MODELING AND SIMULATION OF THE ELECTROMECHANICAL RESPONSE IN PLANAR ELECTROACTIVE POLYMER ACTUATORS

Vlad Cârlescu*, Petru Marian Cârlescu**, Dumitru Olaru*, Gheorghe Prisăcaru*
*Machine Elements and Mechatronics Department, The „Gheorghe Asachi” Technical University, 700050, Iași, România; **Department of Pedotecnics, University of Agricultural Science and Veterinary Medecine, 700490, Iași, România, carlescu.vlad@yahoo.com

Abstract: Modeling and numerical simulation of electroactive polymers is considered in this work using finite element method (FEM). In this paper are presented some preliminary results regarding the simulation of the thickness compressions of some dielectric elastomers subjected to electrical stimulations. A simple planar configuration is used for actuator model consisting of an elastomer film sandwiched between two circular rigid electrodes. The expressions of the electrostatic pressures exerted by the electrodes in response to an applied voltage were calculated and inserted into the expressions of the actuator mechanical deformations, obtained by assuming linearly stress-strain constitutive equations of the material for small strains. The strain responses of elastomers was observed to increase with decrease of Young’s modulus. Finite element simulation was performed using an elastic model for elastomer film and strains up to 20.5% were obtained. These strains are quite high considering that we used rigid electrodes.

Keywords: Dielectric elastomer, thickness strain, FEM, microactuators.

Introduction

The simulation of electroactive polymers (EAP) [1-5] has been an interesting subject for the last few years due to its application in the analysis of smart materials, wich exhibit large displacement and change their mechanical behavior in response to electrical stimulations [6]. Dielectric elastomers (DE), a subclass of EAP, are soft polymer based smart materials that can be potentially employed in applications such as actuation, sensing and energy harvesting [7-9]. They exhibit large area strains of over 380% [10], activation pressures of up to 16,2MPa [11], specific elastic energy densities of 3,4 J cm⁻³ [11], respectively, and response time of the order of milliseconds. Since the active strain and stress correspond directly to the performance of natural muscles, they are often referred to as “artificial muscle”.

Silicone and acrylic based elastomers are most widely used as the dielectric layer in dielectric elastomer actuators (DEA), due to their excellent mechanical and electrical properties. Several application [10-16] have been envisaged for dielectric elastomer actuators such as mobile mini-and micro-robots, micro-pumps and micro-valves, micro air vehicles, disk drives, prosthetic devices and flat panel loudspeakers. Such actuator consists basically of a capacitor with a thin passive elastomer film sandwiched between two compliant electrodes (Fig.1) [17]. The electromechanical pressure acting on the elastomer film can be calculated with the following equation [18]:

\[ p_{el} = \varepsilon_0 \varepsilon_r \left( \frac{U}{d} \right)^2 \]  

(1)

where \( \varepsilon_0 \) is the vacuum permittivity, \( \varepsilon_r \) is the relative dielectric constant of the material, \( U \) is the voltage and \( d \) is the film thickness. Due to the mechanical compression, the elastomer film contracts in thickness direction and expand in the film plane direction. Thickness strain, based on Hooke’s law can be written as:

\[ S_z = -\frac{p_{el}}{Y} \]  

(2)

where \( Y \) is Young’s modulus of the material which describes the stiffness of material.

High performance actuators can be achieved by design-optimization based on modeling the EAP actuator, which includes the mechanical behavior of the elastomeric film and the electromechanical coupling. In particular, the mechanical behavior of the elastomeric film is quite complex to describe due to viscous effects (time dependency), anisotropy (prestrain) and large strains (hyperelasticity).
Bhattacharya [19] provides a general overview of electromechanical coupling in dielectric EAPs. The electromechanical problem is solved by decoupling it into an electrostatic problem and a mechanical problem.

Kofod [20] has used experimental data from one dimensional tensile tests to verify the range of validity of various hyperelastic material models. The best result was achieved with a four-parameter Ogden model [21] that is valid over a range from 0 to greater than 300% nominal strain. The influence of prestraining has been numerically modeled with a Mooney-Rivlin [22] model by Kim [23]. Viscoelasticity and large strains for uniaxial stress states have been modeled by Sommer-Larsen [24] using the Rivlin-Sawyer equation [25].

Our work refers to modeling a planar actuator and simulate the displacements in thickness direction when high DC voltages is applied to the electrodes. Finite element simulation was performed using an elastic model for elastomer film and preliminary results showed strains up to 20.5%.

**Finite element analysis**

Geometrical model of DEA was realized in SolidWorks software. Figure 2 illustrate a 3D model of DEA.

The diameters of upper and bottom electrode is 7 mm and 24 mm, respectively. Also, the thicknesses of upper and bottom electrode is 2 mm and 1.4 mm, respectively. The Poisson’ ratio of electrode material was taked as 0.33 (copper). The Young’s modulus of about 40GPa was experimantaly determined from indentation tests performed on a microtribometer CETR UMT-2.

The elastomer films were provide by „Petru Poni” Institute of Macromolecular Chemistry (Iasi, Romania). They were cut in square form of 15x15 mm. Their characteristics can be found in [26].

After realizing the 3D geometric model in SolidWorks, the ensemble was imported in Abaqus software. First, a mixt discretization was made with a number of elements that variate with elastomer thickness (0.47 ÷ 0.99 mm). For example, in case of a 0.85 mm thickness elastomer the number of discretization elements was 16511. Figure 4 illustrate a 3D mesh of DEA.

Second, some conditions need to be imposed for finit element analysis.

**Material conditions**

Elastomers are soft materials with low modulus (linear modulus between 1 and 100MPa) that can undergo large strains. Polymer commonly used in making dielectric elastomer actuators include silicone rubber films or polyacrylate films. Founding the properly model (elastic, hyperelastic, viscoelastic, visco-hyperelastic) that describe the behavior of these soft materials is a difficult task. In this simulation, the elastomer is assumed to be an isotropic, homogeneous, incompressible, and nonlinear elastic polymer material. The input parameters for elastic model was Young’s modulus and Poisson’s ratio. Young’s modulus was calculate from the slope of stress-strain curve. Stress–strain measurements were performed on dumbbell shaped cut from thin films on a TIRA test 2161 apparatus, Maschinenbau GmbH Ravenstein, Germany.
Measurements were run at an extension rate of 50 mm/min, at room temperature. All samples were measured three times and the averages were obtained. For elastomers the Poisson’s ratio is about 0.5.

Contour conditions
Another step in simulation procedure is to define the contour conditions. Therefore, we impose a enclosure at bottom electrode (Fig. 5). The bottom electrode is hold fixed and the elastomer film can make movements in all directions (x, y and z direction). This is an important condition, because the ideal electrodes had to oppose minimum resistance to the elastomer deformation and maintain his conductivity.

Load conditions
In experimental setup [27] the elastomers were subjected to high DC voltage of up to 6kV. Using equation (1) we calculated the compression pressures that act on elastomer films. The values of pressures were inputs for load conditions. In figure 5 is illustrate the pressures applied on the surface of the upper electrode.

Simulation of thickness strains of dielectric elastomer film
The simulation of the elastomer microdisplacements on thickness direction under electrical stimulation realized in Abaqus involve applying the compression pressures calculated with eq. (1) on the surface of upper electrode. According to input parameters, the programme will simulate and calculate the thickness strains of elastomer films. Figure 6 presents the results of a simulation for T10 sample. Using equation (2) we calculated the strain for each sample.

Table 1. Input parameters for FEM simulation

<table>
<thead>
<tr>
<th>Sample</th>
<th>Young’s modulus (MPa)</th>
<th>Dielectric permittivity at 10Hz</th>
<th>Actuation Pressure (MPa)</th>
<th>Thickness compression (μm)</th>
<th>Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T7.5</td>
<td>0.011</td>
<td>4.1</td>
<td>0.00226</td>
<td>45.89</td>
<td>20.54</td>
</tr>
<tr>
<td>T10</td>
<td>0.013</td>
<td>4</td>
<td>0.00176</td>
<td>30.24</td>
<td>13.33</td>
</tr>
<tr>
<td>T20</td>
<td>0.016</td>
<td>4.3</td>
<td>0.00219</td>
<td>26.21</td>
<td>13.71</td>
</tr>
<tr>
<td>T5</td>
<td>0.016</td>
<td>3.9</td>
<td>0.00176</td>
<td>24.57</td>
<td>11</td>
</tr>
<tr>
<td>T1</td>
<td>0.037</td>
<td>3.5</td>
<td>0.00504</td>
<td>22.18</td>
<td>13.64</td>
</tr>
<tr>
<td>TM</td>
<td>0.03</td>
<td>4</td>
<td>0.00321</td>
<td>17.81</td>
<td>10.7</td>
</tr>
<tr>
<td>T15</td>
<td>0.19</td>
<td>4.2</td>
<td>0.00136</td>
<td>2.46</td>
<td>0.718</td>
</tr>
</tbody>
</table>

Results
The preliminary results obtained shows that strain strongly depends on Young’s modulus of elastomer (eq.(2)). Strain up to 20.5 % were obtained at 0.00226MPa. The strain depends also with thickness of specimens. These pressures are quite small because the thickness of specimens is large. In literature, elastomers with thickness of 100 μm are usually used to achieve a DEA. T15 specimen that have the highest thickness (0.99 mm) and the biggest modulus (0.19 MPa) exhibit the lowest strain, about 0.71 %.

Conclusions
In this paper we investigate the electromechanical response of some silicone elastomers using finite element analysis. The modeling of dielectric elastomer actuator was realized in SolidWorks software and the simulation of thickness compressions due to the normal applied compression pressures was performed in Abaqus software. Using an elastic model we obtained some preliminary results for thickness reductions in terms of microdisplacements. The estimated time of simulation is quite low. It depends on the number of elements used for discretization. This is an important work for investigating the actuator performance. Using the proper material model in finite element analysis we can accurately
predicted the electromechanical response of dielectric elastomer actuators under load conditions.

Future work refers to perform more simulations using other models with more parameters experimentally measured and using compliant electrodes.

These preliminary results obtained allow us to propose these materials for sensor and actuator applications at micro-scale.

References