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Control of an acoustic mode by a digitally created Nonlinear Electroacoustic Absorber at low excitation levels: Experimental results

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Abstract. In this study, an acoustic mode of a tube is controlled by a digitally created Nonlinear Electroacoustic Absorber (NEA) at low excitation levels, where the nonlinearity cannot be normally activated in passive vibro-acoustical absorbers. A comparison is carried out between a linear Electroacoustic Absorber, similar to a Tuned Mass Damper (TMD) in mechanics, and a digital NEA. The innovative method for creating a NEA lies on Real Time Integration of the dynamics of the device. It permits to choose any behavior of the system by digitally programming the corresponding targeted dynamics. Here, a loudspeaker Impedance Control law with a cubic stiffness is considered, as this system is well known in mechanics and provides nonlinear phenomena that are highlighted at low and moderate excitation levels in our study.

Keywords: Acoustics, Control, Nonlinear Electroacoustic Absorber, Non-linear Energy Sink (NES), Targeted Energy Transfer (TET)

1 Introduction

Reducing Noise and Vibrations by means of passive and active devices is the subject of many research works. In mechanics, the attenuation of vibrations leads to prevention of failures of materials and systems to assure the safety of people, as during an earthquake. Linear and nonlinear absorbers have been studied and employed. In acoustics, passive devices are commonly used, such as acoustic foam [15] or Helmholtz resonators to attenuate noise to create an acoustic comfort and safety for users. Lately, noise became a real health issue, causing pathologies that goes beyond only acoustic comfort. An acoustic foam is not efficient for the absorption of low frequency waves [6], and Helmholtz resonators

are very selective devices, similar to a Frahm absorber [7], also named Tuned Mass Damper (TMD) in mechanics. An Active Noise Control system consists of sending a wave in opposition of phase to cancel the wave in terms of energy [12]. This method of attenuation works efficiently for very localized zones, but is very energy consumer, and as a result expensive. Olson and May [14] created a new electro-active device, but acoustically passive by controlling the impedance of a loudspeaker, and so creating an absorber. The method is called Impedance Control, and has to be distinguished from Active Noise Control. It is at low energy consumption and does not send an wave in phase opposition, it absorbs the wave [2, 3]. For human tolerable acoustic levels, these devices usually stay in their linear regime because one can observe nonlinear phenomena when the amplitudes of motion and pressure reached a certain threshold. Nonlinear passives absorbers are usually activated at high amplitudes. Indeed, Bellet et al. [1] have implemented a visco-elastic membrane behaving as a pure cubic stiffness oscillator which is activated above 143 dB Sound Pressure Level (SPL), to control an acoustic mode. Gourdon et al. [8] have implemented a Helmholtz resonator, similar to a TMD in mechanics, in its nonlinear regime and therefore have succeeded to create a pure acoustical oscillator in nonlinear regime above 138 dB SPL. More recently, Guo et al. [10] placed a microphone in the back cavity of a loudspeaker, allowing to add a nonlinear current proportional to the cubic law of the displacement of the membrane to the linear current, modifying the classic Impedance Control around 100 dB. The aim of the study is to create an Electroacoustic Absorber (EA) based on Impedance Control in its nonlinear regime at low excitation levels, and then to show its potential efficiency. Organisation of the paper is as it follows: in section 2, the NEA is briefly explained and the working principle of an innovative method to implement nonlinear control laws is presented. In section 3, results of two different experiments are shown. Finally the paper is concluded in section 4.

2 The Electroacoustic Absorber for Noise Control

2.1 The concept of impedance control

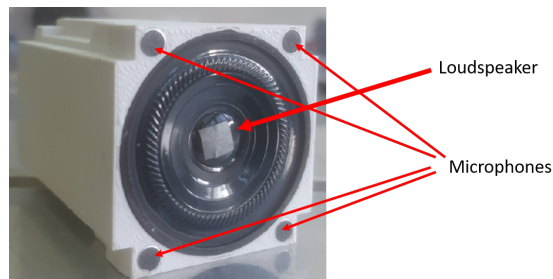


Fig. 1. The Electroacoustic Absorber

The Electroacoustic Absorber is composed of microphones collocated to a loudspeaker, and monitored by a processor, see Fig (1). The processor estimates the electrical current to inject to the loudspeaker coil. This calculation is based on an input: the sensed pressure, and gives the electrical current as an output. It aims to target in its linear regime an acoustic impedance $Z = \frac{p}{v}$ [13] of the loudspeaker, with p the pressure on the membrane of the loudspeaker, and v the velocity of the fluid particles on the membrane of the loudspeaker. The acoustic impedance Z can be also expressed as a function of the Thiele/Small Parameters of the loudspeaker, *i.e.* the modal mechanic parameters M_{m0} , K_{m0} and R_{m0} at its first mode. Governing equation in the modal domain in the absence of any external excitation, *i.e.* without any electrical current ($i = 0$) or pressure ($p = 0$) reads:

$$M_{m0}\ddot{u}(t) + R_{m0}\dot{u}(t) + K_{m0}u(t) = 0 \quad (1)$$

with u the displacement of the membrane along a single axis, that is considered uniform in the membrane loudspeaker, because of the piston-mode approximation that can be done around the first mode.

By changing the modal parameters of the loudspeaker from M_{m0} , R_{m0} , and K_{m0} to M_{mt} , R_{mt} , and K_{mt} , one can target a particular acoustic impedance. As a result, targeting an acoustic impedance permits to choose reflection, and absorption conditions of the loudspeaker for an incoming wave. Once the Thiele/Small Parameters, the force factor of the loudspeaker coil Bl and the measured pressure are known, the current to be injected to the coil can be calculated in order to modify the acoustic behavior of the loudspeaker. In order to achieve this task, the processor has to estimate the target displacement, velocity, and acceleration of the membrane. The method only needs the control law to have been previously digitally defined in the processor.

Linear control law are experimentally implemented through the Z transform, the discrete Laplace domain which is named as Infinite Input Response (IIR) [9]. The linear Electroacoustic Absorber has been deeply studied using this method of implementation [11, 4]. However, in the case of a nonlinear control law, as in our study, this method is not adapted and can not be used. As a result, an innovative method to implement nonlinear behavior at low amplitude excitation has been created and is presented in section (2.2).

2.2 Working principle of the nonlinear control

This section aims at introducing the innovative method of experimental implementation of any desired control law, linear or nonlinear. This method could be used in other domains than acoustics, but it will be presented here in the case of our study. In nonlinear regimes, multiple equilibrium points, stable or unstable, can exist for a single frequency. This explains why a frequency based approach for an experimental implementation, as the IIR method, can not be used. The implementation of the control has to be done at each time step, it is a Real Time Integration (RTI) method. Let us define some equations. Assuming that a source is creating a pressure wave p towards the Electroacoustic Absorber, the

equation of motion of the dynamics of the loudspeaker is:

$$M_{m0}\ddot{u}(t) + R_{m0}\dot{u}(t) + K_{m0}u(t) = -Bl i(t) + p(t)S_d \quad (2)$$

with S_d the surface of the loudspeaker, and u the actual displacement of the loudspeaker membrane.

The desired dynamics of the loudspeaker is defined with the equation :

$$M_{mt}\ddot{u}_t(t) + R_{mt}\dot{u}_t(t) + K_{mt}u_t(t) + F(t, u_t(t), \dot{u}_t(t), \ddot{u}_t(t)) = p(t)S_d \quad (3)$$

with u_t the target displacement of the loudspeaker membrane and F nonlinear function of t , u_t , \dot{u}_t and \ddot{u}_t . This function permits us to choose a completely different behavior for the loudspeaker.

The programming process of implementation of the target behavior consists of following two global steps:

At time step t_n , the microphones measure the pressure named $p(t_n)$. A numerical scheme predicts the target displacement $u_t(t_{n+1})$ and target velocity $\dot{u}_t(t_{n+1})$ of the loudspeaker for the next time step t_{n+1} based on the measured pressure $p(t_n)$ by solving Eq (3).

At time step t_{n+1} , the microphones measure the pressure named $p(t_{n+1})$. The prediction of the target displacement $u_t(t_{n+1})$ and velocity $\dot{u}_t(t_{n+1})$ at the previous time-step is used to estimate the target acceleration $\ddot{u}_t(t_{n+1})$ from Eq (3), based on the pressure $p(t_{n+1})$. Assuming that the when the control is running, $u = u_t$, the current to inject to the coil $i(t_{n+1})$ is calculated via Eq (2), based on $p(t_{n+1})$, $u_t(t_{n+1})$, $\dot{u}_t(t_{n+1})$, and $\ddot{u}_t(t_{n+1})$ as it follows:

$$i(t_{n+1}) = \frac{S_d}{Bl} \left(p(t_{n+1}) - (M_{m0}\ddot{u}_t(t_{n+1}) + R_{m0}\dot{u}_t(t_{n+1}) + K_{m0}u_t(t_{n+1})) \right) \quad (4)$$

For the purpose of a clear explanation, only the novel tasks at each time step have been presented. However, the task of the time step t_n is also done at time step t_{n+1} to prepare the new time step t_{n+2} , and the task of time-step t_{n+1} have been done at time step t_n , using the results of time-step t_{n-1} to calculate the current $i(t_n)$ to be injected at time-step t_n . The complete algorithm is presented Fig (2) One can demonstrate that u tends toward u_t when this control strategy is applied.

This innovative method leads to choosing and digitally programming the dynamics of the loudspeaker by the choice of the Thiele/Small Parameters, but mostly by adoption of the nonlinear function F . To illustrate the control, the experimental work has been done with a well-known nonlinearity $F(u(t)) = K_{mt}\beta_{NL}u^3(t)$ with β_{NL} a parameter that can be chosen to design the NEA.

3 Experimental results

In this section, results are presented for two different experiments. The first one is an open-field experiment, highlighting the modification of the behavior of the

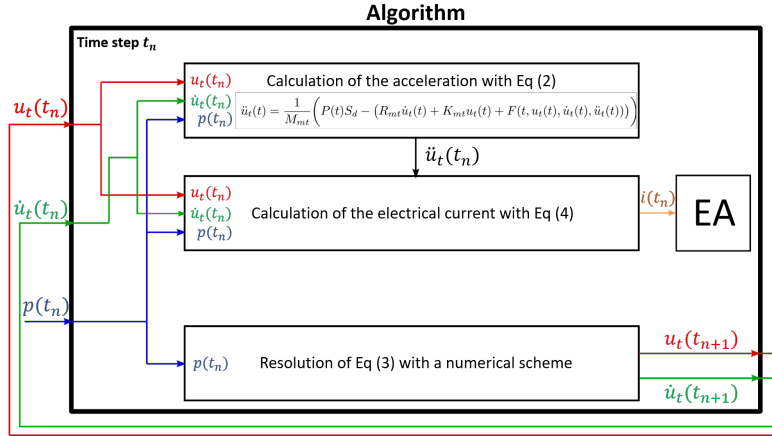


Fig. 2. Bloc diagramm of the control algorithm

loudspeaker for a nonlinear behavior. A comparison is carried out between the loudspeaker without electrical current (Open Circuit), with a linear impedance control ($\beta_{NL} = 0$) and with the nonlinear control. The second experiment weakly couples in normal incidence the loudspeaker to an acoustic tube mode, to illustrate the possible applications of a NEA. A comparison is carried out between a rigid termination of the tube, and the Electroacoustic Absorber with both linear impedance control, and nonlinear control.

The control and the acquisition is performed through a D-Space MicroLaBox DS1202 material, working at a sampling frequency of 50 kHz.

The control is done by the choice of μ_M , μ_R , μ_K and β_{NL} such as $M_{mt} = \mu_M M_{m0}$, $R_{mt} = \mu_R R_{m0}$, and $K_{mt} = \mu_K K_{m0}$. In the case of the study, the Thiele/Small Parameters are $M_{m0} = 3,9 \cdot 10^{-4}$ kg, $R_{m0} = 2,63 \cdot 10^{-1}$ kg.s $^{-1}$, and $K_{m0} = 4,34 \cdot 10^3$ kg.s $^{-2}$

3.1 Open-field experimental results

Let us consider the EA placed in an open field, with a loudspeaker placed towards the EA as an acoustic excitation source. The waves are considered planes. An external Brüel & Kjær microphone is placed at the surface of the loudspeaker, and a Laser Doppler Velocimeter (LDV) is used to retrieve the velocity of the membrane of the loudspeaker. The Thiele/Small Parameters are retrieved by the curvefitting of $Z = p/v$ at the first resonance. The experimental setup is presented Fig (3). A excitation sweep from 100 Hz to 1000 Hz is done in 30 seconds, at an average amplitude of 4 Pa, which corresponds to an acoustic level of 106 dB SPL.

Multiple measures have been done. In Fig (4), the Open Circuit measurement corresponds to the case where the electrical current is equal to 0 : $i(t) = 0$. The Linear Control measurement corresponds to the case where $\mu_K = 1$, $\mu_M = 1$,

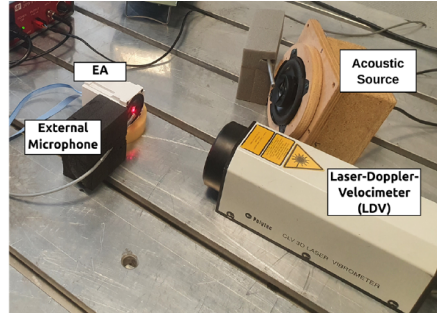


Fig. 3. The Open-field experimental setup

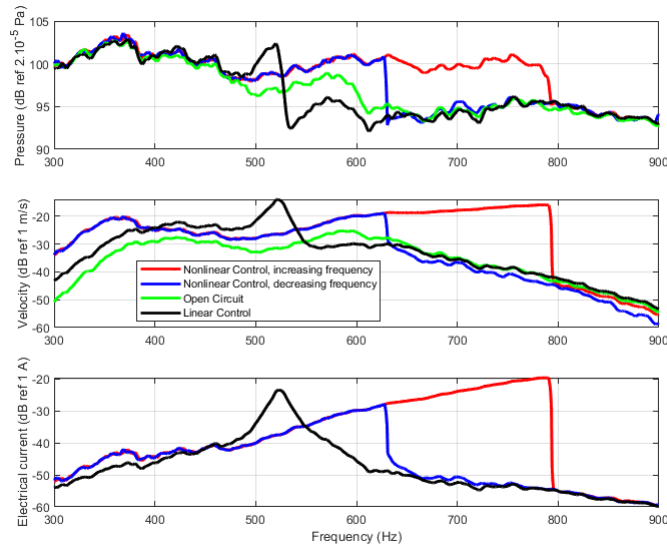


Fig. 4. Experimental results in the form of pressure on the surface of the membrane of the loudspeaker, velocity of the membrane of the loudspeaker and electrical current injected to the loudspeaker coil for sweeping frequency excitation

$\mu_R = 0,125$, and $\beta_{NL} = 0 \text{ m}^{-2}$, meaning that $F = 0$. The Nonlinear Control measurements corresponds to the case where $\mu_K = 1$, $\mu_M = 1$, $\mu_R = 0,125$ and $\beta_{NL} = 10^{11} \text{ m}^{-2}$. For the Nonlinear Control, two measurements are done with different directions of the sweep: with increasing and decreasing frequency. The choice of μ_R has been made to clearly see the effect of the control, and also the nonlinear effects.

From Fig (4), it can be seen that the control works and modifies the behavior of the loudspeaker, as each measurement is different from the Open Circuit

measurement. Moreover, the Linear Control amplifies the first mode of the loudspeaker located at 531 Hz, without shifting it (because of $\mu_R = 0,125$). One can observe jumps in pressure and velocity of the membrane for both of the nonlinear control measurements, probably indicating the presence of unstable zones. The jumps of the nonlinear control with increasing and decreasing frequency happen at two different frequencies, confirming the existence of an unstable zone, and the existence of at least two different equilibrium points between the frequencies of the jump, showing a hardening behavior. The electrical current calculated and injected into the loudspeaker coil for nonlinear control measurements presents the same characteristics and emphasizes the role of the control law. Due to the control law, a nonlinear behavior for the loudspeaker has been shown at moderate excitation levels. Nonlinearities can be created due to this innovative method of implementation for low excitation amplitudes, but the modal damping R_{mt} can be an obstacle to its realisation if it is too high, and plays a major role in the frequency position of the resonance.

3.2 Control of an acoustic mode

The aim is to control an acoustic mode of a tube with the NEA. In order to do so, the experimental setup is composed of a reduced section tube weakly coupled to the NEA placed at the end of a coupling box having a much larger section than the reduced section tube. At the other end a loudspeaker is placed which is coupled to the reduced section tube through a small coupling box, used as an excitation source. The experimental setup is presented Fig (5). The Thiele/Small Parameters have not changed from the previous experience, and the waves can be considered planes in light of the different tube sections up to 2000 Hz. The acoustic mode will be created in the part of the tube with the reduced section under the excitation of the loudspeaker with a sine sweep around its second mode at 680 Hz, from 550 Hz to 800 Hz in 60 seconds, at a maximum pressure of 6 Pa at the resonance. A microphone is placed in this part of the tube to measure the pressure. This system can be seen as a Two Degree of Freedom system composed of a primary system receiving the excitation weakly coupled with an nonlinear absorber. Again, multiple measurements presented in Fig (6) have been realized to compare the efficiency of the non-optimized control of the NEA. The Rigid termination measurement have been realized with a wall instead of the EA position. The Linear Control, similar to a TMD in mechanics, has been tuned on the acoustic mode with the parameters as $\mu_M = 1$, $\mu_R = 0,125$, $\mu_K = 1,7378$ and $\beta_{NL} = 0 \text{ m}^{-2}$. The Nonlinear Control, have been chosen to have the parameters as $\mu_M = 1$, $\mu_R = 0,125$, $\mu_K = 1$ and $\beta_{NL} = 10^{11} \text{ m}^{-2}$, so that the nonlinear mode of the loudspeaker stays around the linear acoustic mode of the tube. Measurements have been done with both increasing and decreasing frequency. The parameter μ_R has been chosen in order to be able to see the effects of the Linear and Nonlinear Controls. About the pressure into the reduced section tube, one can observe that the Linear Control creates the classic two peaks and an anti-resonance between the two peaks, as a TMD in mechanics, compared to

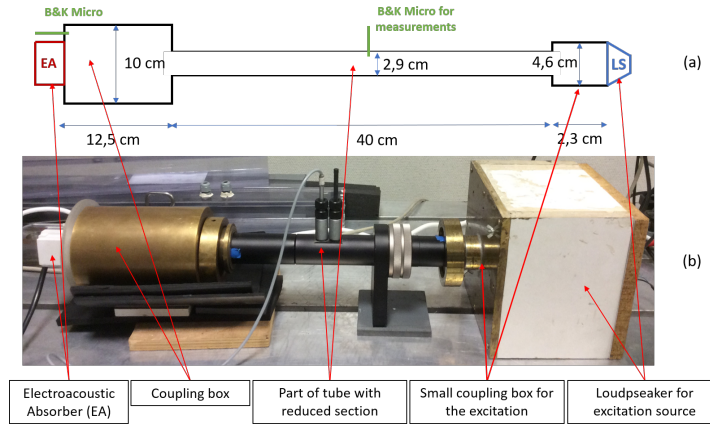


Fig. 5. (a) Schematic description of the experimental setup; (b) Photography of the experimental setup; LS : Loudspeaker, the acoustic source for excitation; EA : Electroacoustic Absorber, that can be replace by a rigid termination

the Rigid Termination measurement. The Nonlinear Control with increasing frequency excitation measurement shows reduction of the noise in the tube, while the two peaks with the anti-resonance vanish for a single peak. These results are similar to the results coming from mechanics studying Nonlinear Energy Sink and Targeted Energy Transfer [16]. Moreover, it can be seen a jump at 762 Hz, indicating an unstable zone. The electrical current jumps at the same time. However, the behavior of the system with the Nonlinear Control with decreasing frequency excitation measurement is almost the same as the one with the Rigid termination, and does not coincide with the increasing frequency measurement. As a result, there are two different equilibrium points at frequencies between 589 Hz and 762 Hz. There is response of the system with a jump down at 589 Hz, where the increasing and decreasing frequencies coincide. Again, the jumps in the electrical current match the frequencies of the unstable zones. It clearly shows a nonlinear behavior of the two degree of freedom system. The explanations of this behavior have not been found yet, but some leads are to be found in a analytical and numerical work. To compare between the differents global acoustic levels that are earned with the control, let us define the norm L_2 of the pressure as : $\|p\|_{L_2} = \sqrt{\int |p(t)|^2 dt}$. The different results for each measurements are :

Type of Control	$\ p\ _{L_2}$
Rigid termination	$5,953.10^3$
Linear Control	$5,8646.10^3$
Nonlinear Control : increasing frequencies	$5,4945.10^3$
Nonlinear Control : decreasing frequencies	$6,0734.10^3$

The results show that the nonlinear control with increasing frequencies is the control with the lower global acoustic level. However, the nonlinear control with decreasing frequencies measurement is worst than the rigid termination measurement in terms of global acoustical level.

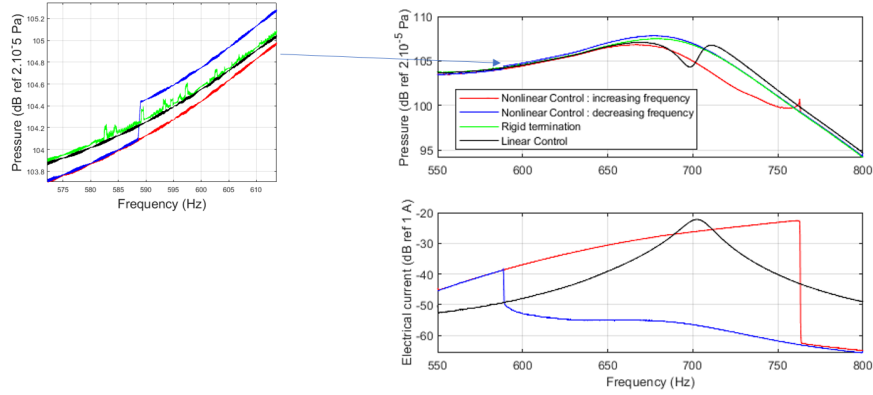


Fig. 6. Experimental results in the form of pressure in the part of the tube with reduced section and electrical current injected to the loudspeaker coil for sweeping frequency excitation

4 Conclusion

Experimental results of an innovative programmed electroacoustic resonator is presented. The Real Time Integration presented method allows to program any behavior wanted into the loudspeaker, for low and moderate acoustic levels. A first experiment illustrates that the control is done in an Open Field, with activation of a nonlinear behavior. A second experiment is performed to show the potential of such a method for reducing noise. A non-optimized implementation allowed to reduce the noise, and to avoid the unwanted effects of a Linear Electroacoustic Absorber. Most of the phenomena explored may be explained with analytical work. However, some experimental facts remain to be explained, probably through analytical and numerical which are perspectives of current paper.

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