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# Modeling of dielectric viscoelastomers with application to electromechanical instabilities

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ABSTRACT

Soft dielectrics are electrically-insulating elastomeric materials, which are capable of large deformation and electrical polarization, and are used as smart transducers for converting between mechanical and electrical energy. While much theoretical and computational modeling effort has gone into describing the ideal, time-independent behavior of these materials, viscoelasticity is a crucial component of the observed mechanical response and hence has a significant effect on electromechanical actuation. In this paper, we report on a constitutive theory and numerical modeling capability for dielectric viscoelastomers, able to describe electromechanical coupling, large-deformations, large-stretch chain-locking, and a time-dependent mechanical response. Our approach is calibrated to the widely-used soft dielectric VHB 4910, and the finite-element implementation of the model is used to study the role of viscoelasticity in instabilities in soft dielectrics, namely (1) the pull-in instability, (2) electrocreasing, (3) electrocavitation, and (4) wrinkling of a pretensioned three-dimensional diaphragm actuator. Our results show that viscoelastic effects delay the onset of instability under monotonic electrical loading and can even suppress instabilities under cyclic loading. Furthermore, quantitative agreement is obtained between experimentally measured and numerically simulated instability thresholds. Our finite-element implementation will be useful as a modeling platform for further study of electromechanical instabilities and for harnessing them in design and is provided as online supplemental material to aid other researchers in the field.



## 1. Introduction

Soft dielectrics are compliant elastic materials, which exhibit electromechanical coupling. In particular, an unconstrained soft dielectric undergoes large mechanical deformation when subjected to an electric field (Pelrine et al., 1998; Zhang et al., 1998; Pelrine et al., 2000), distinguishing them from stiff dielectrics, such as ceramics or glassy polymers. Soft dielectrics are capable of converting between mechanical and electrical energy, and hence, over the past two decades, significant effort has gone into using these materials as electromechanical transducers in a variety of applications (cf., Carpi et al., 2008; O'Halloran et al., 2008), such as artificial muscles (Brochu and Pei, 2010), active lenses (Shian et al., 2013), loudspeakers (Keplinger et al., 2013), energy harvesting devices (Kornbluh et al., 2012), and active architectural designs (Decker, 2015),

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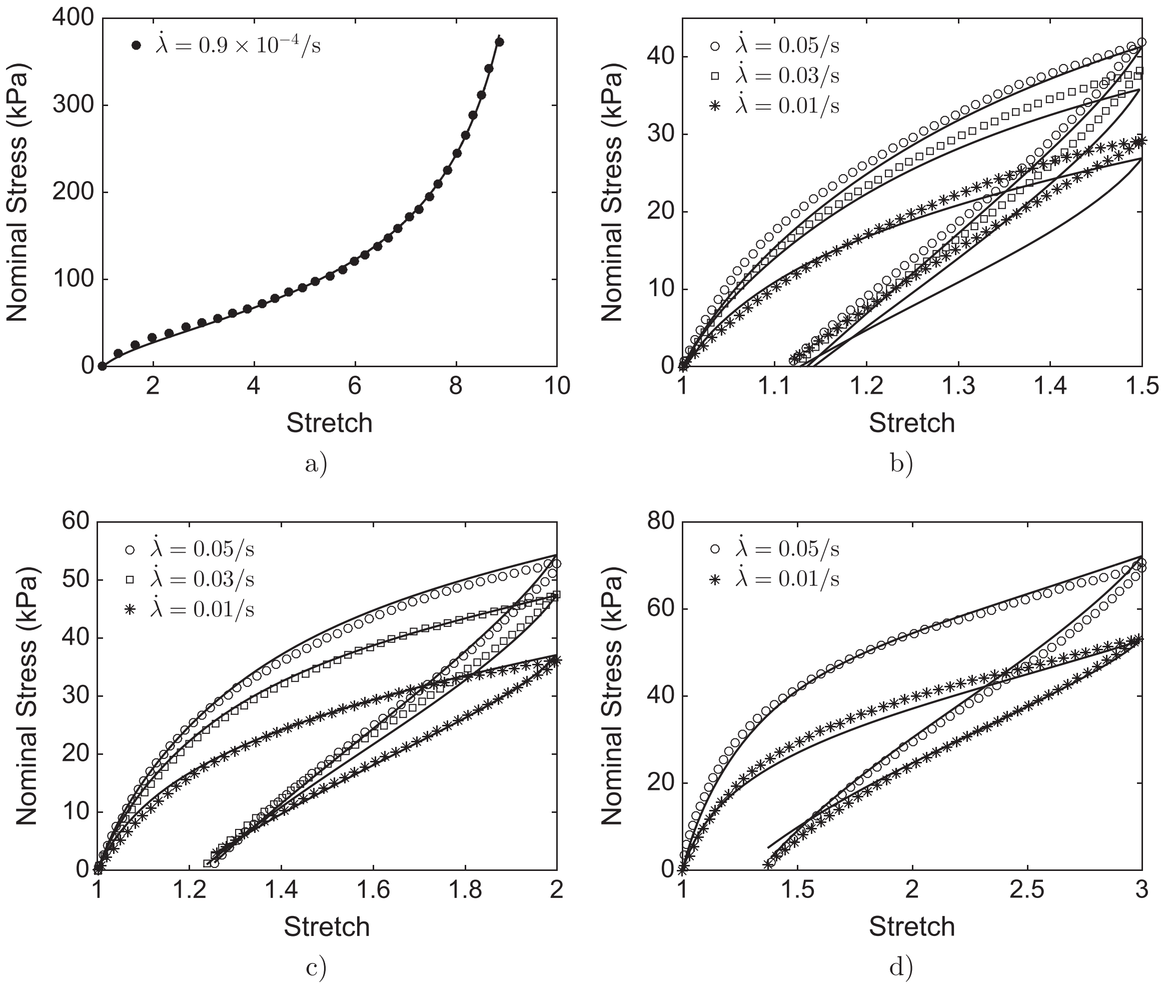


**Fig. 1.** Comparison of experimental data for VHB 4910 (shown as points) to the calibrated model (shown as lines) in simple tension. (a) Quasi-static monotonic tension to a maximum stretch of $\lambda \approx 9$ and the fit to the equilibrium response of (3.6). Load/unload simple tension for several stretch rates to a maximum stretch of (b) $\lambda = 1.5$, (c) $\lambda = 2$, and (c) $\lambda = 3$. The experimental data of (a) is our own, while the experimental data of (b)–(d) is from Hossain et al. (2012).

among many others.

As soft dielectrics deform under the action of an applied electric field, it is not uncommon to encounter one of several modes of instability – a topic which has received significant attention in the recent literature (cf., Zhao and Wang, 2014). Using the terminology of Zhao and Wang (2014), instabilities in soft dielectrics may be categorized into three generic modes: (1) the pull-in instability (Zhao and Suo, 2007; Plante and Dubowsky, 2006), (2) electrocreasing (Wang et al., 2011a, b, 2012a), and (3) electrocavitation (Wang et al., 2012b), with the mode of instability dependent upon the geometric configuration and boundary conditions. Realizing that such instabilities may be harmful, methods of suppressing electromechanical instabilities and enhancing the performance of soft dielectrics have been investigated. Some of the proposed methods include applying a mechanical pre-stretch, using materials with “stiffening” properties, and constructing soft dielectric composites (e.g., Zhao and Wang, 2014; Bertoldi and Gei, 2011). However, instabilities are not universally harmful. Following the recent trend in mechanics of harnessing instabilities for novel functionalities (cf., Reis, 2015), electromechanical instabilities in soft dielectric have been used to achieve enhanced deformations (Keplinger et al., 2012), as control valves in microfluidic devices (Tavakol and Holmes, 2016), for tunable surfaces (Wang et al., 2012a), and in anti-biofouling applications (Shivapooja et al., 2013).

In order to better understand electromechanical instabilities and to harness them in design, predictive constitutive models and numerical simulation capabilities are required. The material behavior of soft dielectrics is quite rich, involving electromechanical coupling, large deformations and associated large-stretch chain locking behavior, as well as a time-dependent mechanical response. Consider, as an illustrative example, the behavior of VHB 4905/4910 – a widely studied material in the literature (cf., e.g., Plante and Dubowsky, 2006; Tagarielli et al., 2012; Hossain et al., 2012; Guo et al., 2015; Hossain et al., 2015) – which is demonstrated in Fig. 1. First, Fig. 1a shows the experimentally measured, equilibrium response of VHB 4910 in quasi-static (low stretch-rate), monotonic simple tension (experimental details in Section 3) to large