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# THE EFFECT OF ELECTRONIC REVERBERATION IN A HYBRID REVERBERATION ENHANCEMENT SYSTEM: CARMENCITA

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## ABSTRACT

Active reverberation systems turn a performance hall with naturally dry acoustics into a multi-purpose venue that can host any type of performance from theatre to symphonic music. Different types of active reverberation systems exist. All systems have loudspeakers spread on the walls and ceiling of the audience area, but they differ in two main concepts: the locations where the sound is picked-up and the use of electronic reverberation algorithms or not. "In-line" systems pick the sound close to the stage, add electronic reverberation and diffuse it in the audience area. "Regenerative" systems such as Carmen pick the sound in the audience area and increase reverberation in the room without using electronic reverberation algorithms but only amplification and delays. Finally, "hybrid" systems like CarmenCita pick the sound in the audience area and add reverberation with specifically designed reverberation algorithms. This work investigates the convolution that happens between electronic reverberation and the natural response of a concert hall with a hybrid reverberation enhancement system as CarmenCita. The effect of the system on various acoustic indicators is explained based on measurements performed at Espace Paul Jargot, a 400-seat multipurpose venue located in Crolles, France.

## 1. INTRODUCTION

To diversify its cultural programme and become a true multi-purpose venue, a performance hall requires variable acoustics. Variable acoustics can be achieved with passive means (such as rotating panels and/or curtains) or with active electro-acoustic systems. Traditionally, passive variable acoustics systems were preferred to active systems because they have a straightforward effect on the acoustic characteristics of a venue and always produce totally natural effects. In the early days of active acoustics solutions, limited computational power in audio processing units tend to induce unnatural artefacts. Nowadays, active systems implement very realistic algorithms and hence create perfectly natural sounding acoustics. Moreover, active systems often extend reverberation time significantly more than the most extensive passive variable acoustics systems thanks to programmable reverberation algorithms.

To achieve natural acoustics with an electro-acoustic reverberation enhancement system, the reverberation enhancement process needs to trick the human ear. The only

way to achieve this is to mimic natural acoustic propagation phenomena. Various approaches were developed during the past decades to achieve this purpose [1]. These approaches mainly differ in two features : the microphones/loudspeakers layout and the reverberation process implemented in the processing unit. This work briefly details different transducers layouts and associated reverberation processing before placing the focus on one particular approach : the hybrid reverberation process of the CarmenCita system. The impact of natural acoustics of a venue on the reverberation induced by a hybrid reverberation enhancement system is analysed by comparing measurements performed in an almost anechoic room and a concert hall, both equipped with a CarmenCita system.

## 2. ACTIVE REVERBERATION SYSTEMS

This section details briefly existing electroacoustic methods to enhance the acoustics of a venue. For exhaustive information and references to all these methods, the reader can refer to the work of Poletti published in [2]. For a comparison of in-line, regenerative and hybrid reverberation systems, the reader can refer to [3].

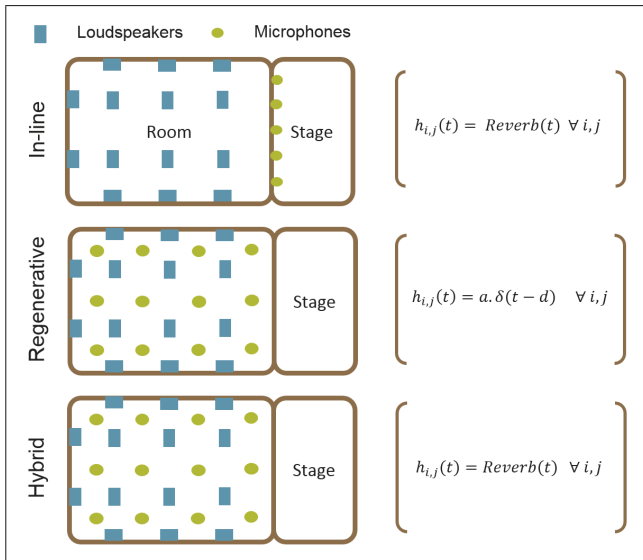
Active reverberation systems pickup sound with microphones, perform operations on the acquired signals (delays, gains, equalization, convolution, mixing, ...) and then cast the processed signals through loudspeakers spread on all walls and ceilings of a venue. This process can be expressed as:

$$x_{LS,j}(t) = \sum_{i=1}^{N_{Mic}} x_{Mic,i}(t) * h_{i,j}(t) \quad (1)$$

where  $x_{Mic,i}(t)$  is the signal captured by microphone  $i$ ,  $h_{i,j}(t)$  is the impulse response of the implemented transfer function between microphone  $i$  and loudspeaker  $j$  in the processing unit and  $x_{LS,j}(t)$  is the signal sent to loudspeaker  $j$ .

Active reverberation systems differ in the content of the transfer functions between microphones and loudspeakers  $h_{i,j}(t)$  and in the placement of microphones : in the audience area or in the stage area (sometimes both). Figure 1 presents most common transducer layouts and the associated reverberation processing.

For in-line systems, sound is picked up with directional microphones close to the stage and the transfer functions  $h_{i,j}(t)$  generally contain some specifically developed reverberation algorithms or recorded impulse responses. As



**Figure 1.** Simplified representation of active reverberation systems. Left) Schematic loudspeaker and microphone layouts for in-line, regenerative and hybrid reverberation systems. Right) Simplified equations of impulse responses of transfer functions implemented between microphones and loudspeakers. Note that these simplified equations do not account for feedback control processing that differs for all active reverberation systems. *Reverb* represents a specifically developed reverberation processing,  $\delta$  is the dirac function and  $a$  and  $d$  are respectively gain and delay values implemented in regenerative systems.

long as the sound source (performer) remains within the stage area, the resulting acoustics are the convolution between the reverberation implemented in the processing unit and the natural acoustics of the room. If the performer leaves the stage area, the system has no effect. The audience acoustic energy (applause for example) is not processed neither. In-line systems are easier to tune in terms of feedback control than their regenerative counterparts but do not enhance acoustics homogeneously throughout the venue due to their limited microphone layout.

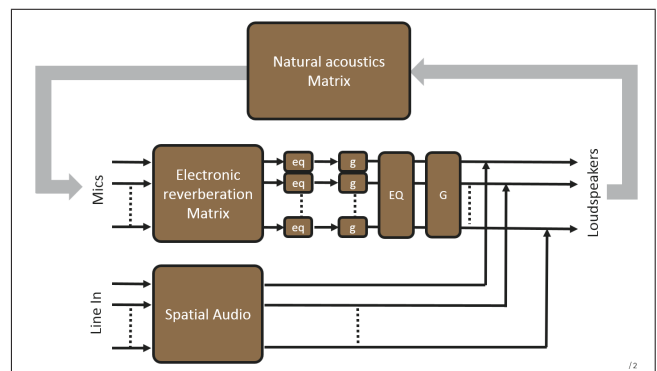
In purely regenerative systems, the sound is picked up all over the venue and the transfer functions  $h_{i,j}(t)$  mostly contain gains, delays and feedback control. These systems only add some discrete sound reflections to enhance the existing soundfield. Purely regenerative systems can truly mimic natural acoustic propagation phenomena but require advanced feedback control processing to avoid unnatural colourations. Also, the reverberation variation range is limited as no controlled electronic reverberation is added.

Hybrid systems, combine the transducer layout of regenerative systems with electronic reverberation used in in-line systems. Such systems are able to produce homogeneous effects over the whole venue (audience and stage areas) and can raise reverberation time to high values. The realism of the produced enhancement mostly relies on the implementation of the electronic reverberation.

### 3. CARMENCITA PROCESSING

CarmenCita is a hybrid reverberation system. Its principle is shown on Figure 2. Microphone signals are the inputs to an electronic reverberation matrix. Each output of the reverberation matrix (one per loudspeaker channel) is the sum of reverberated microphone signals (as presented in equation 1). The reverberation filters ( $h_{i,j}(t)$ ) are derived from allpass reverberation structures and absorbent filters introduced by Jot [4] [5]. In CarmenCita, reverberation structures are the same for all channels but they are configured with different delay tables to ensure that all produced loudspeaker signals are independent/uncorrelated.

An automatic iterative equalization process is performed during the installation for every acoustic preset. This automatic tuning process (detailed in [6]) sets the parametric filters (noted *eq* on Figure 2) used to ensure system stability and absence of spectral colouration. Each channel level is set by gain values (noted  $g$  on Figure 2) in order to control the relative contribution of each loudspeaker to the produced reverberation. It can be used for example to control the lateral energy fraction (*LF*). Parametric equalization (noted *EQ* on Figure 2) adjusts the balance in the produced reverberation. Bass and treble ratio can be controlled with absorbent filters implemented in the electronic reverberation matrix. The master gain (noted  $G$  on Figure 2) sets both the energy of the added reverberation and the reverberation time (RT). This "double effect" specific to regenerative systems is further detailed in the following section.



**Figure 2.** Hybrid reverberation process

Figure 2 also depicts the spatial audio processing of a CarmenCita system. This feature allows to use all loudspeakers as a multichannel sound system to create immersive 3D sound environments.

### 4. INFLUENCE OF ELECTRONIC REVERBERATION

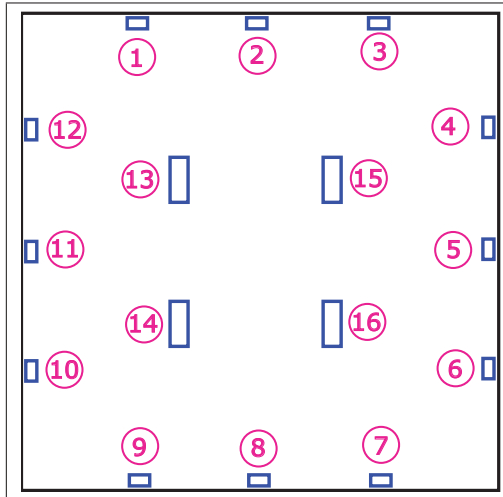
In this section, two CarmenCita installations performed in very different rooms are compared. One system is installed in an almost anechoic laboratory and the second in a real concert hall. The purpose is to understand how passive acoustics interact with electronic reverberation implemented in a hybrid reverberation enhancement system as CarmenCita.

## 4.1 Compared rooms

### 4.1.1 CSTB Lab

The system layout at CSTB laboratory is depicted on Figure 3. It consists in 16 cells spread homogeneously on the walls and ceiling of the room:

- 3 cells on each wall (at different heights)
- 4 cells on the ceiling



**Figure 3.** Cell distribution at CSTB Lab

The room is 14mx14m large and 7m high. All surfaces are covered with absorbing materials:

- Walls are covered with 20cm-thick glass wool
- Floor is covered with 20cm-thick glass wool. A technical grid placed at 2m high allows to work in the room (see Figure 4).
- Ceiling is covered with acoustic tiles.



**Figure 4.** Picture of CSTB Lab

RT in the mid frequencies is 0.1 second. It is therefore an almost anechoic room which acoustics have almost no effect on the regeneration process of a hybrid reverberation enhancement system. Only direct contributions of

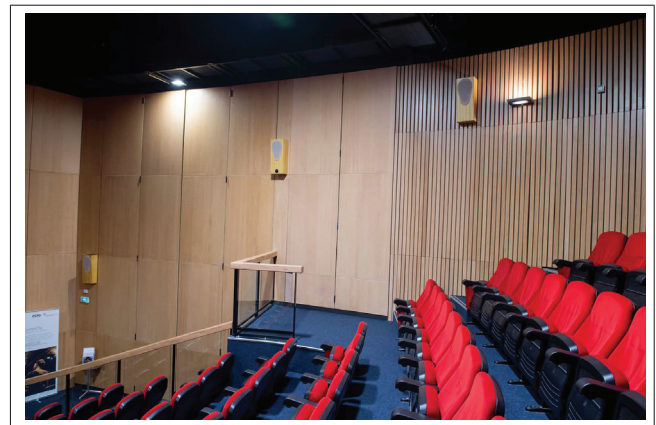
sound sources (performers) and CarmenCita loudspeakers are captured by the microphones and fed to the processing unit.

Five acoustic presets increasing reverberation time up to 5 seconds were tuned in this room.

### 4.1.2 Espace Paul Jargot

Espace Paul Jargot (Crolles, France) is a 400-seat venue with a RT of 1.1s in the mid frequencies. The venue is equipped with a passive variable acoustic solution (rotating panels in the stage area and on the lateral walls) that raises RT to 1.5s when all panels are on their reflective side. CarmenCita extends the acoustic variability of the hall:

- Five acoustic presets were tuned for the absorptive room configuration [RT : 1.1s to 3.5s]
- Four acoustic presets were tuned for the reflective room configuration [RT : 1.5s to 3.5s]



**Figure 5.** Picture of Espace Paul Jargot

The system layout is presented on Figure 6. It consists in 16 cells spread homogeneously on the walls on ceiling of the hall:

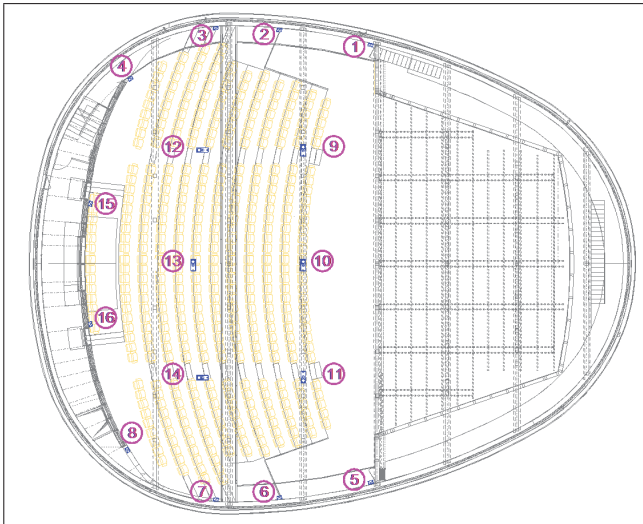
- 4 cells on each lateral wall
- 2 cells on the rear wall
- 6 cells on the ceiling

No CarmenCita cells are installed in the stage area as its acoustics can already be controlled with rotating panels acting as an orchestra shell or as stage curtains depending on their rotation angle.

In this hall, CarmenCita microphones capture both direct and reverberated sounds from sound sources (performers) and CarmenCita loudspeakers. Therefore, the regeneration process benefits from already reverberated sound signals.

## 4.2 Results

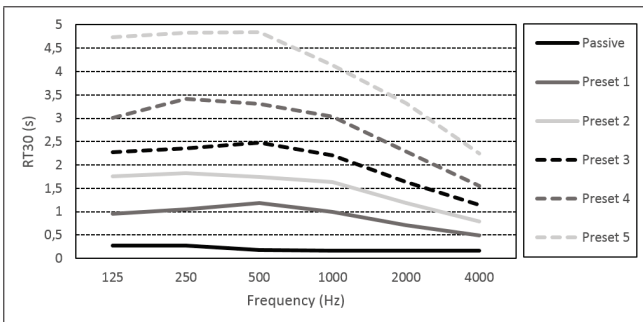
Impulse responses in both rooms were measured in multiple receiver positions with an omnidirectional sound



**Figure 6.** Cell distribution at Espace Paul Jargot

source and a high quality omnidirectional microphone. Measurements were carried out with the CarmenCita system turned off, for all system presets and for different master gain values on a selected acoustic preset. Espace Paul Jargot was in the absorptive configuration (passive RT: 1.1s).

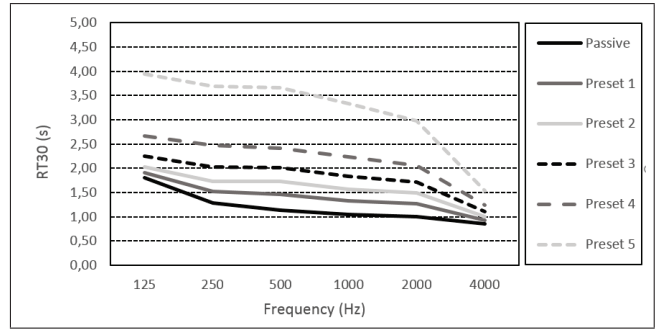
RT for all presets at CSTB Lab and Espace Paul Jargot are shown on Figures 7 and 8 respectively.



**Figure 7.** RT values measured for the 5 presets at CSTB Lab.

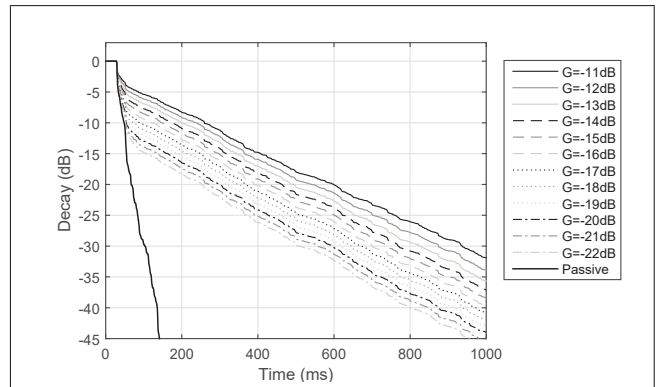
At CSTB Lab, the produced reverberation is electronic. As the room is almost anechoic, there is no interaction between passive and electronic acoustics. For all presets, reverberation curves as a function of frequency are controlled exclusively with equalisation filters implemented in the processing unit.

At Espace Paul Jargot, the produced reverberation is the convolution between passive acoustics and electronic reverberation implemented in CarmenCita. CarmenCita reverberation matrix is an allpass reverb structure with absorbent filters to control the decay in high frequencies. Therefore, when no corrective filtering is applied, CarmenCita simply enhances passive acoustics preserving the natural reverberation frequency balance. In practice, equalisation filters implemented for feedback control slightly alter the natural reverberation balance but overall, the bass and treble ratios are preserved.



**Figure 8.** RT values measured for the 5 presets at Espace Paul Jargot (absorptive configuration).

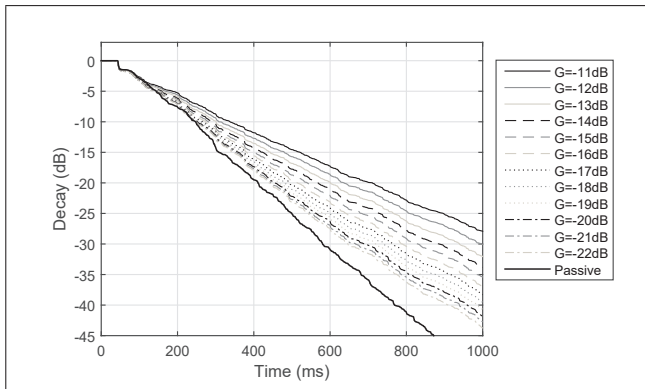
To further analyse the effect of passive acoustics on the regeneration process occurring in CarmenCita, measured decay curves (octave band 1kHz) for different master gain values are shown on Figure 9 for CSTB Lab and on Figure 10 for Espace Paul Jargot. At CSTB Lab, CarmenCita has been set to preset 2 and master gain has been varied from -22 to -11 decibels. At Espace Paul Jargot, CarmenCita has been set to preset 3 and the same variation in master gain has been carried out. In both cases, the approximative RT for octave band 1kHz of the reverberation matrix is 1.65s.



**Figure 9.** Decay curves for octave band 1kHz measured at CSTB lab with a CarmenCita system tuned with increasing master gain.

In an almost anechoic room, for low master gain values, CarmenCita simply produces a double-sloped decay by adding some low level reverberation. The system effect is similar to an in-line system : master gain increases the level of the reverberation but not the reverberation time. The acoustics produced by CarmenCita at CSTB Lab sound natural only for high master gain values when the EDT gets closer to the RT30. But even then, the acoustics remain purely electronic.

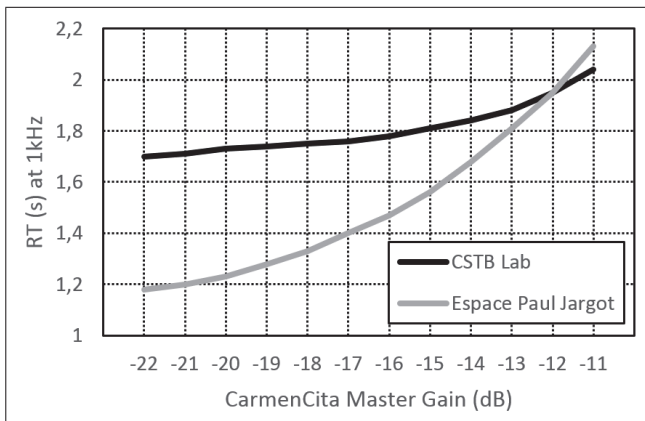
At Espace Paul Jargot, increasing master gain acts almost exclusively on the slope of the decay and not on its level as at CSTB Lab. It is also important to notice that the RT of the reverberation matrix does not set the RT of the room as at CSTB Lab or for any in-line system. Even if the passive RT (1.1s) is lower than the average RT of the reverberation matrix (1.65s) there is no significant double



**Figure 10.** Decay curves for octave band 1kHz measured at Espace Paul Jargot with a CarmenCita system tuned with increasing master gain.

slope effect: the EDT remains close to the RT30. This remains true as long as the passive RT of the room is close to the RT of the reverberation matrix or when the master gain is sufficient to mask the initial sound decay of an almost anechoic room.

Figure 11 shows RT estimated on decay curves presented on Figures 9 and 10. For decays measured at Espace Paul Jargot, RT is estimated on the [-5 -25]dB range. For decays measured at CSTB Lab, RT is estimated on the linear portions to carefully avoid wrong estimation due to the double slope.



**Figure 11.** RT for octave band 1kHz estimated manually on the linear portions of the decay curves presented on figures 9 and 10.

With an in-line system the RT would remain constant (equal to the RT of  $h_{i,j}(t)$  responses) when increasing master gain. At CSTB Lab, RT increases very slowly with master gain values: regeneration is limited to direct sound transfers between microphones and loudspeakers of the system. At Espace Paul Jargot, RT increases quickly with master gain because regeneration truly occurs: microphones pick up both direct contributions of the loudspeakers and their naturally reverberated contributions.

## 5. CONCLUSION

Regeneration is an important aspect in active reverberation enhancement systems as it mimics real propagation phenomena. When feedback is well controlled, it is a good approach to naturally enhance reverberation time. In hybrid systems, adding electronic reverberation in the processing may induce audible artefacts if the reverberation algorithm is not perfectly designed and tuned. In fact, electronic reverberation matches natural sound propagation phenomena only under very strict conditions. In other words, it must be carefully designed to trick the human ear and sound natural. On the other hand, it provides easier control both over the acoustic feedback and the fine tuning of reverberation.

In this paper, it has been shown that in an almost anechoic room, RT increases very slowly with the master gain of a hybrid reverberation system. When the passive RT is greater, RT increases quickly. This results shows that even if homogeneous sound picking is necessary for regeneration, it is not sufficient. A significant passive reverberation time is crucial for regeneration to happen. Hence, without the support of the natural acoustics of a venue, hybrid reverberation systems as CarmenCita can work but will sound just as their electronic reverberation, almost without any regeneration effect. On the other hand, with the support of nicely sounding passive acoustics, hybrid reverberation systems will easily produce naturally sounding acoustics taking advantage of the regeneration effect.

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