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NONLINEAR DIGITALLY CREATED ELECTROACOUSTIC ABSORBER DESIGNED FOR ACOUSTIC ENERGY PUMPING

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ABSTRACT

In the field of acoustics, one can observe nonlinear phenomena when the amplitudes of motion and pressure reach a certain threshold. Nonlinear passive absorbers are usually activated at high amplitudes. In this study, a Nonlinear Electroacoustic Absorber (NEA) is digitally created to control an acoustic mode of a tube at low excitation levels, where the threshold for activation of the nonlinearity is usually not reached with passive nonlinear energy sink devices. The NEA is compared to a linear Electroacoustic Absorber, resembling a Tuned Mass Damper device in mechanics. The NEA is composed of a loudspeaker collocated to microphones and equipped with a processor calculating the current to inject into the loudspeaker coil. The NEA is created thanks to an innovative Real Time Integration method allowing to digitally program any desired behavior for the loudspeaker: linear or nonlinear. Multiple nonlinear behaviors are considered including a duffing type equation. The study highlights the nonlinear phenomena and the advantages of a nonlinear device in sound absorption at low and moderate excitation levels, while being efficient for larger frequency widths than linear devices for both stationary and transient regimes.

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1. INTRODUCTION

Numerous research works have been conducted on the subject of reducing noise and vibrations through the use of passive and active devices and their intermediate categories. Acoustic foams of Helmholtz resonators are commonly used as passive means of noise reduction. However, acoustic foams are not efficient for low frequency noises, under 1kHz [6], and Helmholtz resonators are efficient for a narrow frequency width. Nonlinear devices for reducing noises have not been much developed in acoustic unlike in other fields such as mechanics. This difference is due to the required high amplitudes to activate nonlinear behaviors. Indeed, the required threshold for activation of the nonlinearity is usually beyond the threshold pain for human ears, which is not suitable for common usages. Therefore, Bellet et al. [1] have experimentally implemented a passive visco-elastic membrane behaving as a pure cubic stiffness above 400 Pa. Moreover, Gourdon et al. [7] have placed a Helmholtz resonator in its nonlinear regime above 300 Pa for means of more efficient energy absorption. However, at low frequencies, active devices often propose larger frequency bandwidth and better noise reduction capacities. Active Noise Control (ANC) is now common, but its efficiency is restricted to tight spatial zones, and costs a lot of energy [10]. Olson and May [11] designed the first Electroacoustic Absorber based on Impedance Control, which concept is to differentiates from ANC. An Electroacoustic Absorber is a loudspeaker collocated to microphones and equipped with a processor calculating the current to inject into the loudspeaker coil. The loudspeaker impedance is chosen as optimal to absorb acoustic waves by driving an electric current calculated from the incident pressure wave measured using the microphones [2–4, 9]. This approach is frequency based, so it is not possible to implement nonlinear behavior using the experimental Infinite Input Response method, commonly used. Guo et al. [8] developed a linear impedance control-based device, permitting to add a nonlinear current proportional to the cube of the displacement of the membrane. The displacement is retrieved by the use of an additional microphone in its back cavity, leading to implementation of a NEA at moderate excitation amplitude. In this study, a NEA is created without any additional microphone using an innovative method allowing to digitally program any behavior, and for low excitation amplitudes. This short paper is organized as follows: in section 2, a brief description of the working principle of the programming is presented. In section 3, the experimental setup and experimental evidence are shown. Section 4 is the conclusion of the paper.

2. DIGITALLY PROGRAMMING OF A DESIRED BEHAVIOR

An Electroacoustic Absorber is a loudspeaker collocated to microphones and equipped with a processor. The processor estimates the current to inject into the loudspeaker coil based on the measured pressure. This method permits the loudspeaker to conduct as the imposed behavior. To create a nonlinear behavior, a Real Time Integration method is needed. The classic frequency-based approach can not be used. The two approaches are presented by De Bono in [5].
The goal is to program any behavior thanks to a control law driven by the electrical current. One can consider that the loudspeaker is placed on its first mode and so is modeled as a classic single degree of freedom mass-spring-damper model, with the pressure excitation force, and the Laplace force applied on the loudspeaker as:

$$M_{m0}\ddot{u}(t)+R_{m0}\dot{u}(t)+K_{m0}u(t) = p(t)S_d - Bli(t) \quad (1)$$

with M_{m0}, K_{m0}, R_{m0} the modal mechanical mass, stiffness, and damping when the electrical current is set to 0, u the displacement of the loudspeaker membrane, $\dot{\bullet}$ stands for the derivative of $\bullet$ regarding the time t. p is the pressure on the loudspeaker membrane and S_d the surface of the membrane. B is the constant magnetic field of the coil, l is its length, and i the electrical current injected. The electrical current allows us to change the modal parameters, and also to change the general equation. The equation can be chosen to be as follow :

$$\begin{aligned} &M_{mt}\ddot{u}_t(t) + R_{mt}\dot{u}_t(t) + K_{mt}u_t(t) \\ &+ F(t, u_t(t), \dot{u}_t(t), \ddot{u}_t(t)) = p(t)S_d \end{aligned} \quad (2)$$

with M_{mt}, K_{mt}, R_{mt} the targeted modal mechanical mass, stiffness, and damping that are chosen. The function F and its form are also chosen and can be nonlinear. u_t is the targeted displacement. Knowing $p(t)$ as the measured pressure, one can retrieve u_t, $\dot{u}$ by numerical integration with a numerical scheme as Euler or Range-Kutta at each time step. Once the displacement, speed, and acceleration of the loudspeaker membrane are estimated, the current can be calculated through the Eqn. (3):

$$\begin{aligned} i(t) = \frac{Sd}{Bl}\Big(p(t) - \big(M_{m0}\ddot{u}_t(t) \\ + R_{m0}\dot{u}_t(t) + K_{m0}u_t(t)\big)\Big) \end{aligned} \quad (3)$$

This process, by the introduction of a nonlinear function F, allows to digitally program any desired behavior for the loudspeaker, at any excitation amplitude. Experimental demonstration of obtained nonlinear behavior is shown in the next section for the example of the duffing equation.

3. EXPERIMENTAL RESULTS

3.1 Experimental setup

To demonstrate the nonlinear behavior, the NEA is coupled at normal incidence at the end of a coupling box linked with an enclosed Kundt tube with a reduced section compared to the coupling box section. The first acoustic mode of the tube at $570\ Hz$ is excited by a loudspeaker placed at the other end of the tube. The tube is equipped with a Brüel&Kjaer (B&K) microphone to measure the effects of the NEA on the first excited mode of the tube.
The NEA is composed of a loudspeaker, collocated to a B&K microphone for sensing the pressure. It is alimented by a tension of 10V Amplitude, and the processor for the control of the behavior is made through a D-Space MicroLabBox DS1202 device. The eigen modal parameters are $M_{m0} = 3,9.10^{-4}\ kg$, $R_{m0} = 2,63.10^{-1}\ kg.s^{-1}$, and

$K_{m0} = 4,34.10^3\ kg.s^{-2}$. To demonstrate, a duffing nonlinear function F is chosen:

$$F(u_t) = \beta_{NL} K_{mt} u_t^3 \quad (4)$$

It corresponds to a duffing equation with a hardening behavior. The excitation is a frequency sweep from 350 Hz to 800 Hz at low excitation amplitude, meaning a 0,2 Pa excitation. The sweep is done with increasing frequencies and decreasing frequencies. The results are compared with a rigid termination measure. The experimental setup is shown in Fig 1.

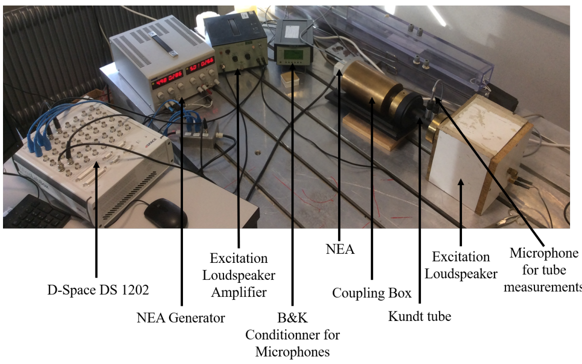

Figure 1. Experimental setup.

3.2 Results

This section introduces the results of the previous experimental setup. Results are presented in Fig. 2 with the parameters $M_{mt} = M_{m0}$, $K_{mt} = K_{m0}$, $R_{mt} = R_{m0}/8$, and $\beta_{NL} = 10^{12}\ m^{-2}$. The Fig. 2a is the variation of the pressure amplitude of the signal pressure for sweeping frequency in the Kundt tube.The Fig. 2b illustrates the variation of the electrical current amplitude for sweeping frequency injected in the loudspeaker coil. The maximum measured pressure in the tube is 0,9 Pa, which is a low amplitude pressure where nonlinear behaviors are not usual. Despite this quite low pressure, one can observe a significant nonlinear behavior. Indeed, the measures with increasing and decreasing frequencies highlight that the electrical current presents two stable equilibrium points for a quite large frequency bandwidth. At each end of this zone, a jump appears. The energy of the acoustic mode of the Kundt tube is reduced in this zone, due to the energy pumping by the NEA that acts as a nonlinear resonator. As a result, when the NEA electrical current returns to low amplitudes, the noise reduction is deleted.it is important to note that the nonlinear behavior starts when the nonlinear threshold is reached. This nonlinear threshold is easily reached thanks to the tunable linear resonance of the loudspeaker placed à 531 Hz, allowing to create nonlinear behaviors at low amplitude excitation. This experience shows that using this innovative method, a nonlinear behavior for the Electroacoustic Absorber can be created at any amplitude excitation.

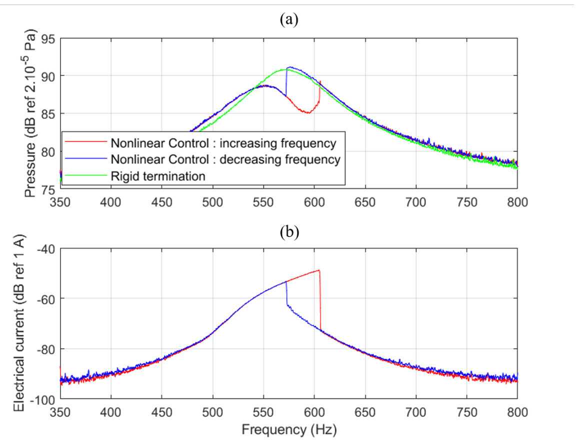

Figure 2. Experimental results of the variation of the pressure amplitude in the Kundt tube (a) and of the variation of the electrical current amplitude injected to the coil (b).

4. DISCUSSION

This innovative method to implement nonlinear behavior at low amplitude excitation is here shown for acoustic noise reduction purposes but can be used in other fields such as mechanics. This method allows to digitally program an actuator with any behavior, linear or nonlinear, and use it in all conditions. It permits bringing the benefits of nonlinear behaviors for noise and vibration reduction at common amplitude levels. This process enables bringing tunable frequencies, larger frequency bandwidth, and amplitude-dependant solutions to common sound pressure levels. It still has to be improved, and other control laws have to be tested and this is the perspective of future papers. Analytical results will be presented during the conference.

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