Pulsed actuation avoids failure in dielectric elastomer artificial muscles

Toma Kobayashi and Stoyan K. Smoukov*

Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, UK
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Dielectric elastomer actuators (DEAs) are a class of artificial muscles capable of large linear strains (well over 100%), and with high energy density, and low cost and weight. One of the most prominent failure modes of a DEA is electrical breakdown, which can damage the device permanently, limiting its deformation capability. Breakdown is also common, since to maximize energy output, devices often operate near the breakdown limit. Elucidating breakdown mechanisms, as well as finding ways to prevent it, are of intense research interest. We show that by applying short electrical pulses, one could minimize the exposure of the DEAs to high leakage current, which is one of the main mechanisms for electrical breakdown. This allows one to operate at significantly higher potentials than the DC breakdown voltage. By applying pulses, we demonstrate up to 81.7% area strain repeatedly, at voltages more than twice the DC breakdown limit, without the risk of failure. The pulsed operation mode of DEAs accommodating higher voltages than possible with DC represents an opportunity for potential applications, safer and simpler device designs, and a technique for further study of DEA breakdown mechanisms.

Keywords: dielectric elastomer; electrical breakdown; pulsed operation; leakage current; high voltage; design safety

1. Introduction

Dielectric elastomer actuators (DEAs) have been extensively researched in the past decade [1]. They possess remarkable actuation properties including strain, energy density, efficiency and reaction speed, which can surpass even the capabilities of biological muscles [2], and represent immense potential in a wide range of applications such as soft robotics [3], microfluidic chips [4], energy harvesting [5], loudspeakers [6], etc.

DEAs are a class of artificial muscles with a simple sandwich structure – a thin dielectric elastomer film (sub-millimeter thick) between compliant conductive electrodes [7]. When electric potential difference is applied across the active layer, opposite charges accumulate at electrodes, and the resulting electrostatic attraction exerts pressure on the dielectric, bringing the electrodes closer together and leading to expansion in the transverse directions [8].

The magnitude of the electrostatic pressure is defined by

\[ P = \varepsilon_r \varepsilon_0 E^2 = \varepsilon_r \varepsilon_0 \left( \frac{V}{\ell} \right)^2 \]  

*Corresponding author. Email: sks46@cam.ac.uk

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where $P$ is the equivalent pressure on the active layer, $\varepsilon_0$ is the free-space dielectric permittivity, $\varepsilon_r$ is the relative dielectric permittivity of the dielectric, $E$ is the electric field, $V$ is the voltage, and $t$ is the thickness of the dielectric elastomer. DEAs can achieve extremely large strain (typically well over 100% and area expansion as high as 1692%) [9], high energy density (up to 3.4 MJ m$^{-3}$) [10], and fast response time (less than 1 ms) [1].

The failure modes of DEAs include electrical breakdown, electromechanical instability, loss of tension and mechanical rupture [11]. The key area of research within this field has been investigating the methods to suppress these failure modes in order to maximize the deformation capability of DEAs.

Electrical breakdown is catastrophic as it causes a permanent damage to DEAs. Controlled experimental conditions are crucial to prevent the breakdown and optimize the performance. The intrinsic breakdown strength of a DEA, however, has been found to vary significantly due to the unpredictability of structural defects in the elastomer [12], making it extremely difficult to correctly predict and prevent the electrical breakdown. For DEAs with 300% biaxially prestretched VHB 4910 tape, it has been experimentally found that they suffer from electrical breakdown at 4–6 kV, limiting the safe operating voltage of a device to lower than this range.

Much of the study on DEAs has been conducted using DC voltage; however, in this article, we demonstrate that DEAs are capable of surviving at higher voltages by applying electrical pulses, causing DEAs to deform momentarily. It minimizes the duration of DEAs’ leakage current exposure, thereby significantly reducing the chance of triggering the electrical breakdown. Pulsed operation of DEAs provides insight into the mechanism of electrical breakdown and represents a promising path for future work.

2. Electrical breakdown

One of the most damaging failure modes of a DEA is electrical breakdown as it results in permanent destruction of the device. However, in order to maximize the deformation and output energy, it is necessary to operate near the verge of breakdown, making it common to induce irreversible damage to a DEA.

Breakdown is known to be caused by the thermal runaway instability, and the condition to instigate it is dictated by the ideal breakdown strength of an elastomer, electromechanical instability, Joule heating, and/or partial discharge [11,12,13]. Thermal runaway instability occurs in the following steps. High electric fields across a DEA result in high leakage current flowing through the elastomer, increasing its temperature and conductivity [12]. The conductivity rise due to the increased temperature leads to flow of even higher leakage current; when the positive feedback between the joule heating and leakage current occurs, the dielectric is heated beyond its melting/boiling temperature quickly, ultimately causing dielectric failure [14].

When DC voltages between 4 and 6 kV are applied to DEAs made of 300% biaxially prestretched VHB elastomer, electrical breakdown does not occur instantaneously, but it takes up to a few seconds before a DEA experiences the breakdown and stops maintaining the voltage. Figure 1 shows the voltage–time plots of DEA samples subjected to a step increase of DC voltage of constant magnitude. The experimental data clearly show that the electrical breakdown is a phenomenon occurring in a finite time.

DEAs with graphite powder electrodes generally last longer than those with carbon grease electrodes. This is because of the longer charge and discharge time resulting from higher resistivity of graphite powder electrodes. Because of the longer charging time, it
requires longer time to accumulate enough charges to instigate thermal runaway instability and ultimately breakdown.

We hypothesized that by applying electrical pulses, as shown in Figure 2, we could limit the extent of heating, preventing the runaway positive feedback with the leakage current. We thus achieved significant area expansion and stability at higher voltages that would otherwise cause electrical breakdown.

3. Frequency response of a DEA

Figure 3(a) shows the principle of DEA operation and the design of a circular DEA actuator Figure 3(b). When using electrical pulses (and AC voltages), instead of constant DC voltages, to drive the deformation of a DEA, it is crucial to consider its frequency response. The frequency response of a DEA is mainly determined by its charging/discharging time when an
input signal of an electrical pulse (and high frequency signal) is applied. A non-ideal DEA has finite resistivity due to the finite conductivity of electrodes. This means that a DEA in principle forms a series RC circuit made of two resistors and a capacitor as shown in Figure 3c), limiting the electrical response speed of the DEA.

The equivalent capacitance can be calculated by the well-known equation,

\[ C = \frac{\varepsilon_0 \varepsilon A}{d} \]  

where \( \varepsilon_0 \) is the dielectric permittivity of vacuum, \( \varepsilon \) is the relative dielectric permittivity of the elastomer, \( t \) is the thickness of the elastomer film, and \( A \) is the area of the active region. Assuming the electrode resistivity to be \( R \), the total resistance of a DEA is

\[ R_T = 2R \]
The time constant of a DEA is then equal to

\[ t_c = R_T C \]  \hspace{2cm} (4)

The cut-off frequency of the RC circuit can then be expressed as

\[ f_c = \frac{1}{2\pi t_c} = \frac{1}{4\pi RC} \]  \hspace{2cm} (5)

Thus, for a given dielectric elastomer, the resistivity of the electrodes strongly influences the frequency response of a DEA. The electrically operable frequency range of a DEA is crucial for a high frequency operation.

The varying nature of DEA’s electrical properties (electrode resistance, capacitance) as deformation occurs makes its frequency response analysis difficult. The basic analysis of DEA deformation to an electric pulse, however, is insightful since it gives us an estimate of the charging time and hence cut-off frequency of a DEA. We clearly demonstrate differences in the charging/discharging times of different DEA designs.

Figure 3. (a) Operational principle. (b) Circular DEA design tested in this article. Electrostatic potential attraction of the compliant electrodes, across the dielectric elastomer film, causes compression of the film and simultaneous stretching of the electrodes from initial area A to area B, as they come closer together. (c) Equivalent circuit model of a DEA.
4. Experimental methods
Circular DEAs were fabricated and tested in this article. Three-hundred percent biaxially prestretched VHB 4910 tape, purchased from 3M, were attached to a rigid circular frame with an internal aperture diameter of 450 mm. The circular active region, 100 mm in diameter, was then defined in the center of the elastomer membrane using conductive carbon grease purchased from MG Chemicals. Carbon grease was also used to draw conductive paths to the edge of the frame so that the external circuits and a DEA could be connected. DEAs with graphite powder electrodes were also fabricated using the same procedures. The design of a circular DEA is shown in Figure 3b).

Electrical pulses of magnitude 0–10 kV were applied, and the consequent deformation was observed. The asymmetric pulse shape (100 ms rise time, ~180 ms FWHM) was the only one possible to apply with our high voltage source, normally designed for a DC operation. The deformation of DEAs in response to the input pulses were optically recorded and measured. The area strain was calculated using the following formula:

\[
\text{Strain} = \frac{(\text{Actuated area} - \text{initial area})}{\text{Initial Area}}
\]

The electrical pulses were observed using an oscilloscope and a precision divider probe. The voltage–strain plot was drawn to investigate the pulsed mode of DEAs. All the experiments were conducted at room temperature.

5. Results
The resultant strain–voltage relationship is shown in Figure 4 along with exemplary images of a DEA with carbon grease electrodes in its reference and activated states. When subjected to an electrical pulse, the DEA deformed momentarily, and immediately contracted back to its initial state. The maximum area strain achieved by a DEA with carbon grease electrodes was 81.7% although loss of tension was observed by a number of samples tested at high voltages (>5 kV).

Much more interestingly, although the curve showed the expected trend up to about 4 kV, the area strains achieved by DEAs with carbon grease electrodes in a twitching mode were self-limited around 80% at voltages beyond 5 kV. Furthermore, DEAs did not suffer from electrical breakdown at higher voltages than the levels which would have caused the breakdown in DC bias (>5 kV).

Electrical breakdown did not occur in over 50 samples tested for this article when the electrical pulses of 10 kV and even 15 kV were applied, clearly indicating that the immunity of DEA to the breakdown was increased. DEAs were able to perform more than 20 pulsed actuation cycles at these high driving voltages without failing.

A similar phenomenon of self-limiting strain–voltage relationships and an increase in their resistance against electrical breakdown were seen for DEAs with various combinations of materials including natural rubbers, graphite powders, and conductive gels when electrical pulses were applied instead of DC voltages.

Figure 4(f)–(j) shows the results obtained for DEAs with graphite powder electrodes. The maximum area strain achieved was 76.9%, and strain levels for a DEA with graphite powder electrodes were on an average lower than those for a DEA with carbon grease electrodes. The strain levels were limited on an average to approximately 62%.
Although the general behaviors observed for DEAs with carbon grease electrodes and graphite powder electrodes were similar, there were distinct differences. Firstly, compared to DEAs with carbon grease electrodes, the strains achieved were less stable and consistent. It was more challenging to pattern graphite electrodes. The reproducibility as well as uniformity of electrodes were uncertain for graphite powder electrodes, contributing to variability in the strain–voltage relationship. Furthermore, even during the deformation, rapid movements of the surfaces occasionally caused the graphite powder to move and electrode dimensions to vary slightly, altering the device parameters. This clearly affected the consistency of the results obtained.

Furthermore, due to the difficulty in patterning electrodes and subsequent non-uniformity of electrodes, DEAs with graphite powder electrodes were more vulnerable to
electrical breakdown. Whilst none of the samples of DEAs with carbon grease electrodes suffered from electrical breakdown, DEAs with graphite powder electrodes occasionally suffered from electrical breakdown due to inhomogeneous electrode dimensions and voltage distribution although they were clearly more insusceptible to electrical breakdown than when DC voltages are applied.

Finally, the relaxation time of a DEA is different depending on the electrodes used. Although DEAs with carbon grease electrodes immediately contracted back to their initial state, DEAs with graphite powder electrodes tended to deform much more slowly and smoothly, taking longer before contracting back to the initial state. The higher resistance of graphite powder electrodes resulted in higher time constant, ultimately leading to longer relaxation time compared to carbon grease electrodes.

6. Discussion

Electrical pulses instead of DC voltages clearly reduced the vulnerability of DEAs to electrical breakdown. DEAs were able to survive through voltages higher than conventionally allowed without suffering from permanent damage to the devices. The actuation is dictated by voltages as Equation (1) evidently demonstrates, thus, maximizing the operable voltage range is crucial.

The time scale of the positive feedback between Joule heating and leakage current, and hence electrical breakdown is often neglected; however, electrical breakdown clearly occurs in a finite time and not instantaneously as sufficient current needs to flow to start increasing the temperature and conductivity to ultimately establish the thermal runaway instability. It can, therefore, be prevented by reducing the duration of the signal, thereby restricting the charge accumulation and current leakage. This is precisely the reason why electrical breakdown did not occur when electrical pulses were applied to DEAs.

In addition to subduing electrical breakdown, the strain levels were self-limited at high voltages (>5 kV). The deformation of DEAs with carbon grease electrodes at high voltages was limited at around 80% whilst the maximum strain for devices with the graphite powder was capped at around 62%.

By controlling the duration of input pulse and time constant, DEAs’s deformation can be self-limited at appropriate magnitudes. DEAs with graphite powder electrodes were self-limited to lower strain levels compared to DEAs with carbon grease electrodes due to the higher resistivity (and hence time constant).

By shortening the input voltage duration, a DEA demonstrated a pulsed mode capable of handling excessively high voltages. Electrical pulse unlike DC voltages does not allow sufficient time to establish positive feedback between Joule heating and conductivity increase, ultimately preventing permanent failures of DEAs.

The study on DEAs’s response to electrical pulses enhanced the understanding of physics behind the breakdown mechanisms of DEAs. The duration of input voltage can be altered in future as appropriately to optimize the DEA performance. The theoretical understanding inferred from this article indicates that by understanding the time scale of the positive feedback and electrical breakdown, the dielectric failure can be prevented, and it is possible to control the failure modes by varying the duration of input signals so that the voltages are stopped before they damage the membrane permanently. Thus, this may be applied to even non-prestretched DEAs to induce deformation without risking the electrical breakdown of the devices.
Furthermore, it has been previously questioned whether the breakdown occurs mainly due to the thermal runaway instability or due to the accumulation of damage through partial discharges and mechanical stresses [12]. The electrical pulses of controlled duration and magnitudes can be applied in future to study the accumulation of damage to facilitate a greater understanding of the physics behind dielectric failures in DEAs.

Further work needs to be done to investigate the time–strain relationship resulting from electrical pulses. A detailed understanding of dynamic DEA deformations would require high voltage generators capable of delivering pulses of different shape and variable time duration as input. Sub milli-second precision recording of synchronized strain, voltage and current data would be desirable, as well as a fabrication method producing DEAs with consistent electrical properties for the time response.

7. Conclusion
By driving DEAs with electrical pulses, we have demonstrated that they can survive excessively high voltages. In this article, we investigated how DEAs react to electrical pulses instead of DC voltages. DEAs were fabricated using 300% biaxially prestretched VHB 4910 tape and a conductive carbon grease/graphite powder. Electrical pulses of 0–10 kV were applied, and the resultant deformation of DEA was observed and analyzed.

By minimizing the duration of the input electrical signals and high leakage current, we have prevented the positive feedback between Joule heating and higher current, which would have led to electrical breakdown. The study of DEAs at electrical pulses provided an understanding of the voltage-dependent time scale of failure and an insight into potentially safer and simpler device designs. The technique represents a significant opportunity for further improvement in the fundamental understanding of DEA breakdown mechanisms.

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