Modeling and Evaluation of Additive Manufactured HASEL Actuators*

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***Abstract*—This work demonstrates fully 3D printed donut type HASEL actuators fabricated using inkjet additive manufacturing. In addition, we also present a coupled electrical, hydraulic, non-linear elastic model of these actuators to predict the actuation strain. This model was tested on 3D printed HASEL actuators and was found to be in good agreement with experimental results. The actuators demonstrated achieve better performance than conventionally manufactured HASEL actuators achieving a pull-in voltage half that of the conventionally manufactured actuators. Max. strain observed in these actuators was about 33 % at 10 kV. These findings open the door to fully 3D printed soft robotic devices**

***Index Terms*—soft robots,3d printing, HASELs, modelling**

I. Introduction

Robots are typically designed in such a way to minimize the number of actuators used. However, plants and animals do not appear to limit the amount of actuators they use. The use more actuators enables more degrees of freedom, control of stiffness and impedance [1]. Fabricating robots with large number of actuators using conventional methods is time consuming and requires more labor. Conventional methods like cutting, molding, casting, spin coating, etc. constrain the design and fabrication flexibility of the devices.

Additive manufacturing (AM) commonly referred as 3D printing has gained lot of attention in recent years. Structures with complicated geometries and multiple materials can be printed in one step using 3D printing. If AM could be used to fabricate actuators then a whole class of robot designs becomes possible. Additive manufacturing has already been used to fabricated various types of actuators. Most of which are pneumatic actuators including flexible micro-actuators [2], bending type actuators [3] [4], bellows type actuators [5] [6], and even fan based actuators [7]. Less common actuators are based are thermal [8], ionic polymer matrix composites (IPMC) [9] [10], and combustion actuators [11]. However, hydraulic and pneumatic actuators require complicated valving and external compressors, IPMC actuators are slow, and thermal/combustion actuators are difficult to control. One interesting development that may enable much more practical actuators is the Hydraulically Amplified Self-healing Electrostatic actuator or HASEL [12] [13]. The HASEL actuator is based around the contraction of two oppositely charged plates the attraaction of which results in displacement of a dielectric fluid resulting in deformation of the actuator. The HASEL actuator can be seen as an evolution of a dielectric elastomer with the fluid serving to decrease stiffness of the actuator and to increase tolerance to dielectric breakdown. However, one of the most interesting facets of HASEL actuators is that unlike dielectric elastomers, no prestrain is required in order for them to function. In addition, one can also sense the deformation of HASEL actuators by measuring their capacitance, which could eliminate the need for added proprioceptive sensors. HASEL actuators have been fabricated using conventional methods which limits freedom of design and is a laborious process.

Here, we present a study on fully 3D printed HASEL actuators fabricated through the polyjet inkjet additive manufacturing process. Our actuators achieve more strain at lower voltages (about 50% less) compared to similar conventionally manufactured HASEL actuators. FEM studies were also carried out to predict the actuation behavior of HASEL actuators and were found in agreement with experimental results.

II. Modelling

We studied a single donut type actuator with a novel bellow like lip around the edge (Figure 1). We consider an actuator with an overall radius of 25 mm, with a 0.625 mm wall thickness, an internal distance of 1.5 mm, and an electrode radius of 12.5 mm, which is of similar dimensions to the donut type HASEL actuators in [12]. We use larger wall thickness than conventionally manufactured HASELs due to resolution limitations of the current polyjet manufacturing process. We added a bellow like lip around the edge to help compensate for the increased thickness due to using a thicker material. The actuators are made from Tangoblackplus which has a relatively low stiffness, and reasonable dielectric strength

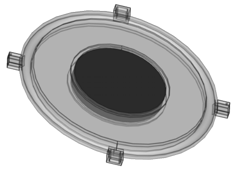

Fig. 1. CAD model of actuator with black regions denoting a CNT coating

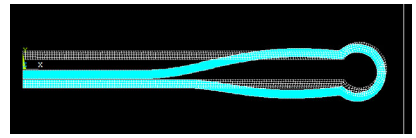

Fig. 2. Predicted Deformation of a donut type actuator with 0.625 mm wall thickness at 10KV

Fig. 3. internal support material removal system

[14]. We used hyperelastic neo-hookean model of Tangoplus FLX930, which has identical properties to Tangoblackplus [15]. Tangoblackplus and other additively manufacturable elastomers are known to be fairly viscoelastic, but in this model we only consider quasistatic loading so we ignore this behavior. Our actuator exhibits radial symmetry so we only consider a 2d axisymmetric slice of the actuator.

We use Ansys' for our FEM model of our device. We employ plane223 elements, that is planar elements capable of modeling electroelastic coupling, to describe our elastomer. We use Ansys' HSFLD241 elements to approximate the dielectric fluid's behavior. These elements can approximate the behavior of a fluid fully enclosed in a volume without pressure gradients by considering a volume defined by the internal surfaces of said volume. This allows us to avoid using computationally expensive CFD to model the behavior of the fluid. However, we must note that such a method of modelling cannot take into account gravitational effects and cannot account for fluid flow transients, but we argue that this can still provide a reasonably accurate model of behavior in quasistatic loading and when the size scale of the actuator is relatively small. In order to model the electrostatic field's interaction through the fluid we use a single layer of triangular plane223 elements between the upper and lower internal surfaces of the actuator with infinitesimal stiffness and without mid-side nodes. This provides us with a grid upon which the electrostatic field inside the fluid is calculated. The negligble stiffness of and lack of mid-side nodes enable it to move with the 'fluid' and collapse under compression. Contact of the internal surfaces is an important phenomenon that must be taken into account in order to realistically model the zipping action of HASEL actuators. We take into account the contact of the internal surfaces all the way to the lip region. We also add a small contact offset to prevent complete collapse of our grid for describing the electrostatic field in the fluid. Tangoblackplus has a perimittivity about 3 and dielectric fluid (mineral oil) has permittivity about 2.2. We consider the electrodes to be 12.5 mm in radius and located at the top and bottom of the actuator, with the bottom electrode being fixed. We consider the electrodes to have negligible stiffness and uniform voltage. A potential from 0-10000 volts was applied between these electrodes in steps of 25 volts in the model. Figure 2 shows final displaced structure. We estimated the no load strain from the model by measuring the maximum nodal Y displacement of the top surface and the minimum nodal Y displacement of the bottom surface,which is where the maximum positive and negative displacements occur. We add the absolute value of the two together and divide by the original actuator thickness.

III. Actuator Fabrication

HASEL actuators with 0.625 mm wall thickness were 3D printed using Stratasys Objet500 Connex3 printer. The actuators were fabricated from Agilus clear and Tangoblackplus. One challenge in fabricating these actuators is removing internal support material which we solved by flowing support removal solution (1% sodium hydroxide and 1% sodium metasilicate in distilled water) through the actuator. The actuator was fabricated with four radially placed ports, and a thin wire was used to establish a channel between the ports, and then support removal solution was pumped in through one port so as to flow through the established channels as shown in Fig. 3. The fluid flow and chemical action of support removal solution erode and carry away the support material. This allows for removal of internal support material significantly faster than than the traditional method of sonication. Complete removal of support material took around 2 hours, while it was noted that negligible support material was removed after sitting in a sonicator, the conventional means by which support material is removed, for 24 hours. The electrode regions of the actuator were coated with a carbon nanotube (CNT) dispersion so as to render them conductive. The dispersion was made from about 1% MWCNT (Nanocyl NC7000) in distilled water along with polymeric dispersant SOLSPERSE46000 (0.5 wt%, Lubrizol, USA) as reported by Magdassi et al. [16] The CNT coating was dried in oven at 80 C. About 3.6 ml of Mineral oil (Lubricant Laxative, CAREOne) was filled in the actuator

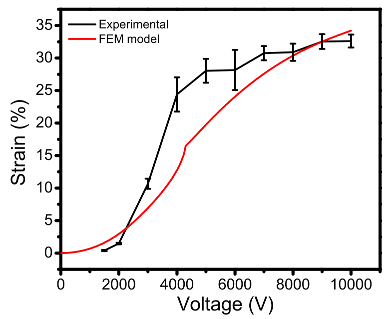

Fig. 4. Strain voltage curves of FEM model and experimental results of actuator fabricated in Tangoblackplus

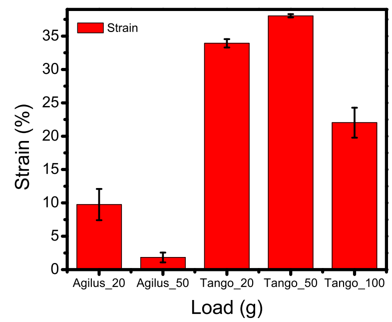

Fig. 5. Strain under load at 10 KV

and the ports were sealed with SUV elastomer [17] with AUD and EAA in ratio 1:1 along with 2% TPO. Curing of the elastomeric ink was performed using a UV flash lamp (Warsun, R838) at 365/395 nm. Strips of aluminum tape were attached to the electrodes to provide a flexible connection to the electrodes.

IV. Actuator Characterization

The actuators were actuated by applying 0-10 kV DC using an emco q101 DC-DC converted hooked up to a regulated DC power supply. To determine the unloaded voltage strain response the actuator was put onto a flat surface and a desired voltage was applied to the actuator, power was removed and the actuator was allowed time to relax back to zero strain for several actuation trials. During actuation the motion of marker attached to a test fixture sitting (about 7.70g and was considered as zero load) on top of the actuator was tracked with a video camera. The photos and videos were recorded using Nikon camera D7100 equipped with Nikon lens (AF-S NIKKOR 50 mm). The videos were recorded using 25 frames per second. The displacement and corresponding strain were calculated from the video files using TEMA software and imageJ.

As can be seen in Fig. 4 the unloaded strain voltage response predicted by the FEM model appears similar to that which was measured. The largest difference between our model and the experimental data is that the pull-in behavior is more gradual in the model. One possible reason for this is that we do not consider frictional or gravitational forces in our FEM model. We found that we achieve better performance than the non-printed HASEL actuators previously reported in [12], even in spite of the fact of using a stiffer material with twice the thickness. Under no load our actuators experience pull in at 4KV with a strain of about 25%, while the original actuators achieve pull in at 8KV with 20% strain [12]. While previous work achieved actuation strains of 50% for a single actuator, this was achieved at 17 KV and our power supply cannot provide such voltages. However, we did not observe any instance of dielectric breakdown in these actuators, so it is quite likely we could use higher actuation voltages and obtain more strain. We also characterized the behavior of our actuators under different loads. In addition an actuator with the same dimensions was fabricated in agilus, and it's behavior under load is shown in Fig. 5. We found that the actuator fabricated from Tangoblackplus exhibited better actuation compared to agilus ones. Oddly we found that under a 50 g load, the actuator made from Tangoblackplus exhibited slightly more strain than when a 20 gram load was applied, although further testing is needed to confirm this. It was also observed that relaxation time was fairly long for Agilus. The actuator fabricated using Tangoblackplus were found to actuate rapidly in about 0.2 seconds to reach full strain in the unloaded case.

V. Conclusion

We have presented a means of modelling the coupled elasto-electrical-hydraulic behavior for HASEL actuators in the quasistatic domain. In future work, a full transient loading model taking into account fluid flow and viscoelasticity is recommended. We have demonstrated that basic HASEL actuators can be fully additively manufactured and that such actuators achieve similar performance to their conventionally manufactured counterparts. The fact that we obtain similar performance to conventionally manufactured actuators bodes well for printable soft robots. Other actuator designs and novel actuator designs that additive manufacturing makes possible should be investigated. We must note that some post processing was required for the actuators, but we argue that inkjet based additive manufacturing is capable of eliminating these intermediate steps. It has already been demonstrated that inkjet based additive manufacturing can be used to print fully enclosed volumes of fluid [18] and there are a wide variety of inkjettable materials with sufficient conductivity [19] [20] [21]. This may enable fully printed robotic systems.

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