Electromechanical performance of a viscoelastic dielectric elastomer balloon

Junshi Zhang\textsuperscript{a,b} and Hualing Chen\textsuperscript{a,c,*}

\textsuperscript{a}State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi’an Jiaotong University, Xi’an, 710049, China; \textsuperscript{b}School of Aerospace, Xi’an Jiaotong University, Xi’an, 710049, China; \textsuperscript{c}School of Mechanical Engineering, Xi’an Jiaotong University, Xi’an, 710049, China

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In this paper, we present a theoretical study about the effect of viscoelasticity on the electromechanical performance of a dielectric elastomer (DE) balloon. The thermodynamic dissipative model is given and the equation of motion is deduced by a free-energy method. It is found that when the balloon is only subject to the pressure or a static voltage, it may reach a state of equilibrium after the viscoelastic relaxation. When the static voltage exceeds a certain value, the balloon will never reach the equilibrium and be in failure eventually. When the voltage is sinusoidal, the balloon will resonate at multiple frequencies. The study result indicates that the natural frequency is independent on the viscoelasticity. However, the presence of viscoelasticity can reduce the amplitude and increase the mean stretch of the DE.

Keywords: DE balloon; viscoelasticity; static equilibrium; dynamic response

1. Introduction

Dielectric elastomers (DEs), which belong to the group of electroactive polymers, consist of the soft membranes sandwiched by compliant electrodes between two surfaces. Upon the electrical stimulation, the DE membrane can exhibit large dimensional changes [1–4]. Because of their high-strain responsive performance, fast response time, high energy density, and low cost, DEs have been developed for applications, such as artificial muscles, Braille displays, life-like robots, tunable lens, balloon-shaped actuators, power generators [5–9].

Most of the existing studies on DEs are focused on quasi-static deformation, with the effect of viscoelasticity and inertia neglected. However, performed as the electromechanical actuators, DEs are often subjected to time-dependent forces and voltages and are expected to deform at high frequencies in applications [10], where inertia can play an important role in the dynamic process. Recently, researchers have been modeling the nonlinear dynamic behavior of hyper-elastic DE membranes [11–15]. Li et al. [11] analyzed the electromechanical and dynamic behaviors of tunable DE-based resonator in pure shear state. Based on a micro-beam DE resonator, Yong et al. [12] studied the dynamic performance of a thick-walled DE spherical shell subjected to the mechanical pressure and electric field. Zhu et al. [13] theoretically investigated the nonlinear oscillation of a DE balloon. Xu et al. [14] studied the dynamic performance of a DE membrane
with stretching deformation by Euler–Lagrange equation. Rudykh et al. [15] analyzed the static deformation performance and electromechanical stabilization (Snap-through) of the thick-walled electroactive balloons under inflation pressure and electrostatic excitation. Although the above studies concentrated on the electromechanical behavior, most of them only adopted the model of ideal DE, without taking viscoelasticity into consideration. Viscoelasticity is an inherent property of all high molecular polymers (including DEs). Experiments have shown that viscoelasticity can significantly affect the electromechanical transduction and application of DEs. The effect of viscoelasticity on the nonlinear behavior of DEs is not clear by now. Thus, studies on viscoelasticity and how it affects the performance of DEs are necessary and expected.

Some researchers have also investigated the force–displacement relationship, the solutions of snap-through instability and electric breakdown of DE balloon-shaped actuators by experiments [16–18], which demonstrated the feasibility and significance of the DE balloons. Based on these researches, this paper studies the electromechanical performance of a viscoelastic DE balloon based on the thermodynamic theory of viscoelastic DEs and the model of nonlinear vibrations. In this study, the equation of motion is derived by the method of virtual work. Then the state of static equilibrium is described with viscoelasticity being considered when the DE balloon is only under pressure or static voltage. After that, the dynamic response is investigated by solving the governing equations. The conclusion of this paper is given finally.

2. Equation of motion

Figure 1(a) shows a DE balloon of radius \( R \) and thickness \( H \) in the reference state. The DE balloon is taken to be incompressible, of density \( \rho \), coated with compliant electrodes of negligible electrical resistance and mechanical stiffness on both surfaces. The balloon is filled with air inside and is placed in a vacuum environment. The initial pressure inside the balloon is \( p_0 \), the pressure outside is 0 (for vacuum environment), and the two electrodes are subject to a voltage \( \phi \). Due to the joint action of pressure and voltage, the balloon deforms to radius \( r \) and the charge accumulated on the two electrodes is \(+Q_p\) and \(-Q_p\), respectively, as shown in Figure 1(b). Here we define that \( \lambda \) as the stretch of the balloon membrane, that is,

\[
\lambda = \frac{r}{R}
\]  

With the expansion of the balloon, the pressure inside the ball will change correspondingly. The temperature is assumed as a constant, according to the Clapeyron equation, we can obtain

![Figure 1](image-url)
\[ p = p_0 \lambda^{-3} \]  

where \( p \) is the pressure inside the balloon during the deformation.

Let \( D \) be the electric displacement of the DE membrane during the deformation

\[ D = \frac{Q}{4\pi r^2} = \frac{Q}{4\pi R^2} \lambda^{-2} \]  

When an AC voltage or an alternating mechanical load is applied, the membrane oscillates around its equilibrium position of stretch. To analyze the electromechanical behavior, we can derive the equation of motion under oscillation by considering its inertia effect. In the process of actuation, the total work done by the inertia force is \(-4\pi R^2 \rho (d^2 r/dt^2) \delta r\).

Viscoelasticity may be represented by a rheological model of two springs and one dashpot [19–23]. As shown in Figure 2, the rheological model in this paper is composed by two parallel units: one unit consists of a spring \( \alpha \), and the other unit consists of another spring \( \beta \) and a dashpot. For spring \( \alpha \), the deformation is characterized by \( \lambda \). For spring \( \beta \), the state of deformation is characterized by a different stretch \( \lambda^e \). For the dashpot, the state of deformation is characterized by \( \xi \). The deformation relationships of \( \lambda^e \) and \( \xi \) are identical to \( \lambda \). We adopt the well-established multiplication rule [19–23], that is, \( \lambda = \lambda^e \xi \). Thus the thermodynamics of the DE is characterized by the density of the Helmholtz free energy as a function of the three independent variables, \( W(\lambda, \xi, D) \). In this paper, the neo-Hookean model is adopted. Consequently, the free energy density function is written as

\[ W(\lambda, \xi, D) = \frac{\mu^\alpha}{2} (2\lambda^2 + \lambda^{-4} - 3) + \frac{\mu^\beta}{2} (2\lambda^2 \xi^{-2} + \lambda^{-4} \xi^4 - 3) + \frac{D^2}{2e} \]  

where \( \mu^\alpha \) and \( \mu^\beta \) are the shear moduli of the spring \( \alpha \) and spring \( \beta \), respectively and \( e \) is the permittivity of DE balloon.

For arbitrary variation of the system, the variation of the free energy of the membrane should be equal to the work done jointly by the voltage, the pressure and the inertia force

\[ 4\pi R^2 \delta W = \phi \delta Q + 4\pi r^2 p \delta r - 4\pi R^2 \rho \frac{d^2 r}{dt^2} \delta r. \]  

Figure 2. Viscoelasticity is modeled by two parallel units, one unit consists of a spring \( \alpha \), the other unit consists of another spring \( \beta \) and a dashpot.
Inserting Equation (3) into Equation (5), we can obtain
\[
\frac{\partial W}{\partial \lambda} = \frac{2 \phi D}{H} \lambda + \frac{R \rho_0}{H} \lambda^{-1} - \rho R^2 \frac{d^2 \lambda}{dt^2},
\]
and
\[
\frac{\partial W}{\partial D} = \frac{\phi}{H} \lambda^2.
\]
Inserting Equation (4) into Equations (6) and (7), and eliminating \(D\), we can obtain that
\[
\frac{p_0 R}{H} \lambda^{-1} + \frac{2 \phi^2 \varepsilon}{H^2} \lambda^3 - \rho R^2 \frac{d^2 \lambda}{dt^2} = \mu^a (2 \lambda - 2 \lambda^{-5}) + \mu^b (2 \lambda \xi^{-2} - 2 \lambda^{-5} \xi^4).
\]
Define that \(\mu = \mu^a + \mu^b\). As reported in literature [23], we can set \(\mu^a = \mu^b = \mu/2\). Then Equation (8) can be rewritten as
\[
\frac{d^2 \lambda}{dT^2} + g(\lambda, \xi, p_0, \phi) = 0,
\]
with
\[
g(\lambda, \xi, p_0, \phi) = \lambda - \lambda^{-5} + \lambda \xi^{-2} - \lambda^{-5} \xi^4 - \frac{p_0 R}{\mu H} \lambda^{-1} - \frac{2 \varepsilon \phi^2}{\mu H^2} \lambda^3,
\]
where \(T\) is the dimensionless time \((T = t/(\sqrt{R/H})\). In Equations (9) and (10), the dimensionless pressure \((p_0 R/(H \mu))\) and dimensionless voltage \((\phi/(H \sqrt{\mu/\varepsilon}))\) are used, too.

The dimensionless natural frequency takes the form [22]
\[
\bar{\omega}_n^2 = \frac{\partial g(\lambda, \xi, p_0, \phi)}{\partial \lambda},
\]
where \(\bar{\omega}_n = \omega_0 R \sqrt{\rho/\mu}\) is the dimensionless natural frequency and \(\omega_0\) is the natural frequency.

In the rheological model, the dashpot is considered as a Newtonian fluid and the state of stress in the dashpot is the same as that in spring \(\beta\). The rate of deformation in the dashpot is described by \(\xi^{-1} d\xi/dt\) and relationship between the rate of deformation and the stress is defined as [21]
\[
\frac{d\xi}{dt} = \frac{\mu^b}{3\eta} (\lambda^2 \xi^{-2} - \lambda^{-4} \xi^4),
\]
where \(\eta\) is the viscosity of the dashpot. The viscoelastic relaxation time is defined by using the viscosity of the dashpot and the modulus of spring \(\beta\)
\[
\tau_v = \eta/\mu^b.
\]
As reported in literature [14], $\mu = 6.71 \times 10^{4}$ Pa. If we set $R = 5 \times 10^{-2}$ m and $\rho = 1.2 \times 10^{3}$ kg/m$^3$[14, 22], we can get $R\sqrt{\rho/\mu} = 0.66 \times 10^{-2}$ s after the numerical calculation. Experiments demonstrate that the viscoelastic relaxation time of DE has multiple values, ranging from hundreds of microseconds to hundreds of seconds [22,24–26]. In this paper, only a single viscoelastic relaxation time is considered and is set as $\tau_v = 65.5$ s[23]. Then theoretically and approximately $\tau_v \approx 10^4 R\sqrt{\rho/\mu}$ is get and the dimensionless time $T = t/R\sqrt{\rho/\mu} \approx 10^4 t/\tau_v$ is also obtained. And Equation (12) can be rewritten as

$$\frac{d\xi}{dT} = \frac{1}{3 \times 10^4} (\lambda^2 \xi^{-1} - \lambda^{-4} \xi^5).$$

(14)

3. Static equilibrium of the viscoelastic DE balloon

When the balloon is only under the application of pressure or a static voltage, the balloon may reach a state of equilibrium after the viscoelastic relaxation. In the state of equilibrium, the equation of motion (9) reduces to

$$g(\lambda, \xi, p_0, \phi) = 0.$$  

(15)

The effect of viscoelastic relaxation on the static equilibrium is studied by combining with Equation (14). Figure 3 plots the stretch of the membrane and the stretch due to the dashpot when the membrane is only subject to the pressure. It can be seen, at the beginning stage, the dashpot does not deform, the pressure is carried by both springs. Then both $\lambda$ and $\xi$ are creeping in time and achieve the equilibrium eventually after the viscoelastic relaxation. And with the increasing pressure, the equilibrium positions of stretch of both $\lambda$ and $\xi$ increase. And we can also infer that when the applied pressure is large enough, the equilibrium position of stretch will be very large, causing the film to fail. So we should reasonably control the applied pressure.

Figure 4 shows the deformed shapes of the viscoelastic DE balloon at different times when the balloon is only subject to the pressures of $p_0 R/(\mu H) = 2$ and $p_0 R/(\mu H) = 3$. It can be found that at the same time, the balloon subject to $p_0 R/(\mu H) = 3$ deforms much larger than that subject to $p_0 R/(\mu H) = 2$. And the deformation of the balloon under the pressure $p_0 R/(\mu H) = 3$ evolves significantly faster.

Figure 3. The stretch of the membrane (a) and the stretch due to the dashpot (b), creep in time only under different pressures.
Figure 5 shows the stretch of the membrane and the stretch due to the dashpot when the membrane is only subject to different static voltages. It can be seen, both $\lambda$ and $\xi$ are creeping in time and achieve the equilibrium positions of stretch when the value of $\varepsilon \phi^2 / (\mu H^2)$ is below 0.5. Similarly, with the increasing voltage, the equilibrium positions of stretch of both $\lambda$ and $\xi$ increase. The difference is, after the value of $\varepsilon \phi^2 / (\mu H^2)$ is above 0.6, the stretches will never achieve the equilibrium, and the membrane will be failure (pull-in instability) eventually [21,22]. Therefore, we also need to reasonably control the applied voltage.

Figure 6 plots the deformed shapes of the viscoelastic DE balloon at different times when the balloon is only subject to the static voltages of $\varepsilon \phi^2 / (\mu H^2) = 0.5$ and $\varepsilon \phi^2 / (\mu H^2) = 0.6$. It can be seen when the balloon is subject to the voltage $\varepsilon \phi^2 / (\mu H^2) = 0.5$, the shape of the balloon changes very small and slowly from $t/\tau_v = 2$ to $t/\tau_v = 10$. When the voltage of $\varepsilon \phi^2 / (\mu H^2) = 0.6$ is applied to the balloon, the shape of the balloon changes very fast and large for a short time from $t/\tau_v = 0$ to $t/\tau_v = 0.999$. After $t/\tau_v = 0.998$, the balloon will never reach the electromechanical equilibrium.
4. Dynamic performance of the viscoelastic DE balloon

When the voltage varies with time, the dynamic behavior of the balloon will be very complex and is described by a time-dependent stretch \( \lambda(T) \). The effect of viscoelasticity on the dynamic performance of the balloon under a sinusoidal voltage \( \phi \) is studied in this section. Let’s say

\[
\phi = \phi_0 + \overline{\phi} \sin(\Omega t),
\]

where \( \phi_0 \) denotes the DC voltage, \( \overline{\phi} \) denotes the amplitude of the AC voltage, and \( \Omega \) denotes the frequency of the sinusoidal voltage. If the viscoelasticity is considered, the equation of motion (9) becomes

\[
\frac{d^2 \lambda}{dT^2} + \lambda - \lambda^{-5} + \lambda \dot{\xi}^{-2} - \lambda^{-5} \ddot{\xi}^4 - \frac{p_0 R}{\mu H} \lambda^{-1} - 2 \frac{\varepsilon \phi_0^2}{\mu H^2} (1 + \overline{\phi} \phi_0) \sin(\overline{\Omega} T)) \lambda^3 = 0,
\]

Without viscoelasticity considered (i.e., hyperelasticity), the equation of motion (9) becomes

\[
\frac{d^2 \lambda}{dT^2} + 2\lambda - 2\lambda^{-5} - \frac{p_0 R}{\mu H} \lambda^{-1} - 2 \frac{\varepsilon \phi_0^2}{\mu H^2} (1 + \overline{\phi} \phi_0) \sin(\overline{\Omega} T)) \lambda^3 = 0,
\]

where \( \overline{\Omega} = \Omega R \sqrt{\rho/\mu} \) is the dimensionless frequency of the excitation.

The time-dependent stretch \( \lambda(T) \) with viscoelasticity considered can be obtained by solving Equations (14) and (17) for given initial condition. And the time-dependent stretch \( \lambda(T) \) without viscoelasticity considered can be obtained by solving Equation (18) with initial condition. We set the initial conditions as \( p_0 R / (\mu H) = 0.05 \) and \( \varepsilon \phi_0^2 / (\mu H^2) = 0.05 \). When the dynamic characteristics of the balloon with different frequency \( \Omega \) are studied, some definitions are necessary, that is, after the numerical solution of \( \lambda(T) \) attains a steady state of oscillation, the amplitude is defined as half of the difference between the maximal and minimal values of the stretch \( \lambda(T) \) and the mean stretch is defined as half of the sum of the maximal and minimal values of the stretch \( \lambda(T) \).
even unbounded when viscoelasticity and hyperelasticity considered. The peak amplitudes at the resonance point are independent of the values of \( \phi_0^2/\phi_0^2 \) and \( R^2/\phi_0^2 \) when \( \phi_0^2/\phi_0^2 \) is a fraction or several times of the natural frequency. As \( \phi_0^2/\phi_0^2 \) increases to 0.03 and 0.05. We can also find that the amplitude decreases with the effect of viscoelasticity. The reason may be that presence of viscoelasticity dissipates part of energy, so the vibration energy will be reduced. Macroscopically, the amplitude of the balloon with viscoelasticity considered decreases compared with the hyperelastic balloon.

Figure 7 plots the amplitude of oscillation as a function of the frequency with \( p_0R/\mu H = 0.05, \varepsilon \phi_0^2/\mu H^2 = 0.05 \) and different values of \( \phi_0^2/\phi_0^2 \). As can be seen, regardless of viscoelasticity, the natural frequency will not change. It may because the natural frequency is determined by the size of structural parameters of the DE balloon. The theoretical model and the external excitation load may not affect it. And the membrane of balloon also resonates when the frequency of excitation is a fraction or several times of the natural frequency. As the values of \( \phi_0^2/\phi_0^2 \) increase, the amplitude has a slight increase with both viscoelasticity and hyperelasticity considered. The peak amplitudes at the resonance point are even unbounded when \( \phi_0^2/\phi_0^2 \) increases to 0.03 and 0.05. We can also find that the amplitude decreases with the effect of viscoelasticity. The reason may be that presence of viscoelasticity dissipates part of energy, so the vibration energy will be reduced. Macroscopically, the amplitude of the balloon with viscoelasticity considered decreases compared with the hyperelastic balloon.

Figure 8 plots the mean stretch of oscillation as a function of the frequency with \( p_0R/\mu H = 0.05, \varepsilon \phi_0^2/\mu H^2 = 0.05 \) and different values of \( \phi_0^2/\phi_0^2 \). As can be seen, regardless of viscoelasticity, both curves keep essentially unchanged apart from the resonance point. But the difference is that mean stretch is independent of the values of \( \phi_0^2/\phi_0^2 \). And the effect of viscoelasticity is that the mean stretch increases compared with hyperelasticity. This phenomenon may be caused by the viscoelastic relaxation. Due to the presence of viscoelasticity, the mean stretch will drift with time gradually as same as the static creep. Thus, the mean stretch of the viscoelastic balloon is larger than the hyperelastic one.

Figure 7. The comparison of oscillating amplitude of the balloon as a function of the frequency between the viscoelastic DE balloon and hyperelastic DE balloon for the initial conditions of \( p_0R/\mu H = 0.05, \varepsilon \phi_0^2/\mu H^2 = 0.05 \) and different values of \( \phi_0^2/\phi_0^2 (\phi_0^2/\phi_0^2 = 0.01, 0.03, 0.05) \).

Figure 8. The comparison of oscillating mean stretch of the balloon as a function of the frequency between the viscoelastic DE balloon and hyperelastic DE balloon for the initial conditions of \( p_0R/\mu H = 0.05, \varepsilon \phi_0^2/\mu H^2 = 0.05 \) and different values of \( \phi_0^2/\phi_0^2 (\phi_0^2/\phi_0^2 = 0.01, 0.03, 0.05) \).
5. Conclusion

We analyze a viscoelastic DE balloon with out-plane deformation in the vacuum environment. The equation of motion is described by the stretch of the balloon and focuses on viscoelasticity. When the balloon is only subject to pressure or a static voltage, it may reach a state of equilibrium after the viscoelastic relaxation. Then the effect of viscoelasticity on the electromechanical response of the balloon subject to a time-dependent voltage is studied. It is found that when the voltage is sinusoidal, the balloon resonates at multiple frequencies both with and without viscoelasticity considered. And the natural frequency is independent on the viscoelasticity. But the effect of viscoelasticity reduces the amplitude and increases the mean stretch of oscillation. To confirm the theoretical predictions, we hope to further analyze the nonlinear behavior with viscoelasticity by experiments.

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