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Article *in* Romanian Review Precision Mechanics · January 2011

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

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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]:

$$p_{el} = \varepsilon_0 \varepsilon_r \left(\frac{U}{d}\right)^2 \qquad (1)$$

where ε_0 is the vaccum permitivitty, ε_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:

$$S_z = -\frac{p_{el}}{Y} \qquad (2)$$

where Y is Young's modulus of the material wich describes the stiffness of material.

High performance actuators can be achieved by design-optimization based on modeling the EAP actuator, wich 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 in to an electrostatic problem and a mechanical problem.

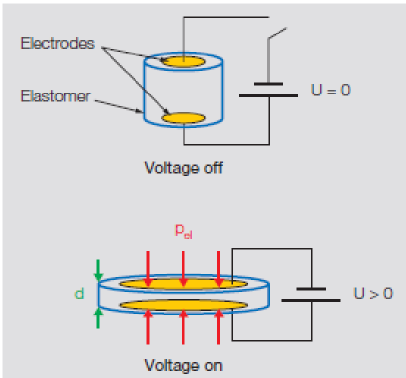

Figure 1: Working principle of a dielectric elastomer actuator [17]

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.

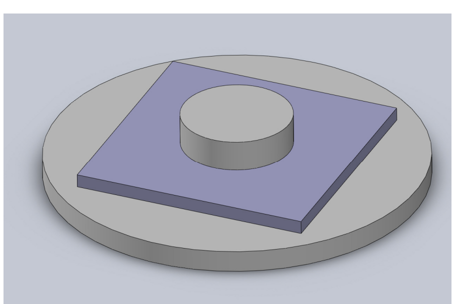

Figure 3 – Electrode-elastomer ensemble drawn in SolidWorks

The dimameters of upper and buttom electrode is 7 mm and 24 mm, respectively. Also, the thicknesses of upper and bottom electrode is 2 mm and 1,4, respectively. The Poisson' ratio of electrode material was taked as 0,33 (copper). The Young's modulus of about 40GPa was experimentaly determined from indentation tests performed on a microtribometer CETR UMT-2.
The elastomer films were provide by „Petru Poni" Insitute 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 exemple, in case of a 0,85 mm thickness elastomer the number of discretization elements was 16511. Figure 4 illustrate a 3D mesh of DEA.

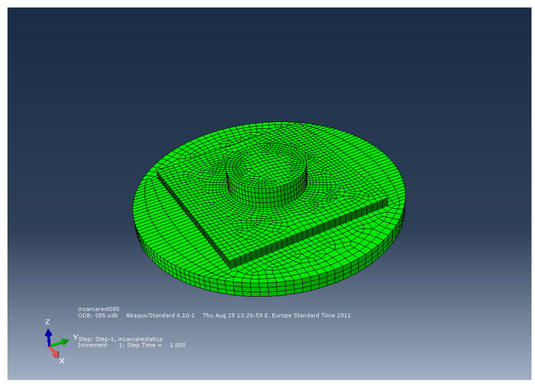

Figure 4: 3D mesh of DEA

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

<u>Material conditions</u>
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, incompresible, 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.

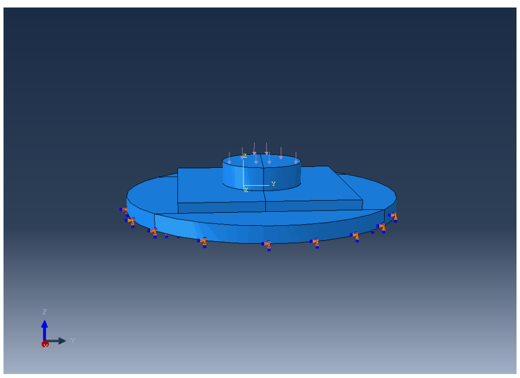

Figure 5: Pressures applied on upper electrode and the enclosure condition on bottom electrode

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 shows the input parameters used for simulation and the thickness strains obtained with finite element analysis.

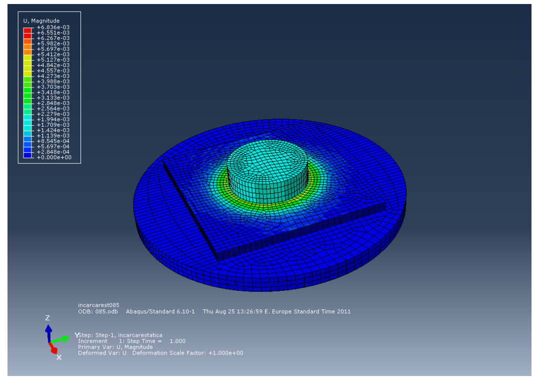

Figure 6: Simulation results of thickness strain for T10

Table 1. Input parameters for FEM simulation

Sample	Young's modulus (MPa)	Dielectric permittivity at 10Hz	Actuation Pressure (MPa)	Thickness compression (µm)	Strain (%)
T7.5	0.011	4.1	0.00226	45.89	20.54
T10	0.013	4	0.00176	30.24	13.53
T20	0.016	4.3	0.00219	26.21	13.71
T5	0.016	3.9	0.00176	24.57	11
P1	0.037	3.5	0.00504	22.18	13.64
TM	0.03	4	0.00321	17.81	10.7
T15	0.19	4.2	0.00136	2.46	0.718

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 experimentaly measured and using compliant electrodes.

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

References

[1] G. de Botton, L. Tevet-Deree, E.A. Socolsky, Electroactive heterogeneous polymers: analysis and applications to laminated composites, Mech. Adv. Mater. Struct. 14 (2007) 13–22.

[2] A. Dorfmann, R.W. Ogden, Nonlinear electroelasticity, Acta Mech. 174 (2005), 167–183.

[3] G. Kofod, P. Sommer-Larsen, Silicone dielectric elastomer actuators: finite elasticity model of actuation, Sens. Actuators A 122 (2005) 273–283.

[4] M. Wissler, E. Mazza, Modeling of a pre-strained circular actuator made of dielectric elastomers, Sens. Actuators A 120 (2005) 184–192.

[5] M. Wissler, E. Mazza, Modeling and simulation of dielectric elastomer actuators, Smart Mater. Struct. 14 (2005) 1396–1402.

[6] Y. Bar-Cohen, Electro-active polymers: current capabilities and challenges, in: EAPAD Conference, San Diego, CA, March 18–21, 2002, pp. 4695–4702.

[7] Kornbluh R., Dielectric elastomer artificial muscle for actuation, sensing, generation, and intelligent structures, Materials Technology 19 (4), 2004, 216–224.

[8] Carpi F., Migliore, A., et al., Helical dielectric elastomer actuators, Smart Materials and Structures 14 (Copyright 2005, IEE), 1210–1216.

[9] Waki M., Chiba S., et al., Electric power from artificial muscles, OCEANS 2008 MTS/IEEE Kobe Techno-Ocean, 8-11 April 2008, Piscataway, NJ, USA, IEEE.

[10] Pelrine R., Kornbluh R., Pei Q. B. and Joseph J., High-speed electrically actuated elastomers with strain greater than 100%, Science 287, 2000, 836–9.

[11] Bar-Cohen Y., Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges (Bellingham, WA: SPIE Press), 2001, p. 671.

[12] Pelrine R., Kornbluh R., Joseph J.P., Sens. Actuators 1999, A64, 77.

[13] R. Heydt, R. Kornbluh, R. Pelrine, V. Mason, J. Sound Vbr. 1998, 215 (2), 297.

[14] R. Trujillo, J. Mou, P.E. Phelan, S.S. Chau, Int. J. Adv. Manuf. Technol. 2004, 23, 176.

[15] F. Carpi, P. Chiarelli, A. Mazzoldi, D. De Rossi, Sens. Actuators 2003, A 107, 85.

[16] Q. Pei, R. Pelrine, S. Stanford, R. Kornbluh, M. Rosenthal, Synth. Met. 2003, 135, 129.

[17] M. Wissler, Edoardo Mazza, Modelling and simulation of dielectric elastomer actuators, Smart Mater. Struct. 14, 2005, 1396-1402.

[18] R. Pelrine, R. Kornbluh, J. P. Joseph, Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation, Sens. Actuators A 64, 77-85, 1998;

[19] Y. Bar-Cohen, Electroactive polymer (EAP) Actuators as Artificial Muscles – Reality, Potential and Challenges, Vol. PM136, SPIE-Society of Photo-optical Instrumentation Engineers, Bellingham, WA 2004.

[20] G. Kofod, Dielectric elastomer actuators, PhD Thesis, Riso-R-1286 (EN), Denmark, 2001.

[21] R.W. Ogden, Proc. R. Soc. Lond., 1972, A 326, 565.

[22] M. Mooney, J. Appl. Phys., 1940, 11, 582.

[23] H. Kim, S. Oh., K. Hwang, H. Choi, J. W. Jeon, J. D. Nam, Proc. SPIE, 2001, 4329, 482.

[24] P. Sommer-Larsen, G. Kofod, M Shridhar, M. Benslimane, P. Graversen, Proc. SPIE, 2002, 4695, 158.

[25] R.S. Rivlin, K. N. Sawyers, Ann. Rev. Fluid. Mech., 1971, 3, 117.

[26] M. Alexandru, M. Cazacu, A. Nistor, Valentina E. Musteata, I. Stoica, C. Grigoras, B.C. Simionescu, Polydimethylsiloxane/silica/titania composites prepared by solvent-free sol-gel technique, J. Sol-Gel Sci Technol (2010), 56:310-319.

[27] V. Carlescu, D. Olaru, F. Breaban, Gh. Prisacaru, Comparative study of electromechanical response in some dielectric elastomers, JOAM Vol. 13, No. 8, 2011, 986-991.