Energy harvesting performance of viscoelastic polyacrylic dielectric elastomers

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Viscoelasticity dissipates the mechanical energy, leading to a reduction of energy conversion efficiency in both dielectric elastomer (DE) actuators and generators. By measuring the uniaxial tension-recovery experiments of very-high-bond-based DE, this article quantitatively presents the effect of viscoelasticity on energy harvesting performance of DE generators. By employing a DE strip energy harvester with constant surface charge, an analytical model is established to calculate the generated electrical energy and energy conversion efficiency. Numerical results demonstrate that viscoelasticity has a significant influence on DE energy harvesting performance.

Keywords: dielectric elastomer; viscoelasticity; energy harvesting

1. Introduction

Dielectric elastomers (DEs) exhibit large dimensional changes upon electrical stimulation: expansion in area and shrinkage in thickness [1–5]. Due to their high-strain responsive performance together with other desirable properties like low cost and high energy density, a variety of promising applications of DE have been extensively developed, such as artificial muscles [6], soft robots [7], loudspeaker [8], tunable lenses [9], and energy generators [10–12]. In 2001, Pelrine et al. [13] first presented DE generators, demonstrating that mechanical energy can be transformed into electrical energy by using DE under certain conditions. Since then, different kinds of configurations and concepts in energy harvesting were reported, with the objective to achieve high electrical energy output and energy conversion efficiency. Koh et al. [10] theoretically investigated the DE energy harvesting process and proposed a method to calculate the maximum energy that can be converted during one cycle. Kaltseis et al. [11] reported the generated electrical energy density per cycle can be 0.102 J/g and the corresponding energy conversion efficiency can be 7.5%. By using the equi-biaxial loading, significant improvements in electrical energy density (0.56 J/g) and energy conversion efficiency (27%) were achieved by Huang et al. [12]; however, the energy density is still small compared with theoretical predictions with a value of 1 J/g. The reason is due to the strong viscoelasticity of the DE materials.

Viscoelasticity (especially the very-high-bond (VHB)) greatly affects their performance [14–19]. The viscoelastic resistance dissipates the mechanical energy, leading to a
reduction of the energy conversion efficiency of DE generators [15,20]. Previously, experiments have shown that the stress–stretch curve of VHB strongly depends on the stretch curve [21–23]. When the DE films are used in energy harvesting, it will experience successive tension-recovery cycles with the external source of mechanical energy. Thus, viscoelasticity, intrinsically being represented by hysteresis, will undoubtedly have a significant impact on the amount of the generated energy and the energy conversion efficiency. Up to now, there have been a number of reports which mainly focus on the mechanism and optimization on DE energy harvesting [10–12,15,20,24–26], while, most of the studies [10,11,24–26] only take DE as hyper-elastic continuum materials, without taking into account the viscoelasticity and induced loss of mechanical energy.

2. Experimental details

In this article, we simply adopt the uniaxial tensile configuration to quantitatively study the effect of viscoelasticity on energy harvesting performance of DE. We define that the thickness direction is direction 3, the tension direction is direction 1, and another direction is direction 2. DE material used is VHB4910 film manufactured by 3 M, and the initial length, width and thickness of the VHB membrane are \( L_1 = 75 \) mm, \( L_2 = 20 \) mm, and \( L_3 = 1 \) mm, respectively. The stretch \( \lambda \) is defined as the ratio between the deformed size and the undeformed size. Uniaxial tension-recovery experiments are carried out at different stretch rates (from 0.029 s\(^{-1}\) to 0.71 s\(^{-1}\), the stretch rate is defined as \( \dot{\lambda} = \frac{d\lambda}{dt} \), where \( t \) denotes the time), and the Tytron 250 microforce testing system is employed as the experimental set-up, as shown in Figure 1.

Figure 2 plots parts of the nominal stress–stretch curve of DE at several different stretch rates. As seen in Figure 2, the stretch rate has a great effect on the stress–stretch curve of DE material, which is consistent with the previous reported works [21–23]. For the same stretch, both tension stress and recovery stress increase with the increasing

![Figure 1. Experimental set-up for uniaxial test: the Tytron 250 microforce testing system [18].](image-url)
stretch rate. Due to viscoelasticity, the recovery stress appears a noticeable hysteresis compared with the tension stress, bringing out a large internal dissipation.

3. Method

In principle, a basic cycle requires two batteries: the low-voltage one supplies charge to the DE generator and the high-voltage one stores charge. The energy harvesting cycle of DE was reported by Koh et al. [10], including four states during the process. From state 1 to state 2, subject to the external mechanical load, the DE generator extends, reaching the maximum capacitance. From state 2 to state 3, first, the low-voltage battery is applied on the DE film to output charge, then, the low-voltage battery is disconnected to maintain the charge on the DE surface as a constant. From state 3 to state 4, due to the decrease of external load, the film recovers, reducing the value of capacitance and increasing the voltage simultaneously, under the condition of a constant charge. From state 4 to state 1, when the DE generator reaches the condition of loss of tension, the DE generator is connected to the high-voltage battery, allowing the charge to transfer to the high-voltage battery.

The generated electrical energy results from the work done by the Maxwell stress. In order to calculate the energy easily, the Maxwell stress in direction 3 can be equivalent to the directions 1 and 2, based on the theory developed by Suo [4]. Thus, as shown in Figure 3 (a), \( \sigma_{M1} = \sigma_{M2} = -\sigma_{M3} \) can be obtained, where \( \sigma_{M3} \) denotes the Maxwell stress in directions 3, \( \sigma_{M1} \) and \( \sigma_{M2} \) represent the equivalent Maxwell stresses in directions 1 and 2.

Under the condition of uniaxial tension with the application of voltage, the relationship of the stretches in directions 1 and 2 can be related as [27]

\[
\lambda_2^2 = \frac{1 + \left( Q / \left( A_0 \sqrt{\mu \varepsilon_0} \right) \right)^2}{\lambda_1}
\]  

(1)

Figure 2. The nominal stress–stretch curves of DE membrane under several stretch rates including both the tension and recovery stress.
where $\lambda_1$ denotes the stretch in direction 1 and $\lambda_2$ denotes the stretch in direction 2; $Q$ is the charge accumulated on the surface of DE; $A_0 = L_1L_2$ is the initial area of the DE, $\mu = 5.2 \times 10^4$ Pa [28] is the shear modulus; $\varepsilon_0 = 8.85 \times 10^{-12} F/m$ and $\varepsilon_r = 4.2$ [28] denote vacuum permittivity and the relative permittivity of DE, respectively. The Maxwell stress in direction 3 can be expressed as

\[
\sigma_{M3} = \frac{Q^2}{\varepsilon_r\varepsilon_0 A_0^2 \sqrt{1 + (Q/(A_0\sqrt{\mu\varepsilon_r\varepsilon_0}))^2\lambda_1}}
\] (2)

As the experiments is processed at a steady speed condition, during the recovery of DE, the relationship of the stresses in direction 1 is

\[
\sigma_{rec1} = \sigma_{M1} + \sigma_{ext}
\] (3)
where $\sigma_{\text{rec}}$ denotes the true elastic stress of DE during recovery and $\sigma_{\text{ext}}$ denotes the external stress which is used to keep the speed steady.

Figure 3(b) plots a schematic diagram showing the elastic stress and Maxwell stress in direction 1 during the tension-recovery process. The elastic stress of DE is determined by the stretch and corresponding stretch rate. Thus, the elastic stress in the recovery process is independent of the charge on the DE surface as long as the stretch and stretch rate are given. The total mechanical energy is equal to the work done by the tension stress. The generated electrical energy in direction 1, $\Delta U_1$, is the work done by the Maxwell stress in this direction.

During the recovery process, if the total stress becomes negative (elastic stress is smaller than Maxwell stress), a DE is in a condition of loss of tension and may arise wrinkle instability [10,27]. So the stress equilibrium point, $\lambda_e$, is selected as the position to harvest electrical energy [10,27], as shown in Figure 3(b). After the charge is harvested, Maxwell stress will decay to 0 for a sufficient time since the presence of dissipation [16]. The DE membrane can be restored to the initial configuration, and a second cycle of energy harvesting is guaranteed. In other words, the device can achieve recycling of energy harvesting. In recovery process, part of the reduced elastic energy is transformed to electrical energy, and the rest of the elastic energy is used to do work on the external environment, $W_{\text{ext}}$, as shown in Figure 3(b). After obtaining the equilibrium stretch $\lambda_e$, the net generated electrical energy can be calculated. Since the equivalent Maxwell stresses exist in both directions 1 and 2, $\sigma_{M1}$ does negative work to increase electrical energy while $\sigma_{M2}$ does positive work to decrease electrical energy. The differential equations of the work density for $\sigma_{M1}$ and $\sigma_{M2}$ are expressed as

$$dU_1 = \frac{1}{V} \sigma_{M1} \lambda_2 L_{20} \lambda_3 L_{30} d(\lambda_1 L_{10})$$  \hspace{1cm} (4)$$

$$dU_2 = \frac{1}{V} \sigma_{M2} \lambda_1 L_{10} \lambda_3 L_{30} d(\lambda_2 L_{20})$$  \hspace{1cm} (5)$$

where $V = L_1 L_2 L_3$, is the volume of the DE membrane. Combined with Equation (1), Equations (4) and (5) can be simplified as

$$dU_1 = \frac{\sigma_{M1}}{\lambda_1} d\lambda_1$$  \hspace{1cm} (6)$$

$$dU_2 = -\sqrt{1 + \left(\frac{Q}{(A_0 \sqrt{\mu \varepsilon_0})}\right)^2} \frac{\sigma_{M2}}{\lambda_1} d\lambda_1$$  \hspace{1cm} (7)$$

Basically, the net generated electrical energy is defined as the difference between output electrical energy and input electrical energy [12] and should be equal to the sum of the work done by $\sigma_{M1}$ and $\sigma_{M2}$. The density of generated electrical energy can be obtained as

$$\Delta U = \left(1 - \frac{1}{2} \left[\frac{Q}{(A_0 \sqrt{\mu \varepsilon_0})}\right]^2\right) \int_{\lambda_e}^{\lambda_1} \frac{\sigma_{M1}}{\lambda_1} d\lambda_1$$  \hspace{1cm} (8)$$
During the recovery, the external mechanical load is needed to keep the uniform speed; thus, the elastic stress of DE does mechanical work to the external environment. The work density can be written as

$$W_{\text{ext}} = \int_{\lambda_r}^{\lambda_m} \frac{\sigma_{\text{rec}} - \sigma_{M1}}{\lambda_1^2} d\lambda_1$$

(9)

The density of total mechanical energy during the tension process can be calculated by the tension stress as

$$W_{\text{total}} = \int_{\lambda_1}^{\lambda_m} \frac{\sigma_{\text{ten}}}{\lambda_1} d\lambda_1$$

(10)

Using Equation (8), the electrical energy density can be obtained. Furthermore, the energy conversion efficiency during the energy harvesting process can be given as

$$\eta = \frac{\Delta U}{W_{\text{total}} - W_{\text{ext}}}$$

(11)

According to the developed equations and the uniaxial tensile experiments, the effect of viscoelasticity on the generated electrical energy density and the energy conversion efficiency can be obtained. Based on the developed equations, we can maximize the energy conversion efficiency by tuning the stretch rate and the surface charge, which is shown in the following.

4. Results and discussions

Combining with both the experimental data and above analysis of energy harvesting process, in the following, we discuss the effect of viscoelasticity on the energy harvesting performance of VHB-based DE. Figure 4(a) plots the three-dimensional images of the generated electrical energy density versus the stretch rate and surface charge. When the surface charge is kept constant, the generated electrical energy density increases slightly with the increasing stretch rate. Especially when the surface charge is $Q = 4 \times 10^{-6}$ C, the extent of the enlargement of electrical energy density reaches the maximum. For a constant stretch rate, the electrical energy density increases first and then decreases subsequently with the increasing surface charge. The reason is that large surface charge adds the dissipation of electrical energy in direction 2, resulting in the reduction of the total generated electrical energy, as shown by Equations (7) and (8). Figure 4(b) plots the three-dimensional image of energy conversion efficiency versus the stretch rate and surface charge. When the surface charge is given a specific value, energy conversion efficiency decreases gradually with the increasing stretch rate, although the electrical energy density increases slightly as the stretch rate increases (Figure 4(a)). The reason is that large stretch rate increases the input mechanical energy significantly, reducing the energy conversion efficiency. Under a constant stretch rate, when the surface charge increases, the energy conversion efficiency increases first and a subsequent decrease followed, which is consistent with the trend of the generated electrical energy density. The electrical energy density and corresponding energy conversion efficiency in our results is lower than the work reported before [11,12]. The reason is that the uniaxial tension mode is utilized in this article and the equivalent Maxwell stress in direction 2 dissipates...
the total electrical energy, causing the reduction of the generated electrical energy density and corresponding energy conversion efficiency.

As seen in Figure 4, under the same stretch rate, the energy conversion efficiency can be tuned by the surface charge. When the stretch rate is kept at a constant, with the increase of surface charge, both the generated electrical energy density and the energy conversion efficiency initially increase and subsequently decrease. Specifically, when the surface charge is $Q = 4 \times 10^{-6}$ C, both the generated electrical energy density and the energy conversion efficiency reach the maximum. That is, by tuning the value of surface charge and stretch rate, a higher electrical energy density and energy conversion efficiency can be achieved, which is equivalent to the suppression of the effect of viscoelasticity.

Furthermore, the maximum surface charge in our simulation is $Q = 8 \times 10^{-6}$ C, as seen in Figure 4. If the surface is above $Q = 8 \times 10^{-6}$ C, there will be no electrical energy generated because the equivalent Maxwell stress in direction 2 dissipates the electrical

Figure 4. The three-dimensional images of the generated electrical energy density (a) and the energy conversion efficiency (b) versus the stretch rate and surface charge.
energy completely. As shown in Equation (8), when the surface charge exceeds a critical level, $\Delta U$ will be a negative number. The negative work done by the equivalent Maxwell stress in direction 2 causes the lower generated electrical energy density and energy conversion efficiency. Thus, in order to add the values of the two quantities, the equibiaxial tension mode should be applied in the further research and applications.

5. Conclusions

In summary, combined with the uniaxial tension-recovery experimental results, the impact of viscoelasticity is incorporated into the study of VHB-based DE energy harvesting. By applying a method of calculating the work done by the elastic stress and the Maxwell stress respectively, the generated electrical energy density and corresponding energy conversion efficiency are quantitatively obtained. According to the numerical results, in the proposed range of stretch rate, the maximum electrical energy density of the uniaxial stretched DE energy generator is approximately below 0.01 J/g, and the energy conversion efficiency is no more than 3%, which are far less than both the theoretical values in ideal case and the experimental results reported before. Such a comparison demonstrates that the viscoelasticity and the tension mode play an important role in determination of the energy harvesting performance. This article provides a potential theoretical prediction which may contribute to the analysis, design and application of DE energy generators. Reasonable stretch rate and tension mode can therefore reduce the viscoelastic dissipation and achieve high electrical energy output and energy conversion efficiency.

Disclosure statement

No potential conflict of interest was reported by the authors.

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