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BASIC CHARACTERIZATION OF A LINEAR ELASTOMER ACTUATOR

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ABSTRACT

Innovative types of actuators are required for several applications, especially in the field of medicine, robotics and micro-systems. In this context, Electroactive Polymers represent a promising group among all smart materials. They can change their dimensions and shape when an external voltage is applied, and their mechanical flexibility and ease of processing offer advantages over traditional electroactive materials expanding the options for different mechanical configurations. Dielectric elastomers are among the most promising EAPs for many applications, including actuators and sensors for the microfactory: they work in a dry environment, can achieve great deformations and support high voltage. They can be represented by a parallel plate capacitor: under an electric field the elastomer is squeezed in the thickness causing expansion in the transverse direction. Dielectric EAP actuators require large electric fields (hundreds of kV/mm) but can produce very large strain (up to 400%). Due to their unique properties and potential applications, in this paper the study of the electromechanical behaviour of a dielectric elastomer and a possible application related with the microfabrication of hybrid microsystem is presented.

INTRODUCTION

Despite the advanced state of conventional actuation technologies, there is an increasing demand for new actuation devices with high power-to-weight ratio, high efficiency and large degree of compliance. These devices would provide an improvement in several applications which involves critical and delicate tasks e.g. in the field of medicine, robotics and microsystems. In order to fulfil these needs innovative types of actuators based on smart materials have recently been proposed. They are based on polymeric materials able to change their dimension and/or shape in response to a specific external stimulus such as thermal, chemical, electrical, magnetic or optical.

A promising group of such materials is represented by the Electro Active Polymers (EAPs), which exhibit interesting properties, including a controllable high ratio strain versus

applied voltage, low specific gravity, high grade of processability, down-scalability and, in most cases, low costs (1). Nevertheless, successful implementation of electroactive polymers mainly depends on the degree of understanding of their behaviour and properties since the selection of the material in the design of smart systems involves considerations of different factors, including the maximum achievable strain, stiffness, spatial resolution, frequency bandwidth and temperature sensitivity. Moreover, it is still essential to develop innovative testing methodologies, consistent material characterization and formulation of advanced theoretical models (2).

In the next section a short introduction on electro active polymers is presented with particular attention on dielectric elastomers. In the third section the material and the realization process of the samples are illustrated. In the fourth section the experimental analyses are described and the results discussed. In the fifth section a possible application of EAP is presented and, finally, the conclusions are drawn.

ELECTROACTIVE POLYMERS

Electroactive Polymers are polymeric materials whose shape can be modified by applying a voltage to them. The large displacement that can be obtained with EAPs, their low mass, low power and, in some of these materials (ionic polymer) also low voltage, make them very attractive as actuators. Moreover, their mechanical flexibility and ease of processing offer advantages over traditional electroactive materials expanding the options for mechanical configurations. The group of EAPs comprises a wide array of different materials, each characterized by its unique properties and functional abilities (2).

Dielectric elastomers are among the most promising EAPs for many applications including actuators and sensors for the microfactory: they work in a dry environment, can achieve great deformations and support high voltage. When an electric potential difference is applied across the polymeric film, coated with electrodes on both sides, a compressive stress, parallel to the electric field, is generated. This is a well-known

phenomenon, known as Maxwell stress, which occurs with all insulators subject to an electric field from deposited electrodes. Nevertheless, only the recent development of soft polymeric thin films with high dielectric breakdown strengths allows the achievement of performances exploitable in actuation devices (3).

EAP operation principle is similar to the electromechanical transduction of a parallel two plate capacitor. When an electric potential difference is applied across the polymeric film, coated with electrodes on both sides, a compressive stress, parallel to the electric field, is generated and, consequently, the material is compressed in thickness and expands in planar directions. In order to permit this deformation the electrodes in an EAP actuator must be compliant because the elastomeric polymers are essentially incompressible in volume and so when the polymeric film is compressed in thickness, it must expand in area. Therefore, the electrostriction of the polymer would not occur with rigid electrodes, since they do not allow any planar deformation. Moreover, compliant electrodes allow the expansion of the film and this compliancy means that electrical energy is converted into mechanical energy in form of mechanical deformation, as a result of the repulsion that occurs between like charges on the same electrode (4). Mechanical actuation can be obtained by the compressive stress which causes a compression along the thickness of the material and the consequent planar expansion of the dielectric elastomer. The electrostatic pressure that compresses the film along the thickness direction has been derived via the principle of virtual work assuming that the electrodes are much more compliant than the polymer film itself (5). This effective pressure generated on the film can be expressed by the following equation:

$$P = \epsilon \epsilon_0 E^2 = \epsilon \epsilon_0 (V/t)^2 \quad (1)$$

where ϵ_0 and ϵ respectively denote the permittivity of the free space and the dielectric constant of the polymer; E and V denote the applied electric field and voltage, and t is the thickness of the film.

Because of the compliance of the electrodes, P results to be twice higher than the pressure in a rigid parallel plate capacitor. Indeed, the repulsion of like charges on the same electrode generates a tensile stress in the length and width directions, while attraction of unlike charges on the opposite electrodes generates a compressive stress in the thickness direction and both the stresses are coupled into the effective pressure normal to the plane of the film (5).

MATERIALS AND METHODS

EAPs are relatively new materials and, even though their potential applications are spread out in many different sectors, very few EAPs are commercially available and no exhaustive characterization on their electromechanical behaviour exists. For this reason, in order to evaluate their actual limits and potentialities, some experiments have been carried out with a

commercial EAP (the acrylic elastomer VHB™ 4910 produced by 3M). It is one of the most studied EAP and its electrostrictive behaviour is by now widely known (6-10). The material is a clear and colourless film, with a dielectric constant of 4.7 in the un-stretched state. It is very sticky and can be largely stretched in both directions in the plane of the film. In our experimental setup, firstly, the polymer samples have been pre-stretched up to 900% along each linear dimension through a circular and adaptable stretching device. Secondly, the film has been squashed between a thick rigid support (20mm x 26mm) and a thin rigid support, both of which present a window of 11 mm x 20mm in the centre, in order to obtain a pre-stretched completely constrained sample. In the bare and central region the film is free to deform in consequence of an external electric field. Thirdly, a region with the shape of a stripe (20mm x 2mm) on both sides of the film, inside the window and adjacent to one of the bound regions, has been coated with a conductive material. These main components are illustrated in Figure 1.

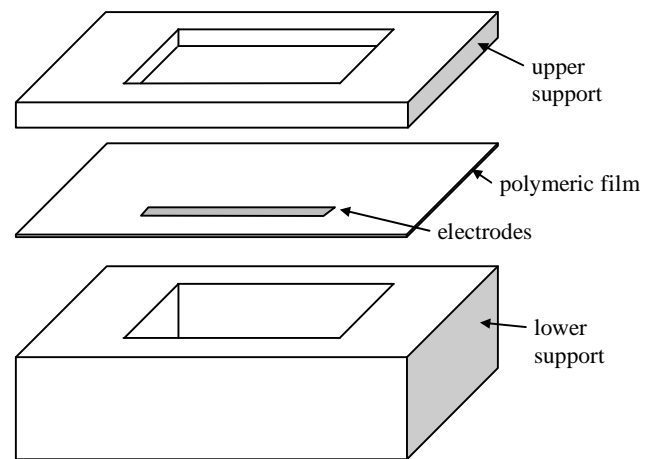


Figure 1 Exploded view of the experimental sample

Finally, some markers have been imprinted to one side of the film, through an inked grid-stamp. A sketch and a picture of a sample, together with the reference axes, are shown in Figure 2 and Figure 3 respectively.

In order to obtain appreciable displacements, the samples have been pre-stretched so that the electric field can be increased without reaching the breakdown voltage (11), in accordance with equation (1).

A symmetric layout has been conceived in order to obtain an almost monodirectional in-plane deformation of the film, along y axis (Figure 3), whereas the deformation in x direction can be neglected. This allows the direct transposition of the decrease of the thickness to the deformation along only one direction.

The choice of the material for the electrodes is an issue concerning the fabrication of EAP actuators. Indeed, not only have they to be robust enough to endure high electric fields (12), up to hundreds of kV/mm, but they have also to be very compliant and maintain a good electrical contact when stretched. Graphite powder and silver grease have been tested. The grease has showed better conductance; hence, Chemtronics Circuit Works™ silver conductive grease has been preferred and, in some samples, graphite powder has been added to increase the conductivity.

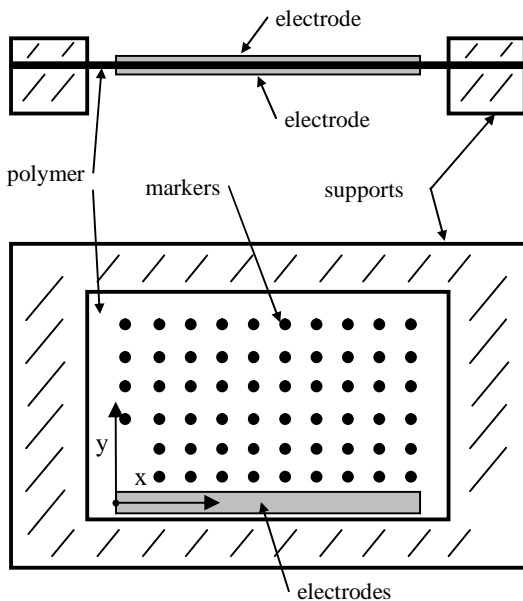


Figure 2 Sketch of the sample: section view and top view

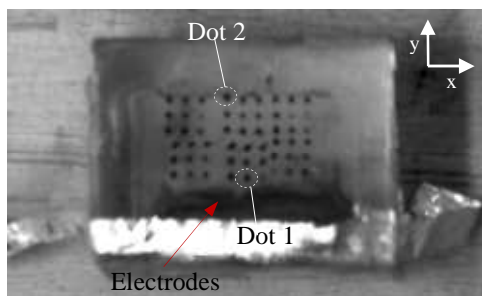


Figure 3 Picture of a sample with the system reference

Through a suitable vision system the displacement of the markers has been measured in order to quantify the deformation of the polymer when an electric field is applied.

Several samples have been prepared and analyzed applying different values of the external voltage, from 1kV to 6 kV with steps of 1kV. The voltage has been applied to the conductive region of the polymer, coated with the compliant electrode, through a small and thin aluminium wire and the reaction of the central region of the polymer has been recorded through a vision system, equipped with a telecentric objective. The collected images have been elaborated via image processing techniques in order to obtain information about the position and the displacement of the markers and, therefore, the planar deformation of the polymer.

For each sample six charge/discharge cycles have been done: firstly the lowest voltage (1kV) has been applied and turned off for few seconds and then, turned on again for 5-7 times, the same procedure has been followed applying 2, 3, 4, 5 and finally 6kV.

Between two following charge/discharge cycles a time interval of approximately 2 minute has been waited to monitor possible residual deformation, permit to overcome transitories and avoid failures due to significant loads for long periods of time (13).

All the process has been recorded by the vision system with a 30 frames-per-second rate.

EXPERIMENTAL RESULTS

The images have been analysed by applying image processing techniques. The steps followed in the measuring process are:

1. the marking dots have been recognised and labelled through a standard blob detection algorithm;
2. the position of the blobs have been identified for each photogram;
3. the displacements of the markers during the charge-discharge cycles have been calculated per each photogram, calculating the displacement vector with respect to their position at rest, *i.e.* their position in the first photogram of the sequence. The x and y components of the displacement of each blob in each image have been calculated as the difference of the x and y coordinates of each blob in the frame under examination and its coordinates at the rest position;
4. among all these displacements and for each blob the highest values of the x and y component have been isolated. Therefore, for each voltage a map of the maximum deformation of the polymer has been obtained plotting the maximum displacements of the film (Figure 6). All the calculated displacements have been mapped and numerically interpolated in order to obtain the global electromechanical response of the sample.

Moreover all the charge/discharge cycles have been analysed at once, tracing the displacements of the dots respect to their positions in the very first image (before applying 1kV) and over the entire period of time. The displacement along x and y of a dot near the electrodes (dot 1 in Figure 3) and one far away from the electrodes (dot 2 in Figure 3) has been plotted versus

the time in Figure 4 and Figure 5 respectively. In both the figures the deformation cycle due to the 1kV tension is not appreciable (because the deformations are comparable to the camera resolution), while deformations due to higher tensions can be clearly identified. In both the figures the displacements along the y direction (perpendicular to the main axis of the electrode) are much bigger than the ones in the x direction; this confirms that the asymmetry of the layout contributes to an almost monidirectional movement, as desired. Furthermore, comparing the magnitude of the displacements in Figure 4 and Figure 5 it is evident that the closer to the electrodes the dot, the bigger the displacement, as expected. This can be also see in Figure 6 where the displacement field of the sample is shown, and where it can be seen that small movements are notable along x almost only in the upper part of the plot where the movement along the y direction are significantly small.

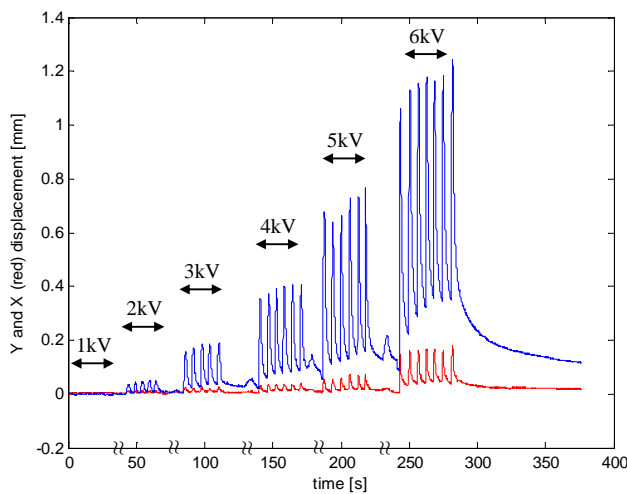


Figure 4 X-Y displacement of dot 1 in Figure 3 vs time

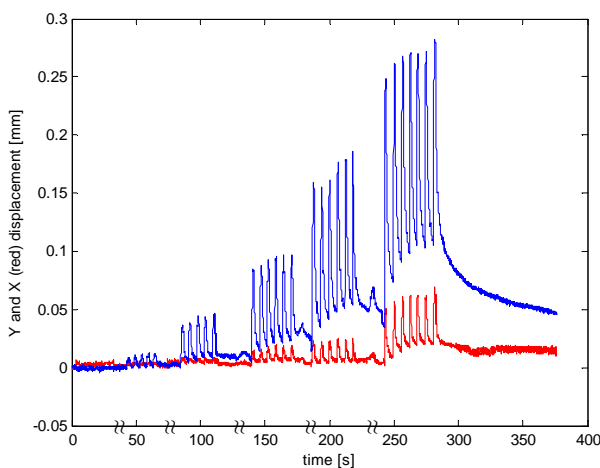


Figure 5 X-Y displacement of dot 2 in Figure 3 vs time

Further analyses of the displacements along x will be carried out in order to estimate the influence of boundary effects.

In Figure 7 the maximum measured displacement in the y direction of two samples with different thickness (0.028mm and 0.062mm) has been plotted versus the applied voltage.

The thickness of the samples has not been experimentally measured, but evaluated from the magnitude of the mechanical pre-stretch. Indeed, since the Poisson ratio of the material is equal to 0.49 (14), it has been considered incompressible and the thickness of the sample has been calculated according to the following formula:

$$x^2 + y^2 + z^2 = \text{constant} \quad (2)$$

where x, y and z are the three dimensions of the film.

Moreover this estimation has been confronted with the results obtained describing the material hyperelastic behaviour with the Yeoh's strain energy formulation, and a good agreement has been found.

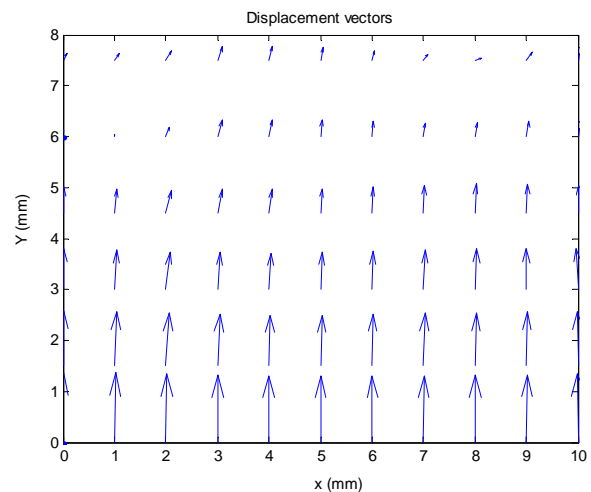


Figure 6 The arrows refer to the displacement field of the sample, their direction and module represent the maximum displacement of the reference points on the sample. The image is referred to a sample of 62 micron thick subjected to 6kV

The displacement increases in a non linear way when the applied voltage is increased and the results obtained for both the samples have been interpolated with a second order polynomial curves, shown in Figure 7. The consistency of the interpolating curves with the results seems to be in agreement with equation (1) even if further investigations on the deformation along the z direction have to be carried out to fully understand the behaviour of the materials. Moreover, this behaviour is in agreement with the hypothesis by which the electrical compression in the z direction (perpendicular to the

plane of the polymeric film) is mainly transformed in a stretch along the y, whereas the x displacement is strongly limited by the bounds and the asymmetric shape of the electrode region. Finally, it can be noticed that the two curves are slightly shifted along the y coordinate due to the different thickness of the film of the samples. Indeed, the voltage applied to both the samples is the same (from 1kV to 6kV), but, due to the thickness, the electric field strength is different, according with equation (1).

Finally, Figure 7 shows that displacements bigger than 1mm can be obtained with 6kV and that a range of about one order of magnitude can be achieved varying the voltage between 1 and 6kV.

AN APPLICATION EXAMPLE

Electroactive polymers are very promising in a variety of sectors and, in particular for applications in the Microfactory. Indeed, due to the light load and the reduced space available, the devices required at small scale have specific needs, such as lightness, compactness, precision and rapidity, which are essential requirements for microactuators together with common needs, such as suitable force and stroke.

The idea behind the realized samples can be directly converted into a monodimensional linear actuator.

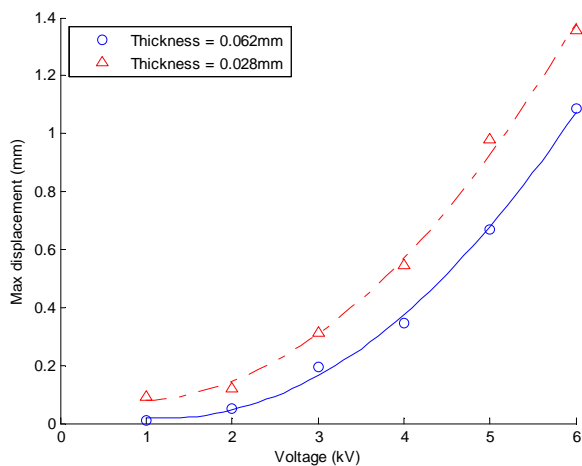


Figure 7 Maximum displacement along the y direction versus the applied voltage

Moreover, a more advanced bi-dimensional micropositioning actuator, made of dielectric elastomer has been conceived. In Figure 8 a sketch of it is drawn: a rigid square-shaped frame holds a single piece of dielectric polymer (white in the figure), which is partially coated on both sides with compliant electrodes (active regions) represented with the 4 grey squares. The active regions expand when an external voltage is applied, they compress in the thickness and, as a consequence, compress the central passive region of polymer, which is no subject to

any electric field. Hence, if a component is placed in the central region of the polymer it can be moved, acting on the electrodes. Moreover, this configuration should allow to activate one or more active regions at time in order to precisely control the position of the central region in the plane, thus allowing the precise positioning of the parts

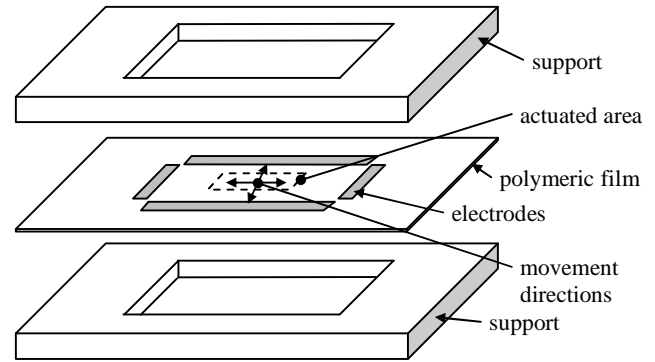


Figure 8 Sketch of a potential configuration of a micropositioning made of dielectric elastomer.

CONCLUSIONS

Although a lot of potential applications of electroactive polymers could enable many innovations in several fields, their diffusion is still limited by the lack of clear understanding of all their properties. Indeed their structure-property response interrelations is complex and a further issue is due to the sensitivity of electroactive polymers to their fabrication conditions, time and temperature dependent effects, and nonlinearity of their coupled mechanical, physical and chemical properties.

In this paper the electro-mechanical behaviour of an acrylic EAP has been studied and a few physical properties, such as the maximum strain for different input loads and different boundary conditions have been analysed. Moreover an application of the polymer in the microfabrication of hybrid MEMS has been introduced. Further analyses will be carried out in order to characterize and model the hyperelastic behaviour of the material both under a theoretical and an experimental point of view.

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