ELECTROACOUSTIC ABSORBERS I: BRIDGING A GAP BETWEEN ACTIVE SOUND ABSORPTION AND SHUNT LOUDSPEAKERS

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Variable acoustic properties can be obtained at the diaphragm of an electroacoustic transducer, with the help of very basic control strategies, among which is the simple electrical shunting of the transducer. These shunt techniques are compared to active feedback techniques for controlling the acoustic impedance of an electroacoustic transducer. It is shown here that the formulation of feedback-based acoustic impedance control reveals formal analogies with shunt strategies, and highlights an interesting strategy for synthesizing electric networks capable of mimicking feedbacks on actual acoustic quantities, bridging a gap between passive and active acoustic impedance control. The present paper describes the underlying theory unifying all these passive and active acoustic impedance control strategies, introducing the concept of "electroacoustic absorber". The formal equivalence between shunt and active feedback control is first formalized, on the one hand through the introduction of a 1-degree-of freedom active acoustic resonator accounting for both electric shunts and acoustic feedbacks, and on the other hand through the introduction of equivalent electric networks that mimic the performances of acoustic feedbacks. Simulated acoustic performances are presented, followed by discussions on the design of active electric shunts in view of active sound absorption. At last, experimental assessments of the studied configurations are presented, with general discussions on the concept.

1. Introduction

The term "Electroacoustic Absorbers" (EA) [1], inspired by Olson and May's "Electronic Sound Absorber" [2], designates loudspeakers employed as absorbers of sound, through active control of impedance based on feedback on acoustic quantities, or even through simple shunt resistors. Indeed, shunt loudspeakers [3, 4] represent a straightforward strategy for absorbing sound through electroacoustic means, the acoustic energy being partially absorbed through a simple electric resistance of positive value connected to the electric terminals of a loudspeaker. This shunt resistance can be seen as a mean to modify the value of the acoustic impedance of the diaphragm, up to the point at which the loudspeaker system becomes an excellent absorber around its resonance frequency. These shunt techniques can be seen as passive ways of achieving EAs. Active sound absorption with electroacoustic transducers can be achieved with Direct Impedance Control (DIC) [5]. DIC techniques employ two acoustic feedbacks, one on the acoustic pressure at the front face of a loudspeaker, and the other on the loudspeaker diaphragm velocity, the combination of which is demonstrated to achieve broadband
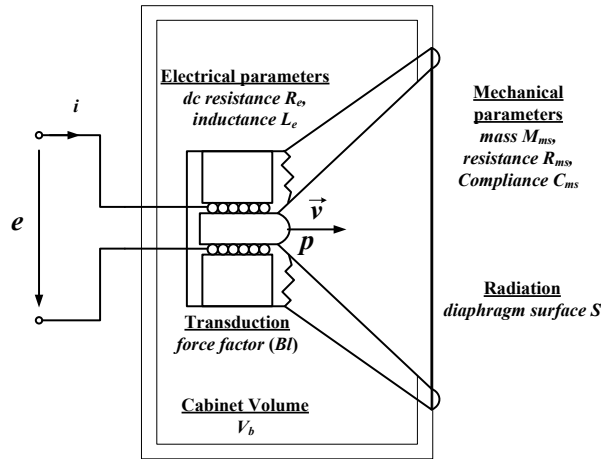
Figure 1. Electrodynamic loudspeaker.

acoustic resistance at the loudspeaker diaphragm, thus the capacity to turn it into a perfect absorber on a wide frequency bandwidth. It has been especially shown that, viewing this combination of feedbacks from the electric side of the loudspeaker, a specific electric networks can be designed and substituted for the feedbacks on acoustic quantities, so as to constitute "active" shunt loads, namely regulating the electric current circulating through the coil, thus controlling the acoustic reaction of the loudspeaker diaphragm to an exogenous sound field.

In the following, the EA concept is presented, through the formulation of the acoustic and electric properties of such devices. The formal equivalence between active sound absorption and shunt control is highlighted, on the one hand, through the description of the 3 independant parameters of a 1 degree of freedom acoustic resonator accounting for feedback gains, and on the other hand, through an equivalent electric load which, used as an active shunt, achieves the same acoustic impedance than the feedback control. This last result is then confirmed by experimental validations.

2. The electroacoustic absorber concept

2.1 Formulation of the acoustic performances

Let's consider an electrodynamic moving-coil loudspeaker (Visaton® AL 170 low-midrange loudspeaker), the rear face of its diaphragm being enclosed in a box (volume V_b), and the front face of which is radiating at the termination of a waveguide, the opposite extremity being considered as perfectly absorbent. The Thiele-Small parameters of the loudspeaker are defined in Fig.1 and numerical values are given in Table 1. In the following, we denote p the acoustic pressure at the front face of the loudspeaker, v the velocity of the diaphragm, e the voltage applied to the electric input of the loudspeaker, i the current circulating through the coil, $\rho = 1.2$ kg.m^{-3} the density of air, and $c = 345$ m.s^{-1} the celerity of sound in the air.

Table 1. Visaton® AL 170 small signal parameters.

Parameter	Notation	Value	Unit
DC resistance	R_e	5.6	Ω
Voice coil inductance	L_e	0.9	mH
Force factor	Bl	6.9	N.A^{-1}
Moving mass	M_{ms}	13.0	g
Mechanical resistance	R_{ms}	0.92	N.m^{-1}.s
Mechanical compliance	C_{ms}	1.2	mm.N^{-1}
Effective area	S	133	cm^2

A closed-box electrodynamic loudspeaker is a linear time-invariant system that, under certain hypotheses, can be described with differential equations [7]. From Newton's law of motion on the acoustic side, and from the mesh equation on the electric side, expressed in terms of Laplace transforms, one can obtain the following equation system:

$$
\begin{cases}
SP(s) = & -\left(sM_{ms} + R_{ms} + \dfrac{1}{sC_{mc}}\right)V(s) - BlI(s) \\
E(s) = & (sL_e + R_e)I(s) - BlV(s)
\end{cases}, \tag{1}
$$

where $P(s)$, $V(s)$, $E(s)$ and $I(s)$ are the Laplace transforms of sound pressure p, diaphragm velocity v, electric voltage e and current i. Here, C_{mc} is the equivalent mechanical compliance, resulting from the enclosing of the rear face of the loudspeaker in a cabinet of volume V_b. The equivalent mechanical compliance of the cabinet being $C_{mb} = V_b/(\rho c^2 S^2)$, thus $C_{mc} = C_{ms}.C_{mb}/(C_{ms} + C_{mb})$.

It is always possible to derive the system of Eq. 1 in order to express the normalized acoustic admittance of the loudspeaker face as a function of the sound pressure $P(s)$ and velocity $V(s)$, whatever the load or feedback at its electrical terminals:

$$
Y(s) = -\rho c.\frac{V(s)}{P(s)}. \tag{2}
$$

The extraction of the magnitude $|Y(f)|$ of $Y(s)$ yields the sound absorption coefficient $\alpha(f)$:

$$
\alpha(f) = 1 - |\frac{1 - Y(f)}{1 + Y(f)}|^2, \tag{3}
$$

valid for the steady-state response of the system to harmonic excitations.

Let's now apply a voltage $E(s)$ at the terminals of the loudspeaker as the combination of a voltage proportional to velocity $V(s)$ and a voltage proportional to the sound pressure $P(s)$ (DIC [5]):

$$
E(s) = \Gamma_v V(s) + \Gamma_p P(s), \tag{4}
$$

where Γ_v [resp. Γ_p] denotes the velocity-[resp. sound pressure-] proportional feedback gain (neglecting the sensors dynamics in view of easing the discussions). Substituting Eq. 4 in Eq. 1 and expressing the normalized acoustic admittance of Eq. 2, it is now possible to write the acoustic admittance resulting from DIC as (in the low frequency range):

$$
Y(s) \approx Z_{mc}\frac{s}{s^2 M_{mEA} + sR_{mEA} + \dfrac{1}{C_{mEA}}}, \tag{5}
$$

where $Z_{mc} = \rho cS$ and

$$
\begin{cases}
R_{mEA} \approx \dfrac{R_e R_{ms} + Bl(Bl + \Gamma_v)}{R_e + \Gamma_p \dfrac{Bl}{S}} \\[4mm]
M_{mEA} = M_{ms}\left[1 + \dfrac{\Gamma_p Bl}{S(R_e)}\right]^{-1} \\[4mm]
C_{mEA} = C_{mc}\left[1 + \dfrac{\Gamma_p Bl}{S(R_e)}\right]
\end{cases} \tag{6}
$$

are the mechanical resistance, the moving mass, and the mechanical compliance resulting from the active load at the electrical terminals. This first result shows that, on the acoustic side, the loudspeaker can be seen as an "active" resonator (absorber). Here DIC operates a modification of the

apparent acoustic resistance of the loudspeaker, leading to a modification of the sound absorption performances at the resonance, together with a decrease of the apparent moving mass and an increase of the apparent compliance of the diaphragm, resulting in a decreasing quality factor of the resonance, thus an increasing bandwidth of absorption. This result can be compared to the case where the loudspeaker is only loaded by a passive shunt resistance R_s, in which case the normalized acoustic admittance becomes:

$$Y(s) = Z_{mc} \frac{s}{s^2 M_{ms} + s\left(R_{ms} + \frac{(Bl)^2}{R_e + R_s}\right) + \frac{1}{C_{mc}}}, \tag{7}$$

where the only resistance of the resonator can be further increased.

2.2 Formulation of the equivalent electric load

It also follows from Eq. 1 and Eq. 2 that both velocity $V(s)$ and sound pressure $P(s)$ can be expressed as functions of the electric current $I(s)$:

$$E(s) = \Gamma_v V(s) + \Gamma_p P(s) = -Z(s)I(s), \tag{8}$$

where $Z(s)$ represents the equivalent electric load impedance, ratio of the total control feedback voltage against current intensity. This electric impedance becomes:

$$Z(s) = -(sL_e + R_e) - \frac{L_e s^2 + (\frac{\Gamma_p Bl}{S} + R_e)s}{\frac{\Gamma_p}{SBl}M_{ms}s^2 + \left[\frac{\Gamma_p}{SBl}R_{ms} - \left(1 + \frac{\Gamma_v}{Bl}\right)\right]s + \frac{\Gamma_p}{SBlC_{mc}}} \tag{9}$$

A DIC with control parameters (Γ_v, Γ_p) is then equivalent to an electrical network $Z(s)$, which is composed of a first negative series resistance-inductance $-Z_e(s) = -(sL_e + R_e)$, which can be viewed as a "neutralization" of the electric impedance of the loudspeaker, and a shunt impedance $Z_s(s)$ that depends on the control parameters. The neutralization then reveals the required electric network that, connected to the loudspeaker, should fit the target acoustic admittance. In this sense, this formulation can directly be used for synthesizing electric networks capable of mimicking feedback-based active absorption. Conversely, each shunt has its acoustic feedback counterpart, namely a setting of the acoustic feedback gains Γ_p and Γ_v that plays the same role than the load impedance.

3. Simulations

3.1 Acoustic performances

The different settings considered in this section are given in Table 2. The acoustic absorption coefficients obtained by simulations according to Eq. 3 (with acoustic admittance given either by Eq. 5 or Eq. 7) are gathered on the synthetic illustration of Fig.2, in order to show their common behavior, and assess the influence of the electroacoustic absorber parameters on the acoustic absorption coefficient on a single chart.

The results on Fig.2 (see Table 2 for control parameters) clearly highlight the similarities between the different control techniques detailed in the previous section, unifying passive shunt techniques and active feedback control of acoustic impedance into a single formalism. The passive performances of an electroacoustic absorber (Case 0) can be first improved with a simple passive electric resistance of optimal value (Case 1, here $R_s = 5\Omega$), so as to reach almost perfect absorption within a narrow frequency bandwidth around the resonance, due to the increase of total resistances
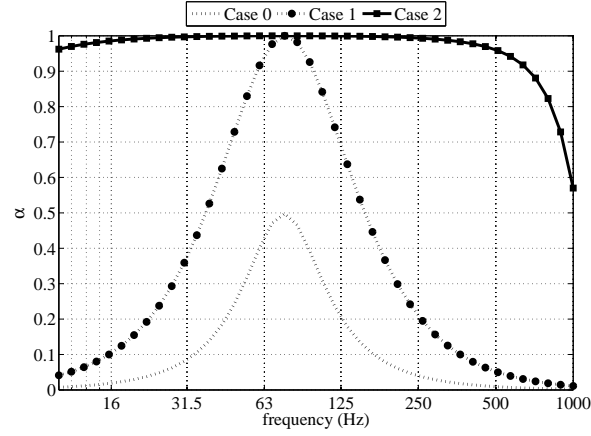
Figure 2. Computed absorption coefficients of the electroacoustic absorber for various setups (Table 2).

Table 2. Examples of setting cases and corresponding control results.

	Control settings			Control results		
	R_s	Γ_v	Γ_p	R_{mEA}	M_{mEA}	C_{mEA}
	(Ω)	(V.m^{-1}.s)	(V.Pa^{-1})	N.m^{-1}.s	g	mm.N^{-1}
Case 0	∞	0	0	0.92	13	1.2
Case 1	5	0	0	5.41	13	1.2
Case 2	0	100	0.25	5.49	0.54	0.03

($R_{mEA} \approx Z_{mc}$). The bandwidth of control can then be significantly increased by choosing appropriate feedback gains in a combined pressure-velocity feedback. This leads to an enhanced resistance at resonance, and a lowering of the apparent mass and compliance of the resonator. Inspired by these formal analogies, a technique for adjusting the active feedback gains can be introduced, consisting in tuning the 3 independent parameters of the equivalent acoustic resonator, presenting interesting perspectives for controlling the acoustic impedance of an electroacoustic loudspeaker.

3.2   Equivalent electric load

Moreover, the equivalent electric shunt of Eq. 9 is processed with the parameters of Case 2, leading to the function of Eq. 10, illustrated on Fig.4(b).

$$Z(s) + (sL_e + R_e) = \frac{0.00041s^2 + 8.5s}{-0.0019s^2 + s - 416.44}. \tag{10}$$

This target electric impedance can be obtained with the electric network of Fig.3, composed of electric resistances (R_1 and R_2) and inductances (L_1 and L_2). Here, Z_s denotes the left part of the electric shunt, excluding the neutralizing electric impedance $-(sL_e + R_e)$. In this case:

$$Z_s(s) = \frac{s^2 L_2 \left(1 + \dfrac{R_1}{R_2}\right) + sR_1}{s^2 \dfrac{L_2}{R_2} + s \left[1 + \dfrac{L_2}{L_1}\left(1 + \dfrac{R_1}{R_2}\right)\right] + \dfrac{R_1}{L_1}} \tag{11}$$

.

We chose a set of electric components (R_1, R_2, L_1, L_2), so that the coefficient of s^2 on the numerator of Eq. 11 equals 0, or in other words, the synthesized impedance fits the target one in the low-medium frequency range. It yields:

$$\left\{ \ R_1 = -R_2 = 8.5\Omega; \quad L_1 = -18.7\text{mH}; \quad L_2 = 17.4\text{mH} \right. \tag{12}$$
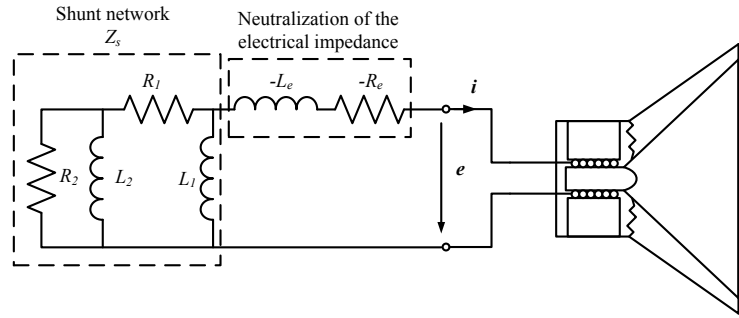
Figure 3. Example of electric impedance synthesis as an active shunt of an electroacoustic absorber.

It yields:

$$Z_s(s) = \frac{8.5s}{-0.0020s^2 + s - 454.5},$$ (13)

that can be compared to the expression of Eq. 10, as illustrated on Fig.4(b). Thus, the synthesized electric impedance matches the target one, within the frequency bandwidth of interest.

Conversely, this synthesized electric impedance $Z_s(s)$ forms a new shunt impedance in series with $-(sL_e + R_e)$ that we can then substitute for R_s in Eq. 7, to compute the corresponding "synthesized" acoustic admittance denoted Y_s. The synthesized acoustic admittance is then:

$$Y_s(s) = Z_{mc} \frac{s}{s^2 \left(M_{ms} + (Bl)^2 \frac{L_2}{R_1 R_2} \right) + s \left(R_{ms} + \frac{(Bl)^2}{R_1} \right) + \left(\frac{1}{C_{mc}} + \frac{(Bl)^2}{L_1} \right)}$$ (14)

.

This normalized admittance, with the chosen values of Eq. 12, should present the same acoustic performances as with actual feedbacks on acoustic quantities represented by Eq. 5. The acoustic absorption coefficient processed with the normalized admittances of Eq. 5 and Eq. 14 are compared in Fig.4(b).

This last result illustrates the formal equivalence between shunt loudspeakers and feedback-based active sound absorption, showing similar results in terms of sound absorption. One can observe that, with the chosen electric network, the coefficients of s^2 and s^0 in the denominator of the synthesized acoustic admittance $Y_{s,3a}(s)$ can actually be lower than in the passive shunt case (see Eq. 7). This is in accordance with the objective of lowering the equivalent mass and increasing the equivalent compliance of the loudspeaker, in order to extend the bandwidth of the control. The electrical network allows the adjustment of the 3 parameters of the acoustic resonator to the target. This result paves the way to new strategies for the optimization of electric networks shunting a loudspeaker in view of active sound absorption.

4. Measurements

In order to assess experimentally the equivalence between the active feedback control and electric shunts, a closed-box (volume V_b=10 l) Visaton® AL 170 low-midrange loudspeaker is employed as an electroacoustic absorber. The acoustic absorption coefficient of the electroacoustic absorber is assessed after ISO 10534-2 standard [6], as described in Fig.5.

In this setup, an impedance tube is designed, one termination of which is closed by the electroacoustic absorber, the other extremity being open with a horn-shape termination so as to exhibit anechoic conditions. A source loudspeaker is wall-mounted close to this termination. Two 1/2" microphones sense sound pressures p_1 and p_2 at positions x_1 and x_2, processed on a 01dB-NetdB Multichannel Analyzer. Simultaneously, with a view to process the equivalent electric load Z at the
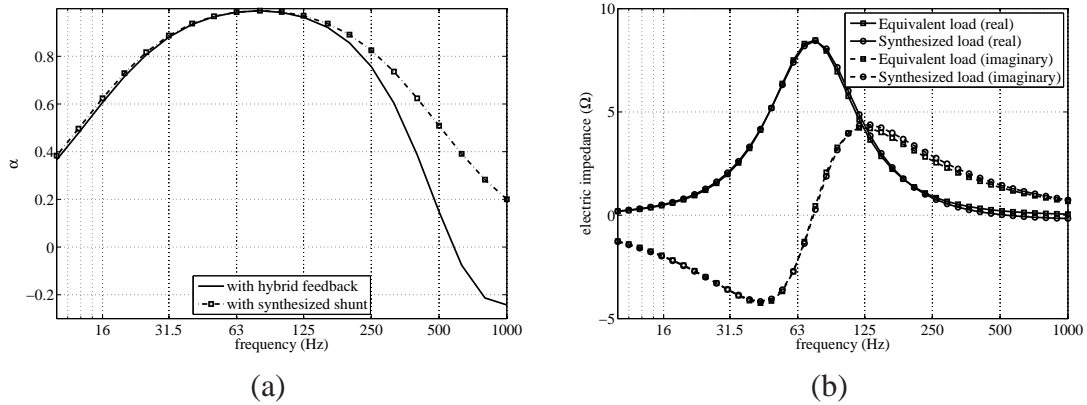
(a) (b)

Figure 4. (a) Acoustic absorption coefficient corresponding to Case 2, with the two methods (plain line: with DIC; square markers: with the shunt electric network of Fig.3); (b) Computation of the electric impedance of Eq. 10 (square markers), and the synthesized electric impedance of Eq. 13 (round markers) for Case 2 (plain lines: real part; dotted lines: imaginary part)
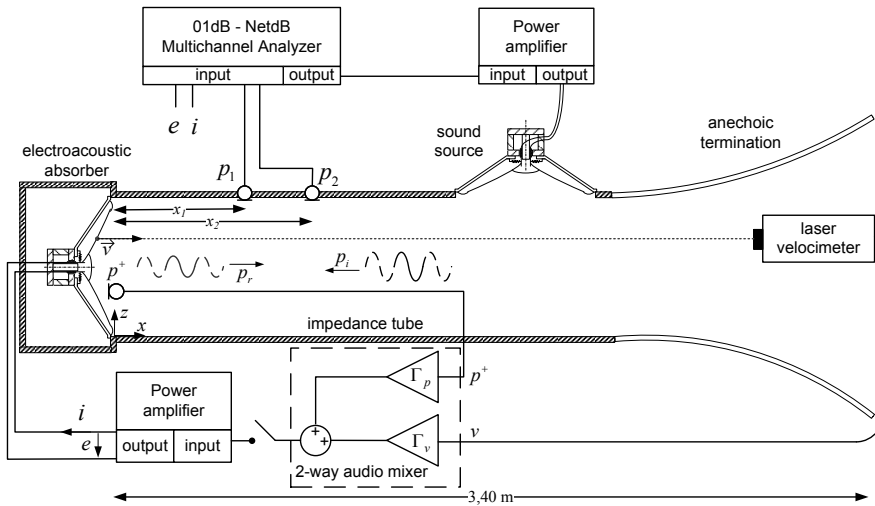

Figure 5. Experimental setup for the assessment of electroacoustic absorbers absorption coefficient.
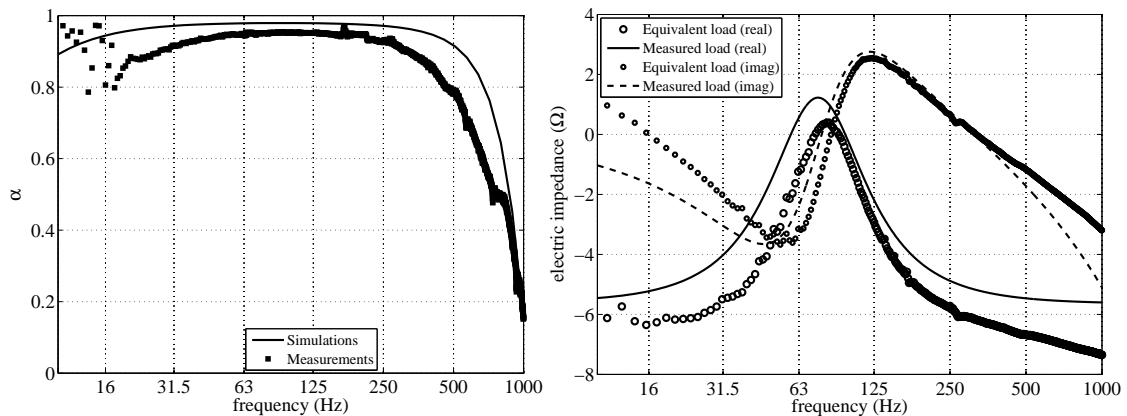

Figure 6. Experimental assessment of the electroacoustic absorber and comparison to numerical simulations: (a) absorption coefficient obtained with DIC; (b) measured and simulated equivalent electric load.

electroacoustic absorber electric terminals, the electric voltage e and current i circulating through the coil are measured, and processed with the same instrumentation.

In this experimental study, the DIC parameters (Γ_v=70.0 V.m^{-1}.s and Γ_p=0.13 V.Pa^{-1}) have been applied at the electroacoustic absorber electric terminals. The velocity feedback is sensed through a Polytec OFV-505/5000 laser velocimeter positioned at the output of the open tube, as illustrated in Fig.5. The pressure is sensed with an external PCB 130D20 microphone at the vicinity of the diaphragm. The experimental assessment confirm that the linear model is relevant relatively to the acoustic absorption performances of the controlled loudspeaker, with perfect absorption on almost one frequency decade. Moreover, the electroacoustic transducer actually behaves as if it were connected to a specific electric network, the parameters of which can be identified quite easily. The model of the equivalent electric load gives good results, compared to the assessed equivalent load, yielding to a straightforward novel technique for designing active electric shunts allowing such acoustic performances.

5. CONCLUSIONS

A unifying theory of active acoustic impedance control has been introduced, covering different control techniques from passive shunt to pressure/velocity feedbacks in a single formalism. An acoustic feedback is shown to be equivalent to an electrical load at the transducer electrical terminals. Conversely, a synthetic electric network has been identified for each active acoustic impedance control, the design of which can be specified in a relatively simple manner. Broadband acoustic performances have been measured on a generic prototype of electroacoustic absorber with active feedback control. Finally, the equivalent electric load of an active feedback has also been experimentally assessed, confirming the theory of electroacoustic absorbers.

6. Acknowledgements

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