Design of Shunt Electric Networks in View of Sound Absorption with Loudspeakers

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Summary

The acoustic impedance at the diaphragm of an electroacoustic transducer can be varied using a range of basic electrical control strategies, amongst which are electrical shunt circuits. These shunt techniques have been demonstrated to present similarities with active acoustic feedback control of the acoustic impedance of a loudspeaker. Based on this observation, an interesting strategy has been developed, intending at designing electric networks which, when connected to the loudspeaker, can make the latter reach a desired acoustic impedance over a certain frequency bandwidth. This paper presents a methodology for designing electric networks, that can be passive or active, capable of achieving variable sound absorption at the loudspeaker diaphragm. In a first part, the theory underlying the concept of electroacoustic absorber is presented, highlighting formal equivalences between shunt and active feedback control, especially 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 potential improvements and applications.

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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 feedback-based active control of impedance, or even through simple shunt resistors. Indeed, shunt loudspeakers [3] 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 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 paper especially focuses on a novel strategy for synthesizing a target acoustic impedance that the loudspeaker should present to the medium, that can be performed by setting 3 independent parameters of a 1 degree-of-freedom resonator. A synthetic formulation of the acoustic admittance resulting either from an electric shunt or an acoustic feedback is specifically developed. Then, direct feedbacks on acoustic quantities

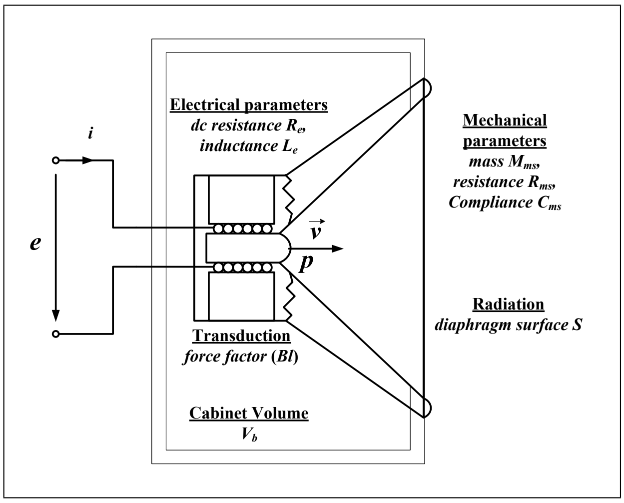

Figure 1. Electrodynamic loudspeaker.

Table I. 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}	15.0	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

are shown to be equivalent to electric shunts that are formalized hereafter, allowing the synthesis of electric networks in view of active sound absorption. 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 I. 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.

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:

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

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:

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

The corresponding reflection coefficient can be derived after:

$$r(s) = \frac{1 - Y(s)}{1 + Y(s)}. \quad (3)$$

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

$$\alpha(f) = 1 - |r(f)|^2, \quad (4)$$

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

Let's now consider a direct impedance control of the loudspeaker. In this case, the voltage $E(s)$ at the terminals of the loudspeaker is, generally, the combination of a voltage proportional to velocity $V(s)$ and a voltage proportional to the acoustic pressure $P(s)$. This yields:

$$E(s) = \Gamma_v V(s) + \Gamma_p P(s), \quad (5)$$

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). It is now possible to substitute $I(s)$ for both $V(s)$ and $P(s)$ in Eq. 1, and then write the acoustic admittance resulting from DIC as:

$$Y(s) = Z_{mc}\frac{s^2 a_2 + s a_1}{s^3 b_3 + s^2 b_2 + s b_1 + b_0}, \quad (6)$$

where $Z_{mc} = \rho c S$ and

$$\begin{cases} a_2 = L_e \\ a_1 = R_e + \Gamma_p \dfrac{Bl}{S} \end{cases} \begin{cases} b_3 = L_e M_{ms} \\ b_2 = R_e M_{ms} + L_e R_{ms} \\ b_1 = R_e R_{ms} + \dfrac{L_e}{C_{mc}} + Bl(Bl + \Gamma_v) \\ b_0 = \dfrac{R_e}{C_{mc}} \end{cases}, \quad (7)$$

Moreover, if we neglect the high-order terms of the numerator and the denominator, the acoustic admittance is even simpler:

$$Y(s) \approx Z_{mc} \frac{s}{s^2 M_{mEA} + s R_{mEA} + \dfrac{1}{C_{mEA}}}, \quad (8)$$

where

$$\begin{cases} R_{mEA} \approx \dfrac{R_e R_{ms} + Bl(Bl + \Gamma_v)}{R_e + \Gamma_p \dfrac{Bl}{S}} \\ M_{mEA} = M_{ms} \left[1 + \dfrac{\Gamma_p Bl}{S(R_e)}\right]^{-1} \\ C_{mEA} = C_{mc} \left[1 + \dfrac{\Gamma_p Bl}{S(R_e)}\right] \end{cases} \quad (9)$$

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:

$$Y(s) = Z_{mc} \frac{s}{s^2 M_{ms} + s\left(R_{ms} + \dfrac{(Bl)^2}{R_e + R_s}\right) + \dfrac{1}{C_{mc}}}, (10)$$

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 $I(s)$:

$$E(s) = \Gamma_v V(s) + \Gamma_p P(s) = -Z(s) I(s), \quad (11)$$

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

$$Z(s) = -(sL_e + R_e) - \frac{n_2 s^2 + n_1 s}{d_2 s^2 + d_1 s + d_0} \quad (12)$$

where

$$\begin{cases} n_2 = L_e \\ n_1 = \dfrac{\Gamma_p Bl}{S} + R_e \end{cases} \begin{cases} d_2 = \dfrac{\Gamma_p}{SBl} M_{ms} \\ d_1 = \dfrac{\Gamma_p}{SBl} R_{ms} - \left(1 + \dfrac{\Gamma_v}{Bl}\right) \\ d_0 = \dfrac{\Gamma_p}{SBlC_{mc}} \end{cases}, \quad (13)$$

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

Let's consider the configuration where the EA is fed by DIC, with control parameters (Γ_v=70V.s.m^{-1} and Γ_p=0.13V.Pa^{-1}), which corresponds to a configuration that can be assessed experimentally. In this case, the equivalent electric load of Eq. 12 is:

$$Z(s) + (sL_e + R_e) = \frac{0.00041 s^2 + 8.5 s}{-0.0019 s^2 + s - 416.44}. (14)$$

This target electric impedance can be obtained with the electric network illustrated on FIG. 4, 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:

$$Z_s(s) = \frac{s^2 L_2 \left(1 + \dfrac{R_1}{R_2}\right) + sR_1}{s^2 \dfrac{L_2}{R_2} + s\left[1 + \dfrac{L_2}{L_1}\left(1 + \dfrac{R_1}{R_2}\right)\right] + \dfrac{R_1}{L_1}}. (15)$$

The identification of the parameters of this network is not straightforward and requires much care, since

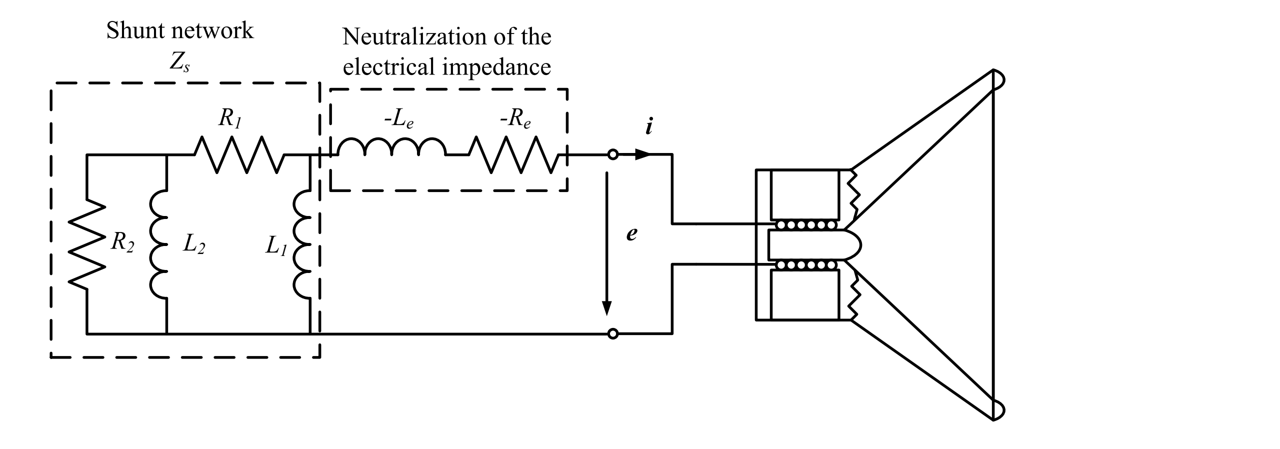

Figure 2. Example of shunt electric network substituted for acoustic feedbacks.

the number of degrees of freedom (R_1, R_2, L_1 and L_2) is lower than the number of coefficients of the target electric impedance. Nevertheless, illustrating the equivalence between shunt and feedback control, a set of electric components has been chosen, so that the coefficient of s^2 on the numerator of Eq. 12 equals 0, or in other words, the synthesized impedance fits the target one in the low-medium frequency range. It yields:

$$\begin{cases} R_1 = -R_2 = 8.5\Omega \\ L_1 = -18.7\text{mH} \\ L_2 = 17.4\text{mH} \end{cases} \tag{16}$$

By replacing the values of (R_1, R_2, L_2, L_1) in Eq. 13, one can obtain the following synthesized impedance:

$$Z_s(s) = \frac{8.5s}{-0.0020s^2 + s - 454.5}, \tag{17}$$

that can be compared to the expression of Eq. 12, as illustrated on FIG. 3(a). 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. 8, to compute the corresponding "synthesized" acoustic admittance denoted $Y_s(s)$ (in order to distinguish this synthesized admittance and the target one $Y(s)$). The synthesized acoustic admittance is then analogue to Eq 8, with:

$$\begin{cases} R_{mEA} = R_{ms} + \dfrac{(Bl)^2}{R_1} \\ M_{mEA} = M_{ms} + (Bl)^2 \dfrac{L_2}{R_1 R_2} \\ C_{mEA} = \dfrac{(Bl)^2}{R_1} \end{cases}. \tag{18}$$

This normalized admittance, with the chosen values of Eq. 14, can be used to process the "synthesized" absorption coefficient, according to Eq. 4.

It is then compared in FIG. 3(b) to the one obtained with direct impedance control (with $\Gamma_v = 10$ V.m^{-1}.s, $\Gamma_p = 0.025$ V.Pa^{-1}, $R_s = 0\Omega$).

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 $Y_s(s)$ of Eq. 18 are lower than in the passive case (see Eq. 10). 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. Moreover, the equivalent acoustic resistance is actually higher than the passive one, which is required to match the acoustic resistance of air. The electrical network allows the adjustment of the 3 parameters of the acoustic resonator to the target. This result opens the way to new strategies for the optimization of electric networks shunting a loudspeaker in view of active sound absorption. Practically, such electric impedance design is not straightforward and needs a very accurate selection of the electric components, especially with respect to stability, but also in terms of absorption performances. The implementation of such impedance synthesis strategy on digital signal processing platforms could help alleviate these issues.

4. Experimental validation

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, as described in FIG. 4.

In this setup, an impedance tube is specifically designed (length L=3.4m; internal diameter $\emptyset$=150mm),

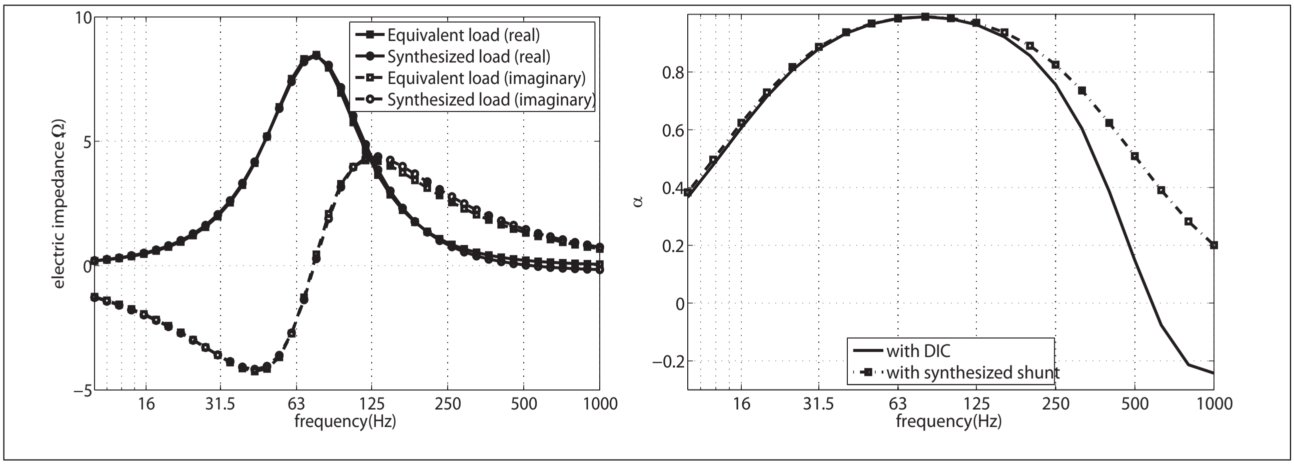

Figure 3. (a) Equivalent electric load Z of Eq. 14 (square markers) and synthesized electric load Z_s of Eq. 15 (round markers) - real and imaginary parts; (b) Absorption coefficient obtained with DIC, derived after Eq. 6 (plain lines) and obtained with the synthesized shunt Z_s of Eq. 15 substituted for R_s in Eq. 10 (dotted lines).

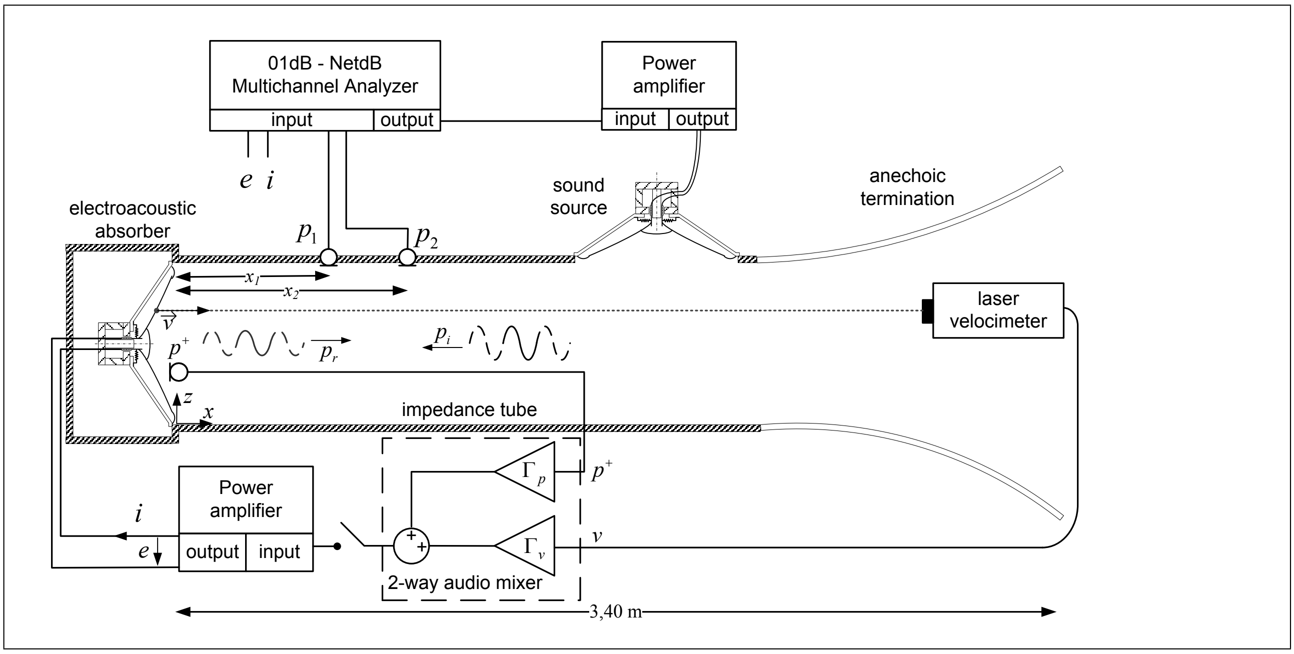

Figure 4. Experimental setup for the assessment of electroacoustic absorbers absorption coefficient.

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 holes located at positions $x_1 = 0.46$m and $x_2 = 0.35$m from the electroacoustic absorber position are the receptacles of 1/2" microphones (Norsonic Type 1225 cartridges mounted on Norsonic Type 1201 amplifiers), sensing sound pressures $p_1 = p(x_1)$ and $p_2 = p(x_2)$, and the transfer function $H_{12} = \frac{p_2}{p_1}$ is processed through a 01dB-NetdB Multichannel Analyzer. Simultaneously, with a view to process the equivalent electric load Z at the 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. Here, the velocity feedback is processed through a Polytec OFV-505/5000 laser velocimeter (sensitivity being set to σ_v=100 V.m^{-1}.s). This velocity sensor is positioned at the output of the open tube, as illustrated in FIG. 4, the laser beam focusing on a single point of the radiator, at the middle of its radius. The pressure is sensed with an external PCB 130D20 microphone (sensitivity of σ_p=47.5 mV.Pa^{-1}), located in the plane $x = 0$ and slightly off-center (at a height of $z = 3.2$cm from the duct wall), yielding

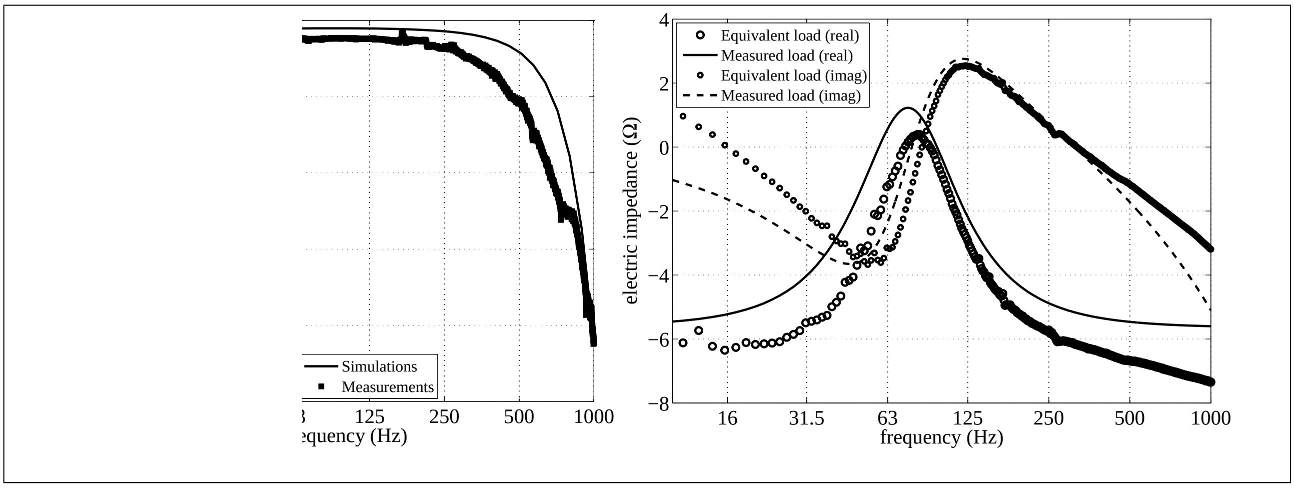

Figure 5. Experimental assessment of the electroacoustic absorber and comparison to numerical simulations: (a) absorption coefficient obtained with direct impedance control (Γ_v=70.0 V.m^{-1}.s and Γ_p=0.13 V.Pa^{-1}); (b) measured and simulated equivalent electric load.

a distance of approximately 5 mm from the loudspeaker diaphragm. The direct impedance control is processed through a 2-way analogical audio mixer, allowing the setting of electric feedback gains $\Gamma'_v = \frac{\Gamma_v}{\sigma_v}$ and $\Gamma'_p = \frac{\Gamma_p}{\sigma_p}$. The sound absorption coefficient measured with the above-mentioned setup are compared to the corresponding model simulations. In parallel, the equivalent electric load, processed as the transfer function between voltage e and current i at the electroacoustic absorber terminals, is assessed for above-mentioned DIC settings, and compared to the corresponding model simulation. 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 synthetic electric network has been identified to be substituted for direct impedance control, the design of which can be specified in a relatively simple manner. The equivalent electric load has also been experimentally assessed, proving the equivalence between active feedback control on acoustic quantities and synthetic shunts. The realization of such shunt electric networks has not been actually achieved with analog circuits. Indeed, a perfect neutralization of the electric impedance of the loudspeaker is difficult to perform, as it would make the system marginally stable. Furthermore, the variations in electric resistance and inductance would make it difficult to maintain the source impedance $Z(s)$ at the correctu instantaneous value. Therefore, actual work is focussing on implementing such synthetic electric shunt impedance through digital filters on FPGA platforms, translated into impedance through a dedicated impedance converter.

Acknowledgement

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