Capacitive extensometry for transient strain analysis of dielectric elastomer actuators

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Dielectric elastomer actuators (DEAs) are promising structural units for artificial muscles and robotic elements. Understanding the safe and failure mode regimes of such DEAs is essential for controlling the actuator. We develop an electrical characterization technique for obtaining information on the transient strain in the actuator and analyze the behavior of the actuator in safe and failure operation regimes, in particular in the pull-in instability mode. Additionally, the technique allows the strain-dependent measurement of the electrode resistance. The current measurement based technique can be also applied for actuator control with feedback loops. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2929383]

Dielectric elastomer actuators (DEAs) started to be a topic of intensive research since their first description by Pelrine *et al.* in 2000,[1] although the physical mechanisms underlying the working principle of DEAs were already studied by Röntgen in 1880.[2] While Röntgen used natural rubber with sprayed-on electrostatic charges, modern DEAs consist of synthetic elastomers sandwiched between two highly compliant electrodes. When a voltage is applied between these electrodes, a significant Maxwell stress is acting on the DEA. Thereby, the elastomer film is squeezed in its thickness direction and expands in the film plane due to the incompressibility of the material. DEAs are lightweight and are capable of more than doubling the area with low response time; hence they are promising for bionic and robotic applications.[3] Reliability requirements in such applications necessitate better knowledge of the safe operation regimes and possible failure modes of DEAs. The dominating failure mode, especially in the low prestretch range, is the pull-in instability,[4] which was recently studied theoretically.[5,6] To further improve its understanding, one has to obtain detailed information about the transient strain in the actuator. A standard technique to record strain data is to analyze digital optical images of the electrode area.[7] This is quite laborious and slow. Moreover, it is difficult to account for out-of-plane deformations (wrinkles), which results in an underestimation of the strain values.[1,4] From another point of view, to optimize the functionality of DEAs one has to use reliable electrodes that combine high mechanical compliance with good conductivity. In that context percolation effects seriously limit the performance of commonly used carbon-oil electrodes at high strain values.[8–10] Thus, the electrode resistance should be monitored when working with DEAs.

Here, we develop an electrical measurement technique for characterizing the deformable capacitors of DEAs, which meets the desired requirements: (i) transient information on the strain in the actuator without limitations to planar geometries can be obtained and (ii) *in situ* tracking of the electrode resistance is feasible.

The experimental arrangement for both capacitive extensometry and video optical analysis is shown in Fig. 1. dc voltages of ~1–4 kV are applied to a DEA in order to produce significant Maxwell stresses. An additional ac voltage with an amplitude much smaller than the dc bias is applied to allow for impedance analysis. Thus, a dc voltage with a superimposed ac signal from an Agilent 33250A function generator is fed to a Trek 610D HV amplifier and then applied to the DEA. The current through the DEA is read via a measurement resistance of $R_m = 1\ \text{k}\Omega$, using an EG&G 7260 DSP lock-in amplifier. A high common mode rejection isolation amplifier ensures galvanic separation and protects the lock-in amplifier from electrical damage in case of dielectric breakdown of the DEA. Therefore, the setup makes possible electrical characterization of samples under high voltage. The radial and axial stretch ratios λ_r and λ_z are obtained from the amplitude of the current, while its phase delivers the resistance of the electrodes.

For circular (symmetrically stretched) DEAs,[1] incompressibility results in $\lambda_r^2\,\lambda_z = 1$, where λ_r and λ_z denote the radial and axial stretch ratios (with respect to the prestretched state, if relevant). For the capacitance, we can then write,

$$C = \varepsilon_0 \varepsilon(\lambda_r, \lambda_z) \frac{\lambda_r^2 A_0}{\lambda_z z_0} = \varepsilon_0 \varepsilon(\lambda_r, \lambda_r^{-2}) \frac{A_0}{z_0} \lambda_r^4. \quad (1)$$

Here ε_0 is the vacuum permittivity, A_0 and z_0 are the initial area and thickness. If the dielectric constant does not depend on the stretch ratios, $\varepsilon(\lambda_r, \lambda_z) = \varepsilon$, the capacitance is proportional to the fourth power of the radial stretch ratio $C \propto \lambda_r^4$. If the stretch dependence $\varepsilon(\lambda_r, \lambda_z)$ is known from independent measurements, it can be easily taken into account. In any case, as the capacitance is related to the radial stretch λ_r, impedance analysis can be used to monitor λ_r. No assumption on the planarity of the actuator is involved in the basic framework of capacitance measurements for thin elastomers.

A 3 M VHB 4905 acrylic elastomer tape was prestretched and attached to a planar, circular rigid frame for investigating the transient strain in DEAs. A mixture of carbon black from ABCR with an average particle size of 0.42 μm and ELBESIL B50 silicon oil was prepared by stirring. When coated on both sides of the elastomer homogeneous electrode films were formed. The conductivity of the electrodes strongly depends on the preparation procedure,[8] but was always measured as discussed below. When the actuator is undergoing high tensile strain, fragmentation occurs, significantly increasing the electrode resistance.

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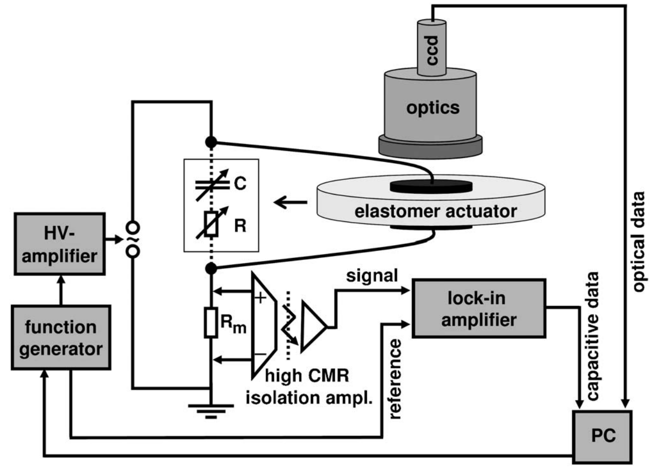

FIG. 1. Capacitive extensometry setup with optical control, allowing for real-time *in situ* electrical measurements of stretch ratios and for simultaneous quality control of the compliant electrodes.

Since DEAs are deformable capacitors, the equivalent circuit is a series R C connection shown in Fig. 1. Here, C denotes the strain-dependent capacitance described by Eq. (1), whereas R accounts for the strain-dependent resistance of the electrodes. The measured amplitude of the complex current I through the DEA is related to the radial stretch ratio λ_r, since $I \propto C\omega \sin \varphi$ where ω and φ are the frequency of the sinusoidal measurement signal and the phase shift of the current. The resistance of the electrodes is obtained from the loss angle, $R+R_m \propto I^{-1} \cos \varphi$. In addition, a video optical system controls the electrode area, which is later compared with the capacitive extensometry data.

In the left part of Fig. 2, the measured current amplitude and phase are shown for a circular DEA. The initial thickness of the unstrained VHB 4905 tape in all experiments was 500 μm. Here, the elastomer with a prestretch ratio of 2.5 is fixed in a rigid frame with a diameter of 50 mm. The electrode diameter prior to the application of a dc voltage is 10 mm. The radial stretch ratio λ_r and the electrode resistance R are obtained from the data in Figs. 2(a) and 2(b) and displayed in Figs. 2(c) and 2(d) respectively. The dynamics of the expansion process reveals the viscoelastic drift of the elastomer that follows after stepwise increase in the dc voltage. The abrupt increase in the electrode resistance upon each dc voltage increase is mainly due to fragmentation of the electrodes as a result of the increasing electrode area. Advantages of capacitive extensometry in comparison to the optical methods are the ease and speed of evaluation also allowing for DEA implementation in electrical control circuits. For controlling actuators, electrical pulse width modulation signals have been recently reported.[11] Furthermore, the capacitive extensometry technique is not limited to planar actuator geometries.

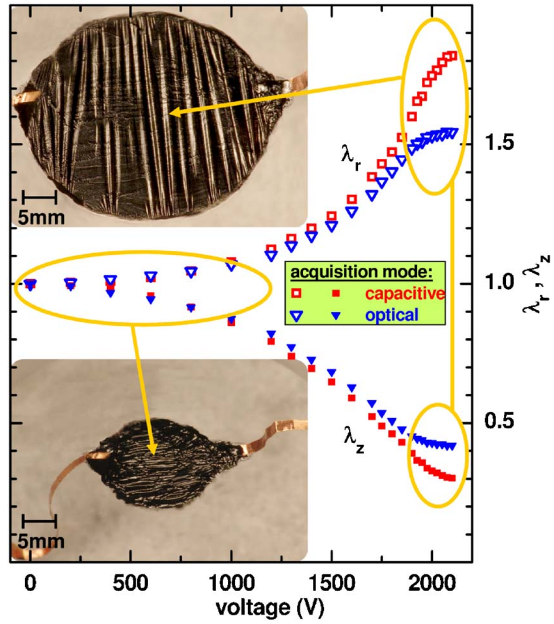

FIG. 3. (Color online) Comparison between capacitive extensometry and optical control for measuring the electrode area and film thickness of DEAs versus applied voltage. Optical measurements underestimate the area and the radial stretch ratio λ_r, especially when wrinkles appear in the elastomer at voltages exceeding 1.8 kV.

Figure 3 shows a comparison between the capacitive and optical data acquisition method used to obtain the stretch ratios λ_r and λ_z versus applied voltage for a circular DEA with a prestretch ratio of 2.5. The elastomer is fixed in a rigid frame with a diameter of 50 mm, the electrode diameter is 8.5 mm before a dc voltage is applied. The voltage was increased stepwise each 200 s. Displayed data points are averages over the last 10 s. Figure 3 shows the investigated ac-

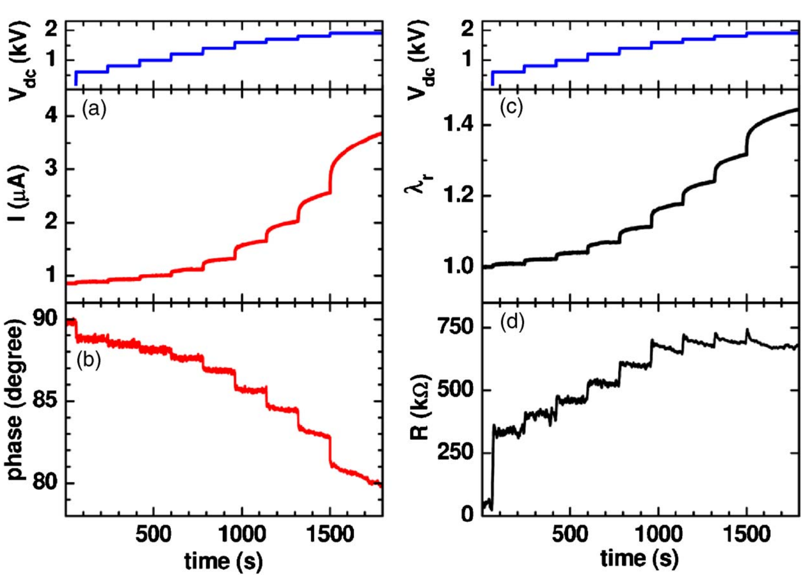

FIG. 2. (Color online) Evolution of a circular DEA under stepwise dc voltage increase (top). (a) and (b) depict the measured current amplitude and phase shift, while (c) and (d) show the deduced radial stretch ratio λ_r and the electrode resistance R.

tuator undergoing low (bottom photo inset), intermediate, and high strain actuation. Wrinkled out-of-plane deformations are likely to occur at high stretch ratios (see upper photo inset in Fig. 3). Buckling partially relaxes tensile stress in the direction perpendicular to the wrinkles, and simultaneously makes the overall strain greater than that inferred from the optical measurements of the visible electrode area. As can be seen in Fig. 3, the discrepancies between the optically and electrically measured stretch ratios occur at high voltages exceeding 1.8 kV, exactly where the wrinkles appear. In this regime, the thickness of the elastomer (~25 μm) is small compared to the wavelength of the approximately sinusoidal wrinkles (~500 μm). In addition, the parallelism of the electrodes is sustained. Therefore, although the electrodes of the wrinkled DEA are nonplanar, one can still approximate them by a plate capacitor in calculations. When this is done, Fig. 3 indeed shows, that at high dc voltages, where film buckling occurs, the video optical measurements underestimate the stretch ratios and the capacitive measurements yield more accurate strain values. The small discrepancy between the capacitive extensometry and the optical analysis at medium strain levels seen in Fig. 3 may be due to a strain-dependent $\varepsilon(\lambda_r, \lambda_z)$. This opens up possibilities to investigate the strain dependence of the dielectric permittivity in such a setup.

One of the failure modes of DEAs currently studied theoretically[5,6,12] and experimentally[4] is the pull-in instability, which frequently occurs in electrostatically driven systems. It has been first observed in microelectromechanical devices (MEMS) (Ref. 13) and is thoroughly analyzed in Ref. 14. Since DEAs also work on electrostatic principles, it is not surprising that they show pull-in instabilities as well. Since the strain values may rapidly change in the vicinity of such an instability region, it is helpful to obtain *in situ* transient strain information in order to improve the understanding of this effect.

We have chosen a DEA with a radial prestretch of 1.9, a rigid frame diameter of 38 mm, and an electrode diameter of 4 mm when no voltage is applied. This particular actuator geometry was chosen on the basis of simulations of circular DEA's employing the Arruda–Boyce eight chain model of VHB 4905.[15,16] It implies that all chains deform in the same way. This simplifies averaging and results in an inverse Langevin-type free energy function. The overall energy contains elastomer regions inside and outside of the electrodes, as well as the electrostatic energy under constant voltage conditions. Equilibrium corresponds to the minimum of this total energy function with respect to λ_r. The detailed description is beyond the scope of this work and will be presented elsewhere.[16] Our calculations predicted that such an actuator should show a pull-in instability at $\lambda_r \approx 1.4$ when the electrostatic attraction exceeds the compressive stresses of the sandwiched elastomer, so that the actuator capacitor collapses until dielectric breakdown occurs.

Figure 4 shows the slow viscoelastic drift of a DEA in the pull-in instability and breakdown failure mode. When a voltage of 3.5 kV is applied, the radial stretch ratio $\lambda_r(t)$ first tends to stabilize, but after some delay (~150 s) an inflection point occurs, followed by a rapid increase of λ_r until breakdown. The photos in Fig. 4 illustrate the evolution of

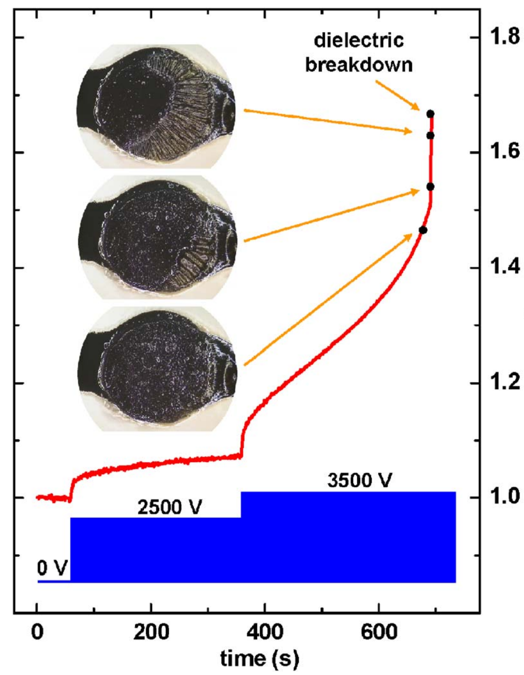

FIG. 4. (Color online) Slow viscoelastic development of the pull-in instability. At 3.5 kV the radial stretch ratio first slows down, after the inflection point the area increases fast until breakdown occurs. The inset photos show the development of wrinkles in the actuator.

wrinkles in the actuator when the system is driven into the failure mode.

In summary, we have developed an electrical characterization method for DEAs. It is capable of obtaining radial and thickness stretch ratios in safe, wrinkled, and failure modes of the actuator. The technique can be applied also to 3D actuators, electrode quality can be assessed and the actuator can be electrically controlled. Complementary information is obtained from optical inspections.

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