On the use of slow sound to time delay a pulse

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Abstract
Periodic structures composed of quarter-wavelength or Helmholtz resonators have been widely used in the design of acoustic metamaterials, mainly to achieve negative compressibility or slow sound. The latter phenomenon results from the strong dispersion produced by the local resonances and gives rise to many applications such as deep sub-wavelength sound absorbers or metadiffusers. All the applications proposed so far are analyzed only in the frequency domain (steady state). In this work, we propose a passive and reconfigurable treatment that can be used in room acoustics. The concept consists in creating a delay line from reconfigurable resonators, thanks to the slow sound propagation. In doing so, we can time delay a pulse and therefore can reproduce the audio sensation of a propagation over a larger distance than the real size of the treatment. The limitations of real-time pulse propagation, dispersion, and losses on the audio fidelity are discussed.

Keywords: Acoustic metasurface, Delay-line, Helmholtz resonators, Slow sound.

1 Introduction

The phenomenon of slow sound, brought to light with the development of acoustic metamaterials, has been widely used for both the design of subwavelength sound absorbers [1, 2, 3] or subwavelength diffusers [4, 5, 6]. Despite all this research based on slow sound, the temporal propagation of a pulse inside such slow-sound metamaterials have not been thoroughly studied.

In this work, we propose to analytically investigate and numerically study, a delay line device for time-delaying a pulse. We first present the concept behind this work and study the influence of the geometry on the effective and scattering properties of the system. We then discuss the challenge of temporal propagation in such metamaterials and explain the design strategy employed. Finally, we show numerical simulation and experimental results of our delay line for three different delay configurations.

2 Results and discussions

The philosophy of this work is to propose a device to be placed on the walls of a room, allowing to give a sound sensation of a room larger than it really is, as sketched in Fig. 1. In other words, we seek to control the phase ϕ_R of the reflection coefficient R, and thus to be able to tune the apparent group delay τ_g

$$\tau_g(\omega) = -\frac{\mathrm{d}}{\mathrm{d}\omega}\phi_R(\omega), \tag{1}$$

with ω being the angular frequency. For the metasurface to propagate the pulse without distorting it significantly, it must have a near-constant group delay, i.e., a near-linear phase, over the bandwidth of the pulse.

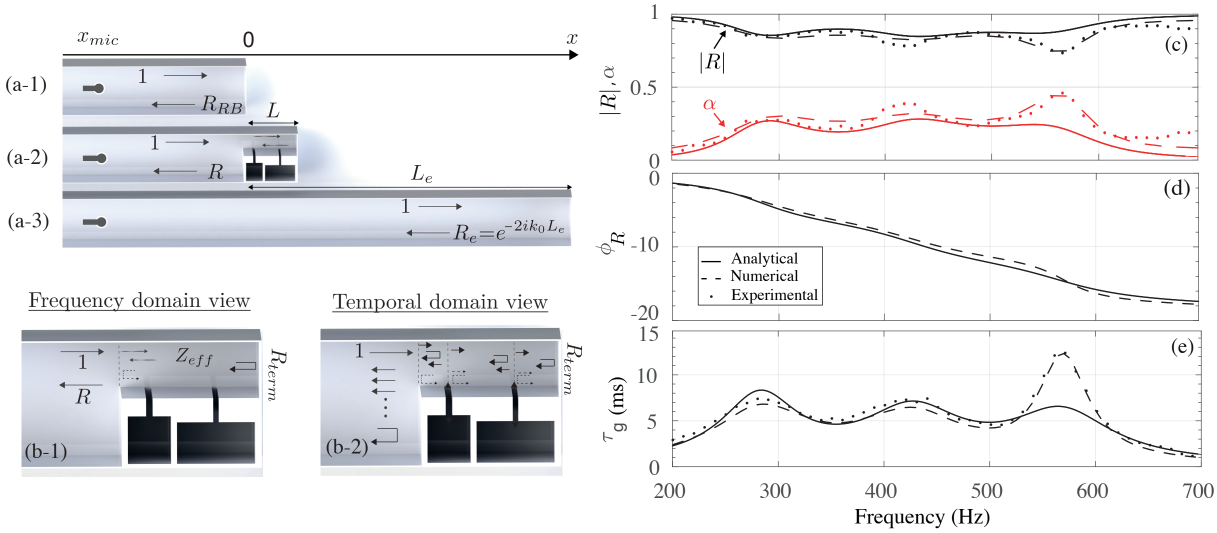

Figure 1: Schematics of the situation under study. (a-b) Schematics of the different configurations measured in a square cross-section impedance tube of width w_{ex}, in which a plane wave is impinging from the left and is reflected on a rigid wall: (a-1) configuration without the metadevice, i.e., empty tube, (a-2) configuration with the metamaterial of length L placed at the end of the rigidly backed tube, and (a-3) target configuration to be reproduced with the metamaterial. (b) Differences between the permanent/frequency regime view and the temporal propagation view. (c-e) Steady state scattering properties of the metasurface reproducing a 1 m propagating distance:(c) reflection and absorption magnitude (red and black respectively), (d) phase of the reflection coefficient, and (e) group delay.

We consider here a metasurface composed of 2 different Helmholtz resonators in series mounted in parallel to a slit opened to the room and backed by a rigid wall as sketched in Fig. 1(a-b) and the dimensions of which are given in Tab. 1. The metasurface is placed in an 149 mm square impedance tube.

Table 1: Dimensions of the metasurface for the different configurations considered.

Configurations	w_{ex}	h	w_{c1}	L_{c1}	w_{n1}	L_{n1}	a_1	w_{c2}	L_{c2}	w_{n2}	L_{n2}	a_2
Config.1 - L_e = 1 m	149	65.8	51.3	56.7	7.8	57	92.7	49.5	28.7	6.6	28.7	102.9
Config. 2 - L_e = 0.75 m	149	65.8	31.3	56.7	7.8	37	56.6	49.5	28.7	6.6	28.7	66.8
Config. 3 - L_e = 0.6 m	149	65.8	21.6	56.7	7.8	27.3	38.9	49.5	28.7	6.6	28.7	49.1

The strong dispersion produced in the slit above the resonators allows to carefully control the real and imaginary parts of the wave number $k(\omega)$, and thus the group velocity $c_g = \mathrm{d}\omega/\mathrm{dRe}\{k(\omega)\}$ and the dissipation ($\propto \mathrm{Im}(\omega)\}$).

The phase of the metasurface reflection coefficient is plotted with the group delay in Fig. 1 (d-e). Each resonator gives rise to a -2π phase jump and a group delay peak at frequencies related to their resonance frequency. A third peak due to a Fabry-Perot mode in the slit is also visible. Please note that, although the group delay can be easily controlled by changing the geometry, special attention must be paid to the dissipation in the resonators (high near resonance). A compromise must therefore be found to reproduce both the right amount of loss and the delay of a propagation over the target length.

While effective properties and total reflectance are a good way to model and design steady-state structures (as is commonly done for metamaterials and metasurfaces), they are not suitable for the time domain, as they do not account for the transient first-reflections. With a frequency-domain view, i.e., steady-state conditions, one can easily control the effective impedance and total reflection to impose both an impedance matching condition and a target group delay over a given frequency range. Impedance matching ensures that the entire incident

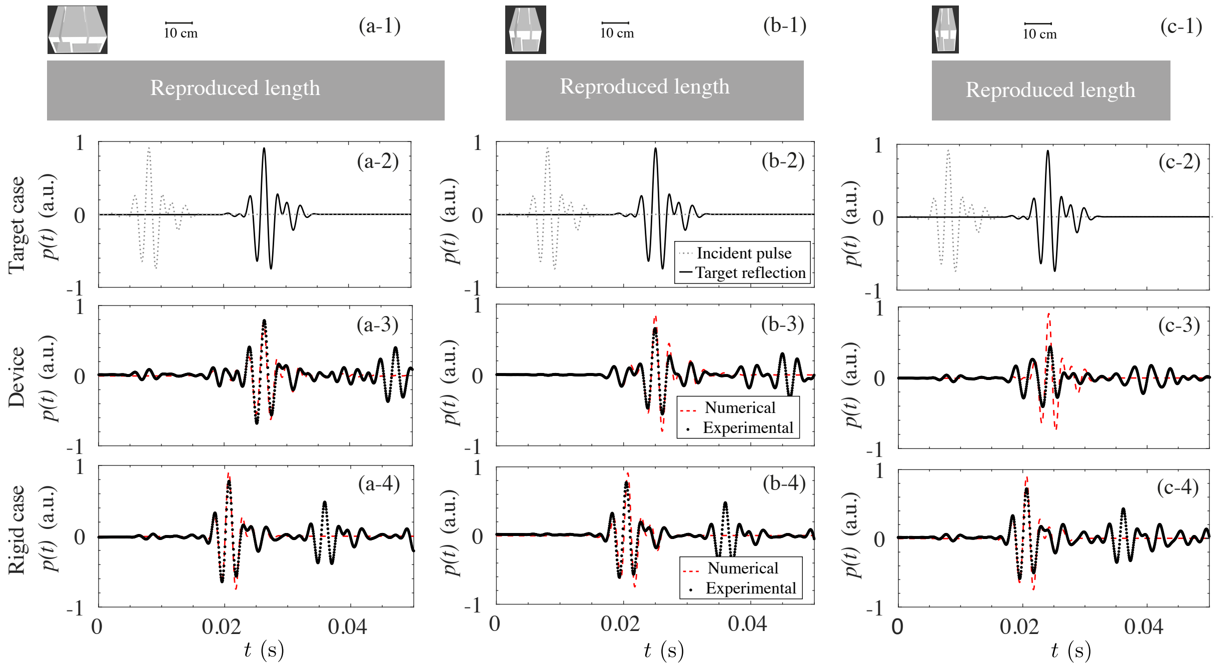

Figure 2: [Color online] Metasurface delayed pulse for the 3 configurations considered: L_e = 1 m (a), 0.75 m (b), and 0.6 m (c).
(-1) steady state group delay, (-2) incident and target pulse (analytical), (-3) measured and simulated pulse delayed by the metasurface, and (-4) measured and simulated pulse reflected off a rigid wall (without metasurface). The red dashed lines and black dots represent the full-wave simulation and experimental results, respectively. The solid black lines represent the analytical target, and the thin black dotted lines the incident pulse.

wave will be transmitted into the slit, propagate with a low group velocity, be reflected by the rigid wall, and propagate back, i.e., be effectively delayed due to the slow sound, as sketched in Fig. 1 (b-1). On the other hand, the treatment of the time domain requires consideration of the reflection at each interface. In particular, the mere presence of a cross-sectional change at $x = 0$ generates a direct first reflection that cannot be delayed in time, because the reflected energy does not penetrate the metasurface.

The design strategy adopted is therefore to optimize the geometry directly with a time-propagating pulse, and to use destructive interference to minimize unwanted reflections (direct reflection at $x = 0$ and coda) and maximize desired reflections to preserve the shape of the delayed pulse.

To reproduce the propagation of the $g(t)$ pulse over a length L_e with our device, we optimize the geometry of its resonators by minimizing the target delayed pulse IFT $\left[\mathrm{FT}\,(g(t))\, e^{-2ik_0 L_e}\right]$ and the propagated pulse in the metasurface, modeled by its total reflection coefficient calculated by TMM, that is, IFT $[\mathrm{FT}\,(g(t))\, R_{\mathrm{TMM}}]$. The considered pulse consists of a combination of two cosine modulated Gaussian pulses with frequencies of 350 Hz and 500 Hz.

Figure 1(c-e) illustrates the steady-state scattering properties of the optimized metasurface reproducing a distance of 1 m and the corresponding group delay. The TMM modeling is numerically validated with a full-wave 3D model using the viscothermal module of COMSOL Multiphysics software. A fine mesh is required for the boundary layers of all rigid walls (cavity, neck, slit) to take into account with good accuracy the viscothermal losses in the device. An experimental validation is also performed. The agreement between the analytical (solid), numerical (dotted line) and experimental (points) results is very good, validating our analytical modeling used for the optimization process.

Figure 2(a-3) shows the numerically simulated and experimentally measured outgoing wave from the device. As expected (see Fig. 2(a-2)), the pulse is effectively delayed by 5.8 ms, which corresponds to the targeted propagation for a distance of 1 m (round trip) (compared to the case without a metasurface, i.e., with a rigid support at $x = 0$, shown in Fig. 2(a-4)). The slight discrepancies visible at the beginning and end of the pulse are due to several unavoidable constraints: the metasurface remains dispersive (albeit weakly), the destructive interferences do not totally cancel the unwanted first reflections and coda.

Finally, starting from the optimized geometry of the 1 m configuration, we then modify the geometry to reproduce two other propagation distances $L_e = 0.75$ m and $L_e = 0.6$ m, changing only the cavity widths w_c by a factor of 0.611 and 0.42 respectively, i.e., see Figs. 2(b-c). In each case, the optimal geometry delays the pulse by the correct delay, $\tau_g = 4.4$ ms and 3.5 ms respectively. Although the pulse is distorted more significantly when we linearly reduce the geometry from the first configuration, i.e., higher HR resonance frequencies, the shape and location of the pulse matches the target values. The experiments are obtained from rigid samples, but this design procedure allows for the design of reconfigurable devices, which can, depending on their configuration, reproduce the audio sensation of propagation over different distances.

3 Conclusions

In this work, we have analytically designed, and numerically and experimentally proven the effectiveness of a delay line metasurface to reproduce the propagation of a pulse over a given distance. Instead of using steady-state computation and effective medium theory, as is usually done for metamaterials and metasurfaces, we here directly optimize our geometry in the time domain, thus taking into account early reflections and coda. We show that from an initial configuration, we were able to reproduce two others, with different propagation distances, simply by changing linearly the geometry of the resonators.

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