Influence of pre-stretch ratio on the electrical actuation performance of VHB elastomer

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Abstract. In this work, the influences of pre-stretch ratio on the electrical actuation performance of dielectric elastomer actuator (VHB 4905) are systematically investigated based on theoretical calculation and experimental tests. As the pre-stretch ratio increases, the maximum actuation strain increases at the initial phase, while decreases as pre-stretch ratio further increases. The peak value of actuation strain is attained when the electromechanical instability is just refrained by the pre-stretch, which is experimentally measured to be 3.25, with the maximum actuation strain of 90%.

1. Introduction
Dielectric elastomer (DE), as one kind of electroactive polymers (EAPs), shows great capability to change its dimensions under the electronic stimulus, which makes it potentially applied as soft actuators and robots [1]. The basic operational unit of dielectric elastomer actuator (DEA) comprises a soft elastomer sandwiched between compliant electrodes on both sides. When voltage bias is applied on the electrodes, the electrically-induced Maxwell stress will compress the elastomer membrane along the thickness direction, which leads to the area extension and thickness contraction, and the electrical energy is converted into the mechanical movement in this process. It has been demonstrated that the actuation strain and the specific actuation pressure of the EAP are similar to those of natural animal muscles [1], which is promisingly utilized as artificial muscles in the medical and industrial domains.

Recently, numerous studies have conducted by researchers aiming at improving the actuation performance of DEA, such as developing new materials with higher electrical permittivity and higher electrical breakdown field [3]. Pelrine et al. [4] reported that by simply pre-stretching the VHB acrylic elastomer membrane, the electrical actuation strain was significantly escalated up to 100%. It was found that pre-stretching of DE membrane is able to increase the electrical breakdown field of acrylic elastomer dramatically [5]. Additionally, the electromechanical instability (EMI) of the DEA can be effectively avoided by the pre-stretching [6]. Therefore, the pre-stretching strategy was widely adopted by many researchers [7]. However, it is noted that over pre-stretching of the membrane will induce significant stiffening of the elastomer [8], which deteriorates the actuation performance of DEA. Therefore, the optimum pre-stretch ratio of DEA should be a trade-off of multiple limiting factors. In this work, the influence of the pre-stretching on the actuation behavior of DEA was systematically...
investigated with VHB 4905 acrylic elastomer, and the optimum pre-stretch ratio was pinpointed based on theoretical calculation and experimental testing.

2. Experimental methods

2.1. Mechanical tests
VHB 4905 acrylic elastomer (3M) with a thickness of 0.5 mm was utilized in this work. In order to establish the constitutive equation of the DEA, the equi-biaxial tension experiment was conducted on a customized test bench. The circular specimen with a diameter of 50 mm was prepared and loaded with 18 clips distributed along the circumferential direction. The clips were connected with a linear motor (GLM20AP, THK Co., Ltd.) through an assembly of steel wires and pulleys, which was controlled by the LabVIEW software, as schematically shown in figure 1(a). The stretching force was measured with a load cell (U3B1-20K-B, Minebea Co., Ltd). A camera was mounted over the VHB membrane to record the stretch ratio in real time during loading process. The stretching velocity of the linear motor was set to be 2 mm/s, with an average strain rate of 0.1/s for the specimen.

2.2. Electrical actuation test
Circular specimens were equi-biaxially pre-stretched to various ratios before being fixed on a rigid frame with an inner diameter of 100 mm, as schematically shown in figure 1(b). The pre-stretch ratio is defined as the ratio of deformed diameter to the undeformed diameter of the DE film, which is selected to be 1, 1.5, 2.25, 2.85, 3, 3.25, 3.5, 4, 4.5, 5 and 5.5 in this work. An active region with a diameter of 5 mm was coated with conductive carbon grease as compliant electrodes. The voltage increase ramp rate was set to be 20 V/s, provided by a high voltage power supply (Model HAR-30P1, Matsusada Precision Inc). A camera was mounted over the membrane to record the deformation during the actuation process.

Figure 1. The schematics for the (a) equi-biaxial tension loading and (b) electrical actuation test.

3. Results and discussion

3.1. Equi-biaxial tension
The relationship between the nominal stress and stretch ratio for the VHB 4905 elastomer under equi-biaxial tension loading is shown in figure 2. Yeoh model is utilized to characterize the mechanical response of the elastomer, which is given as [8]:

$$\sigma(\lambda) = 2(\lambda - \lambda^3) \left[ C_1 + 2C_2(2\lambda^2 + \lambda - 3) + 3C_3(2\lambda^2 + \lambda - 3)^2 \right],$$  

where $\sigma$ is the nominal stress, $\lambda$ is the stretch ratio, $C_1$, $C_2$ and $C_3$ are hyperelastic material parameters determined by fitting the experimental data, which are 0.0488 MPa, $-2.646 \times 10^{-4}$ MPa and $2.734 \times 10^{-6}$ MPa, respectively.
3.2 Electromechanical results

The stress-stretch relationship for the dielectric elastomer film subjected to a combination of external force and voltage is expressed as [9]:

$$\frac{P}{\pi DH} + \epsilon_0 \epsilon_r \left( \frac{\Phi}{H} \right) \lambda_0^2 \lambda = \sigma(\lambda),$$  

(2)

where $P$ is the external force for pre-stretching the membrane, $D$ and $H$ is the initial diameter and thickness of the membrane, $\epsilon_0$ is the free-space permittivity (8.85×10^{-12} F/m), $\epsilon_r$ is the relative dielectric constant (4.03 for VHB 4905), $\Phi$ is the voltage applied on the DE film. The variation of stretch ratio as a function of applied voltage under different pre-stretch ratios ($\lambda_p$) can be calculated based on the equation (1) and equation (2), as is shown in figure 3.

Because the DEA is essentially a deformable capacitor, the charges stored on the DE film, $Q$, are given as:
\[ Q = \frac{\varepsilon_0 \varepsilon_r \lambda^4}{H} \Phi. \]  

(3)

For the dielectric elastomer, over high voltage will lead to the electrical breakdown (EB) of the material, which is given as:

\[ \Phi = E_{EB} H \lambda^{-2}, \]  

(4)

where \( E_{EB} \) is the electrical breakdown field. It is noted that the \( E_{EB} \) of VHB elastomer is related to the stretch of the membrane, which is \( E_{EB}=30.6 \lambda^{1.13} \) (MV/m) [9]. Combining equation (3) and equation (4), the EB boundary line can be numerically derived, as shown in figure 3.

As voltage increases, the deformation of the active region is solely supported by the Maxwell stress, and further increase of the voltage will lead to the compressive stress in the planar direction of the membrane, which results in the wrinkles of the DE film and damages the function of the actuator. This failure mode, also known as loss of tension (LT), can be solved by setting \( P=0 \) in equation (2), which is shown in figure 3.

When voltage is applied, the elastomer membrane thins down because of the Maxwell stress, which results in even higher electric field to further deform the elastomer at the same voltage. This kind of positive feedback may cause extremely high electrical field and bring about electrical breakdown, which is known as electromechanical instability (EMI) failure. The corresponding boundary line for EMI failure can be calculated as \( d\Phi/d\lambda=0 \) with equation (2), which is given as [9]:

\[ 3\varepsilon_0 \varepsilon_r \left( \frac{\Phi}{H} \right)^2 \lambda^2 = \frac{d\sigma(\lambda)}{d\lambda}, \]  

(5)

and the numerical calculation results combining equation (3) and equation (5) are shown in figure 3.

In figure 3, The intersection points of the actuation \( \lambda-\Phi \) plots with failure limiting plots determine the maximum actuation strain that can be attained, which is defined as \( \gamma_{max} = 100\% \times (\lambda_{max} - \lambda_P)/\lambda_P \), where \( \lambda_{max} \) is the stretch ratio at the intersection points. From figure 3, it can be seen that as the pre-stretch ratio increases, the EMI failure can be gradually avoided, and EB failure becomes the only determining factor of \( \gamma_{max} \). The theoretical values of \( \gamma_{max} \) as a function of pre-stretch ratio are plotted in figure 4. It can be seen that discontinuity emerges at the point of \( \lambda_P=2.6 \), where EMI failure is just refrained, and \( \gamma_{max} \) reaches the peak value of 132\%. The experimental data were also presented in figure 4, and it can be seen that the theoretical calculation qualitatively follows the trend of experimental results.

The optimum pre-stretch ratio is experimentally measured to be about 3.25, with the \( \gamma_{max} \) of 90\%. The experimental and theoretical values of breakdown voltage at various pre-stretch ratios are shown in figure 5. It can be seen that the theoretical results matches experiments well, and the breakdown voltage decreases with the increase of the pre-stretch ratio.

![Figure 4. The actuation strain as a function of pre-stretch ratio.](image-url)
It is noted that in figure 4 and figure 5, even though the basic features of experimental actuation tests are reproduced by the theoretical calculation, obvious errors exist between the experimental data and theoretical results. Two reasons may account for this kind of mismatch. Firstly, the theoretical analysis in this work neglects the viscoelasticity of the VHB elastomer, which has significant impacts on the electromechanical response of the actuator. Secondly, the influence of the electrode (carbon grease) is not considered. During the stretching process of the membrane, the electrodes coated on the membrane also endures large deformation, therefore the viscosity and electrical conductivity of the electrodes should dramatically affect the performance of the actuator. Even though the theoretical calculation in this work is simply based on an ideal dielectric elastomer model, it still sheds light on the performance optimization of DEA.

![Figure 5. The breakdown voltage as a function of pre-stretch ratio.](image)

4. Conclusions
Based on the theoretical calculation and experimental tests, the maximum actuation strain of DEA (VHB 4905) increases with the pre-stretch ratio at the initial stage, while decreases when the pre-stretch ratio is over large. The optimum pre-stretch ratio is reached when the EMI failure is just refrained, which is experimentally measured to be about 3.25 with the maximum actuation strain of 90%.

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