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

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Abstract

Noise reduction becomes important to raise acoustical comfort and to prevent the population from additional disorders. The Impedance Control concept lies on a loudspeaker collocated to microphones, and equipped of a processor, named as Electroacoustic Absorber. By calculating and injecting the electrical current into the loudspeaker coil based on the sensed pressure, one can be able to provide a desired linear behavior for any loudspeaker. Passive nonlinear systems are efficient for large frequency widths, both in transient and stationary regimes, but usually activated at high excitation amplitudes. As a result, our work focuses on the creation of a Nonlinear Electroacoustic Resonator (NER) at low excitation amplitudes. This work is based on an innovative method, allowing to digitally program any nonlinear desired behavior for all excitation amplitudes. It is a Real Time Integration (RTI) method, where the current is calculated at each time step, based on the measured pressure. To show the advantages of this device, a NER is coupled with an acoustic mode of a tube at normal incidence. Multiples nonlinear behaviors are shown at low excitation amplitudes, and compared with linear control devices. Analytical and Experimental results will be presented and discussed.

1 Introduction

Noise control has been studied for ages, as the Roman Empire used to place Helmholtz resonators into its amphitheaters. This preoccupation becomes of increasing importance with the rise of the sound level subjected to humans and wildlife. The current state of the art permits us to easily reduce sound level above 1 kHz using acoustic foams [2]. The Helmholtz resonator has a high sound absorption for a narrow frequency width around its resonance frequency. An active solution has been developed with the Active Noise Control (ANC) which needs a lot of energy to be efficient, and only works in local spatial zones [5]. Moreover, due to the high amplitudes required to activate nonlinear behavior, nonlinear noise reduction devices have not been widely exploited in the field of acoustics. However, recent research developed nonlinear aspects for acoustic noise reduction as Bellet et al. [1] created a pure cubic stiffness oscillator using a visco-elastic membrane above 400 Pa. Gourdon et al. [3] created a nonlinear Helmholtz resonator above 300 Pa. These devices are not usable at a hearing amplitude. As a result, Guo et al. [4] created a semi-active device based on the linear impedance control, added to a nonlinear current proportional to the cubic displacement of the membrane enabled by an additional microphone in the back cavity of the loudspeaker at quite a low excitation amplitude. However, the nonlinear phenomena were limited. This study aims at creating highly nonlinear resonators at low sound level to benefit from the nonlinear phenomena.

2 Digitally programmable Electroacoustic Resonator

The goal is to create a Digitally programmable Electroacoustic Resonator, either linear or nonlinear. This Electroacoustic Resonator is composed of a loudspeaker collocated to sensors, and connected to a processor running a specific algorithm. Supposing the loudspeaker is placed on its first mode, the algorithm takes as an input the measured pressure coming from the microphones, and gives as an output the electrical current to send into the loudspeaker. This electrical current controls the loudspeaker behavior, becoming the desired behavior modeled Eq (1):

$$M_{mt}\ddot{u}_t(t) + R_{mt}\dot{u}_t(t) + K_{mt}u_t(t) + F(t, u_t(t), \dot{u}_t(t), \ddot{u}_t(t)) = p(t)S_d \quad (1)$$

with M_{mt}, K_{mt}, R_{mt} the targeted modal mechanical mass, stiffness, and damping that are chosen in the programming. The function F and its form are also chosen and can be nonlinear. u_t is the targeted displacement of the membrane, S_d the effective surface of the membrane, p the incoming pressure on the membrane.
So it is a pressure-based current-driven control of the loudspeaker. This programming is done using two elemental tasks, implemented through a Real-Time Based approach, as the frequency-based approach is not usable for targeting nonlinear behaviors. The first task consists of the prediction of the displacement, speed, and acceleration of the membrane of the loudspeaker. Once this step is done, the calculation of the electrical current can be done using the modelisation of the loudspeaker Dynamics presented Eq (2):

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

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, and Bl the Laplace factor of the Laplace force of the loudspeaker.

3 Experimental results

To demonstrate the process here explained, the NER is coupled to a reduced section tube excited by an additional loudspeaker around its first mode through a coupling box. The coupling is weak and the experiment is similar to the experimental setup of [3]. As a result, the system is a two-degree of freedom system composed of the acoustic mode of the tube, and of the NER. The pressure of the reduced section tube is measured using a Bruel&Kjaer microphone. The programming of the loudspeaker is done using a dSPACE MicroLabBox DS1202. The detailed experience is presented Fig 1.
The acoustic mode of the tube is excited through a slow sweep from 350Hz to 800Hz with either increasing

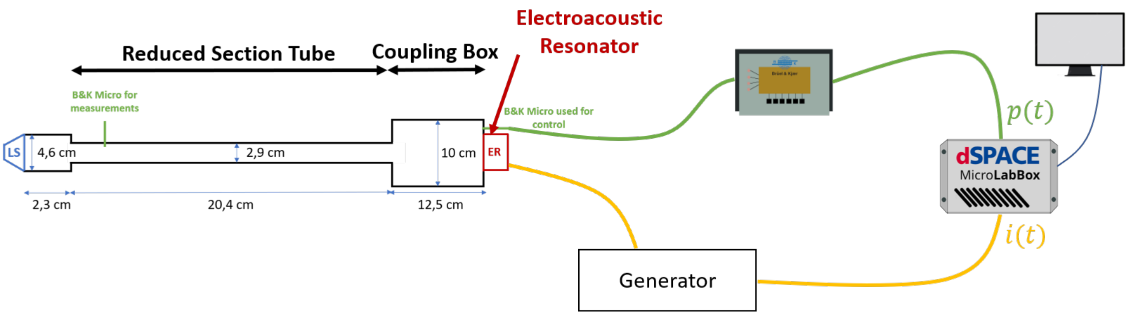

Figure 1: Schema of the experiment

or decreasing frequencies. The function F is chosen as a cubic stiffness with either a hardening or softening behavior:

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

The measured pressure in the reduced tube Fig 2a and the electrical current calculated by the processor Fig 2b are plotted below. The electrical current shows two different behaviors. The hardening behavior corresponding to the duffing type behavior with $F(u_t) = +\beta_{NL}K_{mt}u_t^3$ is shown with the shift of the resonance peak towards higher frequencies. A jump can also be seen. The softening behavior corresponds to the behavior with $F(u_t) = -\beta_{NL}K_{mt}u_t^3$, where the resonance peak is shifted towards lower frequencies, with a decreasing jump as expected. The measured pressure shows the behavior of the primary system when coupled. A significant noise reduction can be seen, at the frequencies of the nonlinear resonance of the NER. The noise reduction is no longer effective when the NER jumps from its state of high amplitudes due to the resonance to a lower equilibrium point.

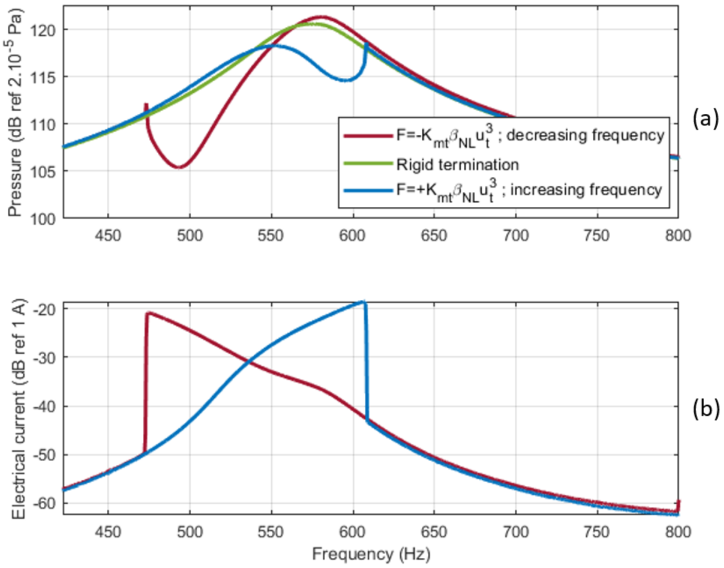

Figure 2: Experimental results of the variation of the pressure amplitude in the Kundt tube (a) and of the variation of the electrical current amplitude injected to the coil (b).

4 Conclusion

A digitally programmable Nonlinear Electroacoustic Resonator is created, and the behavior can be chosen as it is shown by the choice of the hardening or softening behavior here. Other programmable laws than the duffing type can be chosen like piecewise, or square programming. It would be also interesting to optimize the behavior by the choice of the target parameters to obtain better noise reduction.

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