EFFECT OF CONSTRAINTS ON ELECTROSTRICTION

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Abstract: The effect of constraints on the measurement electromechanical coupling from polymer films is quantified. This information is essential to the application of electrostrictive materials. Theoretical analyses are shown to be in good accord with the experimental results.

1. Introduction

Electrostriction refers to the strain induced in a material by an applied electric field. It is a second-order property, occurring at twice the applied frequency with a magnitude proportional to square of the field strength. Whether one is correcting non-linear dielectric measurements for the errors arising from electrostriction, or developing devices (transducers, sensors, etc.) based on electrostrictive materials, accurate and reproducible measurements are obviously essential. In addition to trivial measurement errors, electromechanical strains can depend on various factors, such as sample processing (e.g., crystallinity, orientation, residual polarization) and the test conditions (e.g., field strength, frequency, waveform, sample configuration, clamping method). These myriad potential problems are reflected in the literature. For example, reported values of the electrostrictive coefficient for poly(vinylidene fluoride–co–trifluoroethylene), which is one of the most studied electroactive polymers, vary by more than four orders of magnitude [1].

One recognized but oft-overlooked aspect of the problem is the effect of the constraining pressure on the measured sample displacement. Constraints of some sort are always required for electromechanical measurements, if only to maintain the electrodes in contact with the sample. When measuring the longitudinal strain (thickness strain, parallel to the field), the electrodes are sputtered or vapor deposited on the sample major faces. Such electrodes severely constrain the lateral expansion of the film, reducing the apparent electrostriction. Alternatively, lateral pressure, for example in the form of dead-weighting, is brought to bear on electrodes in physical contact with the sample. This pressure serves an additional purpose, in helping to maintain flatness to avoid out-of-plane bending contributions to the measured strain.

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For applications, the confining pressure is often determined by the geometry of the device. The performance is then a function both of the inherent electrostriction and the magnitude of this constraint. Thus, the electromechanical characterization of materials required knowledge of the response in the absence of constraint. Since direct measurements would be subject to error, the constraint-free response has to be calculated from experimental data. An early analysis of the effect of constraints by Gent and Lindley [2], valid for quite large aspect ratios (film thickness to width ratio, t/w) assumes incompressibility. This leads to the prediction of very large constraint effects, as the sample tries to maintain constant volume. Expressed as the ratio of the strain in the limits of high and zero pressure,

$$f = \frac{3}{4}\left(1 + w^2/2t^2\right)^{-1} \tag{1}$$

For rubber, in which Poisson's ratio, ν, is quite close to 0.5, the accuracy of the relation of Gent and Lindley has been experimentally verified [3]. Arridge [4] extended the analysis to compressible materials, with the results becoming a function of ν, as well as sample geometry. An analytical form of this solution was published recently by Yeoh et al. [5]

$$f = \left(4/3 + \left(1 - \frac{\tanh(\alpha w/2)}{\alpha w/2}\right) \Big/ 3(1-2\nu)\right)^{-1} \tag{2}$$

where

$$\alpha = \left(12(1-2\nu)/t^2\right) \tag{3}$$

Finally, Furukawa and Matsumoto [6] derived an analysis valid for infinitely small aspect ratio ($w >> t$), corresponding to a condition of maximum constraint. Their result depends only on the value of Poisson's ratio of the sample

$$f = (1-2\upsilon)(1+\upsilon)/(1-\upsilon) \tag{4}$$

2. Experimental

We measure electrostrictive strains using two methods. An absolute measure of strain comes from the relative change in the capacitance of an air gap, responding to the sample's change in thickness. The second method uses a commercial instrument, a MTI-1000 Fotonic Sensor, with which the displacement is determined from the intensity of light reflected from the top surface of the sample. The data must be calibrated, for example using a micrometer. The Fotonic Sensor allows measurements to be made at various locations on the film surface, in order to verify sample uniformity. In the present experments, the sample dimensions were w = 25.4 mm and t = 0.11 mm, and Poisson's ratio, calculated from the measured shear and bulk moduli, was equal to 0.492.

3. Results

Plotted in Figure 1 is the electrostriction of a vinylidene fluoride film, measured as a function of the confining pressure (applied to the film faces, parallel to the electric field). The strain decreases by a factor of 11 in going from negligible pressure to the plateau corresponding to fully constrained. (The actual ratio of the free to totally constrained strain may be somewhat slightly larger, since we cannot measure at zero pressure due to the weight of the top electrode, nor is the constraint effect necessarily maximized.) In the table below, we compare the measured effect of the constraint to the predictions of the above analyses. The incompressibility assumption [2] strongly over-estimates the effect of the constraints. Allowing for compressibility [5], the value calculated from eq. 2 under-estimated the constraint effect by roughly 50%. We can also see that for w/t = 230, the calculated result is equivalent to eq. 4 for an infinitely thin film.

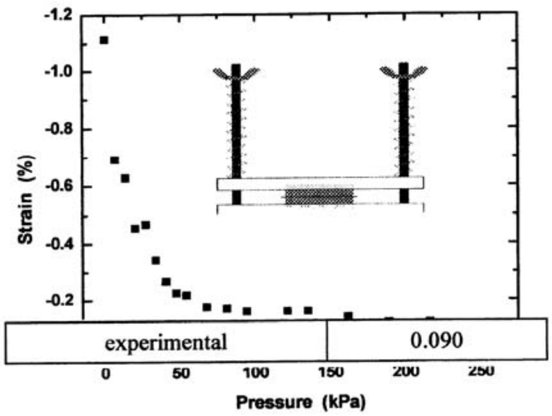

Figure 1. Electrostrictive strain in the thickness direction (parallel to a 10 MV/m, 0.01 Hz field) with various confining pressures applied to the film. The constraints were applied using calibrated springs (inset).

	F
Gent and Lindley [2]	3×10^{-5}
Yeoh et al. [5]	0.045
Furukawa and Matsumoto [6]	0.047
experimental	0.090

A possible source of the disagreement between the calculated effect of constraints and the experimental data could be artifacts from film non-uniformity. At low pressures, out-of-plane bending of the sample would give rise to displacements greater than the change in sample thickness due to electrostriction, thus increasing the apparent value of *f*. We believe that this contribution must be very small, since the films were cast from solution, and because the measured strain was found to be independent of the surface position at which measurements were made (using the Fotonics sensor).is

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6. References

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