

# Tunable acoustic metamaterial with an array of resonators actuated by dielectric elastomer



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## ABSTRACT

Acoustic metamaterial comprising an array of resonators being attached to the side wall of a rigid duct is investigated in this study. We propose a resonator design by employing a pre-stretched dielectric elastomer (DE) membrane to tune the acoustic property of each resonator. Both numerical and experimental techniques are developed to characterize the acoustic behavior of the proposed device in terms of transmission loss (TL). By connecting multiple resonators, we show that a broadband TL can be achieved which combines the multiple attenuation bands provided by each resonator unit. The resulted attenuation band can be tuned by varying the applied voltage to the DE membranes, showing promising potentials such as adaptive sound control devices for ventilation systems and other engineering applications.

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## 1. Introduction

The idea of using acoustic metamaterial with artificially engineered structures to tailor and manipulate sound wave propagation has received significant attentions. Different classes of metamaterials such as locally resonant membrane-type [1–7], periodic resonators/scatters or sonic crystal type [8–16] have been extensively investigated. These metamaterials have shown interesting acoustic properties such as bandgap [14], acoustic trapping [17], negative effective mass [2] and negative modulus [13], etc. Most of the metamaterials proposed to date, however, suffer from the deficiency of being effective in only narrow frequency band and cannot provide the tunability needed for operation in different frequency regions.

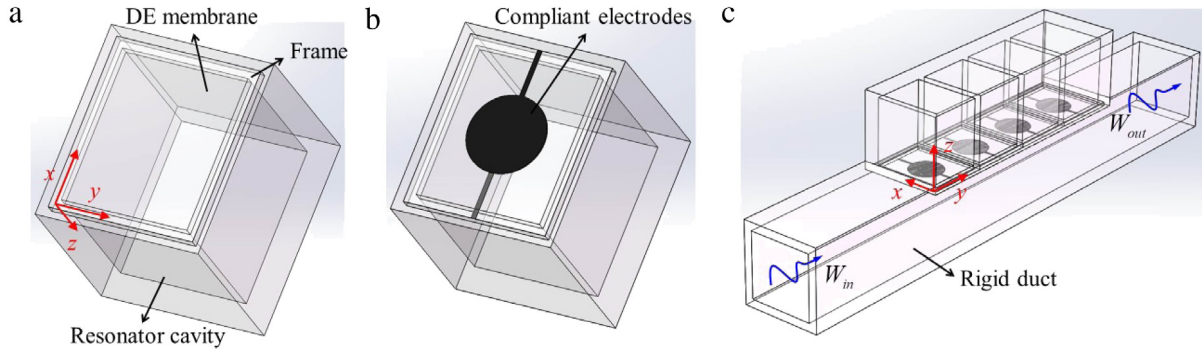
As a new class of electroactive material, dielectric elastomer (DE) has aroused vast research interests because of its fast response and large deformation induced by externally applied voltage [18]. A broad range of potential applications such as mechanical actuators [19], artificial muscle [20] and energy harvesters [21] have been proposed. Aiming at a possible tuning of the acoustic response, we propose a tunable resonator design that incorporates

an air cavity covered with a pre-stretched DE membrane, or hereafter referred to as a DE resonator. As shown in Fig. 1(a), each resonator unit consists of a DE membrane (VHB 4910 manufactured by 3M) being stretched and mounted onto the rigid frame around the cavity opening. The inner dimension of the resonator is  $135 \times 160 \times 160$  mm in the  $x$ ,  $y$  and  $z$  directions, respectively. The stretch-free state of the DE membrane has an initial thickness  $t_0$  of 1.0 mm, and is pre-stretched to a ratio of  $r = X/X_0 = Y/Y_0$ , where  $X$  and  $X_0$  are the dimensions of stretched and stretch-free state membrane in the  $x$  direction, respectively (the same applies to the  $y$  direction). The membrane thickness  $t_m$  is therefore reduced to  $t_0/r^2$  after stretching. For applying voltage control, carbon grease as compliant electrodes is coated on both sides of the membrane as shown in Fig. 1(b), which are circular in shape and cover around 25% of the membrane surface area. The weight of the electrodes ( $\approx 0.3$  g) is typically around 1/10 of the membrane ( $\approx 3$  g), in order to minimize the possible influence on the membrane flexibility and vibrational response.

We have shown that the noise attenuation performance of a single DE resonator can be tuned with varying voltages [22,23], but its effective TL is usually limited within a narrow frequency band. To solve this problem, we propose an acoustic metamaterial design comprising an array of DE resonators as shown in Fig. 1(c), which is attached to the side wall of a rigid duct parallel to the axis of the inlet and outlet. The cross-section area of the duct is  $160 \times 160$  mm. This study attempts to reveal the combined

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**Fig. 1.** Schematics of: (a) DE resonator unit without electrodes; (b) DE membrane coated with compliant electrodes; (c) acoustic metamaterial comprising an array of DE resonators being attached onto a duct.

effect of connecting multiple resonators with varying pre-stretch ratios, and to further explore the tunability of the proposed device. We develop both numerical and experimental methods to analyze the acoustic characteristics of the proposed DE resonator and subsequent resonator array. A remarkable broadened effective frequency band (10 times larger than a single DE resonator) and a feasible performance tuning are achieved.

## 2. Numerical and experimental methods

In order to predict the acoustic performance of the proposed device, a numerical model capable of dealing with structural–acoustic coupling was developed. The acoustic fields inside the duct and resonator cavities are expressed by the Helmholtz's equation:

$$\nabla^2 p - (1/c_0^2)\partial^2 p/\partial t^2 = 0 \quad (1)$$

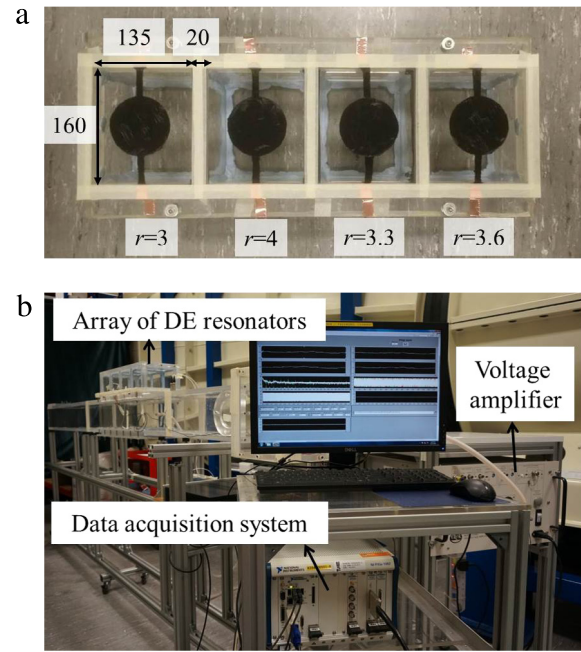
where  $p$  is the acoustic pressure,  $c_0$  is the sound speed in air, taken as  $c_0 = 340$  m/s. The out-of-plane vibration of the DE membrane is governed by [6]:

$$T\nabla^2 w - \rho_m t_m \partial^2 w/\partial t^2 = -\Delta p \quad (2)$$

where  $w$  is the out-of-plane displacement of the membrane,  $\rho_m$  and  $t_m$  are its density and thickness,  $T$  is the in-plane tension force applied to the membrane edges due to pre-stretch,  $\Delta p$  is the distributed force exerted on the membrane surface. Physically, the sound pressure fields inside the duct  $p_{duct}$  and resonator cavity  $p_{cavity}$  are coupled through the membrane vibration, which is determined by the pressure difference as  $\Delta p = p_{duct} - p_{cavity}$ . While keeping the geometric parameters and DE material properties constants, the system response can be tuned by varying the membrane pre-stretch ratio  $r$  and tension force  $T$ .

In order to solve Eqs. (1) and (2), acoustic–structure interaction module under commercial finite element method (FEM) code COMSOL Multiphysics is utilized. As shown in Fig. 1(c), the acoustic duct is excited with a plane wave at the inlet and terminated by an impedance boundary of air ( $\rho_0 c_0$ ) at the outlet, provided that the frequency range of interest is below the duct cut-off frequency. Membrane surfaces with prescribed zero displacement around the four edges are defined, which are selected as the acoustic–structure interaction boundaries with continuous velocity conditions. The TL is evaluated by  $TL = 10 \log_{10}(1/\tau)$ , where the transmission coefficient  $\tau$  is the ratio of the incident and transmitted sound powers as  $\tau = W_{in}/W_{trans}$  [24,25].

For experimental tests, DE resonator samples consisting of a single unit with different pre-stretch ratios [22,23], and metamaterial comprising an array of resonators have been fabricated. The resonator cavity is constructed by acrylic panels with 20 mm thickness to avoid sound leakage through wall vibration. For resonator

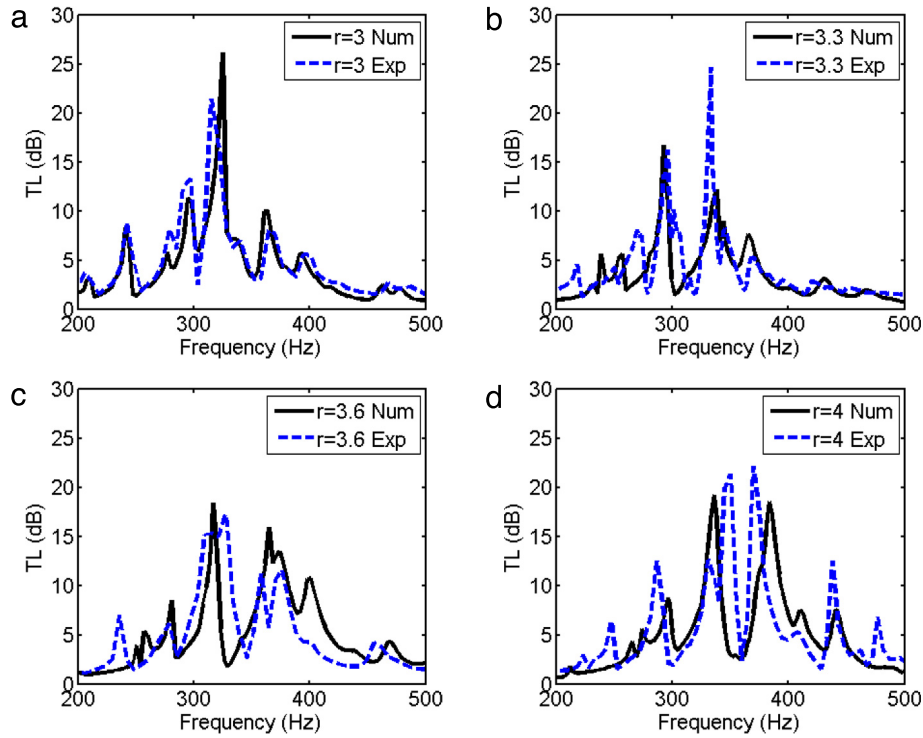


**Fig. 2.** (a) Fabrication of a metamaterial with four DE resonators connected in series as an array, dimension in mm; (b) experimental testing facilities.

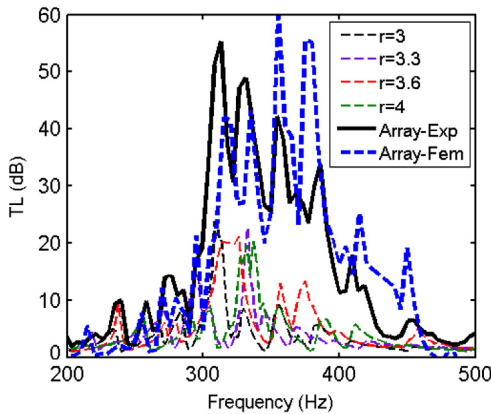
array whose geometric dimension is as sketched in Fig. 2(a), four DE resonator units are serially combined with a separation distance of 20 mm by rigid spacers. The  $r$  value of individual units can be purposely designed or adjusted to allow variations in the combined TL of the metamaterial. For TL measurement, four-microphone two-load method with an efficient data acquisition system [23] has been developed, and a high voltage amplifier allows the added voltage onto the electrodes of each resonator varying in the range of 0–6 kV. The experimental test-rigs are as shown in Fig. 2(b). During the TL measurements, repeatability of the experiment has been carefully checked.

## 3. Results and discussions

The TL characteristics of a single DE resonator with different membrane pre-stretch ratios are first considered, with the duct and resonator dimension in Fig. 1 being fixed. Fig. 3(a)–(d) present the comparisons between experimental results and simulations using the developed FEM model for four DE resonators with  $r = 3.0, 3.3, 3.6$  and  $4.0$ , respectively. It can be seen that for all  $r$  values, the predicted and measured TL match reasonably well in the frequency dominated by the distinct TL peaks. Here, we consider an attenuation band is effective if it provides a TL greater than 10 dB,



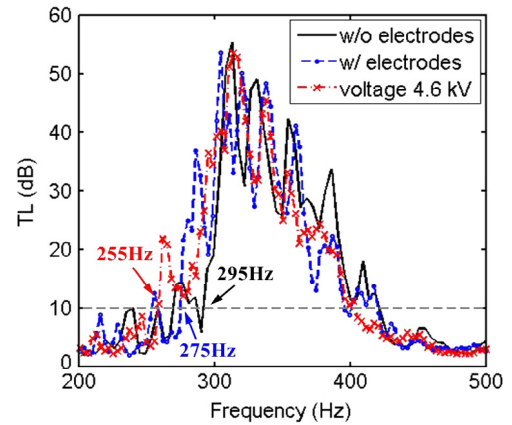
**Fig. 3.** Comparisons between simulated and measured TL results for a single DE resonator with different pre-stretch ratios: (a)  $r = 3.0$ ; (b)  $r = 3.3$ ; (c)  $r = 3.6$ ; (d)  $r = 4.0$ .



**Fig. 4.** Connecting four DE resonators as a metamaterial array, a much broadened attenuation band can be achieved.

which means that the acoustic energy penetrates through the duct segment under the resonator is reduced by 90%. The attenuation bands for resonator with  $r = 3.0$  are located at around 290 Hz and 310 Hz,  $r = 3.3$  at 300 Hz and 335 Hz,  $r = 3.6$  at 315 Hz and 355 Hz, and  $r = 4.0$  at 330 Hz and 370 Hz, respectively. Each attenuation band has a narrow bandwidth of 10–15 Hz in the vicinity of the center frequency, which is rather marginal for providing an effective sound control.

The four DE resonators analyzed above are connected to form an array as shown in Fig. 2(a). In Fig. 4, the attenuation band provided by the DE resonator array is shown, where a generally good agreement between prediction and measurement is again obtained. The system TL combines the multiple attenuation bands provided by each resonator constituent. Further increasing the number of connected resonators resembles the metamaterial with periodic or gradually changing elements. We report experimentally that the proposed resonator array achieves an attenuation band (TL > 10 dB) from 295 to 420 Hz with a bandwidth of 125 Hz, which is about 10 times greater than the narrow attenuation band of a single resonator. The enhanced attenuation band with TL > 20 dB



**Fig. 5.** Effect on the TL of the metamaterial with added electrodes and under an actuation voltage of 4.6 kV, experimental results are plotted.

covers from 300 to 390 Hz, demonstrating the effectiveness of the proposed device in providing an efficient sound attenuation. Different from other membrane-type metamaterials reported with high TL [26,27] which usually require the membrane to physically block the sound transmission path, the proposed metamaterial lined along the duct wall presents no flow blockage, hence making it a better choice to be implemented as sound control device for ventilation systems.

Apart from changing the membrane pre-stretch ratio as discussed in Fig. 3, we further explore the tunability of the proposed device via changing control voltages. An elongation in the surface area of the DE membrane can be triggered by applying voltage to the compliant electrodes, and the induced deformation can be exploited to reduce the tension force  $T$  exerted to the membrane edges by fixed frames. In Fig. 5, the effect of adding lightweight compliant electrodes is first benchmarked, where the lower frequency limit of the attenuation band is changed to 275 Hz, compared to 295 Hz for the case without electrodes. This frequency shift can be explained by the reduced resonant



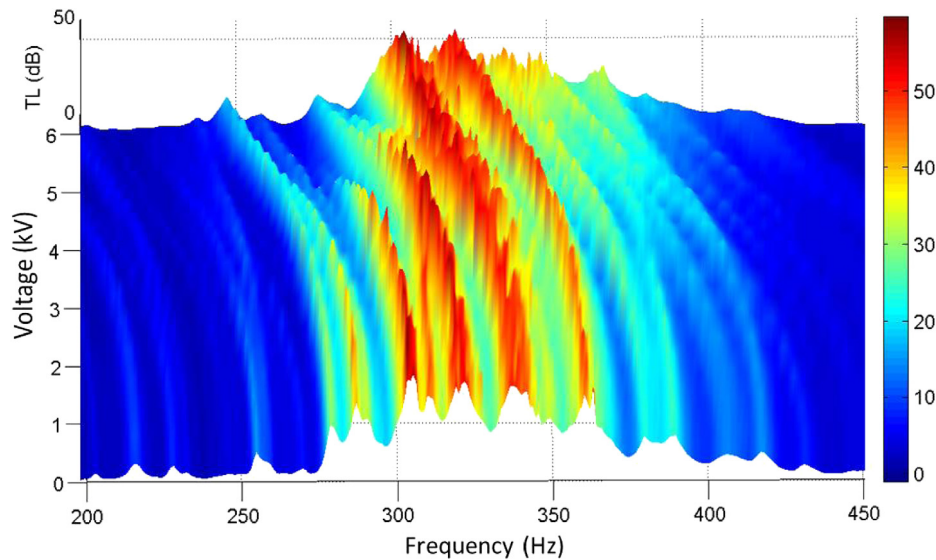


Fig. 6. Tunable attenuation bands of the metamaterial are observed experimentally by controlling the actuation voltage to the DE membrane.

frequency of the system attributed to the added electrodes [28]. Note that the attached mass of the added electrodes can be tuned to realize locally resonant metamaterial [1–7]. By actuating DE with DC voltage in the range of 0–6 kV, the waterfall plot, presenting the experimental TLs versus actuation voltages and frequencies, is shown in Fig. 6. As voltage increases, the TL peaks and attenuation bands of the metamaterial gradually shift toward lower frequencies as a result of the reduced membrane tension  $T$ . Typically as shown in Fig. 5, with an actuation voltage of 4.6 kV, the attenuation band is bounded by a lower frequency limit at 255 Hz. By defining the system “tunability” as the percentage of frequency shift that can be induced by the actuation voltage, the experiments demonstrate that the proposed metamaterial has roughly a tunability of  $(295 - 255)/295 \approx 14\%$  in the frequency of the attenuation band.

In summary, we report a novel acoustic metamaterial with relatively broadband sound attenuation performance. The metamaterial is realized by connecting multiple resonator units along an acoustic waveguide, where the response of each resonator can be tuned by incorporating a DE membrane with desired pre-stretch ratios and/or varying DC voltages. We demonstrated both numerically and experimentally that the resonator array combines the multiple attenuation bands attributed to each resonator, forming an attenuation band which is much wider than its resonator constituents. The metamaterial has up to 14% tunability in the attenuation band frequencies under the present configuration, showing potentials for various applications as adaptive sound control devices.

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