

# An application review of dielectric electroactive polymer actuators in acoustics and vibration control

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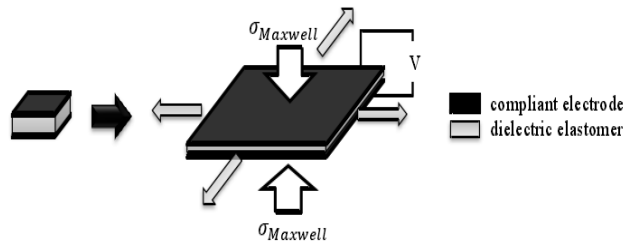
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**Abstract.** Recent years have seen an increasing interest in the dielectric electroactive polymers (DEAPs) and their potential in actuator applications due to the large strain capabilities. This paper starts with an overview of some configurations of the DEAP actuators and follows with an in-depth literature and technical review of recent advances in the field with special considerations given to aspects pertaining to acoustics and vibration control. Significant research has shown that these smart actuators are promising replacement for many conventional actuators. The paper has been written with reference to a large number of published papers listed in the reference section.

## 1. Introduction

Electroactive polymers (EAPs) are smart materials capable of substantial changes in size or shape subjected to electrical stimulation, and can be categorized into two major classes, namely ‘ionic’ and ‘electronic’. The electronic EAPs include electrostrictive elastomers, ferroelectric polymers and dielectric electroactive polymers (DEAPs), also referred to as dielectric elastomers (DEs) (for example silicone, acrylic, polyurethane etc.) The DEAPs have been shown to be potentially useful materials for actuator applications due to their large actuation strains together with a fast response and a high energy density. Much attention has been paid to the application of the DEAPs in actuation technology. [1]-[5]

The basic structure of a DEAP actuator consists of a dielectric elastomer membrane sandwiched between two compliant electrodes. An electric field is applied between the compliant electrodes, causing compression in thickness and stretching in area of the film, as illustrated in figure.1. Compared with the conventional actuators based on the electromagnetic principle such as electroactive ceramic (EAC) or shape memory alloy (SMA) actuators, the DEAP actuators possess low elastic stiffness and high dielectric constant. The anticipated advantage over the conventional actuators is that they can produce high strain levels with large deformations, considerable generated forces, high energy convention efficiencies, lightweight and low-noise. [6]-[8]

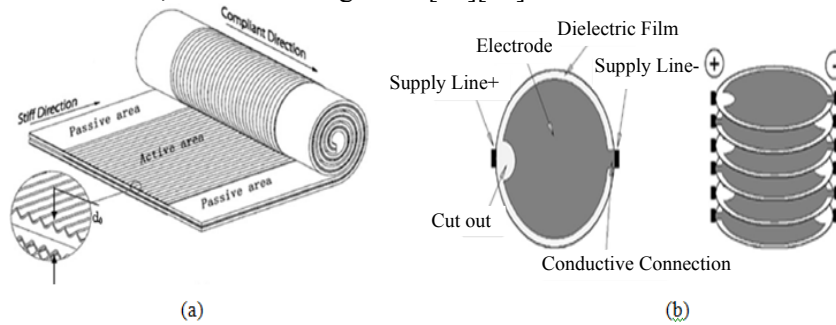


**Figure 1.** Deformation of the dielectric elastomer membrane under high voltage.<sup>[9]</sup>

In the past decades, the DEAP materials have been most widely used in the development of DEAP actuators based on their unique properties. [2] The applications of electroactive polymer (EAP) and dielectric elastomer (DE) were discussed by Yoseph Bar-Cohen [1][10], Ailish O’Halloran [3], Federico Carpi [11][12] and so on. As suggested in earlier research, the applications of the DEAP cover a broad spectrum such as intelligent robotics, bioengineering and automation. This paper reviews the recent advances of the DEAP actuators, with particular applications for acoustics and vibration control.

## 2. Typical configurations of DEAP actuators

A DEAP film can be fabricated into actuators with the way in which the elongation in the plane of the film or its contraction in thickness can be applied for actuation purposes. When it comes to practical application, however, a single layer dielectric elastomer film is very thin and thus cannot lead to a large deformation or a considerable generated force. To overcome this, novel multilayer technologies are proposed so that the deformation or force in one direction are large under controllable conditions. Two fundamental configurations of the multilayer DEAP actuators have shown some promise in the application of active vibration control, and thus are of particular interest in this paper. These include the roll- and stack-actuators, as shown in figure 2. [13][14]



**Figure 2.** Typical configurations of DEAP actuators: (a) roll-actuator<sup>[15]</sup>  
(b) stack-actuator<sup>[18]</sup>

### 2.1. DEAP tubular actuators

As illustrated in figure 2 (a), to produce large deformations or forces, a multi-layer tubular actuator is made by rolling a DEAP film into a cylinder. As a result, the tubular actuators apply actuation forces in the axial direction, thereby providing axial elongations under certain actuated voltage. Generally, there are two main tubular actuator designs. [13] The first design involves a compliant graphite or carbon electrode and a pre-strained acrylic elastomer, wrapped many times around a compressed spring core. Unfortunately the high stress concentration at the interface between the soft polymer film and the spring core may cause mechanical failures, which drastically reduces the durability of the actuator. [16] The second design is a core-free rolled tubular actuator. For example, a patented DEAP actuator developed by a Danish company called Danfoss PolyPower A/S, is formed by a silicone elastomer without pre-load sandwiched between two compliant metallic electrodes. Compared with

the above acrylic-based design, the silicone-based tubular actuator has excellent durability despite a relatively small strain under applied voltages. [5][17]

### 2.2. DEAP stack actuators

For this particular type of actuators, large deformations are realized by a stacking process, as illustrated in figure 2 (b). The devices with the specific configurations are considered to be the most suitable for developing light, compliant and flexible systems at noise free actuation. [18] Recent work has demonstrated that, DEAP stack-actuators can be successfully built with mechanically stable electrodes allowing a stacking process. Substantial research has been focused on the development of DEAP stack actuators by Roman Karsten, Henry Haus, Peter Lotz and Helmut F. Schlaak from Technische Universität armstadt, [19]-[23] J. Maas, D. Tepel and T. Hoffstadt from Lippe University of Applied Sciences, [14] Herold S., Kaal W. and Melz T. from Fraunhofer Institute for Structural Durability and System Reliability LBF [24][25] and Kovacs G from Federal Laboratories for Materials Science and Technology. [18][60] To date, however, the optimization of automated manufacturing processes for such actuators is at a very early stage, and there are still a number of gaps in the existing designs in terms of the inhomogeneity of strain distribution along its length. [14]

## 3. Applications of DEAP actuators in acoustics

As DEAP actuators have the advantages of being very lightweight and able to conform to any shape or surface over a wide range of frequencies, they have been considered to have potential applications in acoustics as low-profile and surface-mounted loudspeakers in rooms or vehicle interiors, [31] and for applications in active noise control like tunable acoustic resonators and so on.

### 3.1. DE loudspeaker in sound generation

The study of novel devices alternative to moving-coil electromagnetic loudspeakers has a long history for sound generation in practice, along with more practical issues such as the size, shape, weight, efficiency, and sound quality. [31] Apart from one of the most successfully applied polyvinylidene fluoride (PVDF) loudspeakers [27][28], the EAPs have been found to be particularly suited to the purpose of the development of acoustic transducers due to the materials being flexible, lightweight and having large actuation deformation in an electric field. In order to integrate lightweight and compact loudspeakers, a great deal of studies has been conducted on sound generation using various types of EAPs. The progress of dielectric elastomer (DE) loudspeakers discussed in previous research is summarized as follows.

In the 1990s, a pioneering study on DE loudspeakers based on a silicone elastomer was presented by Stanford Research Institute (SRI) International. [29][30] More recently, B. Lassen [32] from the University of Southern Denmark developed a theoretical model of the two dimensional hyper-elasticity for SRI's DE loudspeakers, accounting for the morphology of the membrane surface, with particular emphasis on the radiative losses (acoustic losses) of the loudspeakers.

Based on the characteristics of large deformation in the electrical field, Christian Graf [17] generated sound waves using the DE, and demonstrated the advantages of the DE loudspeaker for realization of an excellent impulse and wide-band frequency response. Dennis Nielsen [16] developed a small signal model of the DEAP transducer with validation by using impedance measurements. In this research, a push-pull DEAP based loudspeaker has been proven to be an alternative to the electrodynamic transducer in sound reproduction systems.

C. Thyges *et al* from Technische Universität Darmstadt [61] promoted the sound transmission properties of double-glazed windows through finite element analysis, and the fully integrated EAP loudspeakers were tested as well. Takehiro Sugimoto *et al* [33] from the NHK Science & Technology Research Laboratories proposed a semi-cylindrical acoustic transducer using a thermoplastic polyurethane elastomer film. Later, they developed a lightweight push-pull acoustic transducer using the same DE material, which stably converts the surface expansion of a DE film into the vibration of the diaphragm for sound generation. The resonance frequency of the transducer was derived from

modeling the push-pull configuration to estimate the lower limit of the frequency range. Measurements were made to show an advantage of push-pull driving in suppressing harmonic distortion. [34]

### 3.2. Adaptive acoustic absorber in noise control

The use of acoustic absorbers or resonators is currently practical for noise control in many engineering applications. [35] The main disadvantage of the conventional passive resonators is that they are generally narrow-band control devices since they are designed to achieve optimal performance at a certain frequency. The application of such passive devices becomes less effective, when it is required to suppress relatively broadband noise. In addition, the limitation of weight and size is another drawback in practical applications. In order to overcome these problems, the active tunable resonators have been designed by adopting lightweight materials with scalability to small and large areas in order to be tuned at various frequencies under different voltages. Although previous research has shown the great potential of the DE membrane for noise control, the dynamic performances of such devices have not been well documented, and there is a desire for further exploiting the devices prior to their practical applications. [36]

Research work by Richard Heydt *et al* [31] at SRI focused on two applied aspects of noise control by means of DE loudspeakers. The devices can be utilized in the interior of an automobile, aircraft, or other vehicles to control cabin noise. Moreover, when they are attached to the surface of a vibrating machine or structure, the radiated noise can also be effectively suppressed.

Laehwan Kim [37][38] from Inha university in Korea investigated the properties of Electro-Active Papers (EAPap) which could be used as acoustic actuators, and conducted experiments to study the operational principle of the EAPap. The lightweight EAPap actuators have shown some promise and thereby being potentially useful as active sound absorbing materials and flexible speakers.

Allan J. Moustgaard [39] carried out experimental investigations into the characteristics of sound level and total harmonic distortion of the flat panel using tubular DE acoustic actuators within the frequency range of 20-200Hz. Operating factors such as the D.C. voltage and pre-straining of the actuator were also examined, suggesting the potential application of this low frequency loudspeaker for the purpose of noise cancellation.

Zhenbo Lu *et al* [40] from National University of Singapore developed a novel duct silencer namely 'Dielectric Elastomer Acoustic Absorber' (DEAA), which was a lightweight acoustic resonator formed by a DE membrane (VHB 4910) and a back cavity. The resonances of the device shift in response to the stress changes of the DE membrane of various pre-stretch ratios in the external electric field. As a result, the resonance peaks of the DEAA shift to lower frequencies in order to achieve broadband noise reduction. The electronically tunable characteristic of the acoustic resonator offers a potential improvement over the conventional acoustic treatments for noise control.

## 4. Applications of DEAP actuators in active vibration control

Dielectric elastomer actuators (DEA) have been shown to be effective for active vibration control at low frequencies below 200Hz. [19] Lightweight structures often tend to vibrate with large amplitudes at a relatively low force level at these frequencies. The DEA with a large stroke capability and a short response time have been found to be particularly useful in practical applications, for example, as a protection of a car body metal sheet structure [53] and sensible equipments such as optic components from vibrations. Besides, small adaptive absorbers can be adopted for attenuation at different resonance frequencies of a system by tuning the stiffness of the DEA under certain electrical voltages. [20]

### 4.1. Active vibration isolation

F. G. Papaspiridis [54] provided a general framework for the use of the DEA in an active vibration control system modelled as in a single degree of freedom (mass-spring) system. The results showed

that the vibrations caused by an external force could be suppressed significantly by employing the DEA. As vibration of buildings occurs at very low frequencies, Umberto Berardi [57] pointed out that DEAPs could be used for vibration isolation such as seismic isolation of heavy structures when combined with other resistant materials. Furthermore, it has been suggested that the DEAP patches could be applied efficiently in structural health (vibration) monitoring.

The commercial rolled tubular actuator (InLastor Push) manufactured by Danfoss PolyPower A/S, was adopted in the feasibility study to investigate its performance for active vibration isolation (AVI). Umberto Berardi [41] proposed a multi element theoretical model for this actuator, and showed the effectiveness of this device for active isolation of harmonic excitations at frequency below 10Hz. This DEAP actuator was also investigated by Rahimullah Sarban, Richard W. Jones, Emiliano Rustighi and Brian R. Mace. [5][13][17][43]-[48] They studied the DEAP actuator's fabrication, static and dynamic characteristics and its active vibration isolation performance. In their work, experiment results have shown that a 250g mass can be effectively isolated under both the low frequency periodic and broadband random vibratory disturbances with a reduction of 19dB over a frequency range from 2-8Hz using an adaptive feedforward control strategy. They subsequently validated the grey-box model for three different sizes of the DEA, representing different model-based control for the purpose of AVI. [49] Apart from the push configuration actuator mentioned above, another folded pull actuator was investigated for vibration control. [50]

On the other hand, significant research was focused on the use of DEAP stack actuators for the AVI. Roman Karsten and Helmut F. Schlaak [21][58] discussed the application of dielectric elastomer stack actuators (DESA) as small adaptive absorbers to attenuate varying resonance frequencies of a system, and investigated an active isolation mat for cancelation of vibrations on sensitive devices with a mass of up to 500g. The mat contains 5 DESAs made of silicone Elastosil P7670. Experimental results showed that vertical disturbing vibrations were attenuated actively while horizontal vibrations were damped passively. Sven Herold and William Kaal [25] developed a new DESA with rigid and perforated electrodes for passive and active vibration control. They used the multilayer stack actuator to attenuate vibrations of a truss structure. Compared to the simulation results, a further reduction of the amplitudes at the resonances between 30Hz and 200 Hz was observed.

#### 4.2. Adaptive vibration damping

The viscoelasticity of the DE offers an advantage and thus can be applied as a vibration damper. Hualing Chen *et al* [51] developed a model to achieve the passive vibration control using a spring oscillator. Active vibration attenuation was further achieved by applying alternating oppositely-phased voltages at different frequencies. The vibration damping has proven to be tunable by applying different voltages. Herold S. *et al* [42][55][56] investigated the design and application of active interfaces and semi-active vibration absorbers, suggesting DE actuators as ideal components for setting up control loops to suppress unwanted vibrations. They also studied the actuator's nonlinearity and its negative effects on the controlled system numerically and experimentally. They applied the DEA to achieve active vibration control for two different mechanical systems based on compensation methods and control approaches.

The effect of the mechanical pre-strain of VHB™ 4910 was studied by Kai Wolf *et al* [52]. They proposed a concept for suppressing the resonant vibration of an elastic system due to forced vibration by using a DEA. They employed the adaptive supports of DE strip actuators to change the stiffness of the end support of a clamped aluminum beam under harmonic vibration. A shift of the resonance frequencies of the vibrating beam was realized, enabling an effective reduction of the vibration amplitude by an external electric signal.

Arnulf Spieth [59] developed a mass damper formed of a counter vibrating mass and an EAP-based damping spring for attenuating a vibrating system of a motor vehicle or an exhaust system of an internal combustion engine. The resonant frequency of the mass damper can be tuned to attenuate the structural vibration at different frequencies.

## 5. Conclusion

This paper reviews the development of DEAPs as an emerging smart material in actuator technologies, providing immediate insights into the research progress of the DEAPs including the configurations and applications for acoustic and vibration control. In particular, the multilayer DEAP roll- and stack-actuators are achieved worldwide to realize a large deformation or a considerable generated force in practical applications. The large number of papers reviewed in this paper has indicated that the DEAP actuators offer a potential improvement over the conventional actuators considering their advantages as DE loudspeaker in sound generation and adaptive acoustic absorber in noise control, and prospects in the domain of active vibration and adaptive vibration damping.

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