A tunable, light-weight and compact silencer

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ABSTRACT

A tunable, light weight and compact silencer using dielectric elastomer acoustic metamaterials (DEAMs) is investigated in this study. We propose a light-weight and compact acoustic silencer design formed of arrays of acoustic resonators by employing various pre-stretched dielectric elastomer (DE) membranes with conductive electrodes, central platelets and compact back cavities for achieving tunable and broadband acoustic property in the low frequency ranges. The acoustic performance of the proposed device in terms of transmission loss (TL) is experimentally characterized and analyzed. The resulted TL can be tuned by varying the applied voltages to the DE membranes showing promising potentials as adaptive and light-weight sound control devices for suppressing the targeted propeller noises on a multi-rotor MAV within a compact space and other aeronautical engineering applications.

Keywords: Dielectric elastomer acoustic metamaterials (DEAMs), tunable, light-weight, compact silencer
I-INCE Classification of Subjects Number(s): 35.2

1. INTRODUCTION

Metamaterials with negative refraction index in an electromagnetic wave was first proposed in 1968 by Veselago. [1] He theoretically assumed the possible materials having negative electric permittivity (ε) and magnetic permeability (μ), thus resulting in a negative refractive index. However, this concept did not attract much research attention until decades ago. Pendry suggested the theoretical possibility of making electromagnetic metamaterials [2].Negative values of the electric permittivity and magnetic permeability yield many new phenomena in electromagnetic waves, such as negative phase velocity, evanescent waves, and superlensing. Currently, there are many different classes of metamaterials including locally resonant membrane-type [3-14], periodic resonators/scatters or sonic crystal type [15-21]. These metamaterials have shown interesting acoustic properties such as bandgap [21], acoustic trapping [22], negative effective mass [4] and negative modulus [20].

Among these acoustic metamaterials, the membrane-type acoustic metamaterials (MAMs) made of thin pre-stressed membranes with small platelets attached to the center of membranes [4] exhibit certain advantages such as light-weight for aeronautical engineering applications, but these structures can only provide narrow frequency bands [4-5]. Although the frequency bands can be adjusted by choosing the suitable design parameters such as the membrane pre-stretch [6, 12], the weight of the added platelets [4, 6, 12], the platelets' locations [11-13], and the number of added platelets [7, 14] during the fabrication. Nevertheless, it is impossible to shift the tonal components inside the spectrum of the noise source during operation or to cope with changes of the membrane pre-stress due to temperature changes or aging effects.

Active methods may provide an opportunity for adjusting the narrow band characteristics of MAMs during real operation. Baz [23-24] and Akl [25-26] used piezoelectric materials to tune the effective

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density and bulk modulus of acoustic metamaterials. Chen *et al.* [27] used a magnetorheological membrane and an external gradient magnetic field to control the inner pre-stress. However, it would greatly increase the overall mass and size due to a large permanent magnet used for generating magnetic field. Xiao *et al.* [28] utilized the attractive force generated between an acoustically transparent fish net electrode and the added mass on the MAM counter electrode when applying an external DC voltage to adjust band frequencies. As a result, the extra fish net could increase the complexity and the weight of the whole system. Langfeldt *et al.* [29] used pressurized air inside two stacked arrangements of two MAMs to control the eigenmodes and sound transmission loss of the MAMs, at the expenses of adding extra mechanical parts to lead in and out the pressurized air.

Recently, a new class of soft electroactive material, dielectric elastomer (DE) has aroused vast research interests because of its light-weight, simple structure, no extra mechanical parts, fast response and large deformation induced by externally applied voltage [30]. A broad range of potential applications such as mechanical actuators [31], artificial muscle [32] and energy harvesters [33] have been proposed. Aiming at a possible tuning of the acoustic metamaterial using soft smart material DE, Lu *et al.* [34-38] proposed a tunable resonator design that incorporates a back cavity covered with a pre-stretched DE membrane, or hereafter referred to as a DE acoustic resonator (DEAR). It had been shown that the noise attenuation performance of a single DEAR can be tuned with varying voltages [34-38], but its effective TL is still limited within a narrow frequency band.

To further improve the acoustic performances of the DEAR, a compact acoustic silencer design formed of arrays of DEARs is proposed and experimentally tested in this paper. The silencer design is achieved by employing multiple pre-stretched dielectric elastomer (DE) membranes with conductive electrodes, central platelets and compact back cavities. Being referred to as DE Acoustic metamaterials (DEAMs) hereafter, the device aims at achieving tunable and broadband acoustic property in the low frequency ranges.

2. EXPERIMENTAL SETUP AND DIELECTRIC ELASTOMER ACOUSTIC METAMATERIAL

The acoustic measurement is conducted in the rectangular duct with a cross section of $160\text{mm} \times 160\text{mm}$ (shown in Fig. 1(a)). A loudspeaker is installed at one end of the duct and acts as the sound source. Four PCB array microphones (model 130E20) are used for measuring the sound pressure inside the duct. These microphones are referred to as ‘Mic.1’, ‘Mic.2’, ‘Mic.3’ and ‘Mic.4’ as shown in Fig. 1(a). The distances between Mic. 1 and Mic. 2, Mic.3 and Mic. 4 are chosen as 30mm which determine that the low effective measurement frequency is around 100Hz. And the high effective measurement frequency of the duct is around 1060Hz due to the cut-off frequency determined by the dimensions of the duct’s cross-section. The effective measurement frequency range for the present acoustic duct system is from 100Hz to 1060Hz. The two-load method is used to measure the transmission loss (TL) of the silencer [39], which does not require a complete anechoic termination. A Trek 10/40A high voltage amplifier is used to generate both DC and AC high voltage from 0 to 10kV on the DEAMs. All the acquisition and control signals are conducted based on the NI PXI 6221 platform. The sampling frequency is set to 40 kHz and the record time is 4s for ensuring smaller Δf in the FFT analysis. Mic.1 is chosen as the referred microphone of the system, the magnitudes and phases of other three microphones are then calibrated with respect to Mic.1 [39].

The DEAMs are installed at the working section of the duct. A typical DEAM model is shown in Fig. 1(b) and Fig. 1(e). Generally, it is composed of a pre-stretched DE membrane with conductive electrode and central platelets, which is attached to a back cavity (shown as Fig. 1(c)). The dimension of the pre-stretch DE membrane (3M VHB 4910) is $36mm \times 36mm$. The central copper platelet has a diameter of d=3mm, thickness of t=0.4mm and weight of 0.09g. The weight of one unit, including the membrane and the central copper platelet is only 0.27g. With the help of the central platelet, the depth of the cavity is chosen as 40mm (which will be further reduced to 10mm in future studies). In order to avoid the wrinkle phenomenon, the circular conductive electrode only covers 30% of the whole DE membrane surface around the central copper platelet. In the experiment, four DEAR cells form an array of DEAMs with a common pre-stretch ratio δ. The four arrays of DEAMs are tuned with different pre-stretch ratios, $\delta_1 = 3.0$, $\delta_2 = 3.3$, $\delta_3 = 3.6$ and $\delta_4 = 4.0$, respectively.

A pre-stretch mechanism which can ensure consistent quality of the pre-stretched DE membrane was used to stretch the DE film to the targeted pre-stretch ratio [38]. Adhesive dielectric elastomers VHB™4910 film with low Young’s modulus is cut to suitable size and then adhered to the blocks in the center of the frame. Rotate the eight thread bars to extend the DE film to a special pre-stretched ratio δ. Here ratio δ is defined as $\delta = r_1/r_0$, where r_0 is the original positions of the blocks which are definite as the distance from the inner surface of the initial blocks to the zero point O at the center of the frame, r_1 is the target positions of the block after pre-stretching, all the blocks are circular distributed around the center of the frame. This setup can extend the DE film up to pre-stretch ratio of 5 in good quality.

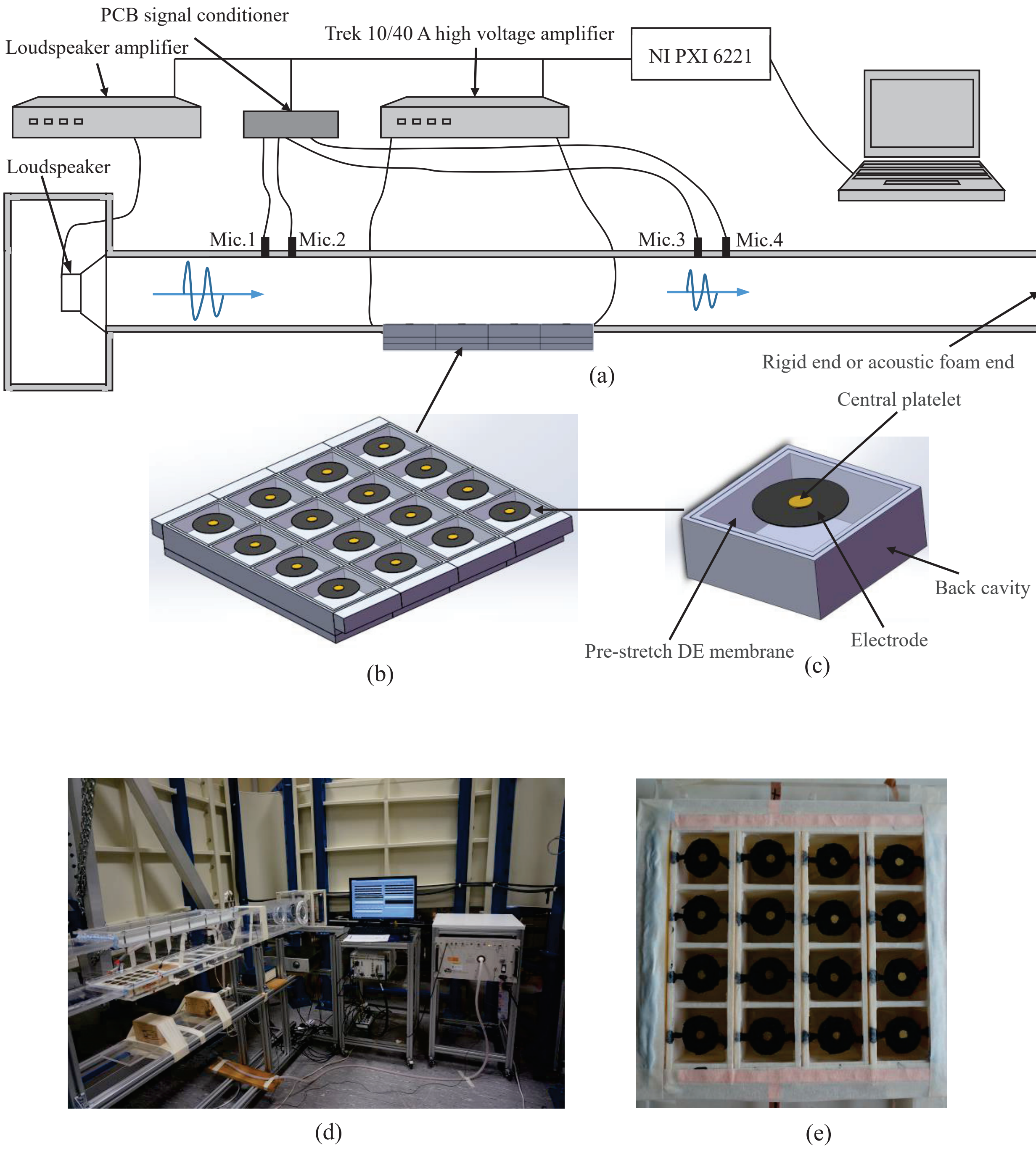

Figure 1 - Acoustic measurement system. (a) sketch of the measurement system; (b) dielectric elastomer acoustic metamaterials (DEAMs); (c) dielectric elastomer acoustic resonator (DEAR); (d) photo of the acoustic duct system; (e) photo of the DEAMs.

As a benchmark test, the transmission loss measurement of the duct with a rigid wall is shown in Fig. 2. It is observed that from 100Hz to 1050Hz, the measurement error of the transmission loss is about 0.4 to 1.0dB. The error might due to the acoustic leakage through the duct wall surface or vibration and the duct friction.

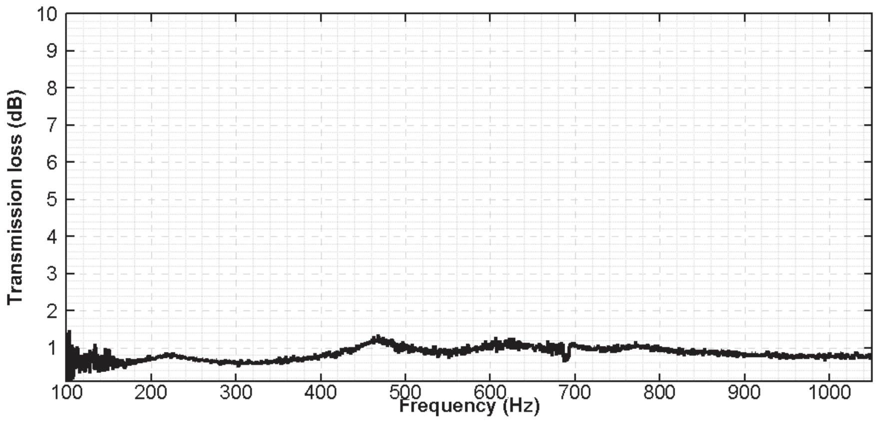

Figure 2 - Transmission loss for the rigid wall installed in the acoustic duct system

3. RESULTS AND DISCUSSIONS

It is observed that when the pre-stretch ratios of the DE membranes are larger than 3.0, the DE membranes can have larger deformation with the same applied voltages. But the breakdown voltage of the DE membrane will decrease with increasing pre-stretch ratio. Therefore, the pre-stretch ratios of the DEAMs are chosen to be $\delta = 3.0, 3.3, 3.6$ and 4.0. DEAMs with four different pre-stretch ratios and a 40mm-depth back-cavity were tested and the results are plotted in Fig. 3. It can be seen TL peaks appear within the measurement frequency range from 100Hz to 1050Hz. The main one is located at 668.6Hz, giving rise to a high transmission loss band from 646.5Hz to 691.2Hz (a band of 44.7Hz). Since the resonance frequency of the 40mm -depth back cavity is at 2125Hz which is outside the measurement frequency range, it may suggest that the TL peak locations are mainly controlled by the resonances of the DEAMs.

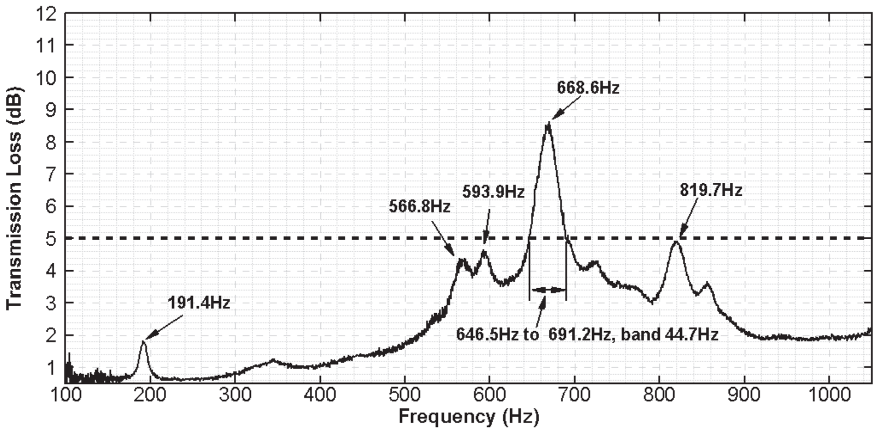

Figure 3 - Acoustic characteristic of the DEAMs with four various pre-stretch ratios ($\delta = 3.0, 3.3, 3.6$ and 4.0) and 40mm-depth back cavity.

When the applied voltage on the DEAMs changes, the corresponding TLs are measured and compared in Fig. 4. It is seen that the main peak at 668.6Hz does not change its position, while two other peaks, one at 819.7Hz and the other at 191.4Hz, are shifted to lower frequencies when the applied voltage increases. With 4.0kV, the peak at 819.7Hz is shifted to 760.6Hz, corresponding to an alteration of 59.1Hz (7.2%). The peak at 191.4Hz is shifted to 175.3Hz with an alteration of 16.1Hz (8.4%). The peak shift phenomenon is due to the inner stress alteration as a result of voltage variations on the DEAMs, in agreement with the previous findings [34-38]. Furthermore, the main peak at 668.6Hz and other two peaks at 566.8Hz and 593.9Hz remain almost at the same corresponding locations. Compared with the DE membrane, the central platelet has a high mass density which can obviously decrease the resonance frequencies of the DE membrane. Thus for a relative shallow backing cavity, the DEAMs can have lower effective frequency range with the help of the central platelet, typically below 1000Hz which is very critical for the engineering applications.

However, the high TL band generated by the central plate is still narrow which requires further studies.

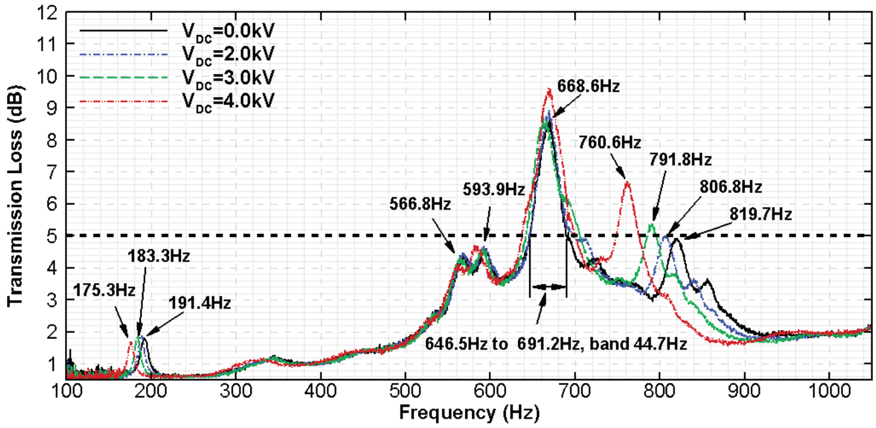

Figure 4 - Tunable acoustic performances of DEAMs with various applied voltages.

Owing to the aforementioned property in terms of dynamic tuning, it should be possible to properly tune the TL peaks so that new high TL band be formed. To this end, the applied voltages are further increased to 5.0kV and 5.5kV and the results are shown in Fig. 5. It is found that at the applied voltage 5.0kV and 5.5kV, the peak at 819.7Hz is shifted to 726.1Hz and 721.5Hz which is quite close to the main peak at 668.6Hz, thus forming a broader high TL band between these two peaks. In the present case, the previous narrow band is extended to 139Hz at applied voltage 5.5kV (3.1 times). Thus with the suitable applied voltages, the DEAMs can be adjusted to have a good broad high TL in the low frequency range.

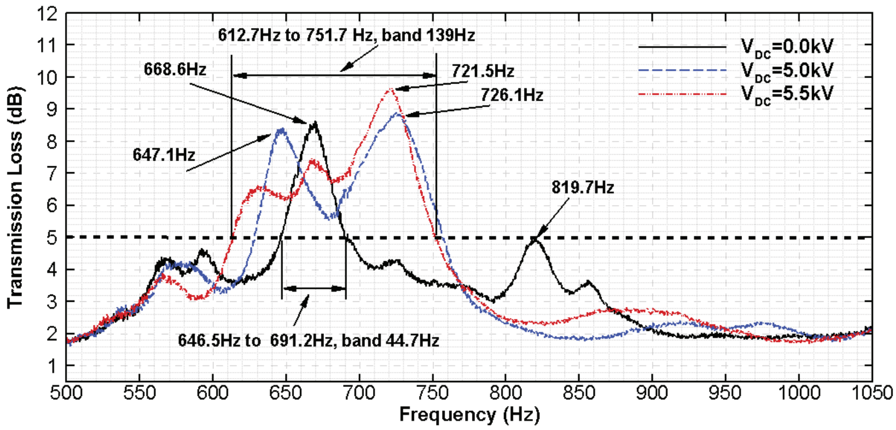

Figure 5 - Broadband acoustic performance of the DEAMs with suitable applied voltages

4. CONCLUSIONS

The acoustic performances of the DEAMs were experimentally characterized and analyzed in the present paper. The main conclusions are listed as follows:

(1) With the help of the central platelet, it is possible to use a compact back cavity for achieving good acoustic performance in a lower frequency range, typically below 1000Hz;

(2) By adjusting the voltage applied on the DE membranes, the inner stresses can be tuned, leading to the TL peak shift phenomenon;

(3) Proper tuning through voltage changes gives rise to new and broader high TL band. In the present case, the high TL band can be further enlarged by 3.1 times at the applied voltage 5.5kV, corresponding to a high TL band increase from 44.7Hz to 139Hz.

Systematic modelling and simulation for the DEAMs will be conducted in the future for further investigating the underlying physical mechanism. Parametric studies and system optimization will also be explored.

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