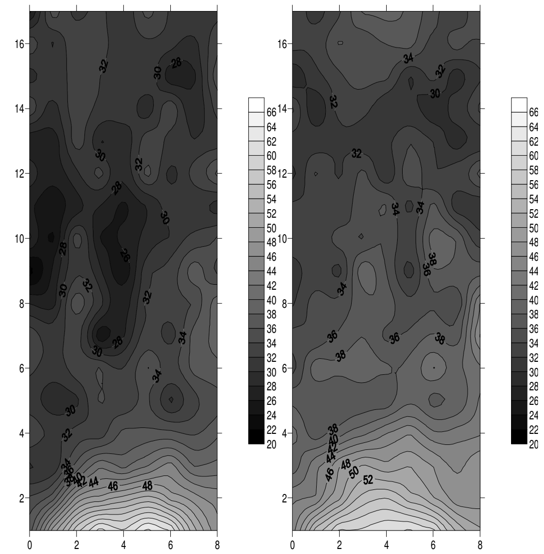
a) b)

Figure 12. Maps of the clarity a) without chairs; b) with chairs

Taking into account the obtained values of the acoustic parameters and the maps of the central time, clarity and definition, the considered room is suited for listening to music and most of the chairs in the room offer a good listening.

IV CONCLUSIONS

The paper is focused on the acoustic analysis of a room. A very large number of experiments were provided to establish an accurate analysis. First several methods for the estimation of acoustic parameters were tested. They involved both soft and hard tools:



a) b)

Figure 13. Maps of the definition D50 a) without chairs; b) with chairs

- the source type was either impulsive (balloons) or sweep sine (software generated);
- the processing of the measurements was done with Winmls, Dirac, Aurora or CARACAD softwares.

Although the reverberation time does not depend considerably on the excitation source type, on the listener position or the room's shape, the early decay time is more sensitive, the other parameters (center time, clarity, definition) are very sensitive; they are not correctly measured for the sweep sine signal, due to the large variations of the SNR and measurement equipment. The impulsive source leads to accurate measurements. As for the processing software, Winmls, Dirac and Aurora give similar results.

The results of measurements with impulsive sources were used for a detailed analysis of the considered room. We obtained:

- the plenacoustic function – 3D images of the impulse response on considered lines in the room as well as its frequency response;
- the maps of the center time, clarity and definition in two situations: without chairs and with chairs (realistic situation).

For the plenacoustic function measurements, the listeners were considered to be from 10 to 10 cm on considered lines in the room, so the temporal frequency not affected by alias is ft = 1700Hz and the temporal sampling frequency is 44100 Hz. If the plenacoustic function is known, then by convolution the sound that reaches any listener may be obtained.

Taking into account the range of the acoustic parameters for music or speech and observing the maps in realistic conditions, the general conclusion is that the considered room is suited for listening to music and most of the listeners' position offer good acoustic properties.

VI ACKNOWLEDGEMENTS

This work was supported by the Romanian National University Research Council under Grant ID 1057 entitled "2.5D Modeling of Sound Propagation in Rooms and Improvement of Room Acoustical Properties using Digital Implementations".

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