## Research Article

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# Influence of loading voltage, domain ratio, and additional load on the actuation of dielectric elastomer

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Abstract: Dielectric elastomer (DE) is widely used in various fields because of its advantages of large deformation, lightweight, and good flexibility. In this article, based on our previous research work, the actuation performance of the cone dielectric elastomer actuator (DEA) is studied first, and the influence of loading voltage, domain ratio, and additional load on the displacement and output force of DEA is analyzed and discussed. Then, a three-dimensional model of displacement and force of DEA is established. At last, the relationship between the structure and the performance of DE is discussed from the microscopic point of view. The results show that the output displacement and force of the cone DEA increase with the increase of loading voltage and additional load. The three-dimensional model graph of cone DEA can reflect the performance change of DEA well. The design with different domain ratios is the key factor that influences the final DEA actuator, which has a great influence on the cross-link density and chain length in the DE structure. By making clear the regulating function of external environment factors, we can design DEA with different configurations, which lays a good foundation for the further development of DEA and enlarges the potential application scope of DEA.

**Keywords:** EAP, dielectric elastomer, actuation, microconformation

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## 1 Introduction

Electronic electroactive polymers (EAPs) are widely used owing to their excellent flexibility and deformability [1,2]. Dielectric elastomer (DE) is a new type of EAP material, which is prepared by coating the upper and lower surfaces of DE with flexible electrode materials [3,4]. Dielectric elastomer actuators (DEAs) have the advantages of simple structure, direct actuation, low cost, lightweight, low density, large deformation, large displacement, and high efficiency [5-7]. It is considered to be an actuation part with important potential application value in the future. After high voltage loading, the positive and negative charges will be distributed to the two flexible electrodes, respectively, and they will be deformed under the action of electrostatic pressure, as shown in Figure 1. Using this feature, DEs can convert electrical energy into mechanical energy, making DEA widely used in cardiac membrane pumps, flexible loudspeakers, flow pumps, energy collection devices, microsystem devices, and robots [8-12].

DEs are mainly made of silicone, VHB, polyurethane elastomer, and so on. The mechanical and electrical instability can be reduced by prestretching [13], and prestretching has been included in different deformation models modeled in DEA [14] and it is also involved in applications such as life jackets, artificial skin, and linear actuators [15,16]. It has been shown that the actuation strain of the DE transducer can be increased by 500% [17] and that the biaxial pretension mode can provide a larger actuation strain because the biaxial mode deformation reduces the thickness of the membrane to a greater extent, which leads to an increase in the actuation performance [18]. Therefore, the prestretching of the dielectric material has a great influence on the work and performance of the actuator, which cannot be ignored. At present, researchers at home and abroad have also carried out a lot of research on DEA. The cone-shaped DEA was prepared by Plante and Dubowsky using two actuation

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units [19]. The maximum displacement and the maximum output force are 12 mm and 6 N, respectively. The finite element analysis of a circular actuator is carried out by Michel et al. [20], the viscoelastic behavior of the actuator is studied, and a new electromechanical coupling model is proposed. Subsequently, Wang et al. showed that the output displacement of the actuator is mainly dependent on the voltage, and the increase of the loading will lead to a significant decrease in the speed of the actuator [21]. More recently, Mathew and Koh investigated DE with inhomogeneous deformation [22] and discussed the influence of the radius ratio and pretension ratio of inner and outer rings on the cone-shaped DEA transducer, finally determining an optimum inner and outer ring ratio and the required prestretching for maximum energy conversion. In order to determine the relationship between material geometry and properties, six DEA models with different shapes were prepared [23]. Based on the assumption that the cross-sections of the cone DEA models are similar and the stress distribution on the membrane is uniform, the influence of the geometry of cone DEA models with offset quality on the performance is studied. Cao et al. [24] designed a double-cone DEA structure, researched its dynamic response, established a research framework of power output performance, and optimized the power output of DEA according to prestretching and the interval length. At the same time, it is found that the performance of DEA is also affected by viscous dissipation and load inertia. Generally speaking, now the research of DE and DEA has made some progress; most of the studies have realized the importance of prestretching but they have not considered the effect of different environments comprehensively, and so, the DEA research is not complete and mature and there are some restrictions on revealing the actuation mechanism of DEA. In this article, the DEA samples with different domain ratios are prepared, the effects of loading voltage, domain ratios, and additional loads on the cone DEA are studied, and the three-dimensional actuation model diagram is established; finally, the theoretical model of the actuation deformation process of DEA is analyzed, which lays a foundation for the later design and application of the cone DEA.

## 2 Experiment

## 2.1 Materials

VHB4910 material of 3M Company is chosen as the base membrane of DE. It is a kind of acrylic tape with a thickness of 1 mm. It has the characteristics of super viscosity, good solvent resistance, and high flexibility. Carbon grease with good electrical conductivity is used as a compliant electrode.

## 2.2 Preparation of cone DEA

The DEA with conical structure mainly consists of an inner frame, outer frame, DE membrane, and an additional loading. The inner and outer frames are printed by Moment 3D printer (2.5-11 micron high precision, 0.02-0.3 mm printing layer) with polylactic acid (PLA) material. The internal and external diameters of the outer frame are 60 and 74 mm, respectively, and the inner frame is 20 mm in diameter. Then, the prestretching, preparation of cone-shaped DEA, electrode painting, and loading are carried out. The detailed preparation steps are described in ref. [25]. It is worth noting that although the copper tape has a certain viscosity, one needs to apply appropriate pressure in contact with the external field electrode so that the bond strength is strong. In addition, the stretching fixation process is divided into two steps. The first step is to fix the stretching elastomer with the inner frame, and the second step is to change the stretching ratio of the elastomer and fix it with the outer frame. In this article, the ratio of different stretching degrees between the inner and outer domains is defined as the domain ratio ( $\omega$ ) under the initial static condition.

After the preparation of DEA is completed, the samples are tested for different environmental factors. Setting the loading voltages to 1, 2, 3, 4, and 5 kV, respectively, the domain ratios are 1.00, 1.25, 1.33, and 1.67, with the additional loads of 10, 100, 200, and 300 g.

#### 2.3 Measurements

The experimental devices consist of a high voltage power supply (PS/FX60R05.0-22), a load sensor (FUTEK LBS200), a displacement sensor (KEYENCE IL300), a DEA sample, a data collector (NI-USB 6356), and a processing module. Under the voltage excitation, the DEA actuator will move down in a longitudinal direction, and the displacement and force sensors are used to test in the vertical direction. All measurements are made at room temperature in air.

## 3 Results and discussion

Due to the special properties of VHB4910, the mechanical properties of VHB4910 have an important influence on the DEA to some extent. The actuation performance of DEA is different because of different external effects. We have successfully prepared DEA samples with different domain ratios and tested the actuation displacement and force of these samples. The influence of different environmental factors on the actuation behavior of DEA is discussed, with emphasis on the influence of the loading voltage, the domain ratio, and the additional load.

## 3.1 Influence of loading voltages on the actuation of DEA

The actuation force of the DE material is the result of loading voltage, and the influence of different external loading voltage on the final deformation and force of DEA is obvious. Under a domain ratio of 1.25 and an additional load of 200 g, the actuation displacement and force of DEA vary with the loading voltage as shown in Figure 2(a) and (b). As can be seen from the diagram, the displacement and force as a whole increase with the increase of voltage. The change range of displacement is relatively large, first increasing rapidly and then gradually becoming slow. The magnitude of the force is smaller than the displacement, increasing slowly at first and then increasing rapidly. That is, a small load voltage is beneficial to the displacement output, and a large load voltage is beneficial to the actuation force output. At the same time, it is obvious that the actuation displacement under 5 kV is larger than that under other voltages, which shows that the high input voltage provides more actuation energy for DEA, which is very beneficial to the deformation of the actuator. Combined with the actuation principle of the DE material, the higher the applied voltage, the lower the response stress of DEA, and the greater the effect of applied voltage on the response stress, that is, the DEA shows an obvious electromechanical coupling phenomenon.

## 3.2 Effect of domain ratios on the actuation of DEA

The different domain ratios are formed by stretching. The tensile deformation of VHB4910 makes the structure of

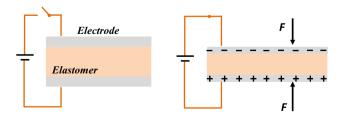


Figure 1: Actuation mechanism of DE materials.

the molecules in VHB slip between the forces, and the molecules entangle each other openly, become straight line slowly, and the molecular chain orients slowly. The breaking of the material is due to the breaking of the chemical bond in the main chain of the molecules, the slippage between the molecules, and the destruction of the intermolecular interaction force. As can be seen, the VHB4910 material is a typical elastic deformation during the tensile process, which is very suitable for DE actuators.

In order to compare the influence degree of different stretchings, the control variable method was used to carry out the actuation test of specimens with different domain ratios under the same additional load (50 g) and loading voltage (5 kV). Figure 2(c) shows the effect of different domain ratios on the actuation displacement of a cone DEA. It can be seen from the graph that the DEA displacement increases first and then decreases with the increase of the domain ratio of the inner domain and the outer domain. Obviously, it is not that the bigger the domain ratio, the bigger the final output displacement, but when the domain ratio is in a certain range, it will be more powerful to the overall DEA's output distortion. The high output displacement of this kind of cone DEA is not dependent on the properties of the material itself but is probably related to the difference of different domain ratios. In the subsequent process of making the cone DEA, the domain ratio of the inner and outer domains should be taken into account, which is more favorable for maximizing the output-driven performance. Figure 2(d) shows the effect of different domain ratios on the output force of a cone DEA. The influence of different domain ratios on the force is similar to that of the actuation displacement. The DEA reaches the maximum output force of 0.37 N when the domain proportion is 1.25. According to ref. [26], the experiment shows that the smaller the transverse ratio of the pretension index, the greater the retardation force, and the maximum retardation force is obtained at the maximum displacement. Therefore, in the process of applying a cone DEA to different equipment pieces, it is necessary to consider the actual requirements of actuators and select different domain ratios so that the displacement and force output of DEA is ideal.

# 3.3 Influence of additional loads on the actuation of DEA

In the process of forming the cone DEA, the additional load plays a key role in the actuation performance of the final DEA, and its influence cannot be ignored. This

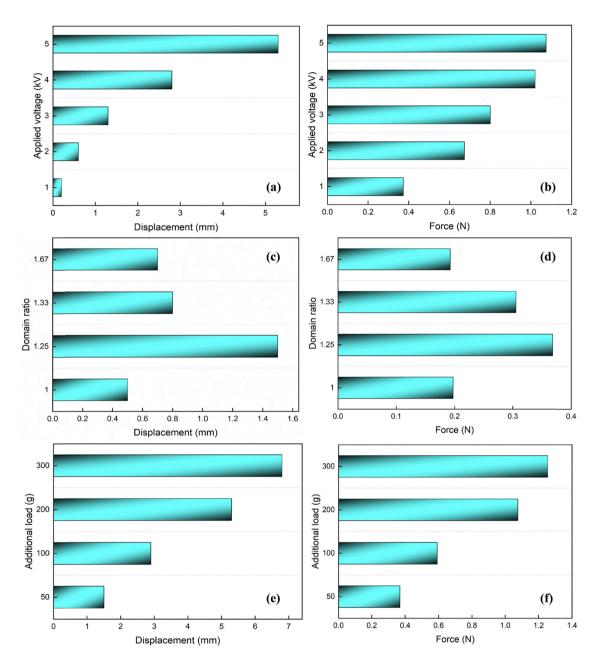


Figure 2: Actuation performance of conical actuators: (a) loading voltage vs displacement; (b) loading voltage vs force; (c) domain ratio vs displacement; (d) domain ratio vs force; (e) additional load vs displacement; and (f) additional load vs force.

article studies the actuation performance of DEA under different load conditions, as shown in Figure 2(e) and (f). For ease of comparison, the same domain scale of 1.25 and loading voltage of 5 kV are selected. As can be seen from the diagram, the output displacement and the force of the cone DEA increase with the increase of the additional load. When the additional load is too large, the performance of the cone DEA will be seriously affected, and the possibility of breakdown failure of the membrane at low voltage is higher. When selecting the load, although the larger the load, the better the actuation performance, it

is important to consider the use of environmental and practical requirements.

# 3.4 Three-dimensional actuation model diagram of the cone DEA

To establish a model that can predict the response of the cone-shaped DEA actuator, the experimental data are fitted. Two independent variables are domain ratio and applied voltage, additional load and applied voltage, and

the dependent variables are displacement and output force. The initial value of the data has an important influence on the convergence of the final model. In order to determine the appropriate initial value quickly, the Broyden–Fletcher–Goldfarb–Shanno (BFGS) algorithm is used to extract the initial value randomly so that the optimal solution can be obtained quickly. The BFGS method does not require high precision of one-dimensional search, and the BFGS matrix generated by iteration is not easy to change into a singular matrix, so the numerical stability can be improved.

The output displacement and the output force of the cone DEA are fitted, and the three-dimensional actuation model of the DEA is obtained as shown in Figure 3. It can be seen that the experimental data are very close to the calculated values, and the fitting function can well characterize the characteristic points, and the data other than the experimental data can be obtained (RMSE: root mean square error; DC: decision coefficient). The maximum RMSE of the fitted value and the experimental value is 0.25, which shows that the deviation of the fitted data from the experimental value is small, and the model selection and fitting are ideal and have good accuracy. The DC of both displacement and force is close to 1, which proves the validity of the proposed method and the

ability of the regression model to describe the dependence effect. The small change graph on the right-hand side is a cross-section of the three-dimensional graph in different directions. From the graph, we can clearly see the influence of various environmental factors on the displacement and force of the DEA actuator. When the voltage is constant, the actuation displacement and the actuation force show a parabola relationship with the increase of the proportion of the domain and a rapid increase with the increase of the additional load. There is an optimal limit point for the influence of domain ratio on the performance of DEA, and the additional load needs further study on the optimal load, which can guide the later engineering design so as to be applied in practice. When the domain ratio is fixed, the actuation performance of DEA increases with the increase of the loading voltage.

To analyze the prediction accuracy of the fitting model graph in more detail, five groups of data were randomly selected to verify the results. Table 1 compares the experimental data with the calculated data. The average errors of actuation displacement and force in DEA are 6.05 and 4.09%, respectively. It can be seen that the model can show the relationship among the parameters in a certain range and under certain conditions,

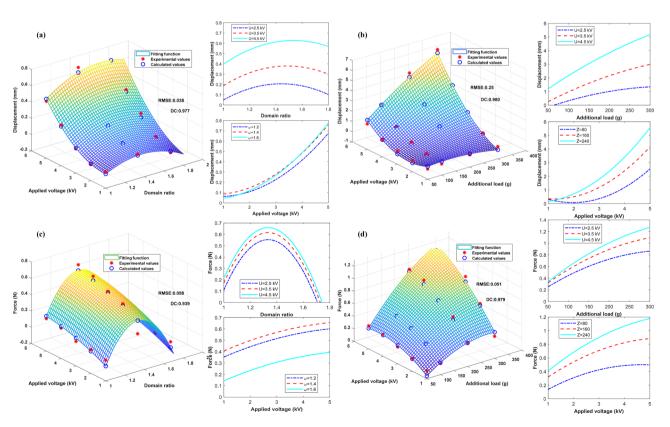


Figure 3: Three-dimensional model diagram for DEA.

Table 1: Comparison of experimental and calculated values

No.	Applied voltage (kV)	Domain ratio	Additional load (g)	Displacement (mm)		
				Experimental value	Calculated value	Error rate (%)
1	2	1.25	200	0.6	0.633	5.50
2	4	1.33	50	0.5	0.467	6.60
No.	Applied voltage (kV)	Domain ratio	Additional load (g)	Force (N)		
				Experimental value	Calculated value	Error rate (%)
3	5	1.25	100	0.591	0.602	1.86
4	4	1.25	300	1.189	1.188	0.08
5	3	1.67	50	0.126	0.139	10.32

which lays a foundation for the further development of DEA in the later period.

## 3.5 Microconformation of the cone DEA

The cone DEA is composed of a planar annular DE membrane and two fixed elements, and the membrane is coated with a stretchable electrode. When voltage is applied to the DEA electrode, the incompressibility of the DE membrane causes a certain proportion of deformation, which leads to the increase of the distance between the inner domain and the outer domain. Assuming that the deformations of the DE membrane are uniform and the electrode can be stretched freely, the deformations of the DEA are characterized by the viscoelastic response of the hyperelastic model without considering the effects of the electrode resistivity and leakage current, so DE's mechanical free energy density (W) function can be seen as a function of stretching  $(\lambda)$ , which can be expressed as

$$W(\lambda_1, \lambda_2) = W(\lambda_2, \lambda_1), \ \forall \lambda_1, \lambda_2.$$
 (1)

Compared with other hyperelastic strain energy models, the Gent model can better characterize the deformation

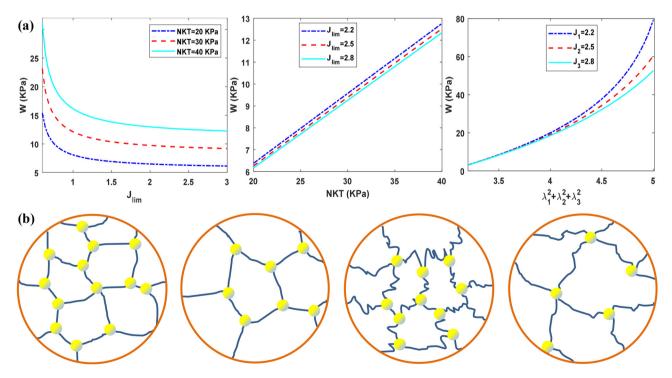


Figure 4: The change of free energy density and microcondensation of the cone DEA.

behavior and nonlinear mechanical properties of DEA [25], and the free energy density can be expressed as

$$W = -\frac{NKT}{2}J_{\text{lim}}\log\left(1 - \frac{\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3}{J_{\text{lim}}}\right),$$
 (2)

where N is the cross-linking number in the unit volume of the polymer, k is the Boltzmann constant, and T is the temperature. NkT is the small strain shear modulus, which shows the cross-linking density of the macromolecular chain in the polymer, while J is a constant related to the ultimate tensile strength and generally represents the chain length of the macromolecular chain. The resulting free energy is caused by the change in the entropy of the polymer chain as it is deformed.

In order to explain the deformation principle of DEA from a microcosmic point of view, the strain energy of DEA is analyzed by random selection of external environmental factors: loading voltage,  $4 \, \text{kV}$ ; domain ratio, 1.33; additional load,  $300 \, \text{g}$ . Figure 4(a) shows the effect of different variables on the free energy density. It can be seen that when the crosslinking density is constant, the free energy density decreases rapidly at first and then becomes slowly constant with the increase of the chain length. When the chain length is fixed, the higher the crosslinking density, the higher the free energy density is. With the increase of  $\lambda_1^2 + \lambda_2^2 + \lambda_3^2$ , the free energy density increases rapidly when both the chain length and the cross-linking density are fixed.

The DE material itself is a kind of polymer elastomer with a cross-linked macromolecule chain, and its microstructure determines the actuation performance of the later voltage excitation. Figure 4(b) shows the microstructural changes of the DEA designed in this article, where the circle represents the cross-linking key and the solid line represents the chain length. The initial DE is a soft state, and, under external tensile deformation conditions, the macromolecule chain will open and stretch. Under external conditions, such as additional load and applied voltage, the DE material will stretch further until it reaches its limit state, then harden rapidly and break, which is mainly due to the nonlinear growth of the elastic modulus of the material before fracture. It is worth noting the state of the third microstructure in Figure 4(b), which is the relaxation operation specially designed in this article after stretching, that is, the difference in the stretching state between the inner and outer domains expressed as the different domain ratios. This process not only increases the cross-linking density per unit volume but also increases the chain length, which ensures the good ductility of DE and shows the strain-strengthening effect of the DE

material; this effect can improve the electric breakdown limit of the material. In the process of deformation, the macromolecule segment of the material is subjected to internal friction due to its high viscoelasticity, and the motion of the flexible segment also produces some physical cross-links. Under uniaxial tension, the chains and cross-links can shrink freely in the width direction but are limited by the stress in the length direction. Under pure shear, the chains and crosslinks cannot shrink freely in the width direction [27], which shows that the behavior of DE in different deformation modes is different due to the tensile constraints of the chains; therefore, its actuation characteristics, failure stress, and other characteristics will be different.

## 4 Conclusion

In this article, the actuation characteristics of DE materials are analyzed and discussed in depth on the basis of our previous research work [25]. First, the influence of different environmental factors on the actuation force and displacement of the cone DEA is studied, including the loading voltage, the domain ratio, and the additional load. Then, the displacement and force three-dimensional actuation models of DEA are established to reveal the actuation characteristics of different environmental factors. At last, the process of DEA's actuation from the microcosmic angle is explained. The results show that the output displacement and force of the cone DEA increase with the increase of the loading voltage and additional load. The different domain ratio design is the key factor that influences the final DEA actuator. The predicted values are in good agreement with the experimental values, RMSE is small, and the DC is close to 1. The cross-linking density and the chain length of DE materials will change significantly under the influence of different environmental factors, in which the macromolecule chain length ensures good ductility of DE materials. By effectively controlling the external environment factors, the performance of the cone DEA can be designed to meet the actual device requirements of the actuator.

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