Experimental assessment of active electroacoustic absorbers for broadband room modes damping

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Active electroacoustic absorbers are membrane absorbers actuated, through a feedback control loop and an electromechanical driver, so as to present optimal sound absorption on a broadband range around the membrane resonance. Taking advantage of the low resonance frequency of conventional loudspeakers, this technique appears as an interesting solution for the damping of low-frequency modes in rooms. This concept has direct applications to real life problems, such as the equalization of sound diffusion in the low-frequency range, or the mitigation of noise immission from external noise sources in habitations, among others.

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The performance of 4 prototypes of active electroacoustic absorbers is assessed inside a reverberant chamber with different sound stimuli (stationary broadband noise, pure tones). It is shown that the 4 electroacoustic absorbers prototypes, which represent only 0.1% of the total wall surfaces, achieve a global noise level attenuation of almost 8 dB, on a broad frequency range from 20 Hz up to 100 Hz, with individual mode attenuations up to 12 dB. Moreover, the modal decay times are significantly reduced, which is also verified with recordings of time-limited pure tones at several resonant frequencies in the room.

1 INTRODUCTION

Even though conventional passive sound absorbers are cheap, and simple to implement, they are absolutely inefficient to address the low-frequency bound of the audible range[1]. This inadequacy of conventional soundproofing treatments for the low-frequency range, as well as the significant progress beyond the state-of-the-art of active noise control techniques observed in the recent years[2], has motivated the development of active loudspeakers with tunable acoustic impedances[3].

In a recent paper[4], the concept of electroacoustic absorber has been proposed as a practical alternative for low-frequency sound absorption. It consists of an electrodynamic loudspeaker connected to a passive or active shunt electric network, the whole acting as a sound absorber in the low-frequency range. The concept was assessed on experimental prototypes that have been thoroughly studied in laboratory conditions, in one-dimensional impedance tubes where the acoustic performance showed almost perfect broadband sound absorption in the [20-200 Hz] range.

In the frame of the INTERACTS project, funded by the Swiss Commission for Technology and Innovation (CTI), two Swiss companies (Goldmund and Relec) and two Swiss academic partners (EPFL and HEPIA) have collaborated to develop technologies to address the damping of room modes at low frequencies. In this paper, we present the preliminary results of assessment of a set of 4 electroacoustic absorber prototypes in a reverberant chamber. The performance will be presented in terms of damping of modes amplitudes, but also in terms of modal decay time reduction. The experiments take place in a reverberant chamber of 215.6 m^3, and the acoustic stimuli are broadband noise and time-limited pure tones.

2 DESIGN OF THE ACTIVE ELECTROACOUSTIC ABSORBER PROTOTYPE

2.1 Control strategy for the electroacoustic absorber

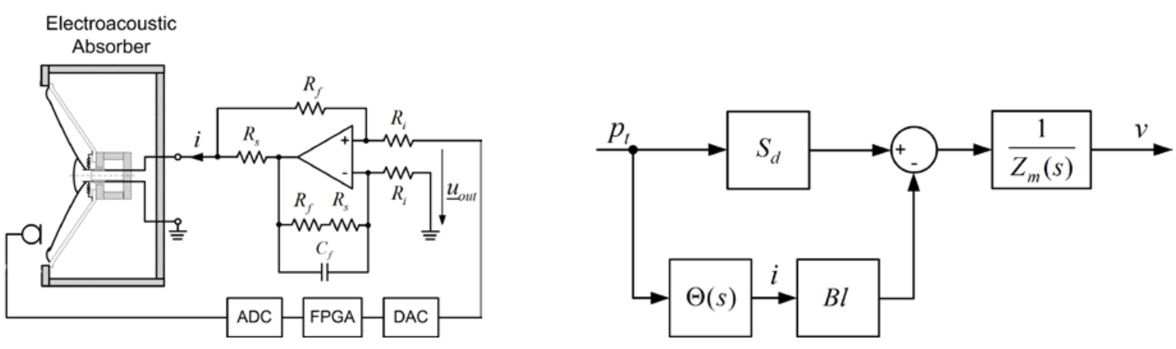


Fig. 1 – Description of an active electroacoustic absorber (left: sketch of a unit of electroacoustic absorber; right: synoptic representation of the control)

The developed electroacoustic absorber is based on the design presented in Figure 1. This setup corresponds to a feedback control architecture, employing a microphone, sensing the total sound pressure p_t on the loudspeaker diaphragm, serving as the input of a controller (transfer function $\Theta_p(\omega)$, where $\omega = 2\pi f$ is the angular frequency and f the frequency), so as to drive the moving coil with a prescribed electrical current $i = \Theta_p(\omega) p_t$.

This setup differs from the one presented by Lissek et al.[5] in the sense that a microphone output voltage is substituted for the electrical voltage at the terminals of the loudspeaker, but the general idea of synthesizing a target acoustic impedance at the loudspeaker membrane remains the same. In this concept, the acoustic impedance is modified by delivering the current to the loudspeaker as a complex function of the total pressure at the membrane. Writing Newton's law applied on the membrane:

$$S_d p_t = Z_m(\omega) v + Bl\Theta_p(\omega) p_t, \quad (1)$$

where $Z_m(\omega) = R_{ms} + j\omega M_{ms} + \dfrac{1}{C_{ms}} + \dfrac{\rho c^2 S_d^2}{V_b}$, and the parameters of Eqn. (1) are defined in Table 1:

Table 1: loudspeaker parameters used in the model of the electroacoustic absorber (measured on a Peerless SDS-P830657 loudspeaker)

Parameter	Description	Value	Unit
M_{ms}	Moving mass	14.7	g
R_{ms}	Mechanical resistance	1.31	$\mathrm{N.s.m^{-1}}$
C_{ms}	Mechanical compliance	242.3	$\mathrm{\mu m.N^{-1}}$
S_{d}	Diaphragm surface	151	$\mathrm{cm^2}$
Bl	Force factor	6.85	$\mathrm{N.A^{-1}}$
V_{b}	Cabinet volume	10	$\mathrm{dm^3}$
ρ	Medium mass density	1.2	$\mathrm{kg/m^3}$
c	Sound celerity in the medium	344	$\mathrm{m.s^{-1}}$

It is then straightforward to derive the resulting acoustic impedance at the loudspeaker diaphragm from Eqn. (1) as:

$$Z_a(\omega) = \frac{p_t}{v} = \frac{Z_m(\omega)}{S_d - Bl.\Theta_p(\omega)}. \quad (2)$$

2.2 Target acoustic impedance and controller design

In this study, the loudspeaker membrane is set to match a certain acoustic resistance R_{at}. The transfer function to implement on the controller, in order to achieve a target $Z_a = R_{at}$, can easily be derived from Eqn. (2) as:

$$\Theta_p(\omega) = \frac{S_d R_{at} - Z_m(\omega)}{Bl.R_{at}}. \quad (3)$$

2.3 Absorber setting and implementation

In this study, we chose to assign the target acoustic resistance $R_{at} = 0.25\rho c$ [*] to the loudspeaker diaphragm. This value differs from $Z_c = \rho c$, following the results of the study reported in Ref.[6],

[*] The controller actually implements a band-pass filtered version of R_{at} in order to avoid stability issues.

since the whole surface of absorption inside the room represents a small ratio of the total surface of the room walls.

The transfer function Θ_p is then implemented on a real-time National Instruments CompactRIO® platform supporting FPGA technology. The voltage signal from the microphone is digitally converted through an AD module NI 9215, and the output signal is delivered through a DA module NI 9263. A voltage controlled current source is implemented as illustrated on Figure 1 to drive the voice-coil with the desired current.

Prior to test the electroacoustic absorber prototypes in the reverberant chamber, their acoustic performance has been assessed in an impedance tube, along the methodology presented in Ref.[3] and Ref.[4]. Figure 2 presents the achieved acoustic impedance (magnitude and phase) measured in the impedance tube terminated by an open-circuit loudspeaker and the corresponding electroacoustic absorber prototype described in Figure 1, with the controller set as in Eqn. (3).
It can be seen that the control allows achieving a perfect matching of the membrane acoustic impedance to $0.25\rho c$ on a somehow broad frequency range, approximately between 20 and 150 Hz.

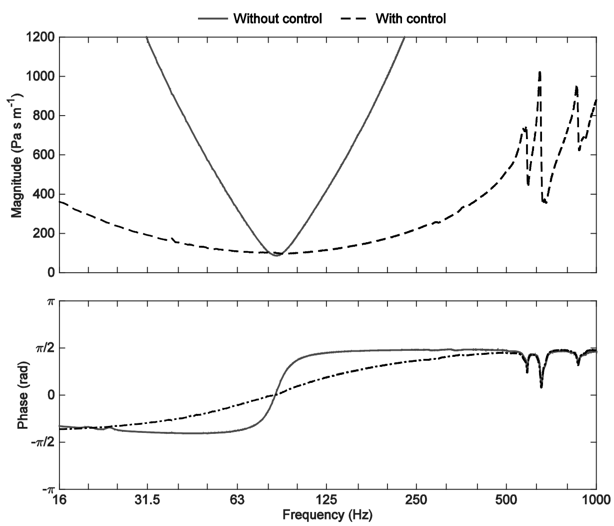


Fig. 2 – Measured acoustic impedance (magnitude and phase) of a sample of electroacoustic absorber at the termination of an impedance tube: without (plain line) and with control (dotted line)

3 ASSESSMENT OF THE EFFECTS OF THE PROTOTYPES ON ROOM MODES

3.1 Experimental setup

Each electroacoustic absorber prototype is composed of a wooden cabinet of dimensions 620 mm x 300 mm x 300 mm, with 4 Peerless SDS-P830657 loudspeakers located on two adjacent sides, and one single microphone sensing the total pressure for the set of 4 loudspeakers, individually controlled with their own controller channel according to Figure 1. The whole cabinet is separated in 4 sub-volumes V_b (see Figure 3). 4 identical prototypes have been built with this design for this study, representing a total surface of 0.24 m^2 of absorber.

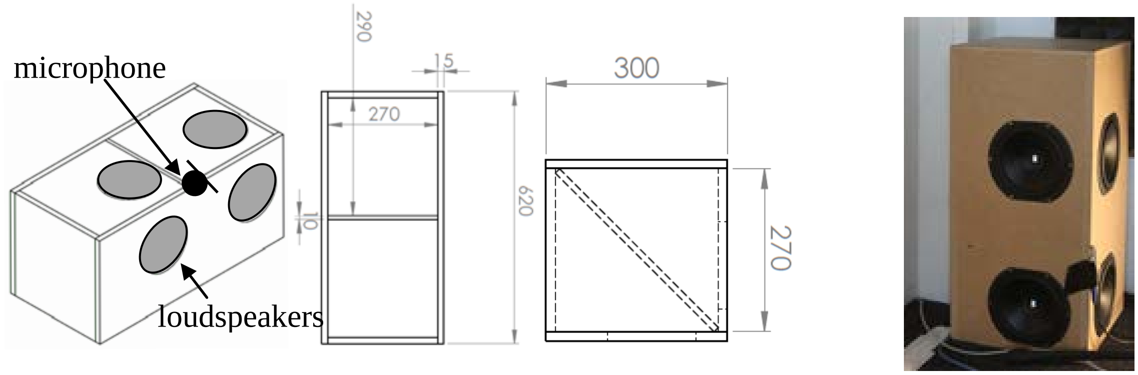


Fig. 3 – left: drawings of the electroacoustic absorber prototype (isometric view, face cut, top cut); right: picture of a built prototype

The room modes damping capabilities of the electroacoustic absorbers have been tested in the controlled environment of the EPFL reverberant chamber (volume: 215.6 m^3, total wall surfaces: 226.9 m^2). The surface of active electroacoustic absorbers represents then 0.11% of the total surface of the room. Therefore, each electroacoustic absorber has been assigned a target acoustic impedance according to Eqn. (4) with R_{at}=0.25ρc, corresponding to the optimal acoustic resistance for the total active surface of absorption in the room[6].

Since the room is used in the very low frequency range, 4 additional panel absorbers (total surface of absorption: 12.8 m^2) have been added so as to lower the effect of reverberation on the middle-high frequency range. They have been installed inside the room (see Figure 4) for the whole experiments (without and with electroacoustic absorbers).

The experimental setup comprises the following elements:
For room mode identification:

- 1 Bruel and Kjaer Type 3160 Pulse Multichannel Analyzer
- 1 PCB Piezotronics type 130E20 ICP microphone at 0.83 m above corner B (see microphone “ICP” in Figure 4 and Table 2)
- 1 Velodyn SPL-800i subwoofer, located in the vicinity of corner « B ».

For mode decay time measurements:

- 1 M-Audio M-Track Eight 8-channel soundcard
- 6 Beyerdynamic M101-N electrodynamic microphones, located according to Figure 4 and Table 2
- 1 Velodyn SPL-800i subwoofer, located in the vicinity of corner « B ».

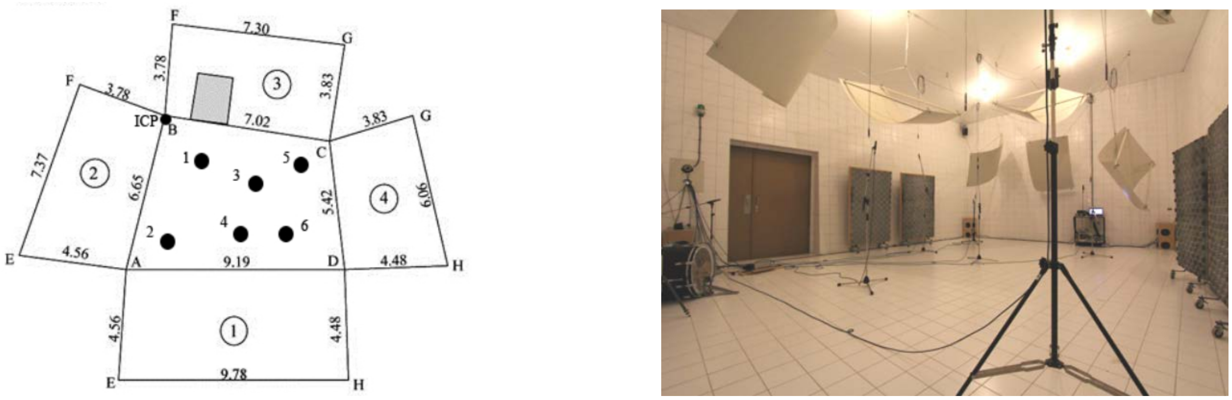


Fig. 4 – left: 2D representation of the reverberation chamber and measurement points; right: picture of the setup (2 electroacoustic absorbers can be seen on the two opposite corners, namely corner C and D)

Table 2 – Microphone positions corresponding to Fig. 4.

Microphone ID	Height (m)	Distance to corner A (m)	Distance to corner B (m)	Distance to corner C (m)	Distance to corner D (m)
ICP	0.83		0.00		
1	1.83	4.89	3.35		
2	2.79	2.07	5.55		
3	1.81	6.40	4.90		
4	2.20		4.17	3.31	
5	1.22			1.62	5.00
6	1.49			4.00	2.84

For room mode identification, the excitation consisted in a band-limited white noise (bandwidth: 10 – 210 Hz) and the output was the autospectrum processed on the microphone “ICP” output signal (in Pa^2, frequency resolution: 31.25 mHz).
For modal decay time assessment, the excitation signal was designed as a succession of time-limited sine (20 s of pure tones, followed by 20 s of silence) at different discrete frequencies corresponding to the room resonances identified without and with electroacoustic absorbers. This second measurement campaign is limited to the 24 first modes, within the bandwidth [20-100 Hz].

3.2 Room modes identification

First the sound pressure at microphone position “ICP” is evaluated and reported on Figure 5, without absorbers (in black) and with 4 active electroacoustic absorber prototypes (in grey). This measurement allows first to determine the first room modes frequencies below 100 Hz. The attenuation of each mode can be seen on Figure 6.

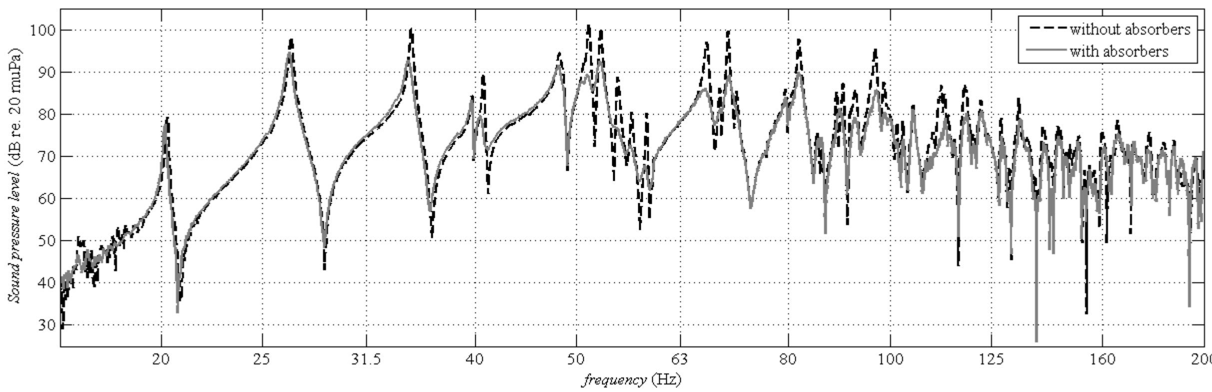


Fig. 5 – sound pressure levels measured at microphone position "ICP" (dB re. 20 μPa) (in black dashed-lines: without absorbers; in grey: with absorbers)

It is noticeable that all peaks amplitudes are reduced between 2 and 12 dB. Moreover, the global "attenuation" over the bandwidth [20 – 100 Hz] is almost 8 dB. It is also interesting to notice that modes 18 and 19 without absorbers (at 85.0 and 86.1 Hz) seem to merge with the absorbers in the room, to form a single mode (denoted 18) at 85.4 Hz. The same phenomenon occurs for modes 20 and 21 without absorbers (88 Hz and 90 Hz) resulting to mode 20 at 89 Hz with the absorbers.

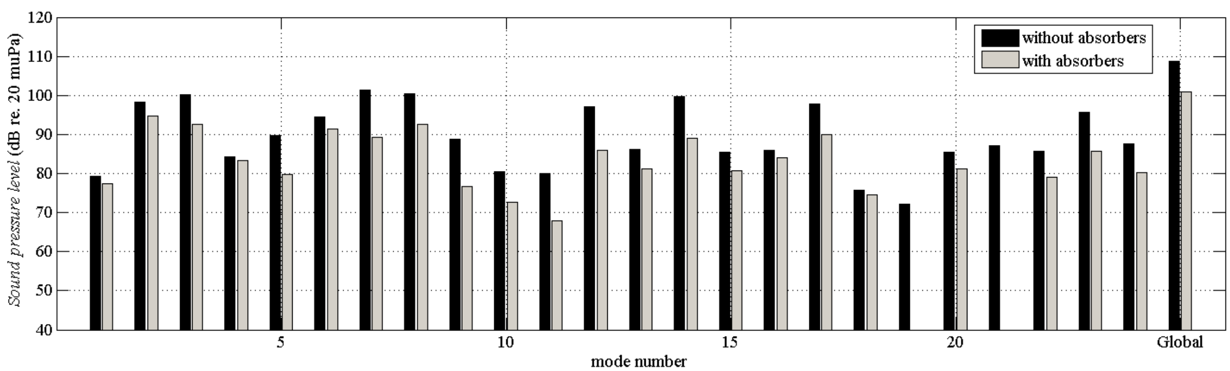
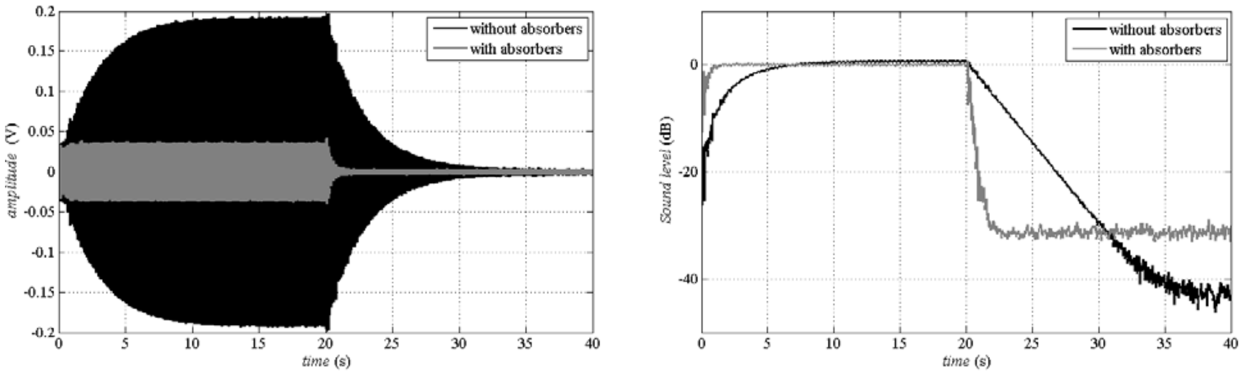


Fig. 6 –amplitudes of the 24 first room modes with and without electroacoustic absorbers (in dB) measured at microphone position "ICP" (black bars: without absorbers; grey bars: with 4 electroacoustic absorbers)

3.3 Assessment of modal decay time

The sustaining of room modes after excitation appears to be a significant parameter in the annoyance perceived in a room subject to strong modes[7]. The following experiment intends to measure the effect of the electroacoustic absorbers on the 24 first modal decay times within the range [20 – 100 Hz] in the reverberant chamber.

The former experiment allowed us to identify the different modal frequencies in the room without and with absorbers. Then, the assessment of mode decays is performed by exciting the room with time-windowed pure tones (20 seconds of pure tones, followed by 20 seconds without signal) corresponding to the identified frequencies, without absorbers first, and then with 4 active electroacoustic absorbers in the 4 corners of the room. An example of such recordings is given in Figure 7 (in black: without absorbers; in grey; with 4 electroacoustic absorbers).



a) b)

Fig. 7 – a) recording at microphone position #3 of a time-windowed pure tone corresponding to mode #11 (around 58 Hz); b) envelope of the waveforms represented in a dB scale (relative to the waveform amplitude within the stationary state)

Figure 7 highlights the decay of mode #11 measured at microphone position 3. It is obvious that the sound pressure level decreases linearly with time (Figure 7-b)). Thus, for each microphone position, we can deduce a modal decay time that can be seen as an extrapolation of the reverberation time in the low-frequency range[1].

To compare the modal decay times without and with absorbers, we can define a quantity MT_{60} (in seconds), corresponding to a decrease of 60 dB of sound pressure level of a mode after the excitation stops. However, since the dynamic range of each signals recorded at each position and for each mode hardly reaches 60 dB, the MT_{20} is computed instead, namely the time for the sound pressure level to decrease by 20 dB, multiplied by 3 (in analogy with the reverberation time evaluated over a 20 dB decay range, RT_{20}). Figure 8 shows the different MT_{20} averaged over all microphone positions, for each mode, without (in black) and with absorbers (in grey).

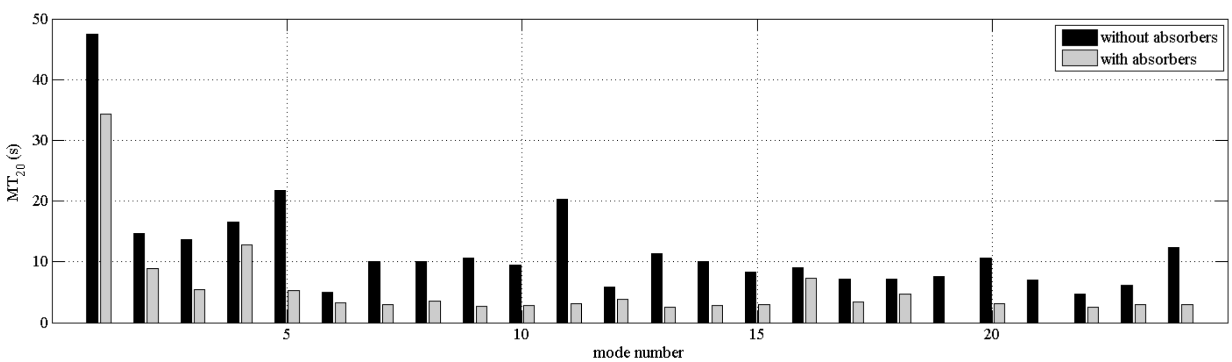


Fig.8 – effect of the electroacoustic absorbers on the mode decay times: representation of the MT_{20} without (black) and with absorbers (grey)

All modal decay times are significantly decreased, with a maximum reduction occurring for mode 11 (at 58 Hz), reduced from 20.2 s down to 3.2 s. Globally, the mode decay time reductions range from 1.7 s for mode 16 (relative reduction of 19%) to 17.0 s for mode 11 (relative reduction of 84%).

4 CONCLUSIONS

This series of measurements highlight the performance of 4 electroacoustic absorbers prototypes in the reverberation chamber. The main characteristics are:

- an equalization of room frequency responses: the significant damping of the different modes amplitudes in the room may improve the rendering of audio signals in the low frequency range. The maximal peak reduction is 12.2 dB ;
- a significant reduction of mode decay times : on certain modes, the decay times may vary from 20 s without absorbers, down to 3 s with absorbers. The maximal modal decay time decrease corresponds to a relative reduction of 84%.

5 ACKNOWLEDGEMENTS

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