Fabrication of Polyurethane Dielectric Actuators

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ABSTRACT

This paper provides a summary of a 3 year Technology Investment Fund Project entitled "Dielectric Polymer Actuators for Active/ Passive Vibration Isolation", which was completed in March 2005. The purpose of this project was to investigate dielectric polymer materials for potential use in active/ passive vibration isolation. Work was carried out at mainly at DRDC Atlantic, Bodycote Materials Testing Canada, Royal Military College, and Martec Limited. Major accomplishments of the TIF project included development of a fabrication method for producing spray-cast rolled dielectric actuators; a proof of concept study to produce hollow fibre actuators; a comprehensive study of the effect of high permittivity and conductive fillers on actuator performance; and the implementation of electric field induced forces into the VAST finite element program, thus enabling this code to contribute to the development of devices and systems based on dielectric polymer actuators.

Keywords: dielectric actuators, electroactive polymers, Technology Investment Fund

1. INTRODUCTION

Dielectric polymeric actuators consist of an elastomeric film sandwiched between compliant electrodes to form a capacitor. When a potential is applied across the electrodes, the induced charge causes an electrostatic attraction between the electrodes. The resulting compressive force, or Maxwell stress, leads to a reduction in film thickness, which in turn results in elongation in the plane of the film. Polymeric actuators that utilize the Maxwell stress effect have generated considerable interest in recent years for use in applications such as artificial muscles, sensors, and parasitic energy capture.

Dielectric actuators are promising candidates for active vibration isolation applications in military platforms where they can combine both passive as well as active isolation characteristics. For passive isolation, the dielectric elastomer may be formulated to have a Young's modulus near that of natural rubber $\sim$ 2 MPa, the most commonly used material for vibration isolation. Other types of actuator materials, including shape memory alloys, piezoelectric polymers and ceramics, are generally too stiff to be useful for passive isolation, typically having Young's moduli hundreds or thousands of times larger than natural rubber.

A research team led by DRDC Atlantic has recently completed a Technology Investment Fund (TIF) project entitled "Dielectric Actuators for Active/ Passive Vibration Isolation". This project involved the preparation, characterization, and modelling of Maxwell stress actuators in the form of single and multi-layer films, as well as a rolled geometry. In this paper, an overview of the TIF project will be presented, and possible future work discussed.

2. PARTICIPANTS

This work was carried out by a team of researchers at DRDC Atlantic, Bodycote Materials Testing Canada, Royal Military College, Martec Limited, MacDonald Dettwiler & Associates, and FACTS Engineering. Table 1 provides a list of participants and their respective institutions.

Bodycote carried out materials formulation and device fabrication. DRDC Atlantic carried out materials characterization, device characterization, materials and device modelling, and project management. Binu Mukherjee and his group from Royal Military College (RMC) carried out characterization and analytical modelling of film actuators. Finite element modelling was carried out at RMC by George Akhras, at Martec by Lei Jiang, and at MacDonald Dettwiler & Associate by Olivier Beslin. Ken KarisAllen from FACTS Engineering built a unxiaxial test apparatus for dielectric actuators, and Ken MacKay from Martec built a biaxial stretch apparatus.

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14. ABSTRACT

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Table 1. List of Participants in TIF Project

Institution	**Participants**
DRDC Atlantic	Jeff Szabo, John Hiltz, Colin Cameron, Royale Underhill, Chris Purcell, Gary Fisher, Irv Keough, John Power, Marc Rawji
Bodycote Materials Testing Canada	Jacob Leidner, Jason Massey, David Cook, Stephen Johnstone, Magda Jaklewicz, Roland Grommer
Royal Military College	Binu Mukherjee, George Akhras, Guomao Yang, Guozhi Yao, Wei Ren
Martec	Lei Jiang, Ken MacKay
MacDonald Dettwiler & Associates	Olivier Beslin
FACTS Engineering	Ken KarisAllen

3. DIELECTRIC LAYER SELECTION AND FORMULATION

At the beginning of the TIF project, it was envisioned that the final device would consist of alternate layers of an elastomeric polyurethane and a compliant electrode deposited on a substrate. This multi-layer actuator would be rolled into a rod shape, and the electrodes would be terminated in some fashion.

A literature survey was initially conducted [1,2] to determine the material requirements for the dielectric and electrode layers. The polyurethane dielectric layer should have low mechanical loss, a hardness between 55 and 75 Shore A (similar to natural rubber), and low creep. It should have high dielectric breakdown voltage, high dielectric constant, and low dielectric loss characteristics. In terms of processing, the dielectric layer formulation should have low viscosity in the uncured state, and working times greater than 30 minutes.

Over 60 polyurethane formulations were prepared and characterized by a variety of techniques including dynamic mechanical analysis (DMA), differential scanning calorimetry (DSC), dielectric analysis (DEA), Fourier Transform Infrared Spectroscopy (FT-IR), and solvent uptake experiments [3]. In addition to providing direct information on material properties such as modulus or permittivity, these techniques provided important information about chemical structure, phase separation, cross-linking, and crystallinity.

One of the formulations, referred to as Rx 156-1, was selected for further investigation and for actuator fabrication. Rx 156-1 is a polyether polyurethane formulation, prepared from a pre-polymerized diisocyanate, a polyether glycol, a short chain diol, and tri-functional alcohol crosslinker. It has a curing time at room temperature $>$ 60 minutes, and a curing time at 60°C of $\sim$ 30 minutes. The dielectric breakdown field for Rx 156-1 films was found to be in the range 30 - 50 MV/m. From stress-strain experiments, it was determined that the tensile strength of Rx 156-1 is $\sim$ 1 MPa, and elongation at break is 600 - 900%.

Dynamic mechanical analysis experiments provided a 1 Hz room temperature storage modulus $Y' = 3.4$ MPa and loss factor $\tan\delta = 0.14$ for samples in the as-prepared state. However, it was observed that the dynamic mechanical properties were dependent on the thermal history of the sample, as illustrated in Figure 1. Specifically, it was observed that samples cooled to -80°C and then warmed to room temperature had higher moduli than samples that were warmed to 50°C and cooled to room temperature. DSC experiments confirmed that this behaviour was due to cold crystallization of the hard segment at temperatures well below its melt temperature (Figure 2).

4. FILLER STUDIES

The Maxwell stress induced by an electric field E is proportional to the elastomer dielectric permittivity ϵ (Equation 1). The resulting thickness strain for a film with no constraints is inversely proportional to the elastomer Young's modulus, Y (Equation 2). The maximum actuation stress and strain that can be achieved also depends on the second power of the maximum electric field that can be applied to the film before dielectric breakdown occurs, $E^2_{\max}$.

$$\sigma = \varepsilon_o \varepsilon E^2 \tag{1}$$

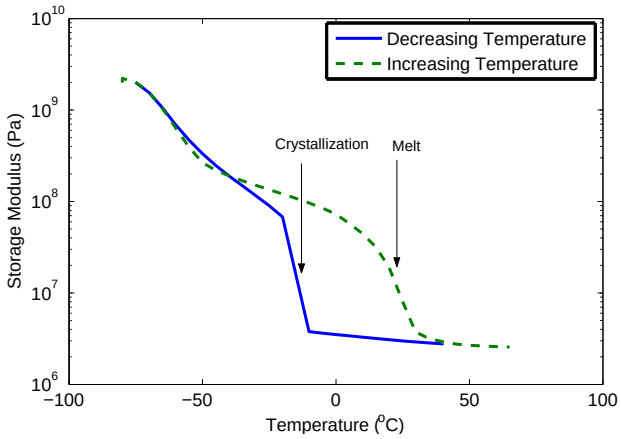

Figure 1. Dynamic Mechanical Analysis data for Rx 156-1 showing dependence of room temperature properties on thermal history.

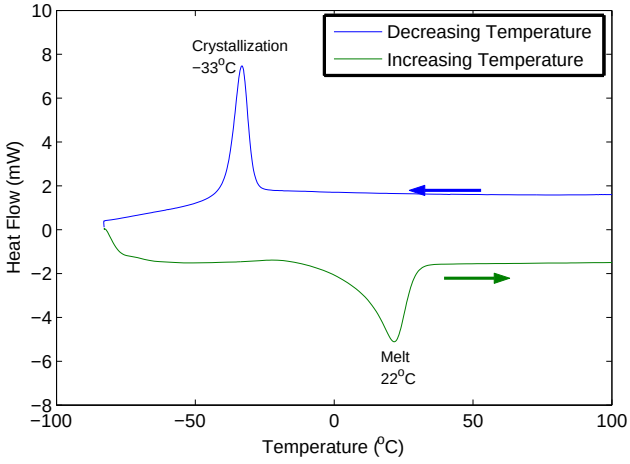

Figure 2. Differential Scanning Calorimetry results for Rx 156-1 showing crystallization and melting peaks.

$$\gamma = \frac{\varepsilon_o \varepsilon E^2}{Y} \tag{2}$$

One approach to increasing the magnitude of the actuation effect is to increase the permittivity of the elastomer through the addition of high permittivity fillers. In a study carried out in 2003 [4], the effect of high dielectric constant fillers on the electrical and mechanical properties of thin elastomeric films was examined. The fillers studied included the inorganic compounds titanium dioxide (TiO_2), barium titanate ($BaTiO_3$), and lead magnesium niobate-lead titanate ($Pb(Mg_{1/3}Nb_{2/3})O_3$-PbTiO). A high dielectric constant filler based on a polymeric conjugated ligand-metal complex, poly(copper phthalocyanine), was also synthesized and studied. Figures 3c and d show that TiO_2 and poly(copper phthalocyanine) did in fact raise the permittivity of the composite ε_c relative to the elastomeric matrix ε_m in a manner consistent with the asymmetric Bruggeman model (Figure 3e) [4]:

$$\left(\frac{\varepsilon_c}{\varepsilon_m}\right) = \frac{1}{(1-\varphi)^3} \tag{3}$$

where φ is the volume fraction of filler.

Maxwell stress actuators fabricated with $BaTiO_3$ dispersed in a silicone elastomer matrix were evaluated and compared with unfilled systems. A model was presented which relates filler volume fraction to actuation stress, strain, and elastic energy density at fields below dielectric breakdown. The model and experimental results suggested that the addition of high permittivity fillers to increase the performance of dielectric elastomer actuators may not be an effective strategy for increasing actuation strain, except in specific cases where the particle - matrix interaction is low [4]. However, these types of fillers could be used to increase actuation stress quite effectively.

Additional studies were carried out on the effect of conductive fillers on the actuation performance of dielectric actuators [5, 6]. For conductive fillers, it is possible to raise the permittivity with very small volume fractions of filler, as shown in Figures 3a and b. Consequently, the Young's modulus is not affected to the same degree as for non-conductive fillers, such as $BaTiO_3$. The increase in permittivity with conductive filler addition was well described by percolation theory, Figure 3f:

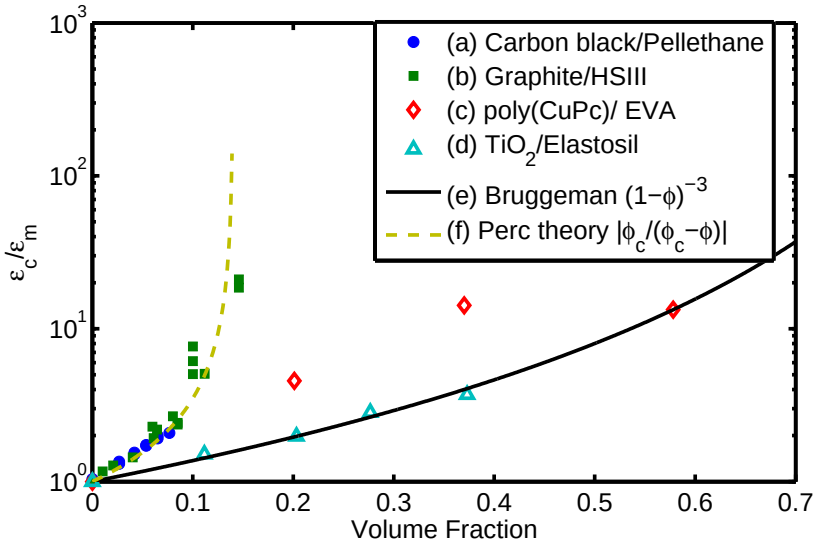

Figure 3. Ratio of composite permittivity ε_c to unfilled matrix permittivity ε_m for various filled systems: (a) Carbon black/ polyurethane. (b) Graphite/ silicone. (c) poly(copper phthalocyanine)/ poly(ethylene-co-vinyl acetate) (d) TiO_2/ silicone. (e) Asymmetric Bruggeman theory, Equation 3. (f) Percolation theory, Equation 4, with $\varphi_c = 0.14$ and $q = 1$.

$$\left(\frac{\varepsilon_c}{\varepsilon_m}\right) = \left|\frac{\varphi_c}{\varphi_c - \varphi}\right|^{-q} \tag{4}$$

In Equation 4 φ_c is the percolation threshold, and q is a fitting parameter.

In a study carried out in 2004 [5], a series of graphite-filled Pellethane composites were prepared. Very large increases in the Maxwell stress effect were seen at the onset of the percolation threshold, in accordance with material models. These increases were expressed as enhancement factors, from which a maximum dielectric constant $\epsilon > 4400$ was estimated in a composite containing 18.76% v/v graphite. As expected, the dielectric breakdown strength was affected negatively by conductive filler addition. Further work needs to be carried out in this area, but at the moment it may be concluded that conductive fillers may be most useful for dielectric actuators at low driving voltages, where large enhancements in performance would be expected over non-filled elastomers.

5. ELECTRODE FORMULATION

Ideally, the electrode material for a dielectric actuator should not constrain its motion, i.e. it should be perfectly compliant. In addition, it should have low resistivity, low mechanical loss, low thickness, and good adhesion to the dielectric layer.

Several approaches to electrode formulation and application were studied during the TIF project. Four different systems were initially explored to develop the compliant electrode layer:

- brushed graphite electrodes
- brushed silver electrodes
- silk screened electrodes
- sprayed electrodes

The brushed silver electrodes and silk screened electrodes were found to be unsatisfactory. Sprayed electrodes were selected for further development. Four different systems were considered for the compliant electrode formulation:

- graphite blended with a thermoplastic polyurethane
- graphite blended with a crosslinked polyurethane
- carbon black dispersed with a thermoplastic polyurethane
- carbon black dispersed with a crosslinked polyurethane

An electrode formulation was developed that could be sprayed using the Actuator Fabrication Device (see Section 6. directly onto the dielectric polymer actuator with a thickness of about 10 μm. The electrode consisted of a mixture of carbon black dispersed and a thermoplastic polyurethane dispersed in an organic solvent. The resistivity of the electrode when sprayed onto a nylon substrate was about 5 kΩ/square and when sprayed onto a two component polyurethane film was approximately 20 kΩ/square. The resistivity increased with elongation, and when it is elongated to 1.4 times its original length, the resistivity was approximately 50 kΩ/square. The electrode appeared to have no effect on the dielectric breakdown strength of the dielectric polymer.

Peel strength experiments were carried out to determine the adhesion between the electrode and the dielectric layers in multilayer actuators. Samples prepared with brushed on graphite as the electrode had low peel strengths (0.5 N/mm) and delamination occurred at graphite/ dielectric layer interface. Samples prepared with sprayed electrodes (see above) delaminated between the dielectric layer and a polyurethane support layer, giving a strength value of 1.8 N/m. Therefore, it is expected that the peel strength values between the electrode and the dielectric layer would be greater than 1.8 N/m.

6. ACTUATOR FABRICATION

6.1. Film Actuators

For many of the experiments conducted, it was sufficient to have a single layer of dielectric elastomer with electrodes applied to each size. Thin elastomeric films were prepared by casting the uncured polymer (in the case of silicones) or solution casting (in the case of thermoplastic polyurethanes) directly onto a glass plate. A drawdown device was used to create a film of uniform thickness, in the range 50 - 300 μm. Film actuators were fabricated from the polymer films using graphite powder as the electrode material. Typically the electrode area on each side of the film was 80mm x 50mm with a 20mm x 15mm tab to make contact with the voltage supply (see Figure 4). A close examination oof photos in Figure 4 reveals areas where dielectric breakdown has occurred.

6.2. Rolled Multi-Layers

The fabrication of rolled multi-layers was considerably more difficult than film actuators, and the development of an appropriate methodology was a major objective of the TIF project.

The actuator geometry desired consisted of dielectric and electrode films built up in layers and then rolled into a rod. To build up a number of these alternating films, a means to consistently lay down these layers was sought. An Actuator Fabrication Device was designed and constructed to prepare thin polyurethane films by spray casting. The device consists of an enclosure, a solution delivery system, a movement mechanism and a heating/curing system. The device was designed to spray uniform two component polyurethane films within thirty minutes in an enclosed vented box. It has a spray head that can move in two directions, make multiple passes, and cure the film within 30 minutes.

Figure 5 shows a portion of this apparatus and a multilayer film prior to rolling. A typical film geometry consisted 50 μm thick dielectric layers and 10 μm thick electrode layers:

- Dielectric layer 50 μm
- Electrode 10 μm

Figure 4. Photograph of film actuators filled with high dielectric constant fillers. Left: Poly(copper phthalocyanine)/ EVA composite film. Right: Barium titanate/ elastosil film.

Figure 5. Apparatus for fabrication of rolled dielectric actuators.

- Dielectric layer 50 μm
- Dielectric layer 50 μm
- Electrode 10 μm
- Dielectric layer 50 μm

After each layer was sprayed, the film was allowed to cure and the solvent evaporated before the next layer was applied. Rolled actuators were prepared by removing the film from the substrate (glass or polyethylene), and rolling by hand into a rod. The electrodes were then terminated using one of several techniques.

The two major fabrication issues for rolled actuators were low dielectric layer resistance (high conductivity), and inconsistent end termination, which was manifested by a low capacitance value. The low resistances were not observed for single layer actuators fabricated from polyurethane formulation Rx 156-1, but became apparent with multi-layer geometry (see above). Increasing the thickness of the dielectric layer helped to increase the device resistance, as shown in Figure 6.

It was expected that the dielectric elastomer ionic conductivity σ would be the major contributor to electrical losses in the film. The complex relative permittivity ε^* may be expressed in terms of a real part (the dielectric constant ε'), and an imaginary part, which is a sum of a dipole relaxation term ε''_{dip} and a term which depends on the ionic conductivity σ and the angular frequency ω:

$$\varepsilon^* = \varepsilon' - i\left[\varepsilon''_{dip} + \frac{\sigma}{\omega}\right] \tag{5}$$

However, the expected actuator resistance $R = d/A\sigma$ calculated from measured conductivity, thickness (d), and area (A) was much higher than what was observed experimentally (compare Figures 6a and b). This suggests that there are additional mechanisms contributing to the conductivity of polyurethane multi-layer actuators, such as through–thickness pinholes. It was observed that silicone rolled actuators resistances were at least 100 times higher than polyurethane rolled actuators of similar geometry. For this reason, both silicone and polyurethane

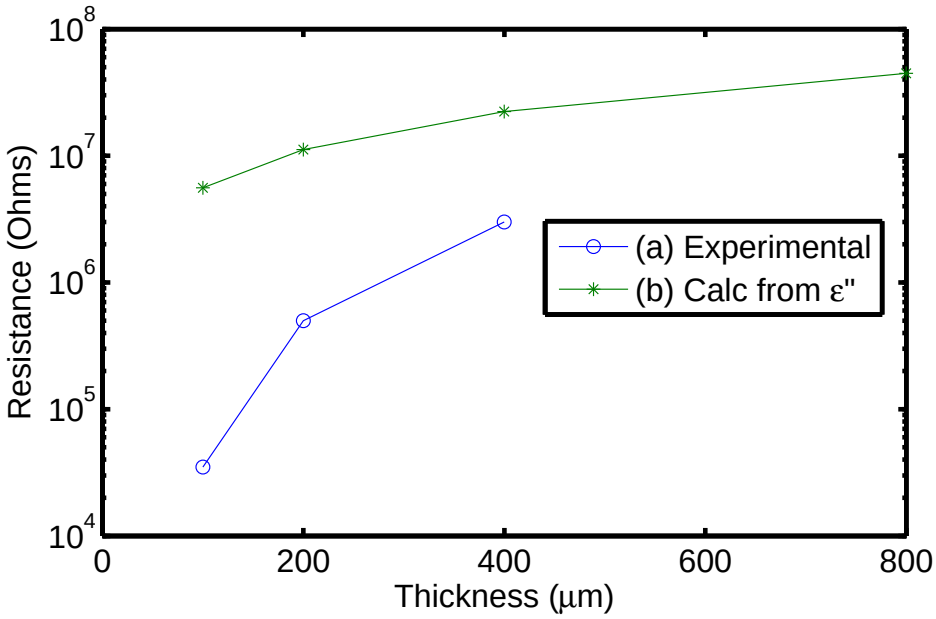

Figure 6. Polyurethane rolled actuator resistance as a function of dielectric layer thickness. (a) Experimental data. (b) Calculated from dielectric loss data.

Figure 7. Rolled dielectric actuators fabricated from silicone and polyurethane dielectric layers.

actuators were fabricated and characterized in this project. A total of 13 rolled polyurethane and 5 rolled silicone actuators were produced, examples of which are shown in Figure 7.

The second major fabrication issue that arose was the problem of electrical termination of the electrode layers. Copper tape was initially tested with only partial success, since the tape was fragile and often broke. Sprayed electrode tabs were investigated late in the project, and needs to be further evaluated. Termination via the actuator cylinder ends was the preferred method and was studied extensively. This was accomplished by trimming the ends of the rolled actuator (sometimes in liquid nitrogen), then applying a conductive elastomer layer and finally copper contacts. This method was found to be satisfactory for the case of polyurethane dielectric with polyurethane based sprayed electrode, but not with brushed graphite electrode (see Table 2).

Table 2. Electrical Termination of Rolled Actuators via Cylinder Ends

Dielectric layer	**Electrode**	**Termination**
Polyurethane	Brushed graphite	No
Polyurethane	Sprayed polyurethane	Yes
Silicone	Brushed graphite	Yes
Silicone	Sprayed polyurethane	?

This issue of electrical termination of rolled actuators was not fully resolved during the TIF project, but will be studied further in planned follow–on studies.

6.3. Fibre Acuators

Although not originally planned as part of the TIF project, a small study was undertaken to investigate the feasibility of producing Maxwell actuators in the form of a hollow fibre with a conductive core and a compliant electrode on the outer wall. This concept offers the potential advantage of utilizing standard, low cost, plastic extrusion fabrication technology with the ability to produce fibres with very thin walls. Individual fibres can be combined into bundles or ropes. In this work, low durometer thermoplastic polyurethane was used as the dielectric, graphite/silicone paste as the inner electrode and the outside surface of the fibre was brushed with graphite to form the outer compliant conductive electrode.

Actuators with hollow fibre geometry were fabricated using melt-spinning technology. The wall thickness was in the range 50 to 80 μm, and external diameters were in the range 0.5 to 1 mm. A cross-section of a fibre is shown in Figure 8. Fibre actuator bundles were also made and characterized.

The characterization and performance of the film, rolled, and fibre actuators is described in Sections 7 and 8 below.

7. ACTUATOR CHARACTERIZATION

Characterization of actuators in film, multi-layer, and rolled geometries was undertaken at DRDC Atlantic and Royal Military College. DRDC Atlantic used a custom built apparatus assembled by FACTS engineering to characterize actuation forces and displacements. Static displacements were measured using either a camera/ microscope combination [4], or a Micro-Epsilon optoNCDT 1400 CCD laser displacement transducer. Dynamic displacement measurements were carried out either with the Micro-Epsilon laser or an accelerometer [7]. Fibre actuator characterization was carried out at Bodycote, using a cathetometer, a non-contact visual measuring device.

At Royal Military College, a Zygo ZMI2000 laser Doppler interferometer was used to measure transverse strains in Maxwell stress actuators fabricated from silicone and thermoplastic polyurethane [8–10]. The system used a heterodyne detection technique and featured a wide bandwidth, high stability, easy optical alignment and the ability to measure a wide range of displacements at frequencies from DC up to 100 Hz. The static and dynamic strains of the materials were measured as functions of mass loading, dynamic amplitude, and frequency under various types of driving electric fields. Figure 9a shows an example of the dynamic response of a silicone film actuator subjected to a 1 Hz AC signal of $V_{AC} = 2000$ V. One can clearly see that the response is at 2 Hz,

Figure 8. Image of fibre actuator cross-section.

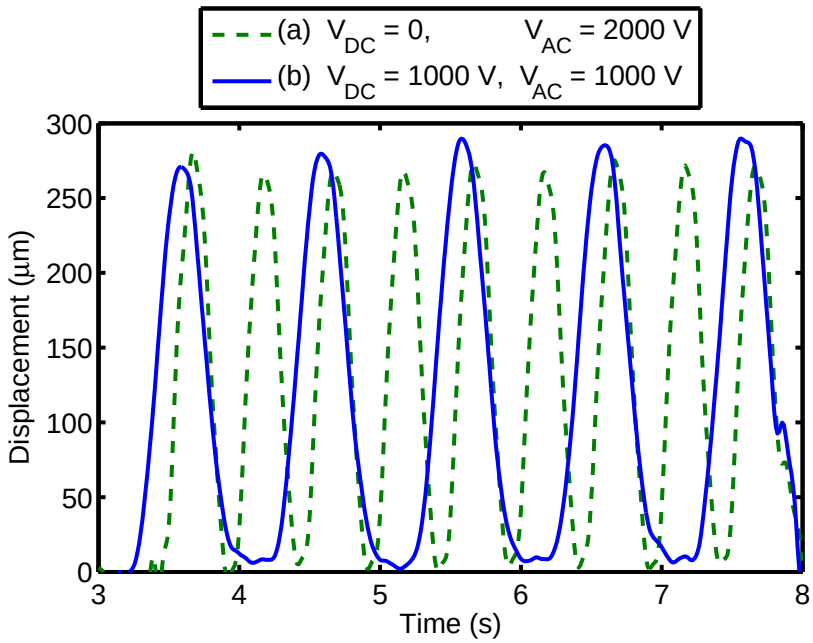

Figure 9. Dynamic actuation displacement for silicone film actuator excited at 1 Hz and different levels of DC bias. (a) $V_{DC} = 0$, V_{AC}=2000 V, (b) $V_{DC} = 1000$, V_{AC}=1000 V.

i.e double the excitation frequency. The frequency response changes with the amount of DC bias, as can be seen by comparing Figures 9a and b. For the latter Figure, the DC bias was $V_{DC} = 1000$ V, and $V_{AC} = 1000$ V. The relationship between DC bias and actuation strain γ was derived in Reference 9 as

$$\gamma = k\left[\left(V_{DC}^2 + \frac{1}{2}V_{AC}^2\right) + \left(2V_{DC}\,V_{AC}\sin\left(\omega t + \delta_1\right)\right) - \left(\frac{1}{2}V_{AC}^2\cos\left(2\omega t + \delta_2\right)\right)\right] \tag{6}$$

In Equation 6, δ_1 and δ_2 are phase shifts relative to the excitation signal, and $k = (\varepsilon_o\varepsilon)/(Yd^2)$. It was found that Equation 6 described the relative magnitudes of DC, 1ω, and 2ω components in experimental data very

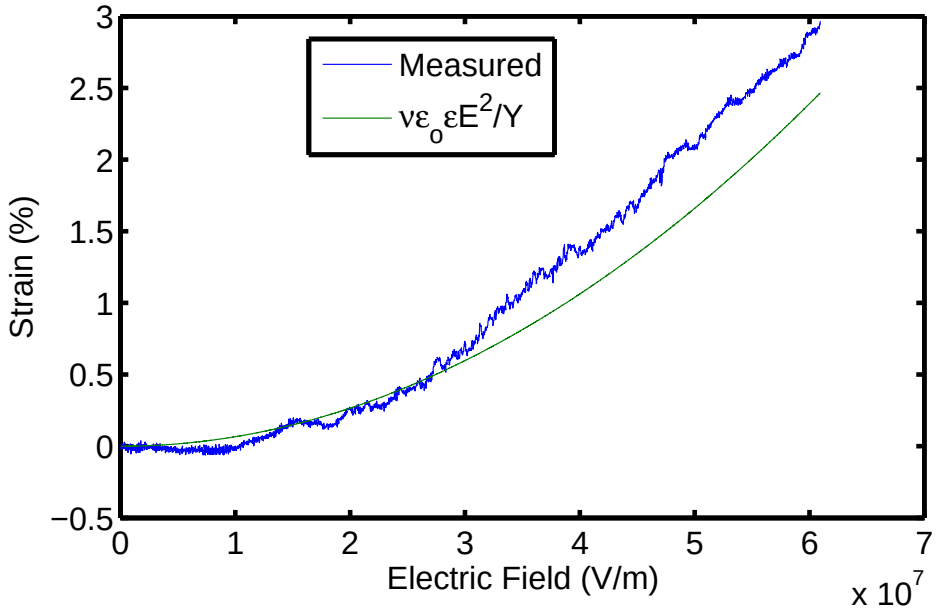

Figure 10. Example of rolled actuator performance for silicone rolled dielectric actuator (blue line). Green line is a plot of expected strain for a film actuator with the same material properties.

well [9].

8. DEVICE PERFORMANCE

For device performance measurements, actuators were typically driven with a linearly increasing voltage ramp until dielectric breakdown occurred or until the amplifier reached its current limit (20 mA). Figure 10 is an example of the strain versus electric field response of a rolled silicone dielectric actuator. The maximum strain reached by rolled actuators was typically in the range of 2-3%, although in a number of cases the actuators did not function because of poor electrical termination (see Section 6.2). For film actuators the maximum strain was in the range 3-11%, where the 11% was achieved using a very soft silicone. Fibre actuators described in Section 6.3 had maximum actuation strains of $\sim 1.5\%$.

It should be stated that it may be possible to increase the magnitudes of these actuation strains by imposing either uniaxial or biaxial pre-strain, which has been demonstrated to greatly increase the dielectric breakdown strength of polymeric films. For some materials such as the acrylic material VHB 4910, this leads to a dramatic increase in the maximum actuation strain [11, 12], while in other materials the performance is not enhanced by pre-strain [13].

9. DEVICE MODELLING

In addition to studies which involved material property modelling of filled composites [4, 5, 14], several device modelling studies were conducted as part of this project. The effect of DC bias, electrode resistance, and material losses on the dynamic response of dielectric actuators were examined in Reference [15]. This was followed by a more thorough study of the effect of DC bias on frequency response [8, 9], and the resulting model was experimentally validated.

In Reference [16], an analytical model of a rolled dielectric actuator was developed. The effect of large dynamic strains due to mechanical or electrical loading were included in the model, which was incorporated into the VIMGEN/VVES suite of programs for studying vibration isolation of marine engines.

Preliminary work on finite element modelling of dielectric polymer actuators (DPA) was carried out by MacDonald Dettwiler & Associates [17, 18]. A variational formulation was proposed to model the behaviour of DPA, and a finite element method was developed, based on this formulation. A reverse mapping requirement was raised that imposed limits on the type of element that could be used.

In 2004, the finite element code VAST was modified to include new large strain hyper-elastic elements and features were added to enable the application of electric field induced forces [19]. Numerical tests of the modified code were conducted on models of actuators of a variety of shapes, and these tests showed that the code was able to characterize the non-linear behaviour of the actuators very well. As a result of this work, the VAST code is now able to contribute to the development of devices and systems based on dielectric polymer actuators.

A series of carefully conducted experimental studies at Royal Military College formed the basis for a modelling study of dielectric film actuators [10, 20]. Experimental results showed that the dynamic strain amplitude had a non-linear dependence on the static pre-load applied to the polymer. The pre-load initially caused an increase in the dynamic actuation strain, but the strains decreased when larger pre-loads are applied. The initial increase appeared to be a function of the relative geometries of the electroded area and of the specimen itself. Since a linear elastic model could not represent the observed dependence of the strain on the pre-load, a hyperelastic model capable of describing the large deformation of polymeric materials was used to interpret the results. Numerical modelling using the ANSYS finite element code was carried out in order to understand the material behaviour and to better predict their general performance. Experimental results agreed with finite element model calculations very well for various electric fields and for different actuator geometries. The effect of static pre-load on actuation response was also studied, and these results were in agreement with model calculations up to about 15% pre-load. It is believed that agreement between model and experimental results at higher pre-loads would be improved if the strain dependence of the Young's modulus were accounted for in the model.

10. SUMMARY AND FUTURE WORK

Over the last three years, a Technology Investment Fund Project entitled "Dielectric Polymer Actuators for Active/ Passive Vibration Isolation", was carried out and completed. The purpose of this project was to investigate dielectric polymer materials for potential use in active/ passive vibration isolation. Work was carried out mainly at DRDC Atlantic, Bodycote Materials Testing Canada, Royal Military College, and Martec Limited. The major accomplishments of this project were:

- Development of techniques for determining the static and dynamic response of film and rolled actuators
- Development of analytical and finite element modelling tools for examining the effect of material properties and actuator geometry on actuation behaviour.
- Development of a crosslinked polyurethane formulation with the appropriate material properties for dielectric actuators
- Development of compliant electrodes based on filled polyurethanes
- Development of a method to produce rolled dielectric actuators based on spray-cast crosslinked polyurethanes and silicones
- Development of a method to produce actuators with hollow fibre geometry
- A comprehensive study on the effect of high permittivity and conductive fillers on actuator performance

Follow on work at DRDC Atlantic will include improving the electrical termination method, studying carbon nanotube composites as electrode materials, and initiating studies on active vibration isolation with rolled dielectric actuators.

11. ACKNOWLEDGEMENTS

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REFERENCES

1. J. Massey, J. Leidner, J. Szabo, and J. Hiltz, "Material design considerations for dielectric polymer actuator based devices," *Proceedings of the 6th CanSmart Meeting - International Workshop on Smart Materials and Structures, editor George Akhras* , pp. 237–245, 2003. CanSmart Group, Kingston ON Canada, 2003. Defence R&D Canada – Atlantic 2003-189.
2. J. Massey, J. Leidner, J. Szabo, and J. Hiltz, "Dielectric polymer actuators: Material design," *Proceedings of 10th CF/DRDC Meeting on Naval Applications of Materials Technology, Halifax, 13-15 May 2003* , pp. 205–216, 2003. Defence R&D Canada – Atlantic SL 2003-140.
3. J. A. Hiltz and J. P. Szabo, "Characterization of cross-linked poly(urethane)s: Fourier transform infrared spectroscopy and dynamic mechanical thermal analysis results," Technical Memorandum 2004-051, Defence R&D Canada - Atlantic, November 2004. 118 pages.
4. J. Szabo, J. Hiltz, C. Cameron, R. Underhill, J. Massey, B. White, and J. Leidner, "Elastomeric composites with high dielectric constant for use in maxwell stress actuators," *Smart Structures and Materials 2003: Electroactive Polymer Actuators and Devices (EAPAD), Yoseph Bar-Cohen, Editor, Proceedings of SPIE* **5051**, pp. 180–190, 2003. Defence R&D Canada – Atlantic SL 2003-026. 11 pages.
5. C. G. Cameron, R. S. Underhill, M. Rawji, and J. P. Szabo, "Conductive filler - elastomer composites for maxwell stress actuator applications," *Proceedings of SPIE Smart Structures and Materials 2004: Electroactive Polymer Actuators and Devices* , 2004. Defence R&D Canada – Atlantic SL 2004-035. 9 pages.
6. R. S. Underhill, I. A. Keough, and C. G. Cameron, "Electrical and mechanical property evaluation of high dielectric polymers for actuators," *Proceedings of 10th CF/DRDC Meeting on Naval Applications of Materials Technology, Halifax, 13-15 May 2003* , pp. 198–209, 2003. Defence R&D Canada – Atlantic SL 2003-130.
7. C. Cameron, R. Underhill, and J. Szabo, "High field assessment of actuator candidate materials," *Proceedings of 10th CF/DRDC Meeting on Naval Applications of Materials Technology, Halifax, 13-15 May 2003* , pp. 229–241, 2003. Defence R&D Canada – Atlantic SL 2003-135.
8. W. Ren, G. Yang, B. Mukherjee, and J. P. Szabo, "An interferometric measurement of the transverse strain response of electroactive polymers," *Proceedings of SPIE Smart Structures and Materials 2004: Electroactive Polymer Actuators and Devices* , 2004. Defence R&D Canada – Atlantic SL 2004-030. 11 pages.
9. W. Ren, B. Mukherjee, and J. P. Szabo, "The transverse strain response of electroactive polymers measured using a laser doppler interferometer," *Proceedings of the 6th CanSmart Meeting - International Workshop on Smart Materials and Structures, editor George Akhras* , pp. 331 – 342, 2003. CanSmart Group, Kingston ON Canada, 2003. Defence R&D Canada – Atlantic 2003-120.
10. G. Yang, G. Yao, W. Ren, G. Akhras, J. Szabo, and B. Mukherjee, "Strain response of silicone dielectric elastomer actuators," *Structures and Materials 2005: Electroactive Polymer Actuators and Devices (EAPAD), Yoseph Bar-Cohen, Editor, Proceedings of SPIE Vol. 5759* , 2004. Defence R&D Canada - Atlantic SL 2004-189.
11. G. Kofod, R. D. Kornbluh, R. Pelrine, and P. SommerLarsen, "Actuation response of polyacrylate dielectric elastomers 4329-19," *Proceedings- SPIE the International Society for Optical Engineering* **4329**, pp. 141–147, 2001.
12. R. Pelrine, R. Kornbluh, and J. Joseph, "High-speed electrically actuated elastomers with strain greater than 100pp. 836–839, 2000.
13. X. Zhang, M. Wissler, B. Jaehne, R. Broennimann, and G. Kovacs, "Effect of crosslinking, prestrain, and dielectric filler on the electromechanical response of a new silicone and comparison with acrylic elastomer," *Proceedings- SPIE the International Society for Optical Engineering* **5385**, pp. 78–86, 2004.
14. R. S. Underhill, C. G. Cameron, P. Sargent, J. Murphy, G. C. Fisher, and J. P. Szabo, "The effect of conductive fillers on the actuation behaviour of dielectric actuators," *Proceedings of the 6th CanSmart Meeting - International Workshop on Smart Materials and Structures, editor George Akhras* , pp. 353–362, 2003. CanSmart Group, Kingston ON Canada, 2003. Defence R&D Canada – Atlantic 2003-187.
15. S. Morrison and J. Szabo, "Modelling the dynamic response of maxwell stress actuators," *Proceedings of 10th CF/DRDC Meeting on Naval Applications of Materials Technology, Halifax, 13-15 May 2003* , pp. 242–253, 2003. Defence R&D Canada – Atlantic SL 2003-133.

16. L. Jiang, M. Polack, and M. Chernuka, "Improvement of the vibration isolation system model generation and visualization code - vimgen," Contractor Report 2003-021, Defence R&D Canada - Atlantic, 2003. 91 pages.
17. O. Beslin, C. J. Purcell, and J. P. Szabo, "Modeling of dielectric polymer actuators (dpa)," *Proceedings of 2nd Canada-US CanSmart Workshop on Smart Materials and Structures, Montreal, October 10-11* , 2002. Defence R&D Canada – Atlantic SL 2002-150.
18. O. Beslin, "Analytical modeling of dielectric polymer actuators," Contractor Report 2002-160, Defence R&D Canada - Atlantic, 2002. 47 pages.
19. L. Jiang, "Finite element modelling of dielectric polymer actuators," Contractor Report 2004-201, Defence R&D Canada - Atlantic, 2004. 132 pages.
20. G. Yang, W. Ren, B. Mukherjee, G. Yao, G. Akhras, and J. P. Szabo, "Transverse strain response of dielectric elastomer actuators," *11th CF/DRDC International Meeting on Naval Applications of Materials Technology, Halifax, 7-9 June 2005* , 2005. Defence R&D Canada - Atlantic SL 2005-103.