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Electrically tunable and broader-band sound absorption by using micro-perforated dielectric elastomer actuator

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Most membrane-type acoustic absorbers for low-frequency sound attenuation are applicable only at a fixed resonant frequency for a narrow bandwidth. Tuning of the acoustic absorption spectrum is desired to match the varying noises. This letter presents a micro-perforated dielectric elastomer actuator (MPDEA) to make a broader-band acoustic absorber electrically tunable. Voltage activation of the MPDEA reduces the membrane tension and hole size and thus enables the active shifting of the acoustic absorption spectrum. Such a membrane tuning method does not require discrete mechanical parts as for the cavity tuning method. Also presented are the analytical models to predict the voltage-induced hole size change and acoustic characteristics of MPDEA.

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Acoustic metamaterials are man-made sub-wavelength structures to control and manipulate sound waves.¹ Examples of them include periodic resonators/scatterers,²⁻⁴ sonic crystals,⁵⁻⁷ and resonant membrane absorbers.⁸⁻¹² Among them, membrane-type absorbers with a sub-wavelength air cavity can absorb the noises in the low to medium frequency range, eliminating the need for thick porous absorbers. However, most of these metamaterials have a narrow absorption band around a fixed resonant frequency;¹³⁻¹⁵ they cannot be actively tuned to match the varying noise conditions. Recently, tunable membrane absorbers have been developed using a biaxially pre-stretched dielectric elastomer actuator (DEA) with a back cavity of fixed depth.¹⁶⁻¹⁹ Voltage activation of the DEA reduces the membrane tension (by applying the Maxwell stress²⁰) and thus enables the shift (reduction) of the absorber's resonant frequency.^{17,21} Yet, the absorption bandwidth of such a DEA acoustic absorber remains narrow, around the tunable resonant frequency.

A broader band of sound absorption is possible using a micro-perforated panel (MPP),²²⁻²⁴ a type of Helmholtz resonator, due to periodic resonance. The MPP consists of a rigid panel with submillimeter perforations (holes) and a back cavity. Its resonant frequency depends on the pore sizes (i.e., diameter and depth) and the back cavity volume.^{22,25} A screw adjustment²⁵ of the cavity volume provides a simple mechanical means to tune the resonant frequency of a Helmholtz resonator. Similarly, a stepper motor^{26,27} was previously used to change the back cavity volume of the MPP absorber, moving the back cavity plate from 6 mm to 12 mm. These cavity tuning methods are however impractical and costly for large-area MPP. These MPPs with negligible panel vibration work only for medium frequencies, ranging from 600 Hz to 1000 Hz, despite being capable of cavity tuning. In contrary, the recently developed membrane-type acoustic

absorber can better attenuate noises at a low frequency (below 500 Hz).

In this letter, we present an electrically tunable acoustic absorber based on a micro-perforated dielectric elastomer actuator (MPDEA) (see Figure 1). It is capable of broader band attenuation of low-to-medium frequency sound and electrical tuning of the peak absorption frequency and bandwidth. This is achieved by voltage activation that reduces the membrane tension and thus hole size. Such a membrane tuning method does not require discrete mechanical parts as for the reported cavity tuning method.²⁵⁻²⁷

This MPDEA has a circular dielectric elastomer (DE) membrane which is radially pre-stretched and has its outer edge fixed to a rigid cylindrical tube of radius R_0 . The membrane was laser drilled with an orthogonal array of holes at a

FIG. 1. A broader band acoustic absorber using micro-perforated dielectric elastomer actuators (MPDEA): (a) an array of electrically tunable holes in DEA; (b) its unit cell with a hole at either passive or active states; (d) schematic showing the effect of voltage activation on hole size change; and (e) an equivalent electro-acoustic circuit.

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pitch of $2b$. The perforated DE membrane is initially subjected to a pre-stress σ_0^∞ . Figure 1 shows a unit cell of MPDEA which consists of a hole of a radius a , a passive annulus, and an active part in the pre-stretched dielectric elastomer membrane. The passive annulus is non-coated and has a hole at its center, while the surrounding active membrane is sandwiched by wrinkled gold compliant electrodes.^{28–30} The laser-drilled holes have the edges thickened upon membrane stress relief. Multi-layer MPDEAs, for example, a two-layer device, are thicker to make deeper holes to improve the sound absorption but reduces the membrane flexibility, as compared to a single-layer MPDEA.

Activation of the MPDEA at a voltage V induces a Maxwell stress $p_e = \epsilon_0 \epsilon_r (V/t)^2/2$ across the active dielectric elastomer membrane of thickness t and relative permittivity $\epsilon_r = 4.7$, where $\epsilon_0 = 8.85 \times 10^{-12}$ F/m is the vacuum permittivity. This isometric loading on the DE membrane with the Poisson ratio $\nu = 0.5$ reduces the distant equi-biaxial stresses in the passive annular membrane by $\Delta\sigma^\infty = -\nu p_e / (1 - \nu)$. Hence, the passive annular membrane with a hole radius a is subjected to the voltage-induced stress changes in the cylindrical coordinates r , θ , and z : $\Delta\sigma_{rr} = \Delta\sigma^\infty (1 - a^2/r^2)$, $\Delta\sigma_{\theta\theta} = \Delta\sigma^\infty (1 + a^2/r^2)$, and $\Delta\sigma_{zz} = 0$, according to the plane stress analysis^{31,32} on the small-displacement assumption.

According to Hooke's law,^{31,32} the radial displacement Δu_r in the passive annular membrane due to the distant stress changes is

$$\Delta u_r = \int \frac{1}{E} (\Delta\sigma_{rr} - \nu\Delta\sigma_{\theta\theta} - \nu\Delta\sigma_{zz}) dr = -\frac{\nu}{1-\nu} \frac{p_e}{E} \left[\left(r + \frac{a^2}{r} \right) - \nu \left(r - \frac{a^2}{r} \right) \right] + c(\theta, z), \quad (1)$$

where E is the tangent Young's modulus of the pre-stretched perforated dielectric elastomer membrane.

The constant $c(\theta, z)$ can be obtained by applying the symmetric boundary condition that $\Delta u_r = 0$ at $r = b$. As such, the voltage-induced reduction of the hole radius (i.e., Δu_r at $r = a$) becomes

$$\Delta a(V) = \frac{\nu}{1-\nu} \frac{p_e}{E} \left[b + \frac{a^2}{b} - 2a - \nu \left(b - \frac{a^2}{b} \right) \right]. \quad (2)$$

This resonant acoustic absorber consists of a MPDEA and a back cavity of an air gap H from a rigid back plate. Consider a sound wave of a frequency f that travels at the sound speed c_0 in air. Upon normal incidence into (impinging on) the rigid wall, the sound produces an equivalent source pressure $2p$. The sound absorption coefficient α of this MPDEA has a similar expression as derived for the perforated membrane absorber,¹³ except the voltage dependence

$$\alpha = \frac{4Re(z(V))}{(1 + Re(z(V)))^2 + Im(z(V))^2}, \quad (3)$$

where z is a total acoustic impedance from an electro-acoustic model (see Figure 1(d)). The equivalent circuit has

a voltage-tunable mass-resistance element in series with a cavity reactance $z_H = j\cot\omega H/c_0$ of the air space, where $\omega = 2\pi f$. The voltage-tunable mass-resistance element consists of a parallel connection of a membrane impedance $z_m(V)$ and a perforation impedance $z_p(V)$. The total acoustic impedance is

$$z(V) = \frac{z_m(V)z_p(V)}{z_m(V) + z_p(V)} + z_H. \quad (4)$$

The membrane under a tension vibrates like a string¹³ when being subjected to a pressure wave Δp in the air of density ρ_0 and viscosity μ . Voltage modulation of the membrane tension $T(V)$ (i.e., force per unit length) helps tuning the membrane's resonant frequency.¹⁷ Consider a tensioned circular membrane with an outer radius R_o and the following material properties: membrane surface density (ρ_m) and internal damping (η). Its membrane acoustic impedance z_m becomes¹³

$$z_m(V) = \frac{\omega\rho_m}{j\rho_0 c_0} \left[\frac{2}{K'_{mem} R_o} \frac{J_1(K'_{mem} R_o)}{J_0(K'_{mem} R_o)} - 1 \right]^{-1}, \quad (5)$$

where $K'_{mem} = \omega^2 \rho_m / (T(V) + j2\omega\eta)$ is voltage dependent (as indicated with a prime symbol), J_1 is the Bessel function of the first kind and first order, and J_0 is the same of zeroth order. This shows the dependence of membrane impedance on the electrically controllable tension.

The acoustic impedance of the perforations in a circular flexible membrane of outer radius R_o is a sum of the contribution by N holes of radius a'

$$z_p(V) = \left[\sum_{n=1}^N \frac{a'^2}{R_o^2} \frac{1}{z_{hole}(R, V)} \right], \quad (6)$$

where $a' = a - \Delta a(V)$ is the activated hole size.

The acoustic impedance $z_{hole}(R, V)$ of a hole at the radial coordinate R in the circular flexible membrane is given by¹³

$$z_{hole}(R, V) = \left[\frac{j2\rho_0 c_0}{\omega\rho_m K_{air} a'} \frac{J_1(K_{air} a')}{J_0(K_{air} a')} \left(\frac{J_0(K'_{mem} R)}{J_0(K'_{mem} R_o)} - 1 \right) + \frac{1}{z'_{Maa} \delta'} \right]^{-1}, \quad (7)$$

where $K_{air} = -j(\rho_0 \omega / \mu)$, $\delta' = Na^2/R_o^2$ is the perforation ratio of the membrane with N number of holes. Maa's estimated acoustic impedance z'_{Maa} of a hole in the rigid panel is given by^{13,22}

$$z'_{Maa} = 36.75 \times 10^{-3} \frac{t}{a'^2 \delta'} \left(\sqrt{1 + \frac{x'^2}{32}} + \frac{\sqrt{2} x' a'}{4h} \right) + j0.294 \times 10^{-3} \frac{\omega t}{\delta'} \left(1 + \frac{1}{\sqrt{9 + x'^2/2}} + 1.70 \frac{a'}{t} \right), \quad (8)$$

where $x' = a' \sqrt{2f/5}$ is the perforation constant. These equations show the dependence of perforation impedance on both hole size and tension, electrically controllable.

Figure 2 shows the fabrication processes of the proposed MPDEA. First, a 1-mm thick polyacrylate elastomer membrane (3M VHB 4910, a 3M trademark for very high bond (VHB) adhesive tape) is radially stretched for $\lambda = 3.15$ times using a custom-made stretcher. The pre-stretch ratio is $\lambda = R_o/R_i$, where R_i is the initial dimension of the membrane and R_o is the pre-stretched dimension. Second, a 1.5 mm thick Teflon mask, which is laser cut (Epilog Helix 24) into the designed pattern, is applied and aligned on each side of an elastomer substrate. Third, a 10 nm gold thin film is DC magnetron sputtered on each side of the exposed elastomer substrate. Fourth, the Teflon mask is lifted off to yield the electrode patterns. Next, the electrode patterning steps are repeated on the other side. A pair of such patterned electrodes sandwich the membrane to make dielectric elastomer actuators. Electrical leads to each sputtered electrode are formed each by a copper foil with conductive grease contact. Fifth, the membrane is laser drilled into $N=325$ sub-millimeter holes (perforations) at an initial pitch of $2b=5$ mm over the non-electrode parts. The passive annulus is 2 mm radial wide from the hole to avoid electric arcing through the hole and air. Sixth, the perforated membrane is partially released to have a 2.9 time radial pre-stretch such that the gold thin films wrinkle under a 6.5% radial compressive strain and make stretchable compliant electrodes. As a result, the hole pitch reduces to $2b=4.5$ mm approximately and the hole radius reduces to be close to 0.15 mm. Next, this MPDEA is adhesively fixed to a cylindrical tube with an inner radius of $R_o=50.5$ mm. A multilayer MPDEA is fabricated using the same steps but requires the extra steps of alignment, stacking, and degassing before the steps of laser drilling. Degassing at -85 kPa (lower than atmospheric pressure) for 3–4 h helps remove the trapped air and improve the adhesion at the interfaces of multilayer DEA. Finally, a device of a two-layer MPDEA is completed on a circular rim as shown in the photograph in Figure 2(b), while Figures 2(c) and 2(d) show its unit cell and a part of the wrinkled gold electrode, respectively.

FIG. 2. Fabrication of a MPDEA acoustic absorber: (a) the fabrication steps for a single-layer MPDEA; (b) photograph of a two-layer MPDEA device; (c) optical micrograph of a MPDEA unit cell; and (d) the photograph of the wrinkled gold electrode.

Three kinds of acoustic absorbers were fabricated, namely, a single-layer perforated one, a double-layer perforated one, and a single-layer non-perforated one for reference. Each layer is a 2.9 time radially pre-stretched VHB4910 tape, with a pre-stretched membrane thickness of $125.0 \mu\text{m}$. The Young's modulus of these radially pre-stretched membranes averages at 1.14 MPa. Initial hole diameters of the MPDEAs are $315 \mu\text{m}$ for a single-layer one and $308 \mu\text{m}$ for a double-layer one. The perforation ratio is $\delta=0.309\%$ for a one-layer MPDEA and $\delta=0.296\%$ for a two-layer MPDEA. The parameters used for theoretical modeling of the two-layer MPDEA are $T(V=0 \text{ kV})=57.69 \text{ N/m}$, $T(V=5 \text{ kV})=49.29 \text{ N/m}$, $\mu=1.846 \times 10^{-5} \text{ kg/(m s)}$, $R_o=0.0505 \text{ m}$, $c_0=346 \text{ m/s}$, $\rho_0=1.184 \text{ kg/m}^3$, $\rho_m=0.1904 \text{ kg/m}^2$, $\eta=0.02$, and $H=0.08 \text{ m}$.

Non-contact measurement techniques were used to observe the actuation of MPDEA: (1) optical microscope or camera to measure the hole diameter and (2) a confocal image profiler (sensofar PL μ 2300) to measure the membrane topography. A tensile tester (Instron) and a custom-made radial stretcher with elastic torsional joints were used to measure the membrane tension as a ratio of the total radial forces to the circumferential cross-sectional area. A setup of the acoustic impedance tube^{17,18} with normally incident sound waves was used to characterize the MPDEA absorber's acoustic performance. It has a loudspeaker installed as the sound source at one end of a 770 mm long and 100 mm diameter tube, while the MPDEA absorber was installed at the other end of the tube. Two electret array microphones (PCB Piezotronics, model 130E20), i.e., "Mic" 1 and "Mic" 2 spaced for a 30 mm distance, were used to measure the sound pressure in the tube. A high voltage (HV) amplifier/supply (Trek 10/40A) was used to activate the MPDEA absorber. Meanwhile, data (NI PCI-6251) were used to acquire the measured signals and send the control signals to the measurement instruments.

Voltage activation of the MPDEA reduces its membrane tension and thus reduces the hole size (see Figure 3). For example, the membrane tension in two-layer MPDEA reduces from 215 kPa at 0 kV to 195 kPa at 5 kV. This 5 kV voltage activation reduces the hole diameter from $307.6 \mu\text{m}$ to $263 \mu\text{m}$, a 14.5% reduction. In comparison, a single-layer MPDEA shows a limited electrical tunability due to higher susceptibility to air breakdown near the exposed high-voltage electrode.

Figure 4 shows the spectrums of sound absorption for various tunable DE acoustic absorbers at zero voltage. Perforations in the DE membrane absorber greatly broaden the absorption band, as compared to the non-perforated one. The two-layer MPDEA has a 560 Hz bandwidth to absorb the low-to-medium frequency sound (300 to 900 Hz) for more than 50% ($\alpha > 0.5$). The major peak of sound absorption is as much as 90% at around 500 Hz, while minor absorption peaks happen to correspond to those of non-perforated MPDEA given the same back cavity. The performance of the two-layer MPDEA absorber is much better due to the deeper holes in the double-thick membrane, as compared to that of a single-layer MPDEA.

Figure 5 shows the effect of electrical tuning on the double-layer MPDEA's absorption spectrum. At zero

FIG. 3. Voltage induced changes in the membrane stress and hole size of the MPDEAs in either a single layer or double layers: (a) membrane stress change; (b) hole size change; and (c) and (d) confocal micrographs of a hole of the two-layer MPDEA's unit cell at 0 kV or 5 kV.

voltage, its peak absorption frequency is 538.5 Hz, while the lower bound of the absorption band ($\alpha > 0.5$) is 345.3 Hz. At the 5 kV activation, its peak absorption is shifted lower by 13.1% (to 467.8 Hz), while the lower bound of the absorption band is lowered by 11.2% (to 306.4 Hz). Our theoretical model also predicts such acoustic characteristics and the electrical tuning of the bandwidth and frequency.

This MPDEA absorber shows superb performance for low-frequency sound absorption, thanks to the viscoelastic effect³³ of the DE membrane (VHB 4910) and the acoustic effect of perforations.²² Its peak absorption and band width are comparable to if not better than the dark acoustic metamaterial³⁴ made of silicone rubber membrane (Silastic 3133) and iron platelets. In addition, this MPDEA with electrically tunable resonances of air can be readily scaled up to make a large-area acoustic absorber.

FIG. 4. Spectrums of sound absorption by various dielectric elastomer membranes: non-perforated one and perforated ones in either a single layer or double layers.

FIG. 5. Voltage tuning of the sound absorption spectrums by a two-layer MPDEA absorber: the passive state at 0 kV and the activated state at 5 kV, as measured or theoretically predicted.

This letter presented an electrical tuning method for broader-band attenuation of low-to-medium frequency sound. Electrical tuning of its membrane tension and hole size enables the active shift of the acoustic absorption spectrum. In the future, such MPDEA can be loaded with point masses to make an electrically tunable super-absorbing metasurface^{13,14} to absorb even lower frequency sound.

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