The Journal of the Acoustical Society of America

SEPTEMBER 08 2015

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J. Acoust. Soc. Am. 138, EL236–EL241 (2015)
https://doi.org/10.1121/1.4929629

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An electronically tunable duct silencer using dielectric elastomer actuators

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Abstract: A duct silencer with tunable acoustic characteristics is presented in this paper. Dielectric elastomer, a smart material with light-weight, high elastic energy density and large deformation under high direct current/alternating current voltages, was used to fabricate this duct silencer. The acoustic performances and tunable mechanisms of this duct silencer were experimentally investigated. It was found that all the resonance peaks of this duct silencer could be adjusted using external control signals without any additional mechanical part. The physics of the tunable mechanism is further discussed based on the electro-mechanical interactions using finite element analysis. The present promising results also provide insight into the appropriateness of the duct silencer for possible use as next generation acoustic treatment device to replace the traditional acoustic treatment.

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Date Received: April 16, 2015 **Date Accepted:** August 12, 2015

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1. Introduction

A duct silencer is used to reduce the noise inside air-handling systems caused by the fan, passage of air through straight ducts, or impact of air flowing through components. The main components for the duct silencer are the resonators.[1–3] The traditional resonators, generally passive resonators, are specifically designed to achieve their optimal performance at a single frequency, and their effective ranges are limited to a narrow frequency range. Recently, adaptive resonators associated with extra mechanical parts have overcome these drawbacks to some extent,[4,5] but the large weight and complexity of the whole system might limit their implementation. New designs with simple structures are strongly required for improving the acoustic performance of the duct silencer.

Recently, the acoustic characteristics of a dielectric elastomer (DE) resonator coupled with a back cavity were experimentally investigated in an impedance tube.[6] This DE acoustic absorber (DEAA) can shift all of the resonances to lower frequencies, when the membrane is subject to a direct current (dc) voltage, which implies that the DEAA can be potentially used for noise suppression as a tunable Helmholtz resonator without adding any additional mechanical parts. The DE actuator is one of the up-to-date actuators that brought applications distinct from the conventional actuators.[7–17] Many researchers have mainly focused on the quasi-static deformation of DE actuators with respect to applications such as artificial muscles[18] or tactile displays.[19] However, DE actuators can deform over a wide range of frequencies, and its acoustical performance is crucial for loudspeakers[16,17] or dynamic performance of the DE membrane.[12,20] For these acoustics researches, DE loudspeakers constructed to date are mostly proof of concept devices and need to be tested rigorously in order to be commercialized,[11,21] and the dynamic performances of the DE membrane which may have great potential for noise control are still not explicitly explored. Along the thinking of this line, a new duct silencer using DEAA was designed and tested in the present paper. The objectives are twofold: (1) Tunable acoustic characteristics of various duct silencer configurations using DE actuators was investigated, and (2) the resonance shift

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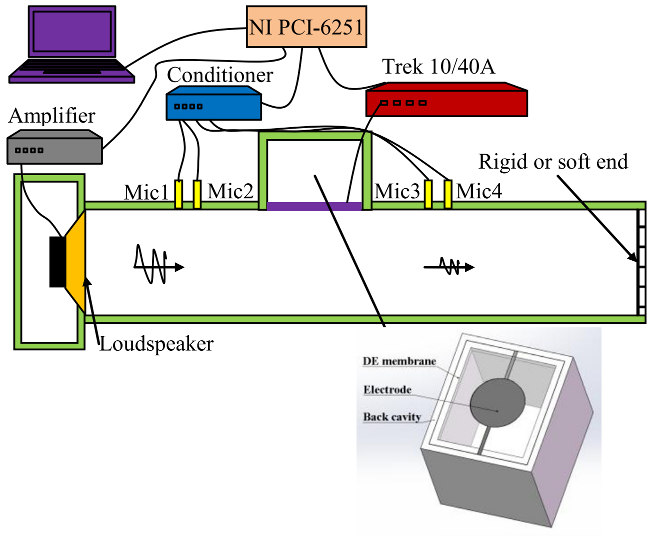

Fig. 1. (Color online) Experimental setup for the tunable silencer.

mechanism was further explored using the finite element analysis for explaining the electro-mechanical interactions and their effect on the sound absorbing property.

2. DEAA model and measurement system

The acoustic measurement was conducted in a rectangle duct with a cross section of 160 mm × 160 mm. Figure 1 shows the experimental setup. A loudspeaker is installed at one end of the duct and acts as the sound source to generate sinusoidal wave or white noise. The DE absorber with a sealed back cavity is installed at the centre of the duct working section. As shown in Fig. 1, a duct silencer consists of a DE membrane coupled with a back cavity. The depth of the cavity is 160 mm. The dimensions of the DE membrane are 160 mm × 135 mm. In order to avoid the wrinkle phenomenon, the circular conductive electrode covers 25% of the whole DE membrane surface. Four printed circuit board (PCB) array microphones of model 130E20 (PCB Piezotronics) 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." A two-load method is used to measure the transmission loss (TL) of the duct silencer;[22] one of the advantages of this method is that it does not need an absorption anechoic end, only the normal rigid and acoustic foam end can be used for the measurements. The frequency range of the present duct is from 50 to 1060 Hz due to the cross section of the duct. A Trek 10/40 A (Trek) high voltage amplifier is used to generate both dc and alternating current high voltage from 0 to 10 kV on the DE membrane. All the acquisition and control signals were programmed using the NI PCI (National Instruments) platform.

A cavity installed on the wall of the duct, acting as an "acoustic resonator," can absorb acoustic energy around its resonance frequency. In the present experiment, a cavity with depth $h = 160$ mm, length $l = 135$ mm, and width $w = 160$ mm was installed on one side of the duct. The TL of this cavity was measured using the TL measurement system and plotted in Fig. 2. It is observed that the resonance frequency of this cavity is at 466.3 Hz. There is only one resonance peak in the frequency ranges from 50 to 1060 Hz. Without changing the dimension of the cavity itself, a porous plate can be placed on the open end of the cavity to adjust the resonance peak of the cavity. The couplings between the porous plates with the back cavity do change the resonance frequency of the whole system as shown in the traditional acoustic treatment designs. However, the resonance peaks are limited by the configurations of the holes on the porous plate, such as the thickness of the plate, the diameters of the holes, and the ratio of the holes on the surface. The disadvantage of this design is that the resonance frequency of the system cannot be easily tuned without the support of addition mechanical parts. Therefore, a membrane was used to replace the porous plate; in this acoustic system the sound energy can transfer into the back cavity when they coincide with the resonances of the membrane, and the sound energy converts into heat as the membrane vibrates. The membrane and the back cavity can be regarded as an acoustic resonator which can be considered as one part of the duct silencer. Following this line of thinking, a membrane of DE was used to cover the open end of the cavity, thus the

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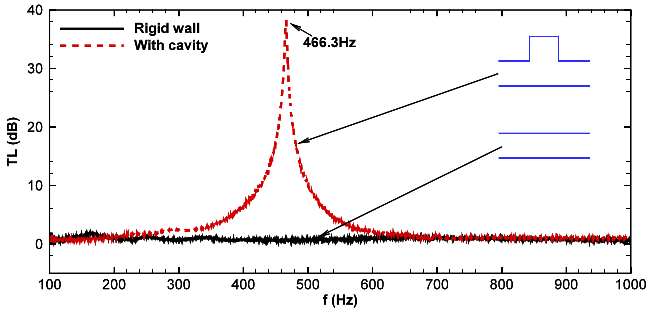

Fig. 2. (Color online) TL for the cavity without DE membrane, DE membrane with cavity, and various pre-stretched ratios.

coupling between the DE membrane and the back cavity becomes a new acoustic absorption system and the resonance frequencies can be tuned using external electric control signals.

3. Tunable duct silencer using DE actuators

A DE membrane with the pre-stretched ratio $\delta = 4.0$ is used to cover the open end of the cavity. Here pre-stretched ratio δ is defined as $\delta = r_1/r_0$, where r_0 is the original dimension of the membrane and r_1 is the dimension after pre-stretching. The TL for the duct silencer with $\delta = 4.0$ DE membrane under various dc voltages is shown in Fig. 3. It is found in Fig. 3(a) that there are two main resonances, one resonance is around 300 Hz, the other peak is around 350 Hz, while the resonance frequency for a pure cavity is at 466.3 Hz which is not within the frequency range from 280 to 380 Hz; it is because the coupling between the DE membrane and the cavity can induce a new resonance characteristic for the whole system. When applying the dc voltage, the resonance shift phenomenon can be clearly observed. The two main peaks change by almost the same values to lower frequencies; at 4.0 kV dc voltage, the two resonant frequencies shift by 31.8 and 29.3 Hz, respectively. This model can be adjusted using auto-adjust dc voltages (by implementing a feedback control system). To absorb the noise in two frequency bands, one is the frequency ranging from 306.7 to 274.9 Hz, and the other one is the frequency from 348.8 to 319.5 Hz, giving a bandwidth about 61.1 Hz in a linear control range. In Fig. 3(b), it can be seen that with higher dc voltages, the bandwidth increases. By applying 6.0 kV dc voltage, the resonance can be shifted from 348.8 to 289.3 Hz ($\Delta f_{\rm shift} = 59.5$ Hz) which is the maximum resonance shift for the present cases. The peak's value is 19.3 dB which indicates that at this

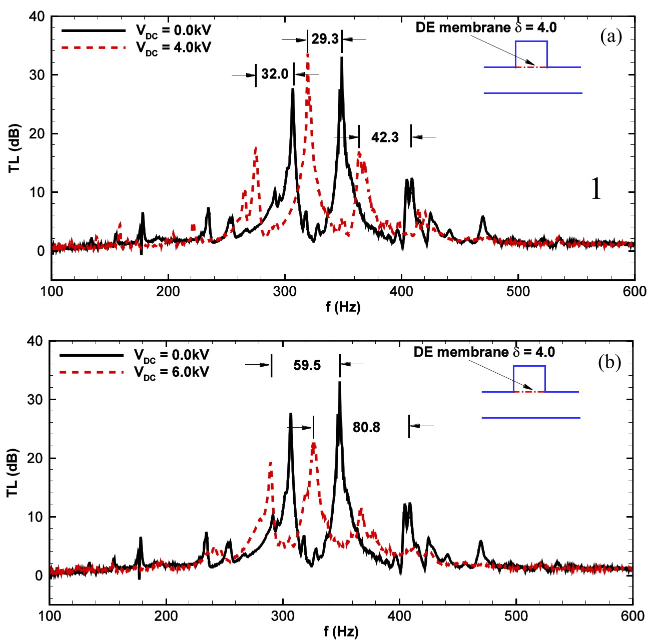

Fig. 3. (Color online) TL for the duct silencers with $\delta = 4.0$ DE membrane under various dc voltages. (a) Applied voltage is 4.0 kV; (b) applied voltage is 6.0 kV.

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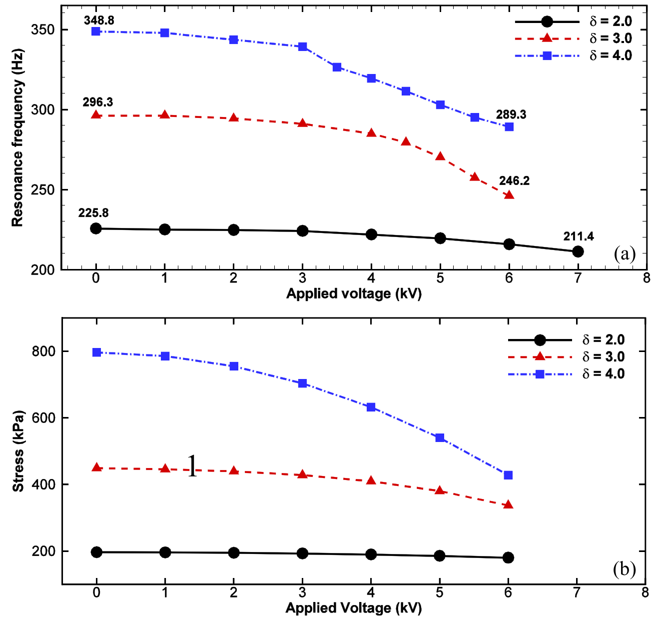

Fig. 4. (Color online) Resonance frequencies and the stresses for various pre-stretched ratios at different applied voltages. (a) Resonance frequencies; (b) stresses in the membrane.

frequency, over 90% of the sound energy can be absorbed. Actually, the stress in the DE membrane will change when we apply voltage on the surface of the DE membrane; the decrease of the stress can lead to a reduction of the first resonance frequency of the DE membrane. The duct silencer is formed by the DE membrane and the back cavity, and the acoustic characteristic of the duct silencer is determined by the coupling between the DE membrane and the back cavity. Once the first resonance frequency and its corresponding resonance frequencies of the DE membrane have been altered, the resonances of the whole system will also be changed; this phenomenon can be regarded as a "resonance shift mechanism" based on the complex electric-membrane-acoustic interactions. Thus, the acoustic characteristics of the duct silencer can be adjusted to absorb noise with different dominant frequencies using external dc voltages without any additional mechanical parts. Furthermore, it also has the following advantages: (1) Fast response by changing the control dc voltage; (2) do not need any extra mechanical parts; (3) unlike resonators with a porous membrane, tiny particles cannot affect its performance; and (4) all these resonance peaks can have almost the same shift when applying dc voltages, therefore, the noise absorption using this duct silencer can be done and shifted at multi-frequency ranges for improving the efficiency of the noise reduction technology.

Resonance shift is the key characteristic for this new duct silencer which determines acoustic performance. Therefore, the resonance shifts for the duct silencers with various pre-stretched ratios and applied voltages were further investigated; the results are shown in Fig. 4(a). It can be seen in Fig. 4(a) that the larger the pre-stretch ratio, the higher the resonance shift. Furthermore, it is also interesting to note that the resonance shift increases almost linearly with respect to the applied voltages for all the pre-stretched ratios, whereas at a lower rate when the applied voltage is smaller than 3 kV and a higher rate when the applied voltage is larger than 3 kV. For the pre-stretched ration $\delta = 3.0$ and $\delta = 4.0$, the rate is smaller when the applied voltage is less than 3 kV than when the applied voltage is greater than 3 kV. It can be interpreted that at the higher pre-stretched ratios and applied voltages, the reduction of the membrane's thickness will further increase the strength of the electric field which leads to a larger stress reduction. Thus, the resonance shift will increase at a higher rate. The monotonic relationship between the resonance shifts and the applied voltage also indicates that the target resonance shift can only be achieved at the corresponding applied voltage which is very important in order to implement a control algorithm.

Furthermore, the DE membrane has been computationally modelled using finite element software, ABAQUS.[23] Stress in the direction of the length has been computed at the periphery of the active layer with coordinates $x = 41.5$ mm and $y = 0.0$ mm. The variation of nominal stress, s_{11} with voltage for pre-stretch ratios,

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$\delta = 2.0$, 3.0, and 4.0, has been shown in Fig. 4(b). The shift in the resonant frequency from higher values to lower values with an increase in voltage can be explained by the reduction of stress in the membrane with an increase in voltage. It can be seen that a membrane with a higher pre-stretch shows a larger drop in the stress which corresponds to a larger drop in resonant frequency for a membrane with higher pre-stretch, as observed in Fig. 4(a).

4. Conclusions

A new duct silencer using the DE actuators was developed in the present paper. The main conclusions are summarized as follows: (1) Duct silencer, formed with the DE membrane and back cavity, acts as an acoustic resonator. It can absorb the sound wave energy when the frequencies of the sound wave coincide with the frequencies of resonance for the whole system. (2) Larger pre-stretch ratios of the DE membranes give higher frequencies of the resonance peaks. The stress in the DE membrane will be changed when applying voltage to the DE membrane, the decrease of the stress can lead to a reduction of the first resonance frequency of the DE membrane, thus the other resonances of the system will also be changed. Therefore, the duct silencer can be adjusted to absorb noise with different dominant frequencies using external dc voltages without any additional mechanical part which can be regarded as a resonance shift mechanism. A maximum resonance shift of 59.5 Hz was achieved by applying 6.0 kV dc voltage to the duct silencer with a pre-stretched ratio $\delta = 4.0$. (3) A duct silencer with various pre-stretched ratios and dc voltages can be combined together as a new duct silencer; each sub-model has its own resonance peaks, thus it is possible that two nearby resonance peaks can combine to new peaks which lead to a broadband noise reduction platform. Therefore, the electronically tunable characteristic of this novel duct silencer also provides insight into the appropriateness for possible use as a new generation acoustic treatment device to replace the traditional acoustic treatment.

References and links

[1] U. Ingard, "On the theory and design on acoustic resonators," J. Acoust. Soc. Am. **25**(6), 1037–1061 (1953).

[2] I. J. Hughes and A. P. Dowling, "The absorption of sound by perforated linings," J. Fluid Mech. **218**, 299–335 (1990).

[3] C. Wang, J. Han, and L. Huang, "Optimization of a clamped plate silencer," J. Acoust. Soc. Am. **121**(2), 949–960 (2007).

[4] R. J. Bernhard, H. R. Hall, and J. D. Jones, "Adaptive-passive noise control," Proc. Inter-Noise **92**, 427–430 (1992).

[5] N. Sellen, M. Cuesta, and M.-A. Galland, "Noise reduction in a flow duct: Implementation of a hybrid passive/active solution," J. Sound. Vib. **297**, 492–511 (2006).

[6] Z. Lu, Y. Cui, J. Zhu, Z. Zhao, and M. Debiasi, "Acoustic characteristics of a dielectric elastomer absorber," J. Acoust. Soc. Am **134**, 4218 (2013).

[7] R. Pelrine, R. Kornbluh, Q. B. Pei, and J. Joseph, "High-speed electrically actuated elastomers with strain greater than 100%," Science **287**, 836–839 (2000).

[8] F. Carpi, D. D. Rossi, R. Kornbluh, R. Pelrine, and P. Sommer-Larsen, *Dielectric Elastomers as Electromechanical Transducers: Fundamentals, Materials, Devices, Models and Applications of an Emerging Electroactive Polymer Technology* (Elsevier, United Kingdom, 2008).

[9] S. Ashley, "Artificial muscles," Sci. American **289**, 52–59 (2003).

[10] F. Carpi, S. Bauer, and D. De Rossi, "Stretching dielectric elastomer performance," Science **330**, 1759–1761 (2010).

[11] A. O'Halloran, F. O'Malley, and P. McHugh, "A review on dielectric elastomer actuators, technology, applications, and challenges," J. Appl. Phys. **104**, 071101 (2008).

[12] P. Dubois, S. Rosset, M. Niklaus, M. Dadras, and H. Shea, "Voltage control of the resonance frequency of dielectric electroactive polymer (DEAP) membranes," J. Microelectromech. Sys. **17**, 1072–1081 (2008).

[13] N. C. Goulbourne, E. M. Mockensturm, and M. I. Frecker, "Electro-elastomers: Large deformation analysis of silicone membranes," Int. J. Solids Struct. **44**, 2609–2626 (2007).

[14] M. Zhenyi, J. I. Scheinbeim, J. W. Lee, and B. A. Newman, "High field electrostrictive response of polymers," J. Polym. Sci., Part B: Polym. Phys. **32**, 2721–2731 (1994).

[15] J. Scheinbeim and B. Newman, "Electrostrictive driving device, process for sonic wave projection and polymer materials for use therein," U.S. patent 5,229,979 (1993).

[16] R. Heydt, R. Pelrine, J. Joseph, J. Eckerle, and R. Kornbluh, "Acoustical performance of an electrostrictive polymer film loudspeaker," J. Acoust. Soc. Am. **107**, 833–839 (2000).

[17] R. Heydt, R. Kornbluh, R. Pelrine, and V. Mason, "Design and performance of an electrostrictive-polymer-film acoustic actuator," J. Sound Vib. **215**, 297–311 (1998).

[18] K. J. Kim and S. Tadokoro, *Electroactive Polymers for Robotic Applications* (Springer, London, 2007).

[19] M. Matysek, "Dielektrische Elastomeraktoren in Multilayer-Technologie für taktile Displays," Ph.D. thesis, Technische Universität Darmstadt, Germany, 2009.

[20] J. Zhu, S. Cai, and Z. Suo, "Resonant behavior of a membrane of a dielectric elastomer," Int. J. Solids. Struct. **47**, 3254–3262 (2010).

14 March 2025 08:51:35

[21]C. Keplinger, J.-Y. Sun, C. C. Foo, P. Rothemund, G. M. Whitesides, and Z. Suo, "Stretchable, transparent, ionic conductors," Science **341**, 984–987 (2013).
[22]T. Y. Lung and A. G. Doige, "A time-averaging transient testing method for acoustic properties of piping systems and mufflers with flow," J. Acoust. Soc. Am **73**, 867–876 (1983).
[23]X. Zhao and Z. Suo, "Method to analyze programmable deformation of dielectric elastomer layers," Appl. Phys. Lett **93**, 251902 (2008).

14 March 2025 08:51:35