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On the spatial variations of double-sloped decay in coupled-volume concert halls

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ABSTRACT

In a system of coupled rooms, a double-sloped can be observed in the room containing the source when the coupled room is more reverberant. This decay is formed of a first quick energy decrease due to the first room and a second slower one due to the energy which is fed back from the coupled room. Today, this effect is used to obtain simultaneously clarity and reverberance in concert halls. Parameters to achieve a strong double-sloped decay are now well known. In this preliminary work, the spatial variation of the double decay strength within the concert hall is studied using numerical simulations. Firstly, the indicators quantifying the double decay used in this study are presented. Then, the results of two configurations with the same coupling characteristics but with different coupling area locations are compared. Finally, an empirical model based on the statistical theory is proposed.

INTRODUCTION

In a system of coupled rooms, a non exponential sound decay can be observed in the room containing the source when the coupled room is more reverberant than the source room. This decay is formed of a first quick energy decrease due to the first room and a second slower one due to the energy which is fed back from the coupled room. This phenomenon is known as double-decay or double-sloped decay. In the past, this effect was only studied as a phenomenon. Moreover, designers thought that this non exponential decay degraded the acoustic of concert halls [1]. Today, the double-decay is used to achieve simultaneously clarity and reverberance in concert halls [2,3]: the clarity giving the sound space feeling and the reverberance the fullness of tone. A few concert halls equipped with secondary volumes creating a double decay have been built around the world, mainly in the United States. Eyring [4] showed the most favourable configuration to obtain a strong double decay when a large dead room is coupled to a smaller more reverberant one. Moreover, he noticed that the double slope is barely noticeable for absorption superior to 0.07.

Double decay indicators

To quantify the double decay, Harrison et al. [5] proposed the coupling coefficient which the ratio between the reverberation times based on the decay from -5 to -35dB and the one from -5 to -20dB. Similarly, Ermann and Johnson [6,7] used the coupling constant: ratio between the reverberation times based on the decay from 0 to -60dB and the one from -0 to -15dB. As pointed by Bradley and Wang, these coefficients cannot rigorously differentiate between different double slope profiles. Bradley and Wang use as an indicator the decay ratio based on the ratio between the reverberation time based on the first decay slope extended to 60dB (noted in the following RT_1) and the one based on the second decay slope, extended to 60dB too (noted in the following RT_2).

Another significant is the moment where the slope change occurs. In their study, Bradley and Wang [2] employed ΔdB based on the sound pressure difference between the first decay slope and the second one extended at time zero. However this indicator can be tricky. For example, when both decays are quite similar, the ΔdB value is low whereas the slope change occurs rather lately. In this study, the sound pressure at which the intersection, noted down crossing point, between the two slopes occurs noted down Cp is used. By extension, the time delay at which the intersection occurs is noted down T_c.

MODELS PRESENTATION

Statistical theory

The energy decay of a system of coupled rooms can be evaluated using the statistical theory. It assumes that each room has its own constant energy density, respectively E_S for the source room (which is the only room containing an acoustic source in the following development) and E_C for the coupled room and that, at the coupling, only diffuse energy is exchanged and the transition between the sound fields aperture is stepwise. The time-varying energy balance of the system allows one to calculate the time energy decay in both rooms. Let us denote δ_S and δ_C the damping constants of the source and coupled rooms as they were uncoupled. The sound decays can be expressed as [2,8]:

$$L_I\left(t\right)=-\frac{60\delta_S}{6.9}t \text{ and } L_2\left(t\right)=-\frac{60\delta_C}{6.9}t-10\log\left(\frac{E_{S1}}{E_{R2}}\right), \tag{1}$$

where E_{S1} and E_{C2} refer to the initial value for the different exponential decays given by [9]

$$E_{S1}=\frac{E_{0S}-E_{0C}k_S/\left(1-\delta_{II}/\delta_S\right)}{1-\kappa^2/\left(1-\delta_I/\delta_S\right)\left(1-\delta_{II}/\delta_S\right)}, \text{ and } E_{C2}=\frac{E_{0C}-E_{0S}k_C/\left(1-\delta_I/\delta_S\right)}{1-\kappa^2/\left(1-\delta_I/\delta_S\right)\left(1-\delta_{II}/\delta_S\right)}, \tag{2}$$

where E_{0S} and E_{0C} are the initial energy densities according to [9]

$$E_{0S}=\frac{4}{c}\frac{P}{\left(A_S+S_c\right)\left(A_C+S_c\right)-S_c^2} \text{ and } E_{0C}=k_CE_{0S}, \tag{3}$$

with P the acoustic power of the source. $\delta_{I,II}$ are the corresponding eigenvalues for the coupled room defined by

$$\delta_{I,II}=\frac{1}{2}\left(\delta_S+\delta_C\right)\pm\sqrt{\frac{1}{4}\left(\delta_S-\delta_R\right)^2-\left(1-\kappa\right)^2\delta_S\delta_C}, \tag{4}$$

where $\kappa=\sqrt{k_Sk_C}$ is the mean coupling factor with $k_C=S_c/\left(S_c+A_C\right)$ and $k_S=S_c/\left(S_c+A_S\right)$. A_S and A_C are the equivalent absorption area of the source room and the coupled one respectively and S_c the coupling aperture surface. The indicator $\mathrm{T_c}$ can be written:

$$\mathrm{T_c}=\frac{6.9}{60\left(\delta_S-\delta_C\right)}10\log\left(\frac{E_{S1}}{E_{C2}}\right). \tag{5}$$

Assuming that the energy from the coupled room moves at c the sound velocity, we can express $\mathrm{T_c}$ as a function of the coupling aperture distance:

$$\mathrm{T_c}\left(x_c\right)=\frac{6.9}{60\left(\delta_S-\delta_C\right)}10\log\left(\frac{E_{S1}}{E_{C2}}\right)+\frac{x_c}{c}, \tag{6}$$

where x_c is the shortest path to the coupling aperture. One can remark that this model is not able to predict accurately the behaviour in the vicinity of the coupling aperture where $\mathrm{T_c}$ is very small. Cp can be evaluated through:

$$\mathrm{Cp}=\frac{\delta_S}{\left(\delta_S-\delta_C\right)}\mathrm{T_c}. \tag{7}$$

NUMERICAL COMPARISON

Numerical parameters

The studied configuration is similar to one of the configuration modelled by Bradley and Wang [2]. The main room dimensions are 34x28x26 m with a source located at 2x14x3. This room is coupled to 26x24x20 m a 48 m² aperture (Fig.1). The coupled room volume, 12480 m3, is half the source room one. The coupling aperture surface is equal to 1% of the source room surface. The absorption coefficients are 0.25 in the source room and 0.01 in the coupled room. This configuration is dedicated to obtain a very strong double-sloped decay in the source room. However, this geometry is very simplified compared to a real concert hall

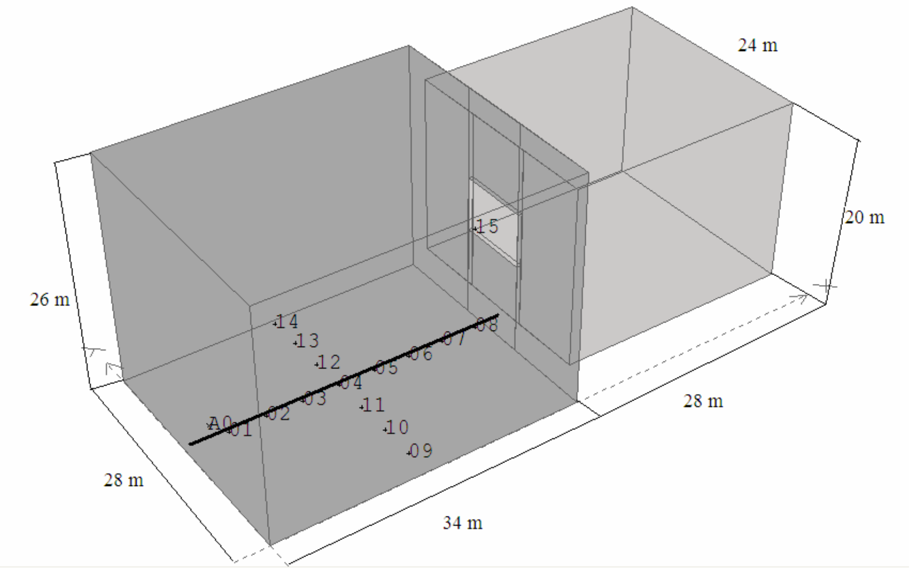

Figure 1.-Model configuration: A0 sound source, (—) line C.

The sound decays are evaluated along line C, every 3 m at 1.2 m. The simulations were carried out using CATT-Acoustic. The number of rays and the ray truncation time are chosen as $4x10^6$ and 10s respectively. The wall reflections are set to 30% diffusive.

Decay ratio

Fig. 2 plots the evolution of the decay ratio along line C. The ray-tracing software results show that the decay ratio is quite constant along line C. The results obtained using the statistical theory are in a good agreement despite a slight overestimation.

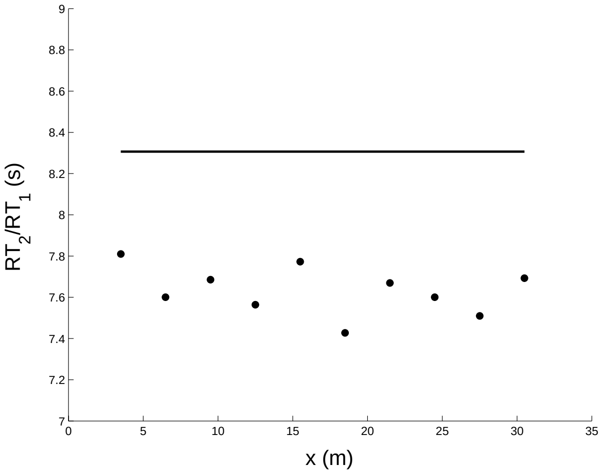

Figure 2.-Evolution of the decay ratio along line C: (●) CATT-Acoustic, (—) statistical theory.

Fig. 3 plots the evolution of the reverberation times along line C. Again, both reverberation times are quite constant along line C with maximal variation of about 3%. The statistical theory is in good agreement with the ray-tracing results; the discrepancy is less than 5%.

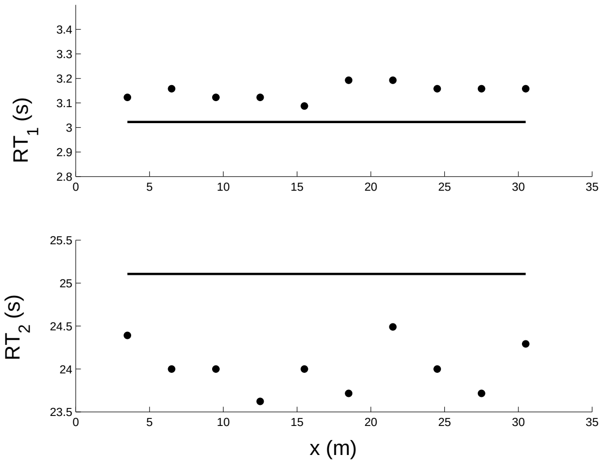

Figure 3.-Evolution of the reverberation times along line C: (●) CATT-Acoustic, (—) statistical theory.

Crossing point

The two parameters describing the crossing point are investigated. Fig. 4 plots the evolution of T_c along line C. With the unmodified statistical theory, a single value is obtained in the source room whereas the ray-tracing software shows that T_c increases with aperture distance. The modified statistical allows to predict this phenomenon. Moreover, the ray-tracing results confirm that T_c is function of the sound velocity.

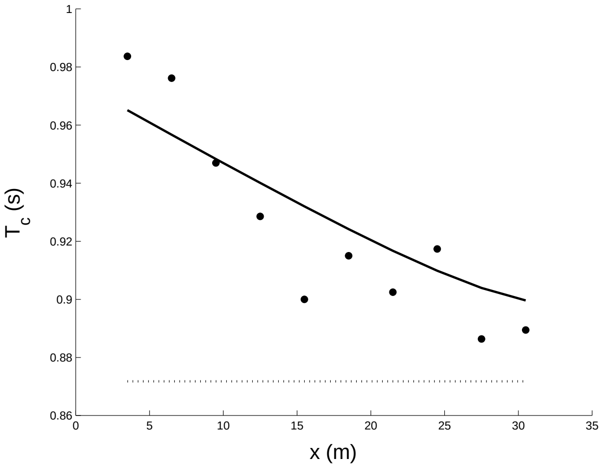

Figure 4.-Evolution of T_c along line C: (●) CATT-Acoustic, (—) modified statistical theory, (▪▪▪) statistical theory.

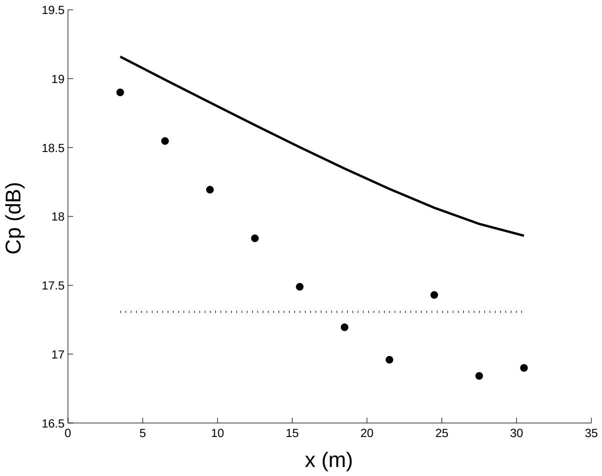

Figure 5.-Evolution of Cp along line C: (●) CATT-Acoustic, (▬) modified statistical theory, (▪▪▪) statistical theory.

Fig. 5 plots the evolution of Cp along line C. The variation of Cp along line C is rather limited, from16.8 to 18.8 dB. For a more absorbent source room, this variation would be higher. The results of statistical models are close, with a maximal discrepancy of 1.5 db for the unmodified model and 1.2 dB for the modified model. The prediction accuracy is limited for this criterion by the uncertainty about the first decay.

CONCLUSIONS

In this preliminary work, numerical simulations were carried out using a ray-tracing software to model a simplified coupled-volume concert hall to investigate the spatial variation of the double-sloped occurring in the main room. The chosen criteria to describe the double decay were the decay ratio (ration of the reverberation time evaluated using the first decay by the reverberation evaluated using the second decay) and the crossing point (intersection of the two decays). It was found that the decay ration is quite constant along a line through the audience plane, with variations of about 3%. Simulations carried out using the statistical theory are in good agreement both in terms of decay ratio end in terms of reverberation times. On the other hand, the crossing point varies with the receiver location, as a function of the sound velocity. A modification of the statistical theory was proposed and tested in this configuration. While better predictions are achieved concerning the moment at which the decays intersection occurs, the improvement concerning the sound pressure level at which the intersection happen is as good.

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