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Under-balcony acoustics improvement with simple electro-acoustic means: A theoretical development and numerical simulations

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ABSTRACT

In concert halls, the acoustic quality below a large balcony is often reduced compared with the acoustic quality of the main volume of the concert hall. This is caused by significant differences in the reverberated energy behavior between these two volumes. The main difference is a global lack of reverberated energy under the balcony, which can be theoretically estimated by Sabine's theory applied to coupled spaces. A solution for enhancing the reverberated energy below the balcony is to inject amplified sound picked up in the main volume. This can be performed with simple electro-acoustic channels such as those used in a regenerative reverberation enhancement system. Thus, each channel is composed of a microphone in the main volume, an amplification processing unit and a loudspeaker under the balcony.

In this paper, a theoretical development based on Sabine's approach is presented to explain and predict how the electro-acoustic channels increase the coupling coefficient between the main volume and the volume below the balcony. The theoretical limits of this coupling enhancement technique are also presented and discussed, especially with respect to feedback problems of electro-acoustic installations in a room. In order to prove the validity of these theoretical developments, numerical simulations based on ray-tracing methods have been implemented. These numerical simulations also show that a properly calibrated electro-acoustic coupling enhancement system (EACES) can sensitively decrease the acoustic shadow effect of the balcony with respect to room acoustic criteria. Hence, electro-acoustic systems appear to be an efficient solution for coupling volumes in concert halls.

1 INTRODUCTION

In an auditorium with a deep balcony, the audience seated under this balcony might suffer from a lack of acoustic quality if the opening aperture between this volume and the main room is too small. As pointed out by *Barron*[1], a balcony overhang might induce a decrease of early decay time and acoustic strength, and an excess of clarity under the balcony compared to the acoustics in the main volume. This phenomenon is due to the coupling effect between the main volume and the volume under the balcony. To increase the coupling between these two volumes, *Van Munster* and *Prinssen*[2] proposed to introduce electro-acoustic channels such as those used for a reverberation enhancement system. In their paper, they described the conceptual design of this system and gave some advice about its installation. *Watanabe* and *Ikea*[3] presented measurements made on a simple model of coupled rooms equipped with an electro-acoustic system used to increase the coupling. These measurements showed that such a system could indeed reduce the effect of the balcony overhang, but this system was an "in-line" reverberation enhancement system which has a more complex design than a regenerative one.

This paper focuses on the theoretical development of the effect of a simple electro-acoustic coupling enhancement system (EACES) similar to a regenerative reverberation enhancement system. Numerical simulations of this system are also presented. Their results are used to verify some aspects of the proposed theoretical approach and to observe the effect of an EACES on four common acoustic criteria. In the first part of this paper, the theoretical aspects of coupled rooms according to the energetic diffuse field approach are presented. The results of numerical simulations of a concert hall with a coupled under-balcony volume are also presented and an objective coupling criterion is proposed. In the second part of this paper, the energetic diffuse field approach is applied to a coupled room equipped with an EACES and the theoretical limits of this system are discussed. The prediction results of the effect of the system on the coupling criterion and on the reverberation time given by equations deduced from the energetic approach are compared with the results obtained from numerical simulations. Finally, the effect of the EACES on the early decay time, the acoustic strength and the clarity are presented and discussed.

2 TWO COUPLED ROOMS WITHOUT COUPLING ENHANCEMENT SYSTEM

2.1 Theoretical impulse responses

The following theoretical development is mainly taken or deduced from the work of *Cremer* and *Müller*[4]. The situation considered here is represented on **Figure 1.**

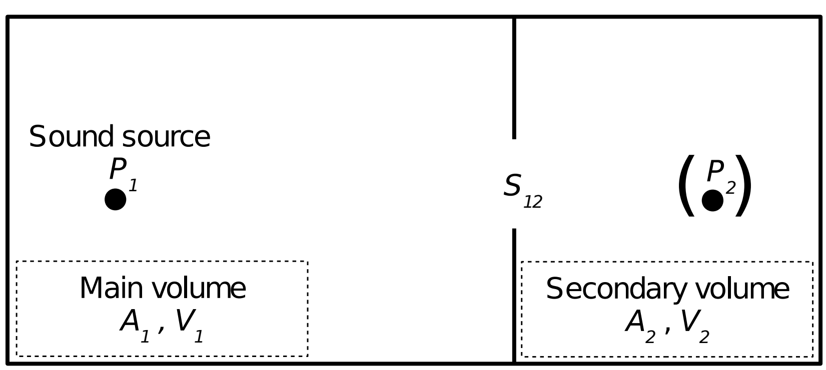

Figure 1: A schematic representation of two coupled rooms.

Each sub-room is governed by the differential energetic equation of the Sabine's diffuse theory considering that the coupling aperture is a totally free surface (i.e., with an absorbing coefficient equal to 1). Thus, the total absorbing surface area of the *i*-th sub-room A_{ii} is the sum of the absorbing area of the walls A_i and the surface of the coupling aperture S_{12} ($A_{ii}=A_i+S_{12}$).The coupling effect in one sub-room can be seen as an addition of acoustic energy equivalent to the diffuse acoustic intensity in the other sub-room passing throw the coupling aperture. Thus, if $\varepsilon_{i \neq j}$ is the energy density in the other sub-room, then the additional energy density due to the coupling effect is equal to $S_{12} c \varepsilon_j / 4$, where c is the sound speed in the air. If an acoustic source with a power P_i is introduced in the i-th sub-room whose volume is V_i, then the equation system governing the energy densities in both sub-rooms is:

$$\begin{cases} V_1 \dfrac{\mathrm{d}\varepsilon_1(t)}{\mathrm{d}t} + \dfrac{A_{11} c}{4} \varepsilon_1(t) - \dfrac{S_{12} c}{4} \varepsilon_2(t) = P_1(t) \\ V_2 \dfrac{\mathrm{d}\varepsilon_2(t)}{\mathrm{d}t} + \dfrac{A_{22} c}{4} \varepsilon_2(t) - \dfrac{S_{12} c}{4} \varepsilon_1(t) = P_2(t) \end{cases} \tag{1}$$

In an auditorium, the only acoustic source that needs to be taken into account is placed on the stage (which is in the main volume). Thus, the equation system (1) must be rewritten with a source power P_2 equal to zero. With the introduction of the coupling factors $k_i = S_{12} / A_{ii}$ and the dumping energetic constants $\delta_i = A_{ii} c / 4 V_i$:

$$\begin{cases} \dfrac{1}{\delta_1} \dfrac{\mathrm{d}\varepsilon_1(t)}{\mathrm{d}t} + \varepsilon_1(t) - k_1 \varepsilon_2(t) = \dfrac{4 k_1}{c S_{12}} P_1(t) \\ \dfrac{1}{\delta_2} \dfrac{\mathrm{d}\varepsilon_2(t)}{\mathrm{d}t} + \varepsilon_2(t) - k_2 \varepsilon_1(t) = 0 \end{cases} \tag{2}$$

which leads to:

$$\begin{cases} \varepsilon_1(t) = \varepsilon_{11} \mathrm{e}^{-\delta_I t} + \varepsilon_{12} \mathrm{e}^{-\delta_{II} t} \\ \varepsilon_2(t) = \varepsilon_{21} \mathrm{e}^{-\delta_I t} + \varepsilon_{22} \mathrm{e}^{-\delta_{II} t} \end{cases} \tag{3}$$

where the coupled dumping constants are:

$$\delta_{I,II} = \frac{1}{2} \left[(\delta_1 + \delta_2) \mp \sqrt{(\delta_1 - \delta_2)^2 + 4 k_1 k_2 \delta_1 \delta_2} \right] \tag{4}$$

and where the coefficients ε_{11}, $\varepsilon_{12,}$ ε_{21} and ε_{22} are given from the initial conditions. In the case of impulse responses, the source signal is an infinitely short impulse of duration Δt. At the initial time value, the coupling effects are not effective yet. The initial energy density in the main volume (i.e., the main room) is due to the source and tends to decrease due to absorption by walls and to the losses through the coupling aperture. At the same time, in the secondary volume (i.e., under-balcony), there is no acoustical energy yet, but the energy density tends to increase due to the energy supplied by the main room through the coupling aperture.

$$\begin{cases} \varepsilon_1(0) = \dfrac{P_1 \Delta t}{V_1} & \left. \dfrac{\mathrm{d}\varepsilon_1(t)}{\mathrm{d}t} \right|_{t=0} = -\dfrac{P_1 \Delta t}{V_1} \delta_1 \\ \varepsilon_2(0) = 0 & \left. \dfrac{\mathrm{d}\varepsilon_2(t)}{\mathrm{d}t} \right|_{t=0} = k_2 \dfrac{P_1 \Delta t}{V_1} \delta_2 \end{cases} \tag{5}$$

Thus, the energy densities in each sub-room are:

$$\begin{cases} \varepsilon_1(t)=\dfrac{P_1\Delta t}{V_1}\dfrac{1}{\delta_{II}-\delta_I}((\delta_{II}-\delta_I)\mathrm{e}^{-\delta_I t}-(\delta_I-\delta_1)\mathrm{e}^{-\delta_{II} t}) \\ \varepsilon_2(t)=k_2\dfrac{P_1\Delta t}{V_1}\delta_2\dfrac{1}{\delta_{II}-\delta_I}(\mathrm{e}^{-\delta_I t}-e^{-\delta_{II} t}) \end{cases} \quad (6)$$

2.2 Numerical simulations

The virtual room considered for the numerical simulations was a realistic auditorium with realistic building materials. The used simulation software was Icare™[5] developed by CSTB. The distribution of the materials and the size of the coupling aperture between the main room and the under-balcony volume were chosen to insure a low coupling factor k_2. The source was placed on the stage as specified in ISO standard 3382[6]. 60 receiver positions were considered, 30 in the main volume and 30 in the secondary volume (see **Figure 2**). The main characteristics of the simulated room are summarized in **Table 1** (the dumping constants listed in this table were calculated from the reverberation time obtained through numerical simulations considering each sub-room individually and by replacing the coupling aperture with a totally absorbing surface. The used equation was $\delta_i=13.82/RT_i$ with $RT_1=1.05$ s and $RT_2=0.27$ s)

Table 1: acoustic and geometrical characteristics of the simulated coupled room

	Volume (m^3)	**Absorption area (m^2)**	**Dumping energy constant (s^{-1})**	**Coupling factor**	**Coupling aperture (m^2)**
Main volume	$V_1 = 8272$	$A_2 = 1281$	$\delta_1 = 13.16$	$k_1 = 0.07$	$S_{12} = 90$
Secondary volume	$V_2 = 618$	$A_2 = 245$	$\delta_2 = 51.18$	$k_2 = 0.27$	

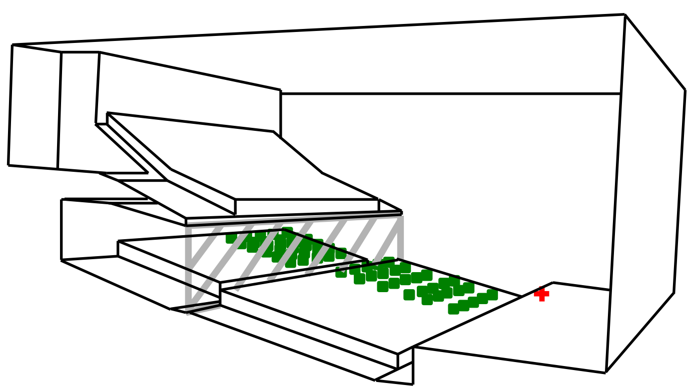

Figure 2: The simulated coupled room
(receiver positions: ■, source position: +, coupling aperture: ▨).

As shown on **Figure 3**, the coupling effect in the early part of the impulse responses is not obvious since the differences between the early echogram in each sub-room are equivalent to the differences between two echograms at two receiver positions in the same sub-room. In the late part of the impulse responses the coupling phenomenon is more obvious and is mainly responsible for the lack of energy in the secondary volume.

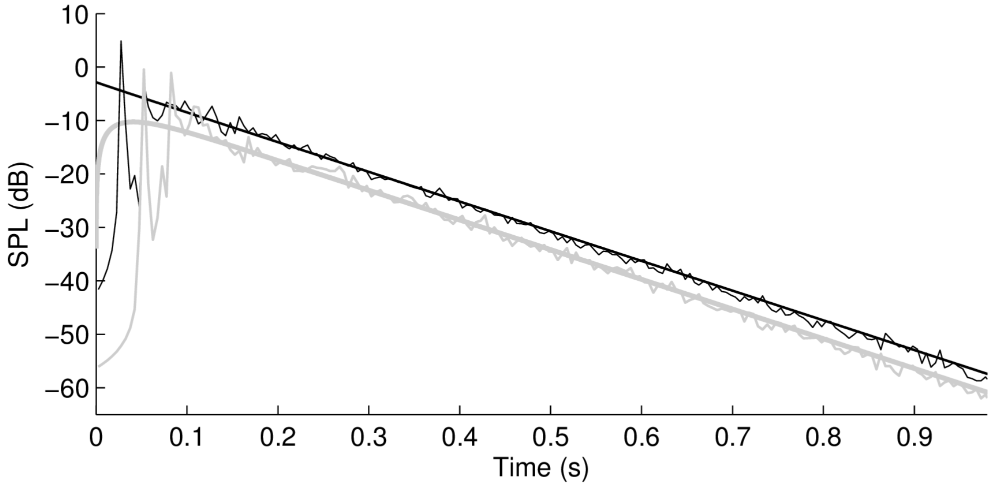

Figure 3: Simulated echograms in the main volume: ─, and in the under-balcony volume: ─ ; theoretical echograms in the main room: ▬, and in the under-balcony volume: ▬.

In order to show the coupling effect on the late energy values, a simple room was also simulated. It consisted in the room illustrated on **Figure 2** but without balcony. The values of the total late energy of each impulse response in each receiver position are plotted in **Figure 4**. In this study, thanks to the wide dynamic range of the simulated impulse responses, the early time limit of the late part of the impulse responses was set to 300 ms to surely avoid the influence of the low order temporal components. From **Figure 4**, two main remarks can be made. First, the presence of the balcony overhang indeed leads to lower late energy values in the secondary volume compared with the late energy values in the main volume. Secondly, in both sub-rooms but mainly in the secondary volume, in the case of the coupled room an effect of the source-receiver distance appears on the late energy values.

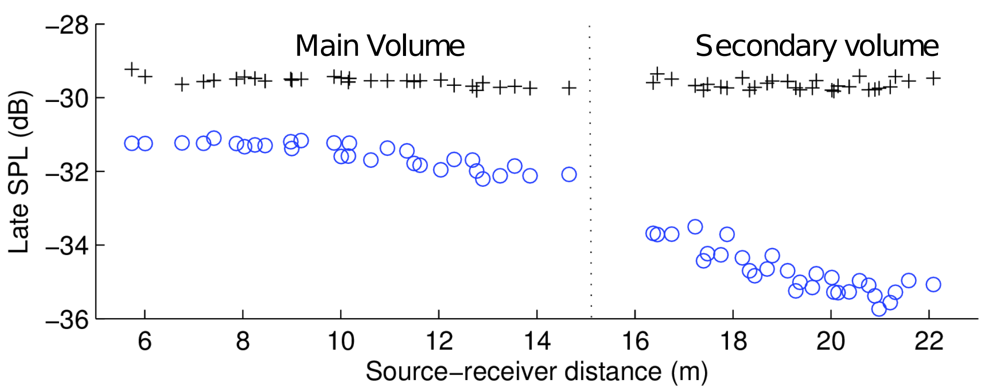

Figure 4: Late energy values in the simulated simple room: +, and in the simulated coupled room: ○.

2.3 A coupling criterion

According to **Figure 4**, an objective coupling criterion $\Delta\varepsilon$ can be defined by the ratio of the late energy in the secondary volume and the late energy in the main volume. Because of the scattering of the late energy values in both sub-rooms, this criterion should be based on averaged values. In order to take into account the sensitivity of the human ear, this criterion should be expressed in decibels.

$$\Delta\varepsilon = 10\log_{10}\left[\frac{\overline{\int_{0,03}^{+\infty} p_2^2(t)\,\mathrm{d}t}}{\overline{\int_{0,03}^{+\infty} p_1^2(t)\,\mathrm{d}t}}\right] \tag{7}$$

where $p_1(t)$ and $p_2(t)$ are the acoustic instantaneous pressures of the impulse responses measured in the main volume and in the secondary volume, and where the over-line indicates the used of averaged values over all receiver positions in each sub-room.

As shown on **Figure 3**, the late part of the impulse responses in both sub-rooms seems to be reasonably approached by the energetic theory. Thus, an equation of the coupling criterion obtained by this theory may not lead to absurd results.

$$\Delta\varepsilon = 10\log_{10}\left[\frac{k_2\delta_2}{\delta_{II}-\delta_1}\frac{\int_{0,03}^{+\infty} 1-e^{-(\delta_{II}-\delta_I)t}\,\mathrm{d}t}{\int_{0,03}^{+\infty} 1-\frac{\delta_I-\delta_1}{\delta_{II}-\delta_1}e^{-(\delta_{II}-\delta_I)t}\,\mathrm{d}t}\right] \tag{8}$$

An asymptotic approximation of equation (8) could be obtained by noting that for important time values, the exponential terms are negligible with respect to 1 because the difference $\delta_{II}-\delta_I$ is always positive.

$$\Delta\varepsilon \simeq 10\log_{10}\left[\frac{k_2\delta_2}{\delta_{II}-\delta_1}\right] \tag{9}$$

In the room without balcony, the coupling criterion obtained from the numerical simulations is about 0.1 dB. In the room with balcony, the value of this criterion obtained from the numerical simulations is -3.2±0.3 dB within a confident interval of 95%. This tends to prove that this criterion is indeed suitable to characterize the coupling effect due to a balcony overhang. The theoretical value of this criterion is -4.1 dB for the room with the balcony (and obviously 0 dB for the simple room). The difference between this value and the value obtained from the numerical simulations is a little less than 1 dB. Thus, in this room, the diffuse field energetic theory of coupled rooms is reasonably acceptable for the prediction of the coupling criterion.

3 TWO COUPLED ROOMS WITH THE COUPLING ENHANCEMENT SYSTEM

3.1 Theoretical effect of the electro-acoustic coupling enhancement system

The electro-acoustic coupling enhancement system is a set of N independent and parallel elector-acoustic channels. Each of them is composed by a microphone placed in the main room, a signal processing unit, and a loudspeaker placed in the secondary volume. The signal processing unit consists of a global electronic gain and a set of narrow-band or shelf filters. These filters are mainly used to reduce the magnitude of the frequency components in the open-loop gain of one channel that could induce the instability of the system or ringing tones. This system is quite similar to a diagonal reverberation enhancement system. The only difference is that the microphones and the loudspeakers are not placed in the same room volume. Thus, the theoretical approach of the EACES developed in this paper, is a combination of the energetic approach in coupled rooms and the energetic approach of a diagonal reverberation enhancement system.

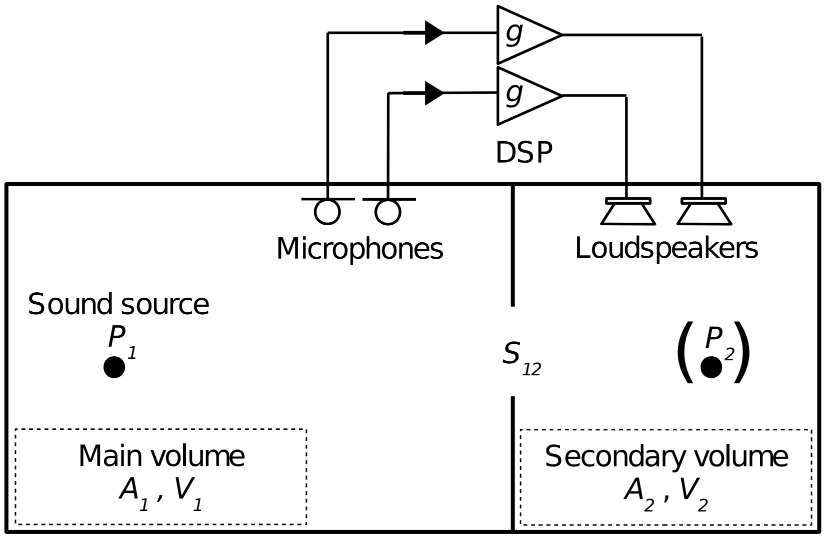

Figure 5: A schematic representation of two coupled rooms with an electro-acoustic coupling enhancement system.

The introduction of an EACES between the two sub-rooms, such as represented on **Figure 5**, can be seen as an addition of N source terms in the secondary volume. The power of each of these source terms depends on the energy density in the main volume and on an amplification factor μ. This factor depends on the air impedance ρc^2, the microphones sensitivity X, their directivity factor Q, the loudspeakers efficiency η, their electrical impedance Z, and the electronic power gain g :

$$\mu = g\frac{\rho c^2 X\eta}{QZ} \tag{10}$$

The equation system based on the energetic theory that governs the energy densities ε_1' and ε_2' in each sub-room is:

$$\begin{cases} V_1\dfrac{\mathrm{d}\varepsilon_1'(t)}{\mathrm{d}t}+\dfrac{A_{11}c}{4}\varepsilon_1'(t)-\dfrac{S_{12}c}{4}\varepsilon_2'(t)=P_1(t) \\ V_2\dfrac{\mathrm{d}\varepsilon_2'(t)}{\mathrm{d}t}+\dfrac{A_{22}c}{4}\varepsilon_2'(t)-\dfrac{S_{12}c}{4}\varepsilon_1'(t)=N\mu\varepsilon_1'(t)+P_2(t) \end{cases} \tag{11}$$

For a unique source in the main volume and by using the coupling factors and the dumping energy constants of each sub-room, the equation system (11) can be rewritten as:

$$\begin{cases} \dfrac{1}{\delta_1}\dfrac{\mathrm{d}\varepsilon_1'(t)}{\mathrm{d}t}+\varepsilon_1'(t)-k_1\varepsilon_2'(t)=P_1(t) \\ \dfrac{1}{\delta_2}\dfrac{\mathrm{d}\varepsilon_2'(t)}{\mathrm{d}t}+\varepsilon_2'(t)-k_2'\varepsilon_1'(t)=0 \end{cases} \tag{12}$$

The only difference between the equation systems (12) and (2) (with or without the EACES) lies in the coupling factor of the secondary volume. With the EACES, this coupling factor, which shall be named the electro-acoustic coupling factor of the secondary volume, is:

$$k_2' = \frac{S_{12}}{A_{22}} + N\mu\frac{4}{A_{22}c} = k_2\left[1 + N\mu\frac{4}{S_{12}c}\right] \tag{13}$$

Thus, in the case of impulse responses, the theoretical expressions of the energy densities in each sub-room with the EACES can be obtained by analogy with the expressions of the energy densities in each sub-room without the EACES (equation (6)):

$$\begin{cases} \varepsilon_1'(t) = \dfrac{P_1 \Delta t}{V_1}\dfrac{1}{\delta_{II}' - \delta_I'}\left((\delta_{II}' - \delta_I')\mathrm{e}^{-\delta_I' t} - (\delta_I' - \delta_1)\mathrm{e}^{-\delta_{II}' t}\right) \\ \varepsilon_2'(t) = k_2'\dfrac{P_1 \Delta t}{V_1}\delta_2\dfrac{1}{\delta_{II}' - \delta_I'}\left(\mathrm{e}^{-\delta_I' t} - e^{-\delta_{II}' t}\right) \end{cases} \tag{14}$$

where the coupled dumping constants are:

$$\delta'_{I,II} = \frac{1}{2}\left[(\delta_1 + \delta_2) \mp \sqrt{(\delta_1 - \delta_2)^2 + 4k_1 k_2' \delta_1 \delta_2}\right] \tag{15}$$

The integration of equations (14) over time shows that one effect of the system is to increase the energy densities in both sub-rooms, but in a more important way in the secondary room. Thus, theoretically, the EACES increases the coupling criterion, which can be expressed as:

$$\Delta\varepsilon' \simeq 10\log_{10}\left[\frac{k_2'\delta_2}{\delta_{II}' - \delta_1}\right] \tag{16}$$

Another theoretical effect of the EACES is to increase the reverberation process in both sub-rooms. A simple asymptotic equation could be established for predicting this effect of the EACES on the late reverberation. For high time values the density energies in both sub-rooms are dominated by the exponential term depending on the constant δ_I' (or δ_I without the EACES). Thus:

$$\Delta RT \simeq \frac{\delta_I}{\delta_I'} \tag{17}$$

3.2 The mean open loop gain of the electro-acoustic coupling enhancement system

Because the EACES is a closed loop system, each channel could be unstable if their electronic gains are too important; or more formally, if any frequency component of their open-loop gain has a magnitude higher than 1. The energetic approach gives the average value of an acoustic transfer and not the maximum value of this transfer over all frequencies. However, assuming the diffused field assumptions, these two values can be linked together[7]. Therefore, in stand of μ, the mean open-loop gain of each channel of the EACES should be preferably used to express the effect of the system. In the literature[8-9], the action of a regenerative reverberation enhancement system is often expressed with the quantity $\Gamma = \mu H$, where H is the mean gain of the energy emitted by the loudspeaker of one channel and picked up by the microphone of the same channel without considering the effect of the other channels (i.e., considering only the acoustic room effect). H is obtained by the ratio ε_m / P_L considering the equation system (1) in steady state. ε_m is the energy density in the sub-room where the microphone of the considered channel is placed, and P_L is the power of a source in the sub-room where the loudspeaker of the same channel is placed. In the case of an EACES, where the microphones are in the main volume and the loudspeaker in the secondary volume, $H=\varepsilon_1/P_2$ with $P_1=0$. Thus:

$$\Gamma=\mu H=\mu \frac{4}{c S_{12}} \frac{k_1 k_2}{(1-k_1 k_2)}$$

It would be a mistake to consider that Γ is the mean open-loop gain of one channel of the system. If μ is the actual direct loop gain of one channel, H is not exactly the feedback loop gain of one channel of a multichannel system since it does not include the effect of the other channels. However, H' , which is the actual feedback loop of one electro-acoustic channel, can be obtained with the equation ε_1/P_2 in steady-state, by considering the equation system (11) applied to a room with an electro-acoustic system composed of $N-1$ channels (thus, a relation between Γ and the real mean open-loop gain $\Gamma'=\mu H'$ could be also established):

$$\Gamma'=\mu H'=\mu \frac{4}{c S_{12}} \frac{k_1 k_2}{(1-k_1 k_2)-(N-1)\mu \frac{4 k_1 k_2}{c S_{12}}}=\frac{\Gamma}{1-(N-1)\Gamma} \tag{18}$$

The electro-acoustic coupling factor of the secondary volume can be rewritten as:

$$k_2'=k_2\left[1+\frac{N\Gamma'}{1+(N-1)\Gamma'}\left(\frac{1-k_1 k_2}{k_1 k_2}\right)\right] \tag{19}$$

3.3 Theoretical limits of the electro-acoustic coupling enhancement system

The first limit of the coupling system that must be considered is related to its instability. As written in the precedent paragraph, the instability could occur when the magnitude of a component of the open-loop gain frequency response function of one channel exceeds 1. Considering the maximum of a theoretical diffuse acoustic frequency response function related to its mean value, *Poletti*[10] proposed an equation to predict the risk of instability Π of a diagonal regenerative reverberation enhancement system as a function of Γ . This equation can be easily rewritten depending on Γ' with the use of the mathematical relation (18). Thus:

$$\Pi(\Gamma')=1-\left[1-\frac{1}{N} e^{-\frac{1+(N-1)\Gamma'}{\Gamma'}} \sum_{k=0}^{N-1}\left(\frac{1+(N-1)\Gamma'}{\Gamma'}\right)^k \frac{N-k}{k!}\right]^{N\frac{B\,RT}{C}} \tag{20}$$

where B is the considered frequency bandwidth and C a constant related to the auto-correlation of a diffused room frequency response function. According to the numerical simulations done by *Poletti, C* must be set to 1.4 to give reliable results. Equation (20) was established for a system whose signal processing unit is only a global gain, without taking into account the filters used in practice to limit the instability. However, if a few of them (about ten) are used, the reduction of the risk of instability is here evaluated to 5%. Thus, regarding the instability phenomenon, the maximum mean open-loop gain that must be set to each channel of the EACES is obtained by inversing the equation (20) with a risk of instability of 5%.

The second limit of the coupling enhancement system lies in a coupling factor that can exceed 0 dB. In other words, the use of the EACES could result in a situation where the energy in the secondary volume is higher than in the main volume. Such a situation is undesirable since the purpose of using the EACES is to homogenize the acoustic conditions between both sub-rooms.

Figure 6 illustrates the two discussed limits. The figure on the left corresponds to the simulated coupled room presented in **Table 1** and on **Figure 2**. In this case, the limiting phenomenon of the mean open-loop gain is due to a too high value of the coupling criterion regardless the number of channels. The figure on the right corresponds to a room with a coupling factor of the main volume higher than the coupling factor of the secondary volume. In this case, for a large number of channels, the phenomenon limiting the gain of the EACES is also a too important value of the electro-acoustic coupling factor, but for a small number of channels the limiting phenomenon is the instability of the EACES.

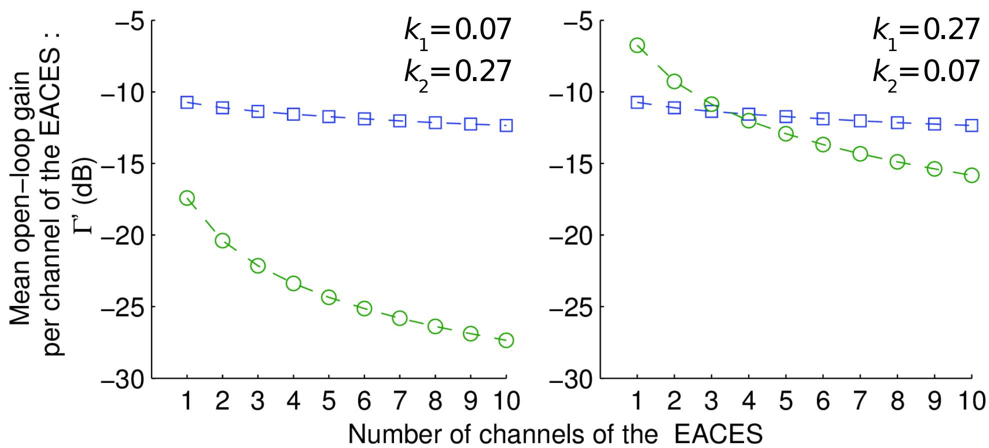

Figure 6: Theoretical maximum limits of the mean open-loop gain of each channel of an EACES due to instability: □, or due to a coupling criterion above 0 dB: ○.

3.4 Numerical simulations of the electro-acoustic enhancement system

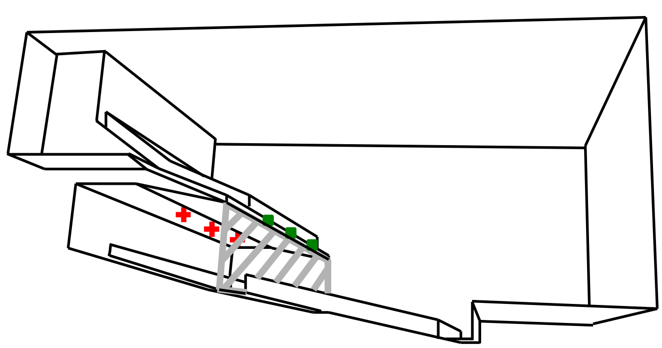

Figure 7: Positions of the microphones: ■, and the loudspeakers: + of the EACES, in the simulated room (coupling aperture: ▨).

The EACES simulated in this study was composed of three channels. As shown on **Figure 7**, the loudspeakers were placed under the balcony and the microphones were placed in the front of the balcony in the main volume. Thus, the direct sound from the loudspeakers was not picked-up by the microphones, thereby insuring a maximum decoupling between these transducers, as in the case of an ideal installation of a regenerative reverberation enhancement system.

As any linear electro-acoustic system, the numerical simulation of the impulse responses h_{sr}' of a room equipped with an EACES can be based on the multivariable loop systems equation in the time domain, or on the inverse Fourier-transform of the same equation in the frequency domain $\hat{f}^{-1}[H_{sr}']$ [7]:

$$h_{sr}' = \hat{f}^{-1}[H_{sr}'] = \hat{f}^{-1}[H_{sr} + \underline{H_{lr}} \cdot [(\underline{\underline{I_d}} - \underline{\underline{u_{ml}}}\,\underline{\underline{H_{ml}}})^{-1}\underline{\underline{u_{ml}}}\,\underline{H_{sm}}]] \tag{21}$$

Where H_{sr} are the acoustic frequency response function values between the source and the receiver, $\underline{H_{sm}}$ is a column vector of the acoustic frequency response functions values between the source and each microphone, $\underline{H_{lr}}$ is a line vector of the acoustic frequency response functions values between each loudspeaker and each receiver, $\underline{\underline{H_{ml}}}$ is a matrix of the acoustic frequency response functions values between each loudspeaker and each microphone, $\underline{\underline{I_d}}$ is the unity matrix and $\underline{\underline{u_{ml}}}$ is a matrix of the direct-loop frequency response functions values between each microphone and each loudspeaker. In this study, the values of the acoustic frequency response functions were obtained with the Icare™[5] software. The values of the direct-loop frequency response functions of each channel were calculated with a recursive algorithm. This algorithm incorporated a patented numerical method developed at the CSTB and designed to fine-tune the signal processing units of the EACES with respect to the desired mean open-loop gains and by avoiding the instability phenomenon[11] .

Three different configurations of the system were simulated. Each of them differed from other by the mean open-loop gain of each channel as shown in **Table 2**. For each configuration, 60 impulses responses at 60 seat positions were calculated. These positions were the same as those shown on **Figure 2**.

Table 2: Configurations of the simulated EACES. Mean open-loop gain for one channel.

	Configuration 0	Configuration 1	Configuration 2	Configuration 3
Γ' (dB) (full frequency range)	Without the EACES	-21.7	-18.5	-15.9
Γ' (dB) 500 Hz 1 KHz		-21.8 -21.7	-18.1 -18.2	-17.3 -17.6

3.5 Effect of the decoupling enhancement system on the coupling criterion

The late energy values of the simulated impulse responses with and without the EACES are shown on **Figure 8**. From this figure it can be seen that the EACES has an effect in both sub-rooms, but that this effect is more important in the secondary volume than in the main volume. For the EACES with a low gain (configuration 1), the late energy values in the secondary volume are still lower than the late energy values in the main volume. For the EACES in configuration 2, the late energy values in both sub-rooms seem to be almost equal on average. For the EACES with a high gain (configuration 3), the late energy values in the secondary volume are more important than in the main volume. It must also be noted that an increase of the mean open-loop gain of the channels of the EACES leads to a change in the dependency of the late energy values with the source to receiver distance. For configurations 1 and 2, the influence of the source to receiver distance on the late energy values seems to be absent or very small as in the room without balcony; whereas without the EACES, this influence is pronounced. For the configuration 3, this influence is also present but inverted since in this case the late energy values increase with the source to receiver distance. All of these results tend to confirm two expected aspects of the effect of the EACES. First, this system could indeed increase the homogeneity of the late energy values between each sub-room, such as what could be observed in a room without balcony. Secondly, the maximum gain of the system is not necessary governed by the instability phenomenon, but could be related to a too important effect of EACES which leads to a too important addition of energy in the secondary volume.

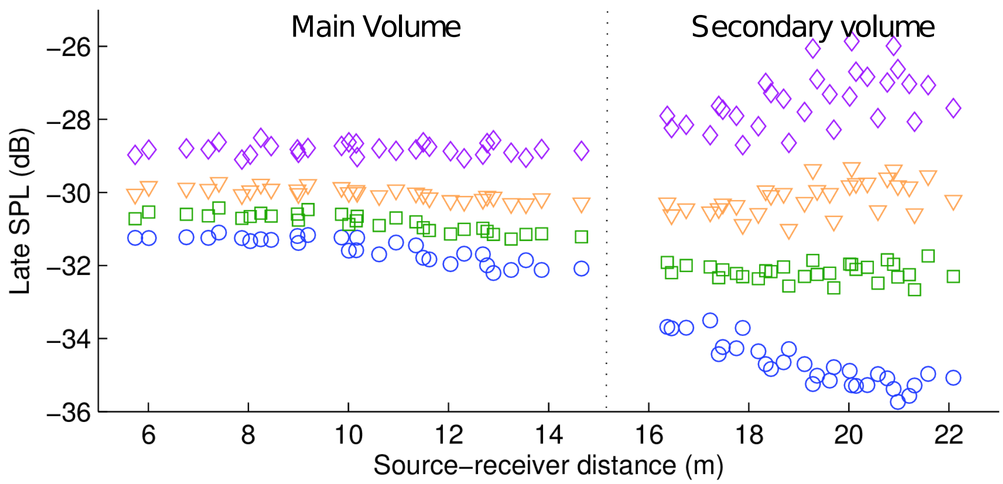

Figure 8: the late energy in the simulated impulse responses without the EACES: ○, and with the EACES in configuration 1: □, 2: ▽ and 3: ◊ (all frequencies).

The coupling criterion calculated from all these late energy values, and those obtained from equation (16), the rooms parameters (**Table 1**) and the mean open-loop gain values (**Table 2**), are presented in **Table 3**. In this table it can be read that the values of the coupling criterion obtained from the numerical simulations are in agreement with the qualitative analysis made above. The coupling criterion with the EACES in configuration 2 is quite close to 0 dB, thus this configuration corresponds to the optimal configuration of the EACES. The theoretical values of the coupling criterion are close to the values obtained from the numerical simulations within 1 dB. This tends to show that the proposed energetic approach is an acceptable approximation for the prediction of the effect of the EACES on the coupling criterion.

Table 3: coupling criterion for the three configurations of the EACES (all frequencies).

	Configuration 0	**Configuration 1**	**Configuration 2**	**Configuration 3**
Coupling criterion from numerical simulations (dB)	-3.2±0.3	-1.3±0.2	0.1±0.3	1.4±0.4
Coupling criterion from the theoretical equation (dB)	-4.1	-1.6	0.3	2.6

3.6 Effect of the decoupling enhancement system on four common room acoustic criteria.

The effect of the EACES in its most optimal configuration (configuration 2), on the reverberation time (RT_{20}) is presented in **Figure 9**. The average increase of the RT_{20} is 6.9±0.8% in the main volume and 5.7±0.6% in the secondary volume. These two values are almost the same, thus it can be concluded that the EACES has almost the same effect on the reverberation time in both sub-rooms. It should also be noted that this effect, even if it is small, is slightly noticeable since it is slightly above the just noticeable difference (JND) of the RT which is about 5%[6]. The predicted value of the increase of RT according to equation (17) is 6.9% in both sub-rooms. Thus, this equation gives acceptable results since its predictive error is less than the JND.

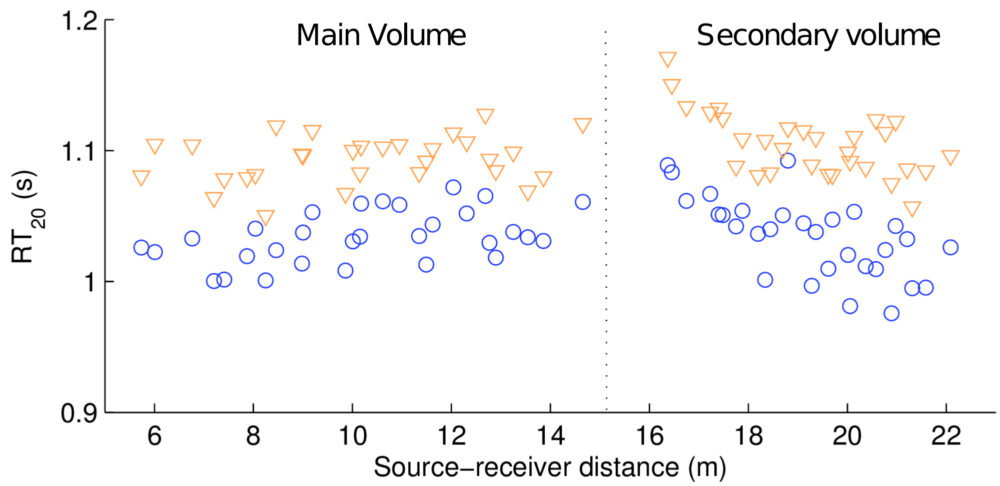

Figure 9: Reverberation time without the EACES ○, and with the EACES in configuration 2: ▽ (500 HZ-1 kHz).

The effect of the EACES on the early decay time (EDT), the acoustic strength (G) and the clarity (C_{80}) is presented on **Figure 10** and in **Table 4**. In both sub-rooms the effect of this system is an increase of EDT and G, and a decrease of C_{80} for each receiver position. It should be noted that this behavior is also observed in a room equipped with a classical regenerative reverberation enhancement system, but that the particularity of the EACES lies in a more important effect in the secondary volume than in the main volume. The difference between this effect in the main volume and in the secondary volume is superior to the JND of EDT, G and C_{80}. Thus, the EACES contributes to correct the imbalance of the acoustic conditions that originally exist between the main volume and the under-balcony volume. It should also be noted that even in the main volume, the effect of the EACES could be superior to the JND of the acoustic criteria. Thus, the introduction of the EACES is not completely neutral to the acoustic conditions of the main volume.

Table4: Effect of the EACES in configuration 2 on EDT, G and C_{80} (500 HZ-1 kHz).

	Δ EDT (%) - (JND: 5%)[6]	**Δ G (dB) -** (JND: 1dB)[6]	**Δ C_{80} (dB) - (**JND: 1dB)[6]
Main volume	9.8±1.3	0.3±0.1	-0.9±0.1
Secondary volume	37.6±6.4	2.0±0.2	-3.1±0.3

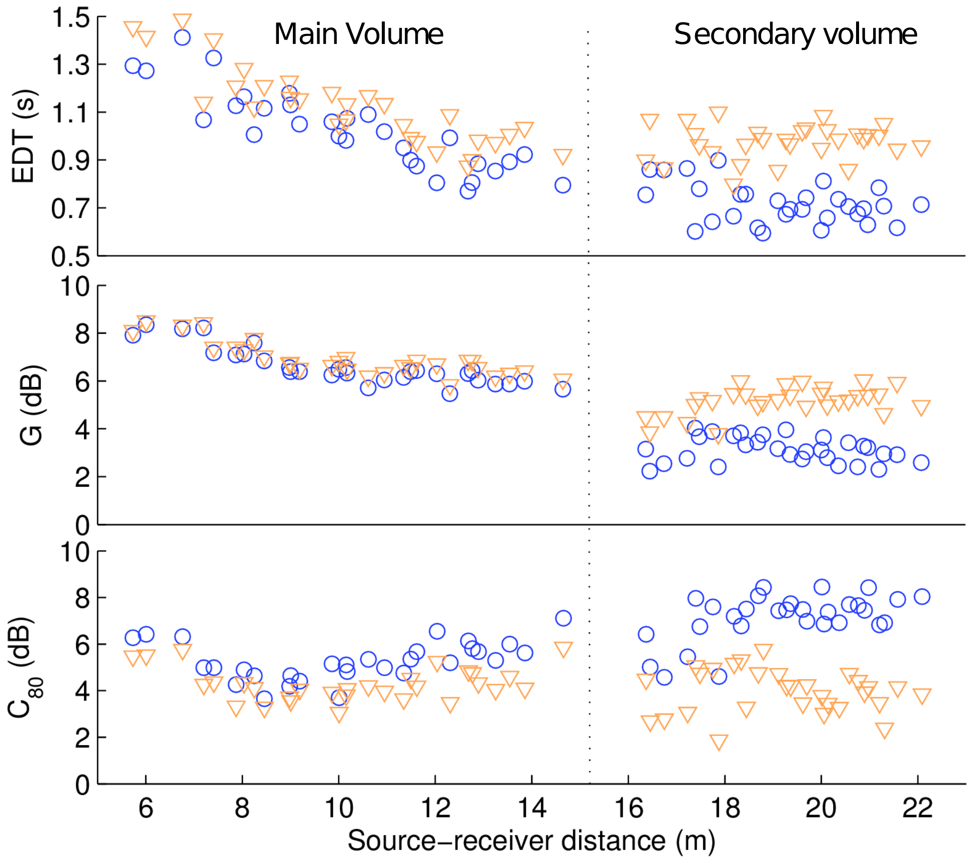

Figure 10: EDT, G and C_{80} without the EACES ○, and with the EACES in configuration 2: ▽ (500 HZ-1 kHz).

4 CONCLUSIONS

In order to enhance the acoustic conditions in the seated area under a deep balcony, a simple electro-acoustic decoupling system was presented and studied. This study was carried out along two different but complementary axes: theoretical developments and numerical simulations of a realistic concert hall with a poor coupled under-balcony volume. From the theoretical developments, equations for predicting the effect of the system on a proposed coupling criterion and on the reverberation time was established. The theoretical limits of this system regarding the instability problem and a too important addition of energy in the under-balcony volume were also presented. The results of the numerical simulations have appeared to be in agreement with the theoretical results, and thus they have confirmed that this system could indeed reduce the coupling effect. From the numerical simulations it has also been shown that the electro-acoustic coupling enhancement system could increase the early decay time and the acoustic strength, and could decrease the clarity in the under-balcony volume more noticeably than in the main volume. Thus, this system could indeed reduce the shadow effect of a balcony overhang in rebalancing the listening conditions between the main room and the volume under the balcony.

This study didn't include any measurements in a real concert hall. It could be interesting to make such measurements to verify in a real situation the conclusions presented above, but also to conduct psycho-acoustic studies, for instance, to explore how this system is tolerated by a real audience.

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