

Electro-Active Polymer (EAP) actuators for planetary applications

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ABSTRACT

NASA is seeking to reduce the mass, size, consumed power, and cost of the instrumentation used in its future missions. An important element of many instruments and devices is the actuation mechanism and electroactive polymers (EAP) are offering an effective alternative to current actuators. In this study, two families of EAP materials were investigated, including bending ionomers and longitudinal electrostatically driven elastomers. These materials were demonstrated to effectively actuate manipulation devices and their performance is being enhanced in this on-going study. The recent observations are reported in this paper, include the operation of the bending-EAP at conditions that exceed the harsh environment on Mars, and identify the obstacles that its properties and characteristics are posing to using them as actuators. Analysis of the electrical characteristics of the ionomer EAP showed that it is a current driven material rather than voltage driven and the conductivity distribution on the surface of the material greatly influences the bending performance. An accurate equivalent circuit modeling of the ionomer EAP performance is essential for the design of effective drive electronics. The ionomer main limitations are the fact that it needs to be moist continuously and the process of electrolysis that takes place during activation. An effective coating technique using a sprayed polymer was developed extending its operation in air from a few minutes to about four months. The coating technique effectively forms the equivalent of a skin to protect the moisture content of the ionomer. In parallel to the development of the bending EAP, the development of computer control of actuated longitudinal EAP has been pursued. An EAP driven miniature robotic arm was constructed and it is controlled by a MATLAB code to drop and lift the arm and close and open EAP fingers of a 4-finger gripper.

Keywords: Miniature Robotics, Electroactive Polymers, Electroactive Actuators, EAP Materials

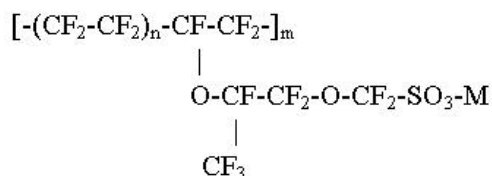
1. INTRODUCTION

NASA missions are faced with growing constraints on mass, power, volume and cost with the need to perform increasing number of tasks and experiments. Inexpensive, compact, low-mass, miser actuators can be used to effectively address these constraints. Examples of space mechanisms and devices that require actuators include robotic arms, miniature rovers, release mechanisms, and positioning devices. Actuation materials are finding increasing use to drive mechanisms, where electroceramics (EAC) and shape memory alloys (SMAs) are the leading alternatives. Examples include the use of electrostrictive actuators for the correction of the aberrations on the Hubble Telescope using the WF/PC II module. EAC offer effective, compact, actuation materials and they are incorporated into such mechanisms as ultrasonic motors, inchworms, translators and manipulators. In contrast to electroceramics, electroactive polymers (EAP) are emerging as new actuation materials [Furukawa and Wen, 1984] with displacement capabilities that cannot be matched by the striction-limited and rigid ceramics. A comparison between EAP, EAC and SMA shows that EAP are lighter and their striction level capability can be as high as two orders of magnitude more than EAC [Bar-Cohen, et al, 1998]. The mass producibility of polymers and the fact that EAPs do not require poling (in contrast to piezoelectric materials) can help producing them at low cost. EAPs can be easily formed in various shapes and can be used to fabricate micro-electro-mechanical systems (MEMS), including both actuators and sensors. EAP materials can be designed to produce actuators [Hunter and Lafontaine, 1992; Shahinpoor, 1994; and Kornbluh, et al, 1995] that in the future may emulate the operation of biological muscles having unique characteristics of high toughness, large actuation strain constant and inherent vibration damping. Further, their response speed is significantly higher than Shape Memory Alloys and their fatigue characteristics is superior to SMAs, which have fatigue life limit of about 1-Kcycles when actuated at displacement strain of about 8%. The authors' current study is directed towards developing effective EAP materials and taking advantage of polymers' resilience and the ability to engineer their properties. Overall, applications of these materials are helping to change the paradigms of design and construction of robotic manipulators where such active materials can substitute conventional sensing and actuation components such as motors, gears, bearings, screws, etc.

The development and application of EAP actuators requires an enhanced infrastructure and involves multidisciplinary expertise in materials science, chemistry, mechanics, electronics, and robotics. The authors identified two categories of electroactive polymers that induce large actuation strains. These categories are (a) bending actuators: ion exchange membrane metal composites, so-called ionomers; and (b) longitudinal actuators: electrostatically activated EAP. These two EAP categories offer the capability to bend or stretch/extend, which essentially could emulate the operation of biological muscles and limbs. In parallel to the development of the material, efforts are made to identify robotic and planetary applications and demonstrate the capability of EAP actuators. A series of mechanisms that include actuators of robotic arm components (lifter and gripper), dust wiper and a rake were developed. Current efforts are concentrated on determining the constraints and limitations of the EAP materials and the requirements to assure their reliable operation in space conditions of low temperatures and vacuum. In parallel, studies are taking place to determine the capability to control and obtain feedback using EAP actuators in order to produce miniature robotic devices with servo-control capability.

2. IONOMERS AS BENDING EAP ACTUATORS

The bending EAP actuator is composed of perfluorinated ion exchange membrane metal composite (IPMC), where metallic electrodes are deposited on the surface in a depth of tenth of microns from both sides. These materials have been used as fuel cells and production of hydrogen (hydrolysis) for many years and their operation as actuators is the reverse process of the charge storage mechanism. In this reported research, the authors used platinum as the metallic electrodes. However, other researchers reported a great success using such metals as gold [Yoshiko, et al, 1998]. Further, in this study the cationic base has been sodium (Na^+) but the authors are well aware of the fact that using lithium (Li^+) as cations can result in greater displacement and force density per volt. In a separate study, a cooperation with the Osaka National Research Institute, Japan, effort is underway to employ gold-coated lithium cation type bending EAP. In this reported study IPMC films with platinum electrodes and sodium ions were used. Once the Nafion® sheet is loaded in its boundary surface with the metal electrodes, it is cut to strips that are 25.0x3.5-mm in size and weighing 0.1-g. The reported IPMC actuator is based on a processed Nafion® film, mostly #117 (Dupont product), which in its processed form has a thickness of 0.18-mm and it has the following chemical formula,



where $n \sim 6.5$, $100 < m < 1000$, and M^+ is the counter ion (H^+ , Li^+ or Na^+). These polymers consist of hydrophobic (fluorocarbon backbone, semi-crystalline) and hydrophilic ($-\text{SO}_3^- \text{H}^+$) regions. The proton can be exchanged for other mobile cations (counter-ions) such as Li^+ or Na^+ . Nafion® has the ability to absorb a considerable amount of water, which increases the cation's mobility and therefore electrical conductivity. These cations appear to migrate through hydrophilic channels on the order of 5nm in diameter [Abe, et al, 1998]. Nafion® is a perfluorosulfonate ionomer membrane and its structure and properties have been the subject of numerous investigations (see for example [Heitner-Wirguin, 1996]). Also, Nafion® was studied for it numerous other applications including fuel cells [Holze & Ahn, 1992], water electrolyzers [Yamamoto, et al, 1991] and reaction catalysts [Xie & Okada, 1996], provides a large knowledge base for understanding its behavior. One of the interesting properties of this material is its ability to absorb large amounts of polar solvents, i.e. water. In order to chemically electrode the Nafion®, metal ions are dispersed throughout the hydrophilic regions of the polymer, and are subsequently reduced to the corresponding zero valent metal atoms. This results-in the formation of a dendritic type electrodes. Scanning electron micrographic tests show [Bar-Cohen, et al, 1998, and Kim, et al, 1998] that the metal covers each surface of the film with some of the metal penetrating the subsurface regions of the material (see Figure 1). When equilibrated with aqueous solutions the ionomer membrane is swollen to absorb certain amount of water. Swelling equilibrium results from the balance between the elastic forces of the polymeric matrix and the water affinity to the fixed ion-exchanging sites and the moving counter ions. The water content depends on the hydrophilic properties of the ionic species inside the membrane and also on the electrolyte concentration of the external solution. Issues associated with the ion species and the effect of the content on the bending behavior has been discussed in a recent study by [Yoshihiko, et al, 1998]

When exposed to water, in addition to homogenous swelling of the Nafion® membrane, hydrated samples with platinum electrodes bend under application of small voltages [Asaka, et al, 1995]. Expansion of the membrane occurs

along the cathode and contraction at the anode. The deflection is complicated (see Figure 2) by the resistive nature of the porous platinum electrodes and most of the bending occurs near the electrical leads. Controlling the response is further complicated by a relaxation of the sample back to its original position when a DC voltage is applied for >30 s. Small deflections can be achieved at voltages below the level that is necessary for electrolysis of water to take place. However for full bending to occur it is necessary to increase the voltage to values (>3 V) exceeding that necessary for electrolysis. The general behavior of current as a function of time is shown in Figure 3.

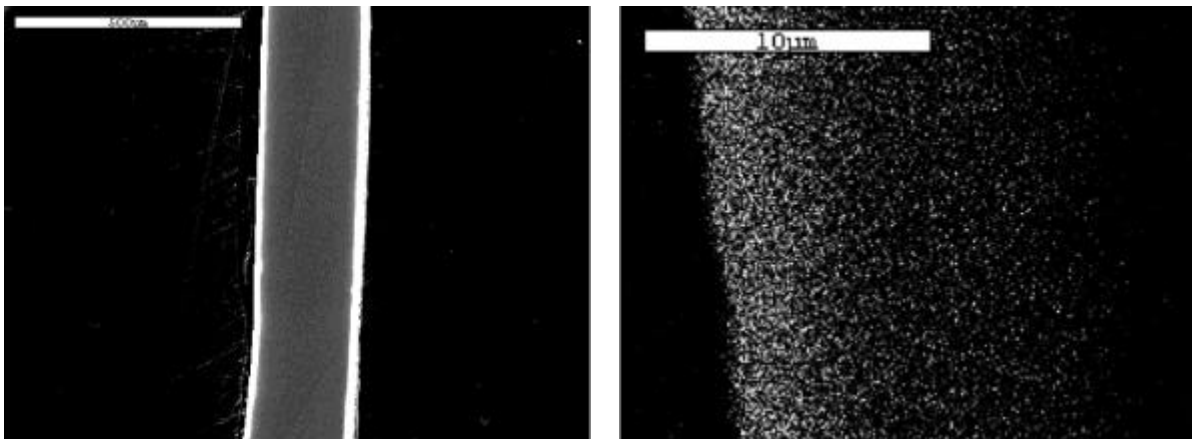


Figure 1: An SEM photograph of a platinum deposited Nafion@-117 strip (left) and a cross sectional Pt X-ray Map (right)

The mechanism for electrical actuation is considered to be due to electro-osmotic pressure [Helfferich, 1995, and Zawodzinski, 1993]. When a voltage is applied to a normal electrolyte, cations and anions migrate in opposite directions with there being no net momentum transferred to the solvent. No solvent is transported except that contained in the solvation shells. However, in ion exchange membranes the solvent can be carried by both ion-dipole interaction and momentum transfer. In Nafion@ the $-\text{SO}_3^-$ group is fixed to the matrix while the counter-ion (cation) is free to move. When voltage is applied to the hydrated sample, the counter-ion will migrate to the cathode and simultaneously push water to this side. Swelling/expansion at the cathode results. A concentration gradient in water will be induced and back-diffusion may be responsible for the observed relaxation of the membrane [Okada, 1998]. Okada et al [Deng, 1992] has measured the water transference coefficient for a variety of cations in Nafion@. Correlation of these values with bending response has been observed [Helfferich, 1995].

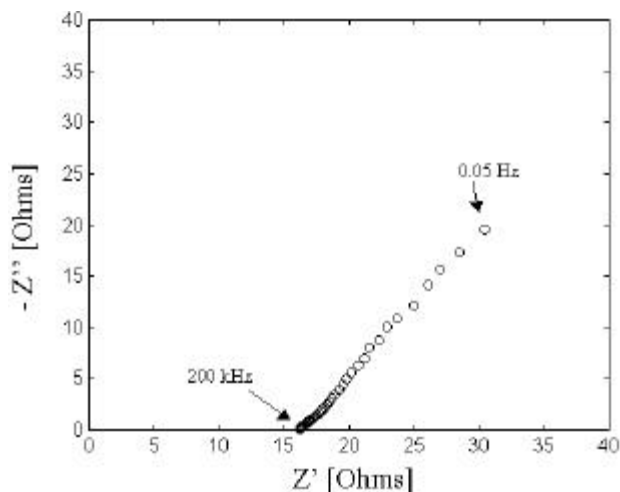


Figure 2: The real Z' and imaginary Z'' impedances of a Nafion sample (40mm length; 6mm wide; 2mm thick) with Na^+ as the counter-ion submerged in distilled water. The applied voltage was 3.0 V from 0.05Hz to 200 kHz with 10 steps per decade. The slope is near -1 , indicating that the dielectric response is governed by diffusional or Warburg [Helfferich, 1995] effects.

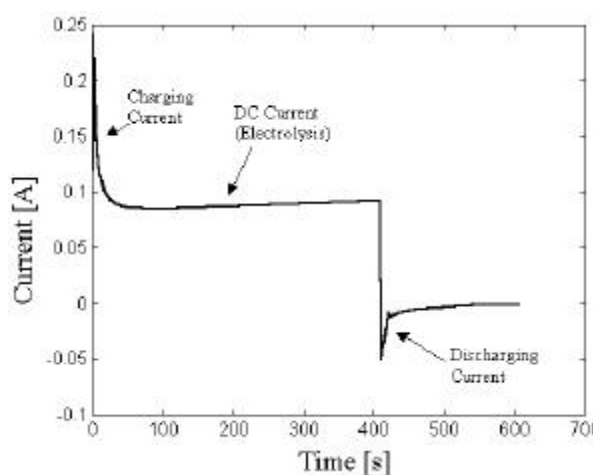


Figure 3: The current response to a step voltage on Nafion Na^+ sample in distilled water. The sampling frequency was 0.5Hz and initially 4 V was applied. The charging current is reduced to a DC value of about 100mA. An electrolytic reaction (hydrolysis) occurs and gas is evolved at the platinum electrodes. The applied voltage is then reduced to zero and the discharging current rapidly goes to zero.

To maintain the actuation capability of IPMC, the material needs to be kept moist continuously providing the media that is necessary for ion mobility that are responsible for the actuation. Without coating the material can work in air for less than 5 minutes, whereas a recent coating, which was introduced at NASA-LaRC, allowed operating the actuator for about 4 months. The required drive voltage was found to range from 1 to 5-volts at room temperature and the voltage was kept as low as possible to avoid the side effect of electrolysis during activation. A test of the fatigue durability of the IPMC has shown that when immersed in water and exposed to 2-V and 1-Hz it would continuously bend without degradation for over a million cycles. Using a coating polymer that was sprayed on sample films they continued to bend upon electroactivation after about 4 months. A concern was raised that the surface uniformity of the coating may be responsible for the loss of performance and a better coating technique is needed. Due to the fluorinated structure of the base Nafion® film, the application and adhesion of a coating to the IPMC is rather difficult. The perfluorinated backbone, the Nafion® film has characteristics similar to that of Teflon® (PTFE) in which adhesion to the surface is negligible. Attempts to coat the IPMC without a surface treatment resulted in coating that was easily removed. To improve adhesion to the IPMC, a chemical etchant (Tetra-etch®) was employed. Initially, the etchant works by removing the fluorine atoms from the surface chains leaving the carbon atoms in the polymer backbone temporarily electron deficient. Then, the etched surface is exposed to moist air, which results in the formation of a monolayer functionalized polymer backbone containing e.g. hydroxyl, carbonyl, and carboxyl groups, and therefore enabling adhesion. Tests of the performance of an etched IPMC did not show any noticeable loss in actuation response. A low modulus polysilicon coating (Dow Corning Dispersion Coating) was applied to the surface of the etched IPMC electrode and it exhibited improved adhesion as compared to the untreated IPMC. This coating material is resistive to ozone, chemicals, moisture, ice and ultraviolet radiation and can operate up to 260°C while maintaining its performance and integrity. Comparison of peel tests with and without coating show four times improved adherence.

When an external voltage is applied on an IPMC film, it causes bending towards the anode at a level that increases with the voltage. The displacement actuation reaches saturation as the voltage rises (see Figure 4). Under an AC voltage, the film undergoes swinging movement and the displacement level depends not only on the voltage magnitude but also on the frequency. Generally, activation at lower frequencies (down to 0.1 or 0.01 Hz) induces higher displacement and it reaches saturation as the voltage increases. The movement of the actuator is controlled by the applied electrical source but it is strongly affected by the water content that serves as an ion transport medium. The ionomer respond to the drive voltage and can be moved left or right depending on the voltage polarity. Recent tests of the performance of the ionomers at low temperatures showed that while the response decreases with temperature, a sizeable displacement was still observed at the temperature of -140°C. This displacement decrease can be compensated by increasing the voltage and it is interesting to point out that, at low temperatures, the response reaches saturation at much higher voltage levels. The deflection level and the consumed power for the ionomer films was tested at both room temperature and -100°C and the results are shown in Figures 4 and 5. Tests of the current as a function of voltage response indicate that the resistance rises with the decrease in temperature, which is in contrast to the behavior of metals and conductive materials.

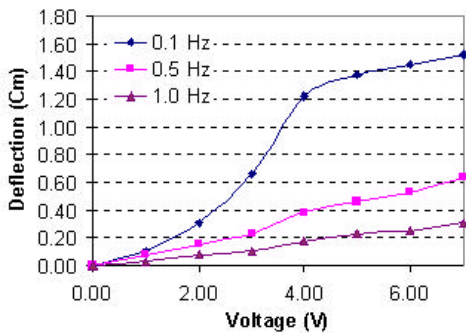


Figure 4: The response of ionomer to various voltage amplitudes at three different frequencies.

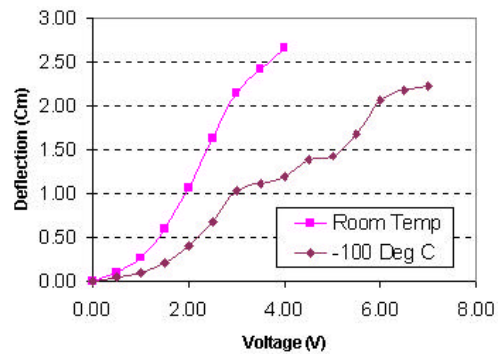


Figure 5: Deflection of the bending ionomer as function of voltage as a function of temperature.

Using square wave drive voltages of 1-V and 2-V the curves of the transient I vs. V were determined as shown in Figure 6a and 6b, respectively. The electric current can be seen in Figure 6 to rise simultaneously with the voltage until reaching the maximum level and at the steady state level of the voltage, the current drops to a small value.

Further, at the decay stage of the voltage drive the voltage returns to zero and a reversal of the current flow is observed. This behavior indicated the characteristics of a charged capacitor, where the ionomer is charged during the voltage rise time and discharge at the stage of the voltage signal decay time. The decay and rise times of the electric current are lasting several seconds. When activated by the 1-V signal, the charging and discharging currents are shown to have

about the same magnitude, with no obvious degradation of the peak current with time. Since the current reaches steady state in several seconds, the ionomer is expected to respond reasonably fast to electro-activation. For a 2-Volt signal, the cycle is seen to have a charging current that is greater than the discharging current. At the rise time stage, the peak current drops to its static value much slower and is showing a larger time constant than the lower voltage case. This behavior indicates that the consumed power is mostly at the rise time stage of activation and if the actuator is held at steady state no power is consumed. Further, upon release of the activation voltage the released power, which is not used for the actuation or heat losses, may be available for reuse. A semi-log plot of the current vs. time does not show a linear relationship with time. This indicates that the ionomer can not be reasonably modeled by using a simple discrete RC circuit. Compared with the semi-circular behavior of the discrete RCs, the complex characteristics of this diagram indicates the need for a distributed parameteric model [Macdonald, 1987]. When the individual ionomer film becomes dried, it was observed that the impedance level rises to level of 8000- Ω and there is virtually no noticeable movement. This change in impedance can provide indication to the wetness status of the ionomer as well as may offer the potential to serve as a sensor for wetness or possibility humidity. Various approaches have been tested to protect the ionomer effectively and to form the equivalent of skin. It is found that an ionomer actuator with a thicker platinum electroding maintains cyclic movement over several hours as opposed to a fraction of an hour for the unprotected ionomer.

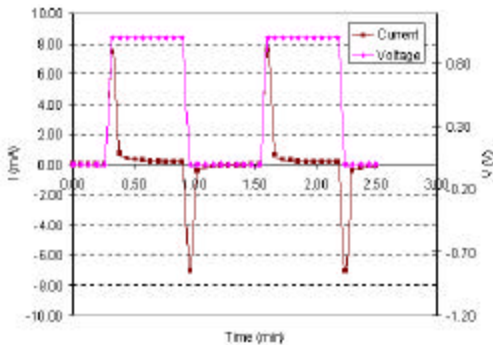


Figure 6a: Current as function of time response to I-V square wave activation.

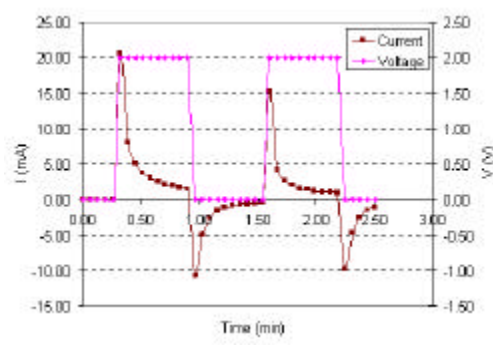


Figure 6b: The effect of increasing the activation voltage of the square wave to 2-Volts.

3. CONCLUSION

Two types of EAP actuators were studied to obtain a large displacement actuation. While the material performance is being enhanced, methods of controlling the actuation performance are being investigated. IPMC are offering a large bending actuation and allow emulating the dexterity of human hand using lightweight material that consumes low power and are inexpensive to produce. For longitudinal displacement actuation, electrostatically activated films were scrolled to form ropes and to serve equivalently to biological muscles. These electroactive polymers are showing a superior actuation displacement, mass, cost, power consumption and fatigue characteristics over conventional electromagnetic, EACs and SMAs. While the force actuation capability of EAPs is limited, their actuation displacement levels are unmatched. Currently, the practical application of IPMCs is constrained by the need to maintain the ionic constituents and preventing the films from drying. The equivalent of producing a biological skin is being investigated to protect the ion content of IPMC films. Encapsulation techniques are also being investigated to preserve the moisture containment and so far success was observed when using thicker platinum electrodes and voltage levels below 2-volts.

4. ACKNOWLEDGEMENT

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