Modelling of High Output Force Dielectric Elastomer Actuator

Haneen J. El-Hamad, Siti Anom Binti Ahmad, and Asnor Juraiza Binti Dato' Hj. Ishak
Department of Electrical and Electronic Engineering, UPM, Selangor, Malaysia
Email: mhj.hamad@gmail.com, {sanom, asnorji}@upm.edu.my

***Abstract*—Restoring the function of a lost limb for an amputee requires the generation of relatively large forces, which remains a challenge in current designs. Dielectric Elastomers (DE) have the desired properties of light weight, low cost, fast response, ease of control and low power consumption. Yet due to the elasticity of the material which requires mechanical support and low output force generation, DEs haven't been suggested for prosthetic devices that mainly require high output forces. This paper proposes a conceptual design for a prosthetic arm, where DE is used as a high output force actuator. A two-bar mechanism was assumed to represent the human arm, with one bar as the Humerus and another for the Radius and the Ulna bones. The flexion action of the mechanism was achieved by a slider-crank mechanism connecting the two bars. A Dielectric Elastomer (DE) was used to actuate the mechanism. In the proposed design, the DE membrane is configured as a planar linear actuator, with about 1000 parallel membranes to maintain the output force and reduce the tensile stress. An Analytic model for the specific configuration of DE materials was developed to analyze the output force of the designed mechanism for a range of input electric fields. The input electric field is below the dielectric strength of the material and induces 97 N of output force which is higher than reported actuator designs.**

***Index Terms*—dielectric elastomer, actuator, thermodynamics, VHB 4910**

I. Introduction

Replacing a lost limb for an amputee is quite a challenge; an intuitive approach would be to mimic the function of the natural lost limb. Research in prosthesis technologies includes a wide variety of options that have potential capabilities of restoring a fully functional human limb. Electroactive polymers (EAP) are polymer materials that respond mechanically to external electric stimuli [1]. Among EAP materials, Dielectric Elastomers (DE) have properties that show great similarities to human muscles [2] which make them suitable candidates for replacing conventional actuators of motors and gears in prosthetics which is a desirable outcome.

DE materials transform electric energy directly into mechanical work and produce large strains [1], [2]. This mechanical strain is induced by an electrostatic attraction between conducting layers [3], leading to compressive stress in the direction perpendicular to the layers referred to as Maxwell stress [4] which induces tensional stress in the direction parallel to the layers that result in large positive strains. 3M Corporation's VHB 4910 is a commercial form of acrylic elastomers [4] where it is originally manufactured as an adhesive and is the dielectric elastomer material used in the proposed design.

The modeling of DE materials could be achieved through a number of approaches such as nonlinear hyper elasticity and thermodynamics, yet the main challenge in modelling DE material is to address associated failure modes [5]. Plante and Dubowsky have addressed four main modes; pull-in failure or electromechanical instability, dielectric strength failure, viscoelasticity and current leakage [6], [7]. One particular model [8] addresses the viscoelastic nature of the material and includes the parameters that describe the dissipative processes a viscoelastic material goes through. It also defines a procedure to define the value at which instability occurs for any DE configuration.

Several designs of planar DE actuators are proposed in the literature. One design presents a joint driven by two antagonistic DE actuators, but the reported output force does not exceed 5 N [9]. While another design employing spring roll DE actuator, reports outputs of 15 N [10]. A planar actuator design employing hyperelastic DE material model reports 35 N output [11]. These output forces are less than the force an average human bicep can exert during flexion which is estimated to be in the range of 40 N to 116 N [12]. In this paper we propose a design that provides higher output force.

II. Research Methods

A. Selected DE Material Model

The selected model [8] defines a simple planar DE membrane where it is subjected to forces P_1 and P_2, and the two electrodes are connected to a battery of voltage Φ, as shown in Fig. 1.

Thermodynamics requires that the increase in the Helmholtz free energy of the membrane, F should not exceed the total work done. The free energy density is a function of the stretches, the nominal electric displacement and internal parameters that describe degrees of freedom associated with dissipative processes. For a viscoelastic material represented through a network

Manuscript received May 25, 2016; revised December 12, 2016.

doi: 10.18178/ijmerr.6.2.100-103

of dashpots and springs, these internal parameters represent the viscous stretch in the dashpot, ξ_1 and ξ_2 for both directions.

The constitutive equations developed describe the viscoelastic behavior of the DE material employing Neo-Hookean elasticity model. For further information please refer to the paper [8].

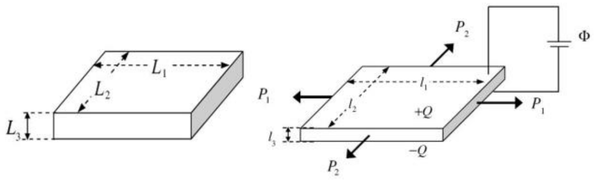

Figure 1. Reference and current state of dielectric elastomer [8]

B. Selected DE Material Model

Fig. 2 shows a structural design for the actuator. Member 'a' represents the DE material block, where it actuates the arm as it elongates pushing bar L3 within the sliding joint, the concept of the design has been proposed by the author and others [11], yet this work proposes a different analysis approach.

Performing a force diagram for bar L1 will define the maximum force on the DE membrane as shown in Fig. 3. The maximum Force is a function of the desired angular position θ.

$$F_{max} = 2\cos\alpha\,(W_2 L_2+F_{ext}) - T\,(\sin\theta_T + \sin\theta_T \cos\alpha + 2\cos\theta_T \sin\alpha) \quad (1)$$

$$\theta_T = 90^o - \alpha - \sin^{-1}(b/L_3 \sin\theta) \quad (2)$$

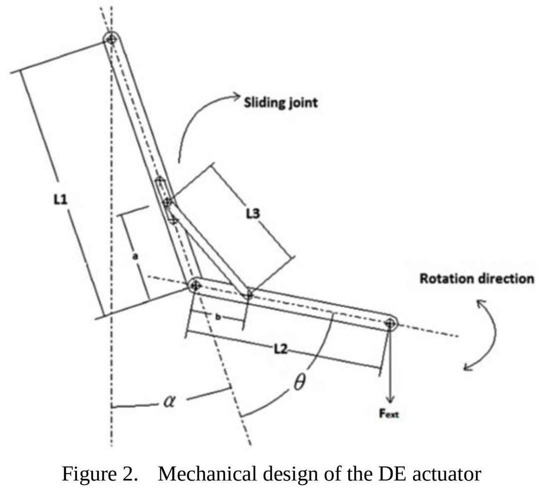

Figure 2. Mechanical design of the DE actuator

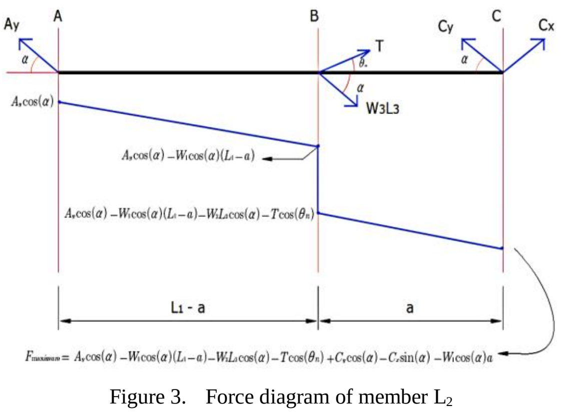

Figure 3. Force diagram of member L_2

C. Adapted Actuator Model

In the suggested design, the DE membrane is set up right, where the mechanical force acts against the generated force and there are no other forces acting on the DE membrane. Therefore, the applied voltage is expected to generate mechanical stress enough to counter act the mechanical compression and pull the bar 'L_2' upwards. To apply this model to the actuator design, new assumptions and parameters are made:

1. The strain in the material is induced only by the applied voltage
2. The mechanical compression stress is in the length direction and is negative $s_1 = -s_{mechanical} = -F_{max} / A$.
3. The width is constrained, therefore $s_2 = 0$, and $\lambda_2 = \xi_2 = 1$.
4. Dimensions of the DE membrane are 'a' the initial length in the direction of the elongation, 'X_d' the constant width of the membrane and 'Z_d' the initial thickness of the membrane. The number of parallel DE membranes is 'n'.

Accordingly, material constitutive equations become as follows,

$$s_1 = -s_{mechanical} = \mu_R(\lambda_1 - \lambda_1^{-3}) + (\mu_u - \mu_R)(\lambda_1 \xi_1^{-2} - \lambda_1^{-3} \xi_1^{2}) - \lambda_1^{-3} \tilde{D}^2/\varepsilon \quad (3)$$

$$s_2 = \mu_R(1 - \lambda_1^{-2}) + (\mu_u - \mu_R)(1 - \lambda_1^{-2} \xi_1^{2}) - \lambda_1^{-2} \tilde{D}^2/\varepsilon = 0 \quad (4)$$

$$\tilde{E} = \lambda_1^{-2} \tilde{D}/\varepsilon. \quad (5)$$

The mechanical stress is a function of the applied force and the stretch value, and to reduce the mechanical stress on the material and reduce actuating voltage accordingly, an addition of 'n' parallel DE membranes would achieve this goal while contributing very little to input power required. Substitute (5) in (3), and substitute mechanical stress with true stress in terms of force and stretch,

$$(-F_{max}/ Z_d X_d n)\,\lambda_1 = \mu_R(\lambda_1 - \lambda_1^{-3}) + (\mu_u - \mu_R)(\lambda_1 \xi_1^{-2} - \lambda_1^{-3} \xi_1^{2}) - \varepsilon \tilde{E}^2 \lambda_1 \quad (6)$$

Derive (6) with respect to time,

$$[\mu_R(1 - 3\lambda_1^{-4}) + (\mu_u - \mu_R)(\xi_1^{-2} - 3\lambda_1^{-4} \xi_1^{2}) - \varepsilon \tilde{E}^2 + (-F_{max}/ Z_d X_d n)]\; d\lambda_1/dt - (\mu_u - \mu_R)(2\lambda_1 \xi_1^{-3} - 2\lambda_1^{-3} \xi_1)\, d\xi_1/dt - 2\varepsilon\tilde{E}\lambda_1\, d\tilde{E}/dt + (\lambda_1/ Z_d X_d n)\, dF_{max}/dt = 0 \quad (7)$$

And from the kinetic model selected in the reference paper [8], $d\xi_1/dt$ is defined as

$$d\xi_1/dt = 1/\tau\,(\lambda_1^{2} \xi_1^{-3} - \lambda_1^{-2} \xi_1) \quad (8)$$

From (7) and (8), with $F_{max}(t)$ and $\tilde{E}(t)$ known from the mechanical structure and a selected step signal respectively, $\lambda_1(t)$ and $\xi_1(t)$ are solved as they evolve to steady state or up to the time when electromechanical instability occurs depending on the applied electric field value. The initial condition $\lambda_1(0)$ is found by substituting $F_{max}(0)$ and $\tilde{E}(0)$ according to the loading program and $\xi_1(0)$ equal to 1 due to viscosity [8] in (6).

III. Results

A. Actuator Parameters

Table I summarizes the set of parameters selected for the actuator and the material, and the actuation input and output values. Parameters 'L_3' and 'b' and the DE membrane length 'a', were optimized through iteration to find the highest output force possible while maintaining low strain. The DE membrane thickness is defined depending on the available manufactured DE adhesive thickness.

TABLE I. Summary of Selected Mechanical and Material Parameters

Parameter	Value	Description	
Mechanical Parameters			
L1, L2 (cm)	40, 30	Roughly estimated [12]	
L3, b (cm)	19, 3.5	Optimum force and input voltage	
ρ (kg/m^3)	946	Polypropylene material density [13]	
F_{ext} (N)	0	External load	
α	0^o	Deviation from perpendicular position of upper arm	
θ	0^o–150^o	Range of elbow joint flexion motion [14]	
Material Parameters			
a (cm)	15.50	Initial length of DE membrane	
Z_d (μm)	50	Fabricated M3 VHB 4910 acrylic elastomer film	
X_d (cm)	5	Selected width of DE membrane	
n	1000	Number of parallel DE membranes	
λ_1	1 – 1.4	Selected range from parameters	
ε	4.5	Relative permittivity of DE materials [15]	
Actuation Parameters			
Input Force (N)	73.2 – 97.5	Input Electric Field (MV/m)	31.4 – 33.8

B. Actuator Parameters

The response of the actuator to the applied electric field is shown in Fig. 4. The applied electric field is regulated to hold each position. While the force decreases from 97.5 N to 73.2 N with increasing angular position, the electric field required to hold that position increases from 31.4 MV/m to 33.8MV/m.

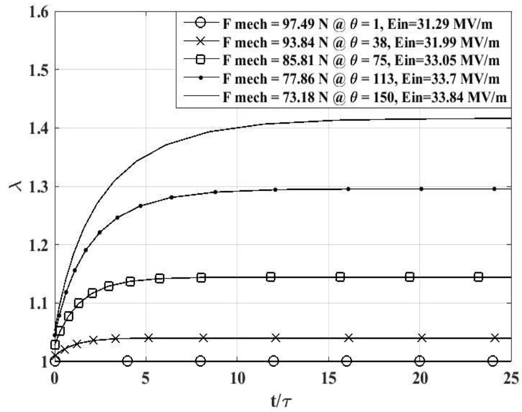

Figure 4. DE actuator actuation responses for selected angular positions

Electromechanical instability occurs instantly if the electric field applied is above 3.25*Ec*, does not occur if it is below 2.05*Ec*, and occurs after some delay if the value applied is between those limits as shown in Fig. 5.

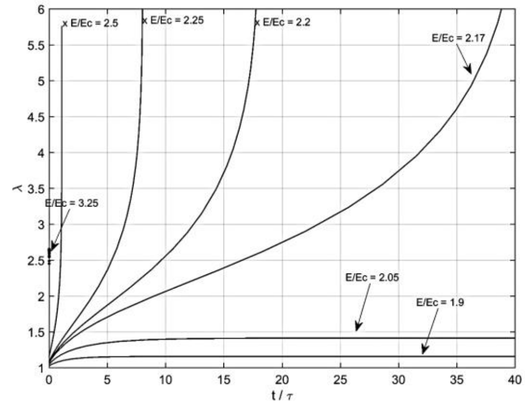

Figure 5. DE Material responses for different electric field values

IV. Discussion

The results show a relatively high output force induced by an electric field for 'n' DE parallel membranes. For a single DE membrane actuator, the stress is very high; around 38 Mpa, yet for a 1000 DE membrane actuator of which the results are for, the stress is distributed reducing the stress per membrane. Therefore the designed actuator maintains high output force without exceeding stress loading limitations reported to be below 690 Kpa [16]. The critical electric field for the proposed design is increased to be 3.25 times the critical value that is derived by the refrence model as equal to $Ec=0.69\sqrt{(\mu_R/\varepsilon)}$ [8], this reduction is physically interpreted as the mechanical compressive stress supporting the DE membrane. The output strain is 40% and can be increased theoretically, but an increased output strain requires more electric input energy, therefore the dielectric strength of the material poses a limitation for the actuation value; which is 40 MV/m for a non prestretched DE material [15]. With the achieved output force, the actuator could be used as prosthetic devices actuators with the aid of proper mechanical supports.

V. Conclusion

The paper proposes a design of a DE actuator. The design employs a developed model from ref [8] and adapts it to the actuator parameters. The mechanical design of the DE actuator produces compressive stress on the DE membrane that ranges from 73 N to 97 N according to the angular position. This compressive stress is counter acted by Maxwell stress that is induced by applied electric field that ranges from 31.4 MV/m to 33.8 MV/m. this actuator could be potentially applied in the field of prosthetic as an upper extremity prosthetic arm that exerts sufficient force for normal activity.

References

[1] R. Samatham, K. J. Kim, D. Dogruer, H. R. Choi, M. Konyo, J. D. Madden, *et al*., "Active polymers: An overview," *Electroactive*

Polymers for Robotic Applications, K. J. Kim and S. Tadokoro, Eds., London: Springer, 2007, pp. 1-36.
[2] J. D. Nam, H. R. Choi, J. C. Koo, Y. K. Lee, and K. J. Kim, "Dielectric elastomers for artificial muscles," *Electroactive Polymers for Robotic Applications*, K. J. Kim and S. Tadokoro, Eds., London: Springer, 2007, pp. 37-48.
[3] R. Pelrine, R. Kornbluh, Q. Pei, and J. Joseph, "High-speed electrically actuated elastomers with strain greater than 100%," *Science*, vol. 287, no. 5454, pp. 836-839, Feb. 2000.
[4] R. Shankar, T. K. Ghosh, and R. J. Spontak, "Dielectric elastomers as next-generation polymeric actuators," *Soft Matter*, vol. 3, no. 9, pp. 1116-1129, July 2007.
[5] P. Brochu and Q. Pei, "Advances in dielectric elastomers for actuators and artificial muscles," *Macromolecular Rapid Communications*, vol. 31, no. 1, pp. 10-36, Jan. 2010.
[6] J. S. Plante and S. Dubowsky, "On the properties of dielectric elastomer actuators and their design implications," *Smart Materials and Structures*, vol. 16, no. 2, p. S227, Mar. 2007.
[7] J. S. Plante and S. Dubowsky, "On the nature of dielectric elastomer actuators and its implications for their design," in *Proc. SPIE 6168, Smart Structures and Materials, Electroactive Polymer Actuators and Devices*, 2006, pp. 61681J-61681J.
[8] X. Zhao, S. J. A. Koh, and Z. Suo, "Nonequilibrium thermodynamics of dielectric elastomers," *International Journal of Applied Mechanics*, vol. 3, no. 2, pp. 203-217, Jun 2011.
[9] M. Randazzo, M. Fumagalli, F. Nori, G. Metta and G. Sandini, "Force control of a tendon driven joint actuated by dielectric elastomers," in *Proc. 12th International Conference on New Actuators*, 2010.
[10] Q. Pei, R. Pelrine, M. A. Rosenthal, S. Stanford, H. Prahlad, and R. D. Kornbluh, "Recent progress on electroelastomer artificial muscles and their application for biomimetic robots," in *Proc. SPIE 5385, Smart Structures and Materials*, *Electroactive Polymer Actuators and Devices (EAPAD)*, 2004, pp. 41-50.
[11] O. M. Al-Hababheh, H. J. Al-Hamad, L. S. Al-Sakka, and H. Al-Sahori, "Viable design of an arm prosthesis system," *International Journal of Advanced Science and Technology*, vol. 35, pp. 1-18, 2014.
[12] National Aeronautics and Space Administration, NASA. Human Performance Capabilities, Man-Systems Integration Standard, vol. 1, 2008.
[13] J. E. Uellendahl, "Prosthetic primer: Materials used in prosthetic part II," in *Motion Magazine*, vol. 8, no. 6, p. 9, 1998.
[14] R. F. Weir and J. W. Sensinger, "Design of artificial arms and hands for prosthetic applications," *Standard Handbook of Biomedical Engineering and Design*, KP McCombs Ed, New York: McGraw Hill, 2003, pp. 32-1.
[15] J. S. Plante and S. Dubowsky, "Large-scale failure modes of dielectric elastomer actuators," *International Journal of Solids and Structures*, vol. 43, no. 25, pp. 7727-7751, Dec 2006.
[16] MatWeb, Your Source for Materials Information. VHB ADH Transfer Tape with ADH 100MP F9460PC. [Online]. Available: http://www.matweb.com

Haneen J. Elhamad is a Jordanian researcher that has earned her Bsc in Mechatronics engineering from The University of Jordan, Amman, Jordan in 2012. She is currently pursuing a Master's degree in Control systems, department of electric and electronic engineering, UPM, Malaysia.

Since she graduated, she worked at a control systems company as an Electrical design engineer in Jordan. Later she worked in Applied sciences private university in Jordan as a Lab supervisor and Teaching assistant. Her current research interests include electromechanical converting materials and their possible applications.

Siti Anom Ahmad is an Associate Professor at the Department of Electrical and Electronic Engineering, Faculty of Engineering, Universiti Putra Malaysia. Dr. Siti Anom received a Ph.D. in Electronics (2009), MSc in Microelectronics System Design (2004) from the University of Southampton, UK and a BEng in Electronic/ Computer from Universiti Putra Malaysia (1999). She is a Chartered Engineer, MIET, SMIEEE and MIEM. Her research interests are biomedical engineering, signal processing and intelligent control system.