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ACTIVE REFLECTORS FOR ROOM ACOUSTICS

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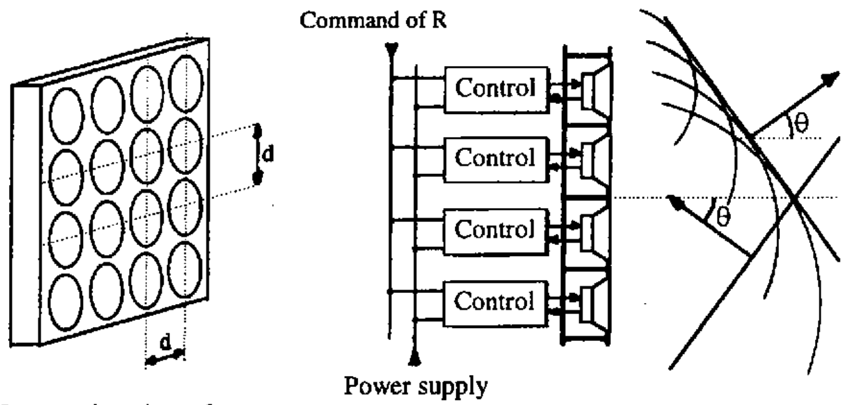
1. INTRODUCTION

Active reverberation enhancement systems (ARES) have been on the market for more than 30 years (see e.g. Kleiner [1] for a review). Their purpose is to control the acoustics of a hall, in order to correct its deficiencies, and/or adapt the acoustics to the requirements of different types of program. As virtually all auditoria are used in a multipurpose way, the latter is of particular interest. Still, relatively few auditoria are equipped with such systems. This probably is due to the fact that none of them is 100% satisfactory, although some of them may give very convincing results. Most of today systems use directional microphones placed over the forestage. This sound pickup arrangement poses problems : coverage of the stage, problems due to the directivity of the sources on stage, non-reciprocal stage/hall behaviour, presence of microphones over the forestage which may conflict with other equipment... Another shortcoming of ARES is that they are able to add energy, but unable to absorb energy. As a consequence, they can raise the reverberation time, but not reduce it ; so that the hall –with system off– has to be designed for minimum reverberation, i.e. minimum volume and/or maximum absorption.

In 1984, Guicking [2] introduced the idea of the active wall. Such walls would have an adjustable reflection coefficient R, ranging from $|R|<1$ (absorption) to $|R|>1$ ("super-reflection"). Their principle is simple, intuitive, and corresponds to those of passive natural acoustics (local reaction, specular reflection, diffraction...). Consequently, the design of halls equipped with such components should be more straightforward than it is with alternative ARES systems. One can even envisage a system which is so self-evident that designers would not need the services of a specialised sub-contractor. An active wall would use an array of locally reacting "cells", each composed of a sensor (microphone), an electronic control circuit, and an actuator (loudspeaker) situated close to the associated sensor. Guicking [3] and Ren [4] have proposed digital filters that can cancel the direct path from the loudspeaker to the associated sensor, but they could not realise an array of such cells (cost, cell interaction). Ideally, the aim is to control the acoustic impedance of the wall ; therefore this topic is often referred to as active impedance control.

In 1995, the room acoustics group of the Centre Scientifique et Technique du Bâtiment has launched a research program on this subject. The approach undertaken was to use the motional feedback principle, which uses a reciprocal transducer both as a sensor and an actuator, thus eliminating the need for sophisticated signal processing in the feedback loop (zero transit time from sensor to actuator). Figure 1 shows the principle of the active wall, and how it specularly reflects sound waves impinging on it. In an earlier publication [5], absorption coefficients ranging from 0.5 to 2.3 on ½ octave around the resonance frequency of a standard dome loudspeaker placed in a tube (1D propagation) have been reported. Then, the frequency bandwidth was enlarged up to 2 octaves using a standard 10mm dome tweeter modified for our application [6]. In the present paper, we shall present results obtained (still in 1D propagation) with a double feedback scheme : the reaction is a linear combination of two signals proportional to the transducer diaphragm velocity and pressure at the diaphragm respectively.

Figure 1 : Arrangement of cells in an active panel. (from [5]).



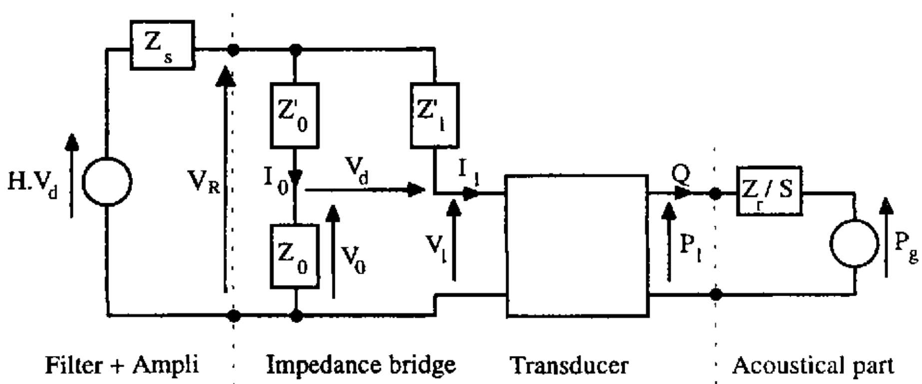
Perspective view of a 4x4 cells panel

Section view and principle

2. ACTIVE IMPEDANCE CONTROL WITH MOTIONAL FEEDBACK

A transducer is placed in an impedance bridge (figure 2), and acts both as a sensor and an actuator, thus ensuring true local reaction. The differential voltage V_D of the bridge is fed to a filter and an amplifier, and the output of the amplifier is connected to the bridge. The transducer is represented by a two-port network (A, B, C, D). Let P_1 be the pressure at the diaphragm, Q the volume flow of the diaphragm, V_R the feedback voltage, and Z_S the output impedance of the amplifier. The acoustical part (sources & room) is represented by a Thevenin generator (P_g ; Z_r/S).

Figure 2 :Electrical network equivalent to a MFB cell. (from [5]).



2.1 Acoustic Impedance of a Cell

It can easily be shown that

$$V_D = \frac{1}{Z_0 + Z'_0} \cdot \left(Z'_0 \cdot (AP_1 + BQ) - Z_0 Z'_1 \cdot (CP_1 + DQ)\right). \qquad (1)$$

Therefore, if the impedances of the bridge are chosen such that $Z'_0.A = Z_0.Z'_1.C$, then V_D is a function of Q only (i.e. independent of P_1). This can e.g. be achieved by choosing $Z'_0 = \gamma.Z_0$ and Z'_1

$= \gamma.A/C$, yielding $\frac{V_D}{Q} = \frac{-\Delta \cdot Z'_1}{A + C \cdot Z'_1}$ with Δ=AD-BC. For an electrodynamic transducer represented by its Thiele-Small parameters, we obtain the well known result $Z'_1 = \gamma.Z_E$, and $\frac{V_D}{Q} = -\frac{Bl}{S} \cdot \frac{\gamma}{1+\gamma}$, Z_E being the blocked electrical impedance of the transducer, Bl its force factor, and S its effective piston area. Thus, since V_D is directly proportional to the diaphragm velocity V = Q/S, the impedance bridge can be seen as a velocity sensor.

Alternatively, if the impedances of the bridge are chosen such that $Z'_0.B = Z_0.Z'_1.D$, then V_D is a function of P_1 only (i.e. independent of Q), and the impedance bridge acts as a pressure sensor.

In a future paper, we shall investigate how one can simultaneously get signals proportional to P_1 and Q using this approach [7]. However, in the present paper the impedance bridge is set as a velocity sensor, and a pressure microphone (placed at the transducer diaphragm) is used for delivering a signal proportional to P_1 (see figure 3). Following Darlington [8], the feedback voltage V_R is a linear combination of the pressure P_1 and the diaphragm velocity V :

$$V_R = \alpha.P_1 + \beta'.V \tag{2}$$

with $\beta'.V = \beta.V_D$. The acoustic impedance of the transducer diaphragm is found to be

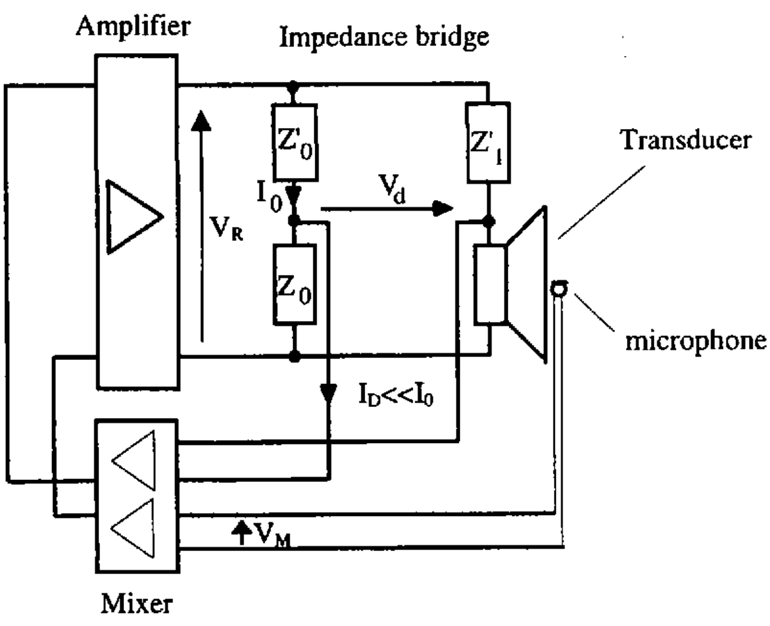
$$Z_A = S \cdot \frac{B - D.X}{A - C.X + \alpha.E} \tag{3}$$

with

$$X = \frac{Z_s + (1+\delta) \cdot Z'_1}{\beta - 1 - \delta} \qquad E = \frac{1}{\beta - 1 - \delta}$$

$$\delta = \frac{\beta \cdot Z_0 + Z_s}{Z_0 + Z'_0} \qquad \beta = -\frac{\beta'}{S} \cdot \frac{A + C \cdot Z'_1}{\Delta \cdot Z'_1}$$

Figure 3 : Transducer placed in an impedance bridge, with double feedback scheme.



Then, one can show that if $Z_0 = Z'_0$, $Z'_1 = Z_E$, $Z_S << \beta.Z_0$, and $\beta >> 2$, then $X \approx Z'_1$, $E \approx 2/\beta$, and we obtain for an electrodynamic transducer represented by its Thiele-Small parameters

$$\beta = -\frac{2}{Bl}\cdot\beta' \text{ , and } \qquad Z_A \approx \hat{Z}_A = -Bl\cdot\frac{\beta}{2\alpha} \quad . \tag{4}$$

This approximation is valid around the resonance frequency f_S of the transducer and for large feedback gains. Under these hypothesis, the acoustical impedance Z_A of a cell can be adjusted simply by varying the ratio β/α of the two feedback gains. If the feedback gains of all the cells of an array of identical cells are set in the same way, then the reflection coefficient of the panel should be controlled.

1.2 Stability of a Cell

Now of course, one has to check the stability of the cells. The stability can be looked at in two steps. First, instability may occur within a given cell. Second, instability may occur from interaction between cells. We call the former "intracell" stability, and the latter "intercell" stability. In this paper, we are presenting results obtained with one single cell only. Therefore only the intracell stability will be discussed. Intercell stability will be discussed in a future paper [9] presenting results of simulations of an array of cells.

The stability can be examined by looking at the open loop gain T_{tot}. Using the superposition theorem, we write $T_{tot} = T_P + T_V$, where T_P is the open loop gain obtained with then feedback on P_1 only (β=0), and T_V is the open loop gain obtained with then feedback on V_D only (α=0).

Let Z_1 be the electrical impedance of the transducer obtained when no acoustical excitation is applied to the transducer (P_g=0). Impedance Z_1 is

$$Z_1 = \frac{A.Z_r/S + B}{C.Z_r/S + D} \tag{5}$$

where Z_r is the radiation impedance of the transducer. Then, assuming for simplicity that Z_S is negligible, T_P and T_V are found to be

$$T_p = \alpha\cdot\frac{1}{Z_1 + Z'_1}\cdot\frac{Z_r/S}{(C\cdot Z_r/S + D)}$$

$$T_v = \beta\cdot\frac{Z_1 Z'_0 - Z_0 Z'_1}{(Z_0 + Z'_0)(Z_1 + Z'_1)}$$

Under the same hypothesis as above ($Z_0 = Z'_0$; $Z'_1 = A/C$), we get

$$T_{tot} = \frac{\alpha\cdot C\cdot Z_r/S - \Delta\cdot\beta/2}{2\cdot A\cdot C\cdot Z_r/s + B\cdot C + A\cdot D} \; .$$

yielding

$$T_{tot} = Bl\cdot\frac{Bl\cdot\beta/2 - \alpha\cdot Z_r}{2\cdot Z_e\cdot(Z_m + S\cdot Z_r) + Bl^2} \tag{6}$$

in case of an electrodynamic transducer (Z_m is its mechanical impedance). Replacing β by its expression derived from eq (4), we obtain

$$T_{tot} = Bl \cdot \frac{-\alpha \cdot \left(Z_r + \hat{Z}_A\right)}{2 \cdot Z_e \cdot (Z_m + S \cdot Z_r) + Bl^2} \quad . \tag{7}$$

$|T_{tot}|$ is maximum when $|Z_m|$ is minimum, i.e. at the resonance frequency f_s of the transducer. For a given desired value of impedance $\hat{Z}_A$ (and of R), we can choose the polarity of α and β in such a way that $\mathrm{Arg}(T_{tot}) \approx \pi$ when $|T_{tot}|$ is maximum, thus ensuring stability as will be seen below.

2- EXPERIMENTAL RESULTS

Figure 4 shows the experimental setup. A pressure electret microphone delivering a voltage V_M proportional to P_1 is placed about 5 mm in front of the centre of the loudspeaker diaphragm. Voltages V_D and V_M are mixed ; the output of the mixer is fed to a power amplifier via a 1st order low-pass filter (not shown). The loudspeaker is a standard 37 mm diameter dome medium from Audax. It is the same one as the one used in [5], its resonance frequency being about 700Hz. The transducer is placed in a 43 mm diameter tube, and a measuring microphone is placed in the middle of the tube. The impulse response of the "active material" (dome medium with control circuit) captured by the measuring transducer is measured using the MLS technique. Incident and reflected waves are windowed, and the reflection coefficient R is derived from the ratio of their spectra.

The acoustic absorbent placed at the open end of the tube prevents possible instability due to "super-reflection" at the other end, i.e. when the plane wave reflection coefficient of the active material exceeds unity, which is obtained when the real part of Z_A is negative :

$$|R| = |(Z_A - Z_C) / (Z_A + Z_C)| > 1 \qquad \text{when } \mathrm{Re}(Z_A) < 0 \ , \tag{8}$$

Z_C being the characteristic impedance of plane waves.

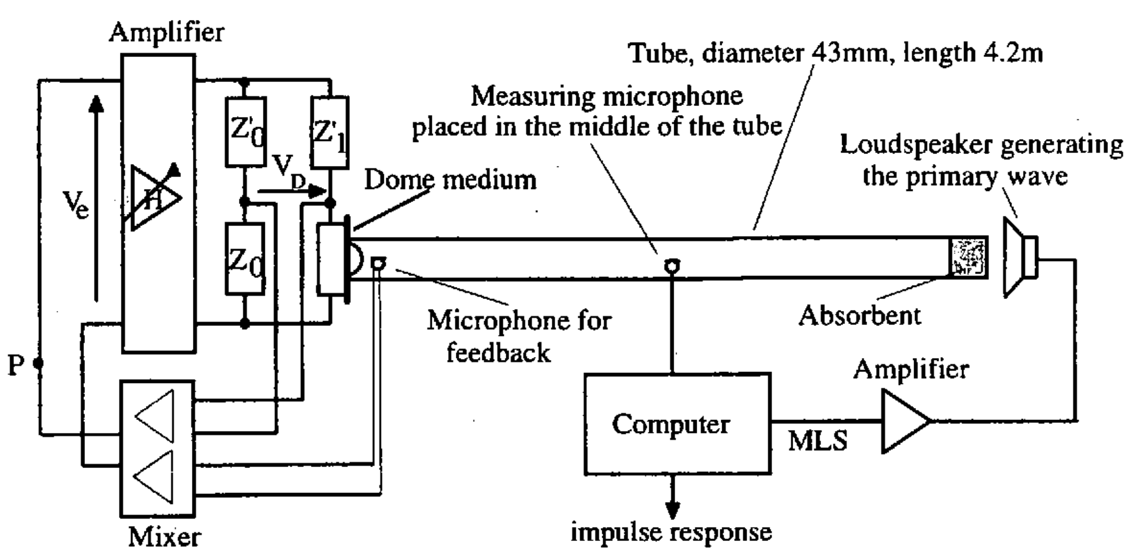


Figure 4 : Experimental setup

Two sets of values of α and β have been calculated using eqn (4) for two different values of the acoustic impedance Z_A, corresponding to two desired values of the reflection coefficient : $R_{desired} = 0$ and $R_{desired} = 2$. Results obtained are presented on figure 5 ($R_{desired} = 0$), and 6 ($R_{desired} = 2$).

Obviously, the signal to noise ratio of these measurements decreases with frequency, due to the absorbent which low-pass filters the primary wave. Still, one can see on figure 5 that we have $|R| < 0.5$ (i.e. absorption coefficient > 0.75) from 200Hz up to nearly 2kHz. Similarly, the upper curve on figure 6 shows that we have $|R| \approx 1.5$ (i.e. absorption coefficient ≈ -1.25) over the same decade [200 ; 2000Hz]. The peak around 4kHz on figure 5a is due to the propagation between the transducer and the feedback microphone. All of these results are in reasonable agreement with predictions of the model of section 1.1.

Figure 7 shows the measured open loop gain T_{tot} for the set of parameters corresponding to $R_{desired} = 0$. As explained in the previous section, the choice of α and β is such that $Arg(T_{tot}) = \pi$ when $|T_{tot}|$ is maximum.

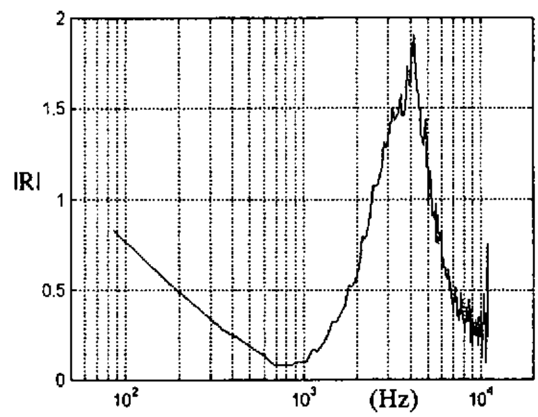


Figure 5a : Reflection coefficient obtained with $\alpha = 0.1$ and $\beta = -16$ ($R_{desired} = 0$).

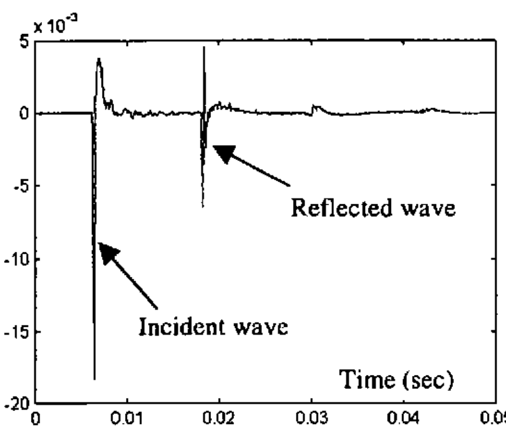


Figure 5b : Impulse response captured by the measuring microphone ($\alpha = 0.1$ and $\beta = -16$). Arbitrary vertical scale.

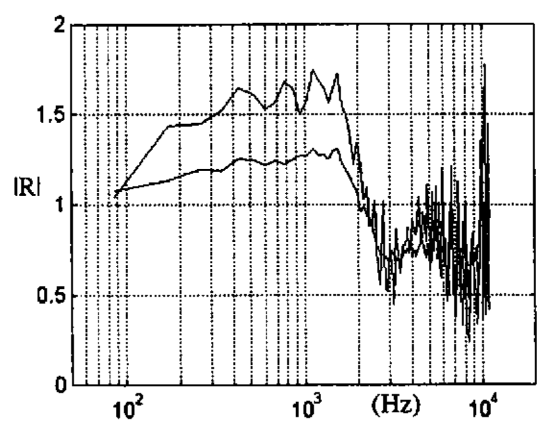


Figure 6a : Reflection coefficient obtained with $\alpha = -0.3$ and $\beta = -80$ (upper), and $\alpha = -0.3$ and $\beta = -80$ (lower) ($R_{desired} = 2$).

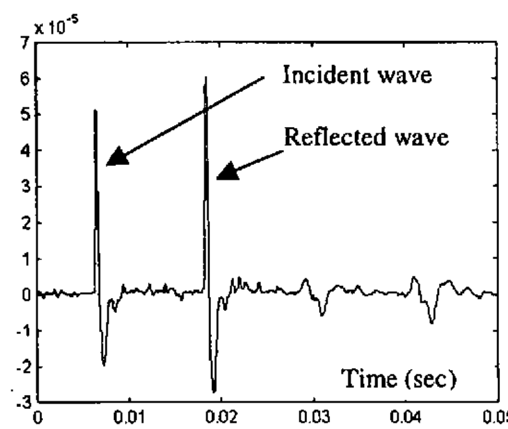


Figure 6b : Impulse response captured by the measuring microphone ($\alpha = -0.3$ and $\beta = -80$). Arbitrary vertical scale.

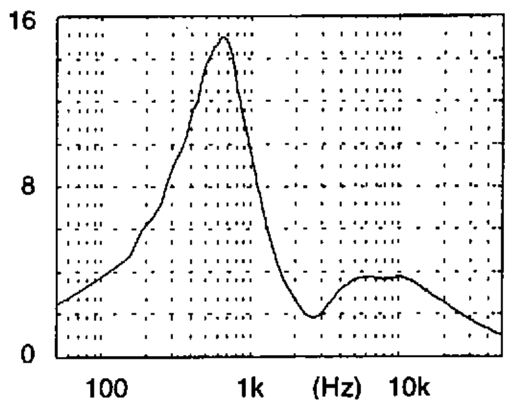


Figure 7a : Modulus of the open loop gain T_{tot} in the case $\alpha = 0.1$ and $\beta = -16$ ($R_{desired} = 0$).

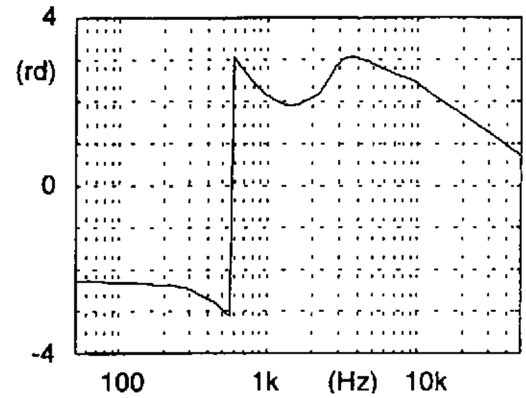


Figure 7b : Argument of the open loop gain T_{tot} in the case $\alpha = 0.1$ and $\beta = -16$ ($R_{desired} = 0$).

We have made the same experiment using a 25mm diameter woofer, and obtained interesting results in the absorbent case ($R_{desired} = 0$). An array of 4x4 such loudspeakers will be used for realising a prototype of active panel.

3- CONCLUSION

In this paper, we have described an active impedance control system using a double feedback scheme, and the motional feedback principle. Results presented (in 1D) show that the impedance can be controlled ($|R|<0.5$ to $|R|\approx1.5$) over 1 decade using a standard "hifi" dome medium loudspeaker. Predictions derived from the model described in this paper show that much better results could be obtained with low moving mass transducers. Thus, we are now working on a new type of transducer based on the "isodynamic" principle [10], which we hope will be well suited to our application, both on performance and industrial aspects.

Of course, a number of major difficulties have to be solved before active materials can actually be installed in auditoria, one of which being the background noise of such devices. Still, we think the potential of active materials is worth the effort. They could open new horizons to the design of next century's auditoria.

ACKNOWLEDGEMENTS

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Active reflectors for room acoustics - X. Meynial, H. Lissek.

Abstract
Having walls of variable absorption coefficient in an auditorium is an old idea. A number of passive mechanical systems have been designed, such as rollable curtains, or rotating panels. Today, progress in DSP and transducer technologies offer new possibilities for achieving this goal by active means. In 1995, the room acoustics group of the Centre Scientifique et Technique du Bâtiment has launched a research program on active materials, and is now working in collaboration with the Laboratoire d'Acoustique de l'Université du Maine. Active materials are composed of locally reacting active cells, using the motional feedback technique in a double feedback scheme. Adjustable reflection coefficient ranging from less than 0.5 ($\alpha_{sabine} > 0.75$) up to 1.5 ("super-reflection" $\alpha_{sabine} = -1.25$) have been obtained over one decade in a tube (1D), with a conventional "hifi" dome medium. We are now working on a special transducer technology devoted to our application. Much better results should be obtained, which could open new horizons for the design of next century's auditoria.