High stress actuation by dielectric elastomer with oil capsules

La, Thanh-Giang; Lau, Gih-Keong; Shiau, Li-Lynn; Tan, Adrian W. Y.

2014

La, T. G., Lau, G. K., Shiau, L. L., & Tan, A. W. Y. (2014). High stress actuation by dielectric elastomer with oil capsules. Proceedings of SPIE - The International Society for Optical Engineering, 9056.

<https://hdl.handle.net/10356/105176>

<https://doi.org/10.1117/12.2046371>

© 2014 SPIE. This paper was published in Proceedings of SPIE - The International Society for Optical Engineering and is made available as an electronic reprint (preprint) with permission of SPIE. The paper can be found at the following official DOI: [<http://dx.doi.org/10.1117/12.2046371>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 19:10:30 SGT

High stress actuation by dielectric elastomer with oil capsules

Thanh-Giang La, Gih-Keong Lau, Li-Lynn Shiau, Adrian Wei Yee Tan
School of Mechanical and Aerospace Engineering,
Nanyang Technological University, Singapore 639798

ABSTRACT

Though capable of generating a large strain, dielectric elastomer actuators (DEAs) generate only a moderate actuation stress not more than 200kPa, which seriously limits its use as artificial muscles for robotic arm. Enhancement of dielectric strength (greater than 500MV/m) by dielectric oil immersion could possibly enable it a larger force generation. Previously, the immersion was done in an oil bath, which limits portability together with DEAs. In this study, we developed portable capsules to enclose oil over the DEA substrate (VHB 4905). The capsules is made of a thinner soft acrylic membrane and they seals dielectric liquid oil (Dow Corning Fluid 200 50cSt). The DEA substrate is a graphite-clad VHB membrane, which is pre-stretched with pure-shear boundary condition for axial actuation. When activated under isotonic condition, the oil-capsule DEA can sustain a very high dielectric field up to 903 MV/m and does not fail; whereas, the dry DEA breaks down at a lower electric field at 570 MV/m. Furthermore, the oil-capsule DEA can produces higher isometric stress change up to 1.05MPa, which is 70% more than the maximum produced by the dry DEA. This study confirmed that oil capping helps DEA achieve very high dielectric strength and generate more stress change for work.

1. INTRODUCTION

Dielectric elastomer actuators (DEAs) have been reported with great actuation potential. For example, a flat pre-strained DEA demonstrated a large areal actuation strain of 158% under high Maxwell stress (7.2MPa at a high electric field of 412MV/m)[1]. Such great actuation potential has attracted intensive research to better the actuator performance and to apply them as artificial muscles to drive human-like robots [2] [3]. However, these soft actuators are not as strong as natural muscles to produce high enough stress change. Rolled DEA was used to drive an arm-wrestling robot, but it only realized a moderate stress change up to 0.23 MPa at 74.1MV/m [2], which is lower than the reported isometric stress for the flat membrane DEA, for example 0.6MPa at 142MV/m [4]. In comparison, human arm muscles can demonstrated a higher stress change up to 0.8-1.2 MPa in a pushing experiment [5]. Not to surprise, the DEA-powered arm wrestling robot lost in a match with a young human opponent [5]. Lower-than-expected actuation stress in the DEA is attributed to reduced dielectric strength under the operating condition.

Recent research showed that oil immersion in a dielectric oil bath quenches electric arcing [6] [7] and thermal runaway [8] and consequently helps DEA achieve a very high dielectric strength up to 800MV/m [7]. This finding is very encouraging towards the development of a stronger DEA. Yet, the oil bath is not portable, and the oil-dipped DEA on the support of a fixed frame do not work well against external load. Instead, DEA under pure-shear condition is better for lifting heavy load, but it is prone to failure by electronic avalanche [8] [9]. Just like oil dipping, oil capping is anticipated to greatly improve the pure-shear actuator in terms of its dielectric strength and work capacity. The oil capping is achievable by integrating soft membrane capsules of dielectric oil over a pure-shear DEA. This liquid capsule is similar in build to a tunable liquid lens, which bulges out-of-plane [10] [11]. But, here, it is intended for axial stretchability such that it conforms to the actuation of the pure-shear DEA. This oil-capsule DEA promises to make a stronger elastomeric muscle.

2. DEA WITH OIL CAPSULES

In this work, both compliant electrodes of a DEA are wetted and encapsulated by oil capsules. The oil-capped DEA is a dielectric elastomeric membrane (VHB4905), which is pre-stretched 5 times by 5 times in the pure-shear condition by lateral clamps and an axial load by a dead weight. The pre-stretched membrane has thickness of $40 \pm 2 \mu\text{m}$ measured by a micro-meter. Compliant electrodes (6 cm x 1cm) on the elastomeric membrane are a very thin coating of graphite flake (with average $6 \mu\text{m}$ size), adhered or immobilized on the DEA substrate. Each oil capsule consists of a soft membrane (VHB9473P) enclosing dielectric oil in the cavity above the DEA substrate. A large portion of the oil is dispensed by syringe injection to the capsule cavity, bulging out the capsule membrane. Like a normal DEA under pure-shear condition, activation of this oil-capsule DEA causes axial elongation as shown in Figure 1. Though the capsule membrane may stiffen the whole actuator, the oil capsules are anticipated to beneficially increase the breakdown field and stress generation for the DEA.

Silicone oil (Dow Corning Fluid 200 50cSt) is used here for quenching localized breakdown [7] because it helps cool down the localized breakdown better than the air and it can better withstand partial discharge than air. In addition to the oil immersion, self-clearable electrode material, i.e. very thin graphite powder, was used to enable DEA a very high dielectric strength. We previously found the oil-dipped DEA with graphite electrode is self clearable from breakdown at very high field [7]. As the graphite powder coating was immobilized on the elastomeric substrate, they were not dislocated by oil immersion and thus they are less likely to contributed to the shorting like flowable carbon grease does during localized breakdown. Yet, there is concern whether silicone oil may swell and weaken the VHB substrate and membrane. This tensile testing, see Figure 2, showed that the 24-hour immersion in silicone oil slightly soften a blank acrylic VHB membrane, which is pre-stretched in the same condition as the actuator. The effect of oil is very marginal in the actuation range below 60% strain.

Figure 1

As a benchmark for comparison, a pure-shear DEA, which is dry and not oiled, is also prepared the same as the active core of the oil-capsuled one. It is pre-stretched the same, and coated with the same graphite-powder electrodes. The dry DEA has a net weight ranging approximately 0.45-0.57 grams, which is lighter than the oil-capsuled one weighing 0.78-1.1 grams, excluding weights of the lateral clamps and a deadweight. In addition, the dry DEA exhibits a lower stiffness as compared to the one reinforced by the oil capsules. Tensile testing of these two types of DEAs, as in Figure 3, showed that the stress required to stretch the dry DEA is less than half that required to stretch the oil capsuled one. Despite the stiffness difference, the two DEAs, with or without oil capsules, have the same active elastomeric core and therefore they are supposed to induce the same actuation stress change at the same electric field.

Figure 2 Effect of oil immersion on the stiffness of a blank VHB membrane, which is pre-stretched the same

Figure 3 Effect of oil capsules on the total stiffness of DEAs

3. ELECTRO-MECHANICAL RESPONSE

Unlike natural muscles that contract upon stimulation, pre-stretched DEAs relax and elongate upon activation. Though it cannot lift weight directly, the pre-stretched DEAs can lower a weight on upon activation and be configured in an agonist-antagonist- pair to do work just like the example of an arm wrestling robot. Work capacity for the DEA can be measured in terms of the free stroke under a constant deadweight (isotonic) or a blocked force when fixed in length (isometric). To do forceful work like human flexor muscles, DEAs need to produce enough working stress change and must deliver real work, despite its actuation potential.

3.1. Isotonic test

In an isotonic test, an actuator is loaded by a constant dead weight and it is activated by a high voltage to produce a free stroke ΔL . The free activated stroke is caused the Maxwell stress that reduces the internal pre-stress, which was initially in equilibrium with a constant deadweight when not activated. Hence, work done by the actuator can be measured as the product of the free stroke under the constant load P . The maximum stroke and work density is realized at the maximum voltage where the actuator almost breaks down electrically. As such the maximum work density realized is defined as s the maximum work per actuator mass m ,

$$W_{max} = \frac{P \times \Delta L_{max}}{m}.$$

Under this isotonic test, both types of DEAs were pre-stretched axially the same, i.e. 5 times the initial axial length, by a dead weight. Pre-stretching the oil-capsuled DEA requires a 422-gram deadweight, heavier than 227 grams for the dry one which is not reinforced by capsule membranes. Both DEAs were activated with a voltage ramp, which increases stepwise for ? seconds each until the breakdown. Figure 4 compare the actuation strain and the maximum electric field achievable by the two types of DEAs. The dry DEA produces more strain at the same field because it is softer than the oil-capsule one. However, interestingly, it is observed that the oil-capsuled DEA can withstand ultra-high electric field of 903MV/m at 22kV without a breakdown and producing a 61% actuation strain. Figure 5 shows the axial elongation for this DEA when activated at 22kV. The oil-capsuled DEA could possibly be activated at an even high electric field, but activation more than 22kV cause high field in air and interferes with digital camera and computer system. On the other hand, the dry DEA can only sustain up to 600MV/m at 17kV and consequently produces lesser actuation strain of 50% before it failed catastrophically. The failed DEA is subjected to puncture and ruptures as shown in Figure 6 after being shorted by electrical arcing. Performance comparison suggests that oil capping helps quench the electrical breakdown, which happens to DEA, and consequently greatly raised the dielectric strength to be very high. As a result of avoiding the early dielectric breakdown, the oil-capsuled DEA realized a work density up to 31.51J/kg, 44% higher than 21.91 J/kg achieved by the dry DEA.

Figure 5.

Figure 6.

3.2. Isometric test

In an isometric test, an actuator is kept at a constant axial pre-stretch and activated with high voltage to induce a stress change in the actuator. Being viscoelastic, the elastomeric actuator takes time (at least 30mins) to full relax to a steady-state pre-stress, before the field-induced stress change can be accurately measured. During activation, Maxwell stress is induced between the opposite electrodes, compressing the dielectrics. The Maxwell stress is proportional to the electric field square, following

$$\Delta T = \frac{\epsilon_0 \epsilon_r E^2}{2},$$

It is expected to reduce to reduce the mechanical in the actuator, which is pre-stretched with a constant length. In this case, the isometric pre-stretch is set to be 60% more than the initial pre-stretch to match with the maximum free stroke measured in the isotonic experiment.

This isotonic test is performed on a tensile tester (INSTRON 5569) using a 10N-capacity load cell. To simulate the maximum isotonic free stroke, the actuator samples is stretched 60% axially more than the initial pre-stretch before they are tested for isometric stress change. Subsequently, the actuator samples are subjected to a stepwise voltage ramp towards the maximum achievable voltages and the field-induced force change is measured by the load cell. The stress change in the activated dielectric membrane is calculated as the force change over its true thickness. The passive membrane of the oil-capsule DEA has no effect on the activated stress change, though it affects the initial mechanical pre-stress.

Two types of DEAs, with or without oil capsule, were under isometric tests. Figure 7 shows the measured and calculated stress change with respect to the electric field. After all, both oil-capsule DEA and dry DEA has the induced stress change increased quadratically with the increasing field up 150MV/m, following the trend for Maxwell stress. However, at higher field, the induced stresses become lesser than the Maxwell stress. This deviation is believed to be attributed to the constraint by boundary and elastomeric compressibility.

Though the two types of the DEA has the same active core, the oil capping affects the maximum achievable electric field. The dry DEA can sustain up to 9kV (i.e. 350MV/m field) beyond which it fails terminally. In contrast, the oil-capsule actuator can sustain a much higher voltage up to 16kV (i.e. 650MV/m field), beyond which the actuator is subjected to wrinkling as shown in Figure 8 and unsteady force measurement though not breaking down. The finding confirmed that oil capping help enhance the dielectric strength of the same-pre-stretched dielectric elastomer membrane. As a result, the oil-capsule DEAs achieve a higher stress change up to 1.5N (i.e. 1.05 MPa), at 16kV, 50% more than the 1N (i.e. 0.60 MPa), achieved by the dry DEA at 9kV.

Figure 7

Figure 8

3.3. Comparison with other works

Effect of electrode materials is profound on the performance of dielectric elastomer actuators. Carbon greases, graphite powders were used to make compliant electrodes for the highly pre-stretched acrylic elastomeric actuator (VHB 4910). Very high actuation strain beyond 100% areal strain was repeated in many previous reports using carbon grease electrode. However, high actuation stress beyond 0.6MPa was also realized in the actuator system though reported in a single membrane. Such practical deviation from the best stress performance could be attributed to the flowable carbon grease, which may short a localized defect at a moderate field below 250MV/m and cause a terminal failure.

Previous theoretical studies [13] [9] pointed out that the pull-in state may not cause catastrophic failure to DEAs. However, failures are inevitable in the experiments with the DEAs, though not necessary in the mode of pull-in failure. In this study, we found that the oil-capped DEA with graphite powder electrodes have avoided electric arcing and thermal runaway, and consequently achieved a very high dielectric strength and high stress generation. In this work, we showed that oil-capping and immobilized graphite electrodes works together as self clearable compliant electrodes to help DEAs achieve very high dielectric strength up to 903 MV/m during isotonic test, which is 58% higher than 570MV/m of the DEA with graphite electrodes alone.

References	Elastomers	Electrode Materials	Pre-stretch ratio (x,y)	Electric field (MV/m)	Actuation strain (%)	Maxwell stress (MPa)	Isometric stress (MPa)	Work output (J/kg)
Kofod (2003)	VHB 4910	Carbon grease	6,6	218	0	-	1.2	-
Pelrine (2000)	VHB 4910	Carbon grease	6,5	150	200	0.92	0.75	-
Kovacs (2007)	VHB 4910	Carbon grease	3,6.5	95	35	0.18	0.165	~17
Meijer (2001)	VHB 4910	Carbon grease	-	~170	0	0.60	0.6	13.17
Kollosche (2012)	VHB 4905	Carbon grease	5,2	~250	~250	1.27	-	-
Current work	VHB 4910	Oil-capped graphite powder	5,5	640 (Isometric)	0	8.3	1.05	31.51
				903 (Isotonic)	61	16.60		
	VHB 4910	Graphite powder	5,5	350 (Isometric)	0	2.4	0.6	21.91
				570 (Isotonic)	50			
Buchana (1995)	Human elbow flexors				-		0.8 – 1.2	-

4. CONCLUSION

Though electrical breakdown of DEA is stochastic, proper material selection and system help make a reliable and robust DEA that could achieve a very high dielectric strength. Use of highly pre-stretched acrylic elastomer and self clearable compliant electrode materials were proven to be a successful recipe to achieve a high strain and a high enough dielectric strength. In this work, we showed that oil-capping and immobilized graphite electrodes works together as self clearable compliant electrodes. DEAs with graphite electrodes encapsuled by oil capsule managed to sustain a very high dielectric strength up 903MV/m and to realize an even higher stress change up to 1.05MPa. This presents a great improvement in comparison with the dry DEA alone.

REFERENCES

- [1] 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, 2000.
- [2] G. Kovacs, P. Lochmatter and M. Wissler, "An arm wrestling robot driven by dielectric elastomer actuators," *Smart Materials and Structures*, vol. 16, no. 2, p. S306, 2007.
- [3] P. Brochu and Q. Pei, "Advances in dielectric elastomers for actuators and artificial muscles," *Macromolecular*

rapid communications, vol. 31, no. 1, pp. 10--36, 2010.

- [4] K. Meijer, M. Rosenthal and R. J. Full, "Muscle-like actuators? A comparison between three electroactive polymers," *Proc. SPIE*, vol. 4329, pp. 7-15, 2001.
- [5] T. Buchanan, "Evidence that maximum muscle stress is not a constant: differences in specific tension in elbow flexors and extensors," *Medical engineering & physics*, vol. 17, no. 7, pp. 529--536, 1995.
- [6] Y. Bar-Cohen, "1st Wrestling Match between Human and EAP Actuated," *WW-EAP Newsletter*, vol. 7, no. 1, pp. 3-8, June 2005.
- [7] W. Yuan, L. Hu, Z. Yu, T. Lam, J. Biggs, S. M. Ha, D. Xi, B. Chen, M. K. Senesky, G. Gruner and Q. Pei, "Fault-Tolerant Dielectric Elastomer Actuators using Single-Walled Carbon Nanotube Electrodes," *Advanced Materials*, vol. 20, no. 3, pp. 621--625, 2008.
- [8] W. Yuan, P. Brochu, S. M. Ha and Q. Pei, "Dielectric oil coated single-walled carbon nanotube electrodes for stable, large-strain actuation with dielectric elastomers," *Sensors and Actuators A: Physical*, vol. 155, no. 2, pp. 278--284, 2009.
- [9] T.-G. La and G.-K. Lau, "Very high dielectric strength for dielectric elastomer actuators in liquid dielectric immersion," *Applied Physics Letters*, vol. 102, no. 19, p. 192905, 2013.
- [10] M. Kolloche, J. Zhu, Z. Suo and G. Kofod, "Complex interplay of nonlinear processes in dielectric elastomers," *Physical Review E*, vol. 85, no. 5, p. 051801, 2012.
- [11] J. Zhu, M. Kolloche, T. Lu, G. Kofod and Z. Suo, "Two types of transitions to wrinkles in dielectric elastomers," *Soft Matter*, vol. 8, no. 34, pp. 8840--8846, 2012.
- [12] F. Carpi, G. Frediani, S. Turco and D. De Rossi, "Bioinspired Tunable Lens with Muscle-Like Electroactive Elastomers," *Advanced Functional Materials*, vol. 21, no. 21, pp. 4152--4158, 2011.
- [13] S. Shian, R. M. Diebold and D. R. Clarke, "Tunable lenses using transparent dielectric elastomer actuators," *Optics Express*, vol. 21, no. 7, pp. 8669--8676, 2013.
- [14] M. Wissler and E. Mazza, "Modeling and simulation of dielectric elastomer actuators," *Smart Materials and structures*, vol. 14, no. 6, p. 1396, 2005.