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IMPROVING SOUND ABSORPTION THROUGH NONLINEAR ACTIVE ELECTROACOUSTIC RESONATORS

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ABSTRACT

Absorbing airborne noise at frequencies below 300 Hz is a particularly vexing problem due to the absence of natural sound absorbing materials at these frequencies. The prevailing solution for low-frequency sound absorption is the use of passive narrow-band resonators, whose absorption level and bandwidth can be further enhanced using nonlinear effects. However, these effects are typically triggered at high intensity levels, without much control over the form of the nonlinear absorption mechanism. In our recent study [1], we propose, implement, and demonstrate a nonlinear active control framework on an electroacoustic resonator prototype, allowing for unprecedented control over the form of non-linearity, and arbitrarily low sound intensity thresholds. Taking the cubic nonlinearity as an example, we show numerically and experimentally that in the low frequency range ([50 Hz, 500 Hz]), the nonlinear control law allows improving the sound absorption performance, i.e. enlarging the bandwidth of optimal sound absorption while increasing the maximal absorption coefficient value, and producing only a negligible amount of nonlinear distortion. The reported experimental methodology can be extended to implement various types of hybrid linear and/or nonlinear controls, thus opening new avenues for managing wave nonlinearity and achieving non-trivial wave phenomena.

1. ACTIVE CONTROL ON ELECTROACOUSTIC RESONATOR

In the low frequency range and under weak excitation, an electrodynamic loudspeaker behaves as a linear SDOF Electroacoustic Resonator (ER). In the present work, we consider a loudspeaker mounted in an enclosure of volume V_b . Denoting $p_f(t)$, $\xi(t)$ and $i(t)$, the applied front acoustic pressure, the diaphragm displacement and the current circulating in the moving coil, the Newton's second law, applied to the loudspeaker diaphragm, reads:

$$M_{ms} \frac{d^2 \xi(t)}{dt^2} = p_f(t) S_d - R_{ms} \frac{d\xi(t)}{dt} - \frac{1}{C_{mc}} \xi(t) - Bl i(t). \quad (1)$$

where M_{ms} , R_{ms} and C_{mc} designate the mass, the mechanical resistance and the overall compliance including the fluid compressibility introduced by the rear pressure p_b . And S_d and Bl denote the effective area of the loudspeaker diaphragm and force factor of the moving-coil transducer.

The objective of active control is to identify the transfer function from the input acoustic quantities to the output current $i(t)$ that is sent back to the loudspeaker. In the current work, the combination of linear and nonlinear control laws is considered. Thus, the feedback current $i(t)$ will be composed of a first part denoted as $i_L(t)$ resulting from linear impedance control, and a second part denoted as i_{NL} introduced through nonlinear active control:

$$i(t) = i_L(t) + i_{NL}(t) \quad (2)$$

For the linear impedance control, it is achieved by sensing the front pressure $p_f(t)$ of the ER, the feedforward current $i_L(t)$ is defined through the transfer function in the Laplace domain (with variable s) as

$$\Phi(s) = \frac{\mathcal{L}(p_f(t))}{\mathcal{L}(i_L(t))} = \frac{Z_{st}(s)S_d - Z_{as}S_d}{BlZ_{st}(s)} \quad (3)$$

with the target impedance related to SDOF resonator as $Z_{st}(s) = \mu_1 M_{as}s + R_{st} + \mu_2/C_{ac}s$.

Thanks to the proportionality between the rear pressure p_b and the displacement ξ in the low frequency range, the cubic nonlinear control law becomes feasible when defining the current i_{NL} as a function of nonlinear transformation of p_b :

$$i_{NL}(t) = G_{ui} \times \beta_{NL} \times (G_{mic} p_b(t))^3 \propto \xi^3(t) \quad (4)$$

where β_{NL} denotes the tunable nonlinear parameter, G_{mic} and G_{ui} are the sensibility of the microphone and the gain that converts the voltage into current respectively.

2. ESTIMATION OF SOUND ABSORPTION COEFFICIENT

In the current work, we are interested in the sound absorption performance of the controlled loudspeaker. The cho-

sen metric of interest is the sound absorption coefficient, which can be determined by sensing both the front pressure and the membrane axial velocity. When the nonlinear Active ER (AER) is achieved with control, the energy transfer from fundamental frequency ω to higher harmonics ($n\omega$ with $n \geq 2$) should be additionally taken into account, thus the following generalized definition of the absorption coefficient is considered:

$$\alpha_{NL} = 1 - \sum_{n=1}^{n=N} |R_n|^2, \quad (5)$$

where R_n represents the complex pressure amplitude of the generated n -th harmonic normalized by that of the fundamental incoming wave.

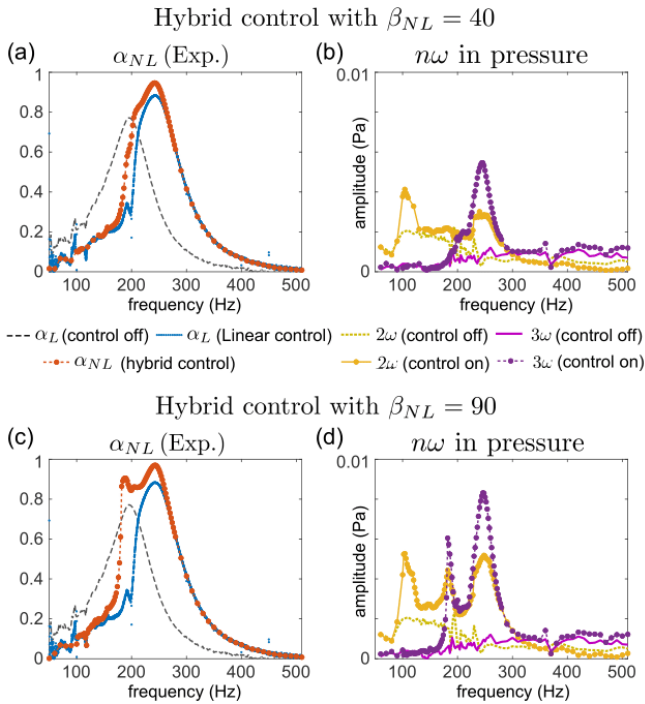


Figure 1. Absorption curves (with α_{NL} defined by Eq. (5)) of the achieved nonlinear AER (red dash-dotted lines) under a hybrid control with $\mu_1 = 1$, $\mu_2 = 1.5$, $R_{st} = 0.5Z_c$ and $\beta_{NL} = 40$ (a) or $\beta_{NL} = 90$ (c) respectively. Absorption results achieved with both cases of control off (black dashed lines) and of pure linear control (blue dotted lines) are shown as well for comparison. For a better demonstration, pressure amplitudes of the generated second and third harmonics are illustrated in (b) and (d) for the two considered hybrid control cases in parallel with absorption curves respectively. Sine excitations are performed at each sampled frequency with fixed level to deliver the same incident pressures in front of the AER.

Fig. 1 and Fig. 2 show some of the results on absorption performance of the achieved AERs, with fixed incident pressure amplitude as weak as 1.1 Pa. The proposed nonlinear control scheme enables the nonlinear effect to be triggered by simply adjusting the control parameter β_{NL} , instead of the conventional way of increasing the excitation

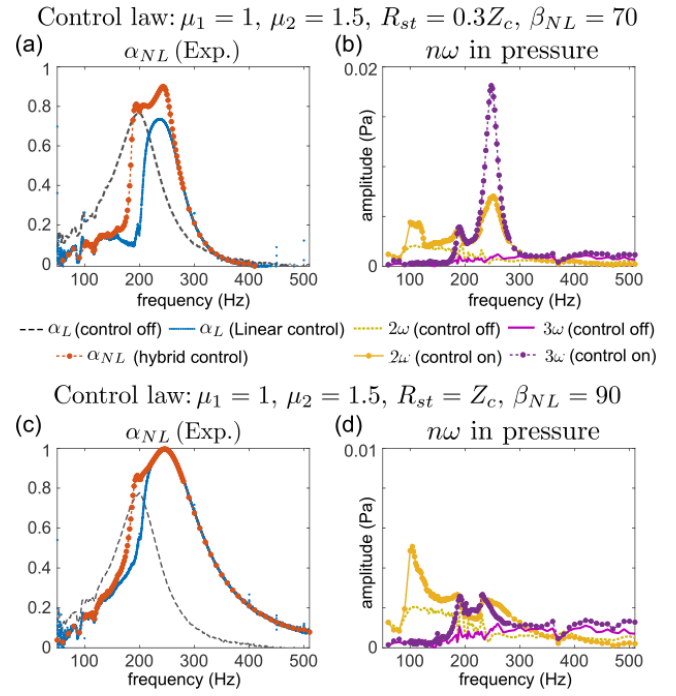


Figure 2. Absorption curves of the achieved nonlinear AER under different hybrid controls with linear design parameters defined as $\mu_1 = 1$, $\mu_2 = 1.5$, and with linear target resistance being $R_{st} = 0.3Z_c$ (a) and $R_{st} = Z_c$ (c) respectively. Nonlinear part of control is applied with achievable value of nonlinear parameter set as $\beta_{NL} = 70$ and $\beta_{NL} = 90$ respectively. For both control configurations, pressure amplitudes of second and third harmonics are illustrated in (b) and (d) in parallel with the corresponding absorption curves (a) and (c) for the two control cases respectively. Pure linear control results with $\beta_{NL} = 0$ (black dashed line) and the control off case (blue dotted lines) are also presented for the comparison with hybrid control result.

level. Moreover, comparing to the linear impedance control, the combination of linear and nonlinear control laws shows great advantages in enlarging the bandwidth of optimal sound absorption while increasing the maximal absorption coefficient value. Whereas the generated higher harmonics remain to be negligible, with maximum pressure amplitude in the range of 0.01 Pa. More details about the experimental methodology in use as well as the results of pure nonlinear control case and of other hybrid control (linear+nonlinear) cases are described in [1]. In fact, our developed active control approach allows the transfer from any detectable acoustic quantities to the feedback current, thus offering opportunity to achieve a variety of linear and nonlinear control laws which should be further explored.

3. REFERENCES

- [1] X. Guo, H. Lissek, and R. Fleury, "Improving sound absorption through nonlinear active electroacoustic resonators," *Phys. Rev. Applied*, vol. 13, p. 014018, Jan 2020.