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ON-DEMAND NOISE MITIGATION WITH TIME-MODULATED ACTIVE ACOUSTIC METAMATERIALS

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ABSTRACT

It is generally accepted that active metamaterials could, in principle, address long-standing challenges in noise mitigation. However, the research of active structures capable to meet these challenges has been slow due to issues of stability and scalability. This work shows that 2D active metamaterials composed of arrangements of sensor-driver pairs can be configured to be excellent sound absorbers very well matched to the background fluid and thus scatter-free. The property is achieved by programming the metamaterial effective mass density and bulk modulus to be complex numbers with matching phases. Moreover, the metamaterials can be switched from being opaque absorbers to transparent media on very small time scales by time-modulating their effective material properties without adverse effects such as ensuing instability. Furthermore, the metamaterial unit cells are completely independent of each other thus promoting scalability.

Keywords: *active acoustic metamaterial, noise control, time modulation, programmable metamaterial*

1. INTRODUCTION

Noise has long been correlated with an increased incidence in cardiovascular diseases [1] making noise mitigation an important area of research. Numerous passive absorbers have been proposed but they tend to be either ineffective, too bulky, narrow band, or scatter sound instead of dissipating it [2, 3]. It has been proposed that metamaterials can advance this strategically important field due to their increased degrees of freedom on sound manipulation. Passive metamaterials have been tried first, but they suffered from the same limitations as conventional passive sound dissipation methods [4]. It was soon realized that active metamaterials can overcome these limitations [5]. A particularly promising active metamaterial architecture consists of arrangements of sensor-driver pairs realizing effective acoustic properties dictated by the chosen transfer function (or gain) between each pair of sensors and drivers [6–8]. These gains are typically set in electronic circuits programmable in real time [9–13]. The advantages of this approach are its scalability promoted by the independence of the sensor-driver pairs (i.e., there is no connection between different pairs) and very low response time and thus broadband operation stemming from the gains being computed apriori for a desired functionality [14] and not adaptively as in conventional controls-based systems [3]. It has recently been shown that active metamaterials composed of sensor-driver pairs achieve very large sound dissipation with minimal scattering [13]. However, the effect has been studied in the steady state regime in which the effective properties of the metamaterial are fixed. Whether switching these properties on-demand can be done in a stable manner is unknown.

Here we show experimentally that active metamaterials following the sensor-driver architecture can be switched instantaneously from scatter-free opaque absorbers to transparent media without adverse effects. To act as a sound absorber, the fabricated metamaterial is designed to mimic the acoustic behavior of a continuous medium with bulk modulus and mass density having complex values with matching phases. We show that these effective properties can be time modulated to switch from

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complex to real quantities matching the properties of air on very short time scales thus realizing the remarkable transition from absorber to transparent medium.

2. ACTIVE METAMATERIAL DESIGN

The goal of this work is to realize a time-modulated 2D active acoustic absorbing medium that does not scatter impinging sound. The medium is represented by the red box placed in the air-filled acoustic waveguide shown in Fig. 1a and composed of two parallel plates driven at the fundamental mode by an external speaker placed on the side of the waveguide. The air has bulk modulus B_0, mass density ρ_0, speed of sound c_0 and characteristic impedance Z_0.

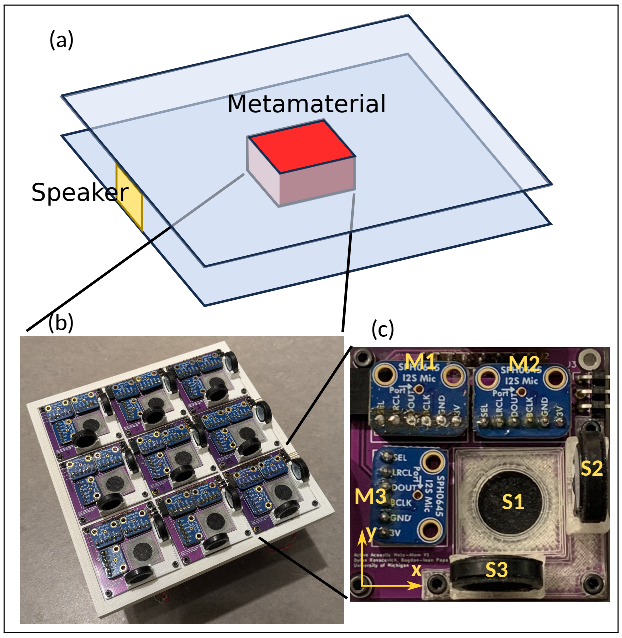

Figure 1. (a) Schematic of the experimental setup showing a homogeneous fluid of bulk modulus B and mass density ρ placed in a 2D waveguide and ensonified by an external speaker. (b) Active metamaterial programmed to realize the B and ρ of the desired fluid. (c) Photo of unit cell showing the labeled microphones Mi and speakers Si, where $i = \overline{1,3}$.

The medium is a very good absorber matched with the background as long as its bulk modulus B and mass density ρ are complex quantities having the following expressions.

$$B = B_0 e^{j\phi}, \quad \rho = \rho_0 e^{-j\phi}, \tag{1}$$

where ϕ is a real phase. Under these conditions, the characteristic impedance of the metamaterial matches that of air ($Z = \sqrt{B\rho} = Z_0$) and the speed of sound inside the metamaterial is complex ($c = \sqrt{B/\rho} = c_0 e^{j\phi}$). High absorption is achieved when the imaginary part of c is large.

This continuous medium is realized with an active metamaterial composed of the 3 by 3 arrangement of active cells illustrated in Fig. 1b. The metamaterial is under a good approximation flat, protruding very little inside the waveguide and thus it is not impeding the flow of air. Consequently, in its off state, the metamaterial has the effective properties of air.

It has been shown that active cells composed of multiple sensor-driver pairs can fully program the effective bulk modulus, mass density tensor, and two Willis coupling vectors depending on the nature of the sensor and driver in each pair [5, 13]. In particular, the bulk modulus is controlled by a monopole sensor capturing the local pressure p and driving a monopole driver whose amplitude is proportional to p. Similarly, each component $\rho_{\alpha\beta}$ of the mass density tensor ($\alpha, \beta \in \{x, y\}$ in 2D) is controlled by a dipole sensor capturing the local particle velocity u_α and driving a particle velocity source parallel to direction β with amplitude proportional to u_α.

Figure 1c shows a 2D metamaterial cell realizing three sensor-driver pairs to control the bulk modulus and all components of the mass density tensor. In this approach, the pressure and particle velocity components are obtained with three microphones Mi sensing the acoustic pressures $p_{\mathrm{M}i}$ and driving the three speakers Si, where $i = \overline{1,3}$. One speaker is horizontal, acting as a monopole pressure source, and two speakers are vertical, acting as dipole sources in the x and y directions. The sensed monopole and dipole quantities p, u_x, and u_y as well as the amplitude of the sound generated by these speakers $A^{\mathrm{S}i}$ are shown in Table 1. The proportionality terms between the sensed and driven quantities (g^m, g_x^{dx}, g_y^{dx}, g_y^{dy}, and g_x^{dy}) are set by a Teensy 4 microcontroller connecting the microphones and speakers of each cell.

Closed-form expressions relating these gain terms to the desired effective material properties B and ρ given by Eqn. (1) are derived elsewhere [13, 14] and implemented in the microcontroller.

In its active state the metamaterial is programmed to have B and ρ given by Eqn. (1), where $\phi = 30°$. As we

Table 1. Driven versus sensed quantities.

Sensed	Driven
$p = \frac{p_{M1}+p_{M2}+p_{M3}}{3}$	$A^{S1} = g^m p$
$u_x = -\frac{\int (p_{M1}-p_{M2})dt}{\rho_0 d}$	$A^{S2} = g_x^{dx} u_x + g_y^{dx} u_y$
$u_y = -\frac{\int (p_{M3}-p_{M1})dt}{\rho_0 d}$	$A^{S3} = g_x^{dy} u_y + g_y^{dy} u_x$

will see in the next section, this phase produces a very large absorption. The microcontroller in each cell can reduce the gains g shown in Table 1 to zero essentially instantaneously.

3. RESULTS

The metamaterial is ensonified by a speaker at 1200 Hz. We programed the metamaterial to switch from the opaque, high absorption state ($\phi = 30°$) to the transparent state ($\phi = 0°$) and back every 1.67 ms, i.e. two acoustic periods at 1200 Hz. Figure 2 shows the time domain acoustic pressure fields measured inside and outside the metamaterial at two time instances separated by 1.67 ms with and without the metamaterial inside the waveguide.

The external speaker excites cylindrical waves in the empty waveguide (Fig. 2 top). The two time instances illustrated in the figure are chosen approximately two acoustic periods apart and thus the two measured acoustic pressure distributions are essentially the same.

The bottom panels represent the acoustic fields measured in the waveguide with the metamaterial inside. The black squares in the figure represent the position of the metamaterial. The same two instances separated by two acoustic periods shows the metamaterial behavior $\phi = 30°$ (absorber state) and $\phi = 0°$ (transparent state), respectively.

In the absorber configuration, the metamaterial dissipates almost all the incident energy as indicated by the very low amplitude pressure inside the structure and behind it (the shadow region). In all other directions, the acoustic pressure looks essentially the same as that measured in the empty waveguide at the same time instant, which confirms the metamaterial's expected scatter-free behavior.

In its transparent state, the metamaterial behaves essentially as air, i.e., the measured fields look like those measured in the empty waveguide, confirming that the effective B and ρ match those of air.

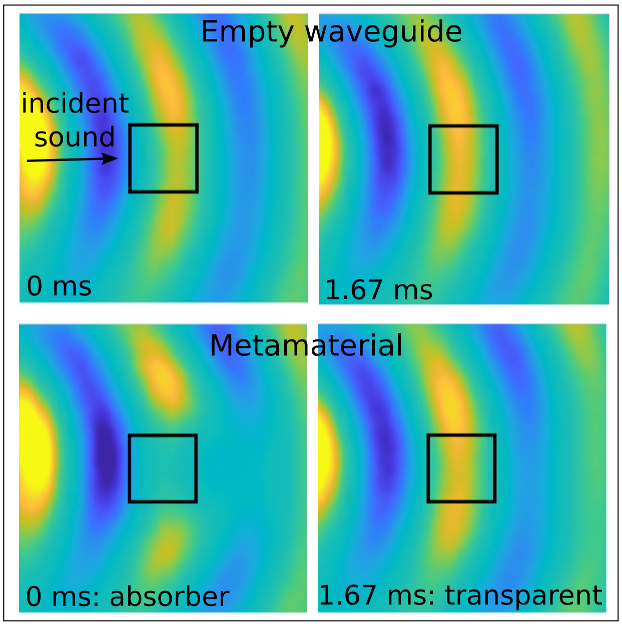

Figure 2. Time domain acoustic pressure measured in the empty waveguide (top) and with the time-modulated programmable metamaterial (bottom). The right pressure fields (transparent state) were measured 1.67 ms later than the left fields (absorber state), i.e. half the modulation period.

4. CONCLUSIONS

This work shows that active metamaterials with carefully tailored effective bulk modulus and mass density behave as highly effective, compact sound absorbers. The metamaterial demonstrated here is composed of independent unit cells composed of sensor-driver pairs that promote scalability, i.e., adding more cells increases the area covered by the metamaterial absorbers without having to change the existing cells. More importantly, the gain between the sensors and drivers in each pair are precomputed from a desired set of effective acoustic properties leading to low dispersion. This approach contrasts with conventional controls methods used in existing noise cancellation devices that use complex, adaptive transfer functions realized with centralized controllers.

Remarkably, this work shows that the fabricated metamaterial can switch functionality essentially instantaneously without any adverse effects such as ensuing instability. This property has been demonstrated experimentally by repeatedly switching the metamaterial from its absorber to transparent configurations. Active metamaterials based on sensor-driver pairs are thus ideal for noise mitigation, but also for other applications that require very fast time modulation of material parameters recently associated with interesting physical phenomena.

5. ACKNOWLEDGMENTS

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