Room Acoustic measurements in non Sabinian enclosures for music: echometry, modal analysis, sound decay analysis.

Lorenzo Rizzi¹, Francesco Nastasi²

¹Studio Ingegneria Acustica Rizzi
{rizzi@suonoevita.it}
²Studio Ingegneria Acustica Rizzi
{nastasi@suonoevita.it}

Abstract
The article reviews modern techniques for analyzing room response of small spaces for listening, recording and rehearsing music both in the time and the frequency domain. After a brief review of theories and norms it discusses the techniques using actual measurement results as examples. This allows to show typical non-Sabinian behaviors of small rooms with short time decays (Volume < 100 m³, T30 < 0.5 sec).

The study of single reflections, modal perduration in time and frequency distribution allows to point out and verify the phenomena that can be controlled by the acoustic designer through surface treatment, source-receiver positioning and room shape modification.

Keywords: room acoustics, modal resonances, non-Sabinian, reflections, short decay time

1 Introduction

The present article gives a rapid overview of classic measurement methods with their positive and negative aspects and proposes some techniques helping the Acoustician control small room acoustics.

Control rooms and rooms for recording and rehearsing music in general are becoming smaller and smaller in dimensions. This is due to the music production business dynamics that moved most of the production phases to personal studios, to electronic equipment lowering prices and to floor surface costs that have been rising in the last two decades.
This fact gives acousticians smaller ‘cavities’ to study and optimize, non Sabinian spaces where modal behaviour dominates the frequency response up to the 125 Hz and 250 Hz octaves. These rooms are often quite absorptive and Sabine’s assumptions of sound field diffuseness do not stand: the acoustical parameters specified in ISO 3382 [1] are often useless.

It is important to develop different analytical approaches to know the room acoustics details and design the acoustic treatment from the beginning or optimize it since automatic control of room acoustics is impossible to be put into practice in professional situations [2]. EBU 3276 [3] introduced a technical approach to evaluate broadcast control rooms. This document also stated that a high quality control room should have a minimum floor area of 30 m² which nowadays is not often an ‘optimistic’ datum in practice.

Small rooms influence and interact with the acoustic and electro-acoustic sound sources emitting sound inside them. The first natural phenomena to be considered are the reflection time pattern and the resonances in the frequency dominion. It is important to know how they are perceived by the listener and how they support or spoil the reproduction of sound.

2 Spectrum analysis in low frequencies

2.1 FFT analysis, an outlook at regime

Traditional spectrum analyzers examine the audio spectrum in third octave bands while the musical note separation of the well tempered scale has 4 semi-tones for each third octave band. Moreover, the human listening apparatus has a difference limen of frequency (DLF) of about 0.5 Hz in the 125 Hz octave band [4].

FFT analysis allows to extend frequency resolution and gives information on the filtering (the ‘equalization’) imposed by the room on the music signal: frequency resolution depends on the observed signal length and hence on the SNR of the measurement system.

\[ \Delta f = \frac{1}{T_{\text{observation}}} [\text{Hz}] \quad (1) \]

This means that a room with a RT of 0.5 seconds can be analyzed with a 2 Hz resolution in the frequency domain. FFT allows to study the regime behaviour of the room by transforming the entire impulse response \( h(t) \). Full scale FFT does not see the transient nature of musical sounds (which have a duration between 0.05 and 2 seconds) while running-FFT has a very poor frequency resolution.

The Fourier Transform is also very dependent on space positioning of the source and the receiver. A spatial average is needed to conform it to the listening experience (every listener has two receivers and slightly moves his head during the hearing experience [5]. )
The Fourier transform is graphed using the Power Spectral Density function (the FFT modulus squared). Its amplitude is given on a deciBel scale over viewing the signal energy distribution in frequency.

Figure 1 plots the PSD of the left channel in a small listening room with a small sofa present (green) or absent (red) behind the listener. It is interesting to notice that its smaller dimension (70 cm) corresponds to the quarter wavelength of 122 Hz where it has a strong effect of smearing the spectral response.

2.2 EFT analysis, room multiple decays.

Energy Frequency Time Curves have been used since the 1980s to juxtapose in a 3D plot numerous short time FFT plots obtained through a moving window in time. It is a way to plot the running-FFT technique and EFT plots are helpful to see the evolution of a system frequency content in time. They use moving, shorter, time windows to transform the impulse response but loose frequency resolution as a trade-off (i.e. 2048 points FFT at a sampling rate of 44100 Hz gives an observation time of 46 msec translating into a frequency resolution of 21.5 Hz).

Noxon [6] proposed an alternative, orthogonal, way to obtain EFT graphs: these can be obtained by convolving the full impulse response with a train of pure-tone bursts. Frequency resolution can be selected on the bursts frequencies while time length is decided by the bursts duration and the natural room decay. Figure 2 plots the EFT curve of a small control room: different decays stand out at 80 and 122 Hz.
2.3 Modal superposition.

The low frequency behaviour of small rooms is dominated by the standing waves forming at definite frequencies. In figure 2 it is clear that each room resonance has its own decay in time. Hence the sound field is deterministic and outside Sabine’s assumptions.

Kuttruff [7] explains Schroeder’s theory on the critic frequency $f_s$ which is a theoretical limiting value between the Sabinian statistical part of the spectrum and the deterministic one in the bass:

$$f_s \approx 2000 \sqrt{\frac{T}{V}} \text{ [Hz]} \quad (2)$$

where $T$ is the reverberation time and $V$ the room volume.

2.3.1 Frequency positioning of modes.

In ‘shoe box’ shaped rooms their resonance frequencies can be calculated from their geometrical dimension $L_x$, $L_y$, $L_z$:

$$f_{n_x, n_y, n_z} = \frac{c}{2} \sqrt{n_x^2 \left(\frac{L_x}{L_c}\right)^2 + n_y^2 \left(\frac{L_y}{L_c}\right)^2 + n_z^2 \left(\frac{L_z}{L_c}\right)^2} \quad (3)$$

Superposition of axial resonance frequency positions on the spectral FFT graphs is very useful. The authors demonstrated [8] that it is a very good analytical device which works both for rigid walls and gypsum-board insulated rooms.
In figure 3 the left (red) and right (green) listening spot frequency responses are plotted, the colored vertical line represent axial mode positions along x (blue), y (green) and z (red). Notice how well correlated are the informations (frequency resolution is 2 Hz in this case).

2.3.2 Defining modal decay, Q factor.

Farina et al. [9] defined the articulation parameter as the amount of modal energy decayed in the first 66 msec. An alternative way to examine a resonance decay is to measure its amount of damping. This is traditionally measured by the Q factor, which is defined in the frequency domain by its –3 dB bandwidth:

\[ Q = \frac{f_0}{\Delta f} \]  

(4)

For high Q values, the Q factor can be measured in the time domain as the number of cycles needed to decay \( e^{2\pi} \) times from the stationary value [10].

A psycho acoustic investigation [11] defined a minimum limit of \( Q = 16 \) for modal detection and the authors applied it to actual measurements [8].

The next figure plots both the FFT (black) and the Q factor (purple) in frequency with the superimposition of axial modal frequencies from the right channel (as shown in figure 1), the 16 value for Q is enhanced by the red horizontal line. Given a precision of 2 Hz the results are good for interpreting the modal phenomenon at about 176 Hz, the small resonance at 72 Hz.
3 Temporal analysis for mid and high frequencies

The mid and higher part of the spectrum can be well studied in the time domain. Here the reflections are well recognizable, especially in the early part of the impulse response when they are sparse.

The analytic impulse response [12] is a useful instrument to estimate the impulse response energetic envelope as perceived by the human hearing system.

3.1 Geometrical model of the first reflections

The classical image source method (well known in Optics) can be used to rapidly estimate the arrival of the first reflections in regular sized rooms.

The authors demonstrated [13] how to superimpose a calculated reflection graph to the analytic impulse response.

This method is very useful when the room dimensions, the receiver and source position are known. It allows to rapidly know which surface created each reflection and to estimate the influence of furniture and large objects within the room as they reflect sound (echometric study).

Figure 5 shows the early part of the analytic impulse response (15 msec or 5 meters of delay from the direct sound arrival) of a small control room for music and superimposes the calculated arrivals from the geometric image model up to the third order. This is clear since the control desk and the video monitors on it create two strong reflections before the first room reflection from the ceiling. Again the geometrical estimate is very good in spotting numerous reflections.
3.2 Perceptual model

Numerous psycho-acoustic experiments were conducted by Olive and Toole [14] in the last decades, their time curves on the perception effects of the first single reflection give both a useful limit to control first reflections and a base for an acoustic correction project. Figure 6 highlights the time-amplitude region where the first reflection modifies the perception of the direct, original, sound which is unwanted in professional and audiophile applications.
Figure 7 expands the plot in figure 5 inserting the perceptual curves defining effects on the image perception and the echo region. It is interesting to notice later reflections at about 50 msec needing control.

3.3 Specular reflections and diffuse reflections.

Flat, hard surfaces create specular, well correlated reflections. Irregular shapes ‘break’ the sound rays creating diffuse reflections. Object edges create diffraction as seen by one of the authors [16]

In figure 5 stand out the first two strong reflections from the video monitor (very 'spiked') and the desk with objects on it (more smeared).

![Figure 7. Superposition of psycho-acoustic limiting curves over the analytic impulse graph](image)

4 Conclusions

The article showed important analytical instruments both in the time and frequency domains to study small room acoustics. The authors field experience as Acoustic consultants allowed to insert two geometrical methods to better interpret the results in regular shaped rooms. Examples from real measurements have been given to explain the concept use and spot some typical natural phenomena needing to be controlled in small rooms for music.

Future research will interest investigation of perception.

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