

Characterization of bending EAP beams

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ABSTRACT

Electroactive polymers (EAP) are attractive actuation materials because of their large deformation, flexibility, and lightweight. The large deformation, especially in the bending mode, poses a challenge to the material and actuator characterization due to the geometric nonlinearity that is involved with the characterization. A CCD camera system was constructed to record the curved shapes of bending during the activation of EAP films and image-processing software was developed to digitize the bending curves. A computer program was developed to solve the inverse problem of cantilever EAP beams with tip position limiter. Using the developed program and acquired curves with and without tip position limiter as well as the corresponding tip force, the EAP material properties of voltage-strain sensitivity and Young's modulus were determined. The experimental setup and the principles of the computer program that were developed are described and discussed in this paper.

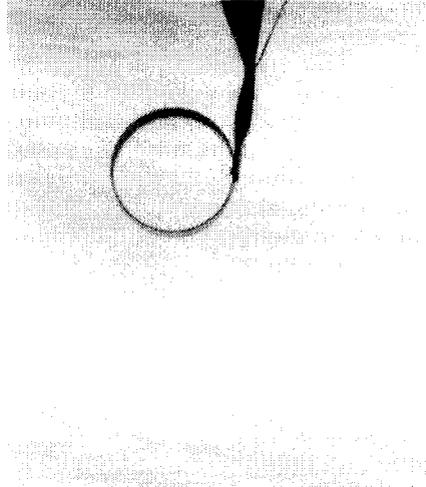
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1. INTRODUCTION

Electroactive polymers (EAP), which are an emerging class of actuation materials [Bar-Cohen, 2001], have many attractive characteristics such as large deformation, flexibility, and lightweight etc. EAP can be divided into two major categories, including ionic and electric-field, based on activation mechanisms. The ionic EAPs are materials that involve mobility or diffusion of ions and they consist of two electrodes and electrolyte [Onishi, et al, 2000; and Nemat-Nasser, et al, 2001]. The activation of the ionic EAP can be made by as low as 1-2 Volts and generally induce a bending displacement. Examples of ionic EAP include gels, ionomeric polymer-metal composites, conductive polymers, etc. Their disadvantages include a need to maintain wetness and difficulties to sustain a constant displacement under activation of a DC voltage (except for conductive polymers). The electric-field EAP include electrostrictive, electrostatic, piezoelectric, ferroelectric etc [Cheng, et al, 2001; and Zhang, et al, 2002]. This type of EAP materials can be made to hold the induced displacement while activated under a DC voltage, allowing them to be considered for robotic applications. Generally, these EAP materials exhibit a greater mechanical energy density than the ionic EAP and they can be operated in air with no major constraints. However, the electronic EAP require high activation fields (50-150 V/ μm).

The unique properties of the EAP attracted researchers and engineers to design EAP actuators. Bending beams are the most popular form of the EAP actuators. The nature deformation of ionic EAP such as IPMC is bending. Actually, the material was characterized by evaluating its bending behavior [Bao, et al, 2002; and Bar-Cohen, et al, 2002]. The nature deformation of the electric-field materials is extension or contraction. By using unimorph or bimorph construction, the displacement of the actuator can be greatly enlarged [Costen, et al, 2001]. Figure 1 shows an example of electric-field EAP unimorph. This originally straight beam bent to a circle under applied voltage. The tip of the beam, where the load is usually located, moved along a curved line. The large deformation results into a geometric nonlinearity that requires special treatment for performance characterization. The related issues are analyzed and discussed. The discussion is limited in static or quasi-static performance characterization. The free bending curvature and stall tip force were chosen as two major characteristic parameters for cantilever-beam actuators. The methods and techniques for the parameter measuring are presented. Formulas and algorithms were developed to predict the performances of the actuators according to the measured characteristic parameters. Characterization results of EAP actuator samples and estimation of the properties of the EAP material are presented in this paper as well.

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2. PRINCIPLE OF CHARACTERIZATION

Cantilever beam is one of most popular structures of bending actuators. The unimorph or bimorph actuators made of EAP film show impressive large bending deformation. An example is shown in Fig. 1. This originally straight beam bent to a circle under applied voltage. The large deformation results into a geometric nonlinearity that needs to be dealt with in performance characterization.

Generally, the capability of deformation of actuators can be characterized by the displacement without load (free displacement) and the capability of deliverable force by the output force with zero displacement (stall force). For the linear actuation, the performance with limited force and displacement can be predicted easily according to linear relationship.

First, consider the case of free bending under DC voltage. Suppose a DC voltage is applied to the electrodes of a cantilever beam of bending rigidity R . If the beam is uniform in structure, the voltage will create a uniform moment of m_e in the beam. We have the formula for the deformed curvature as

$$k_e = \frac{m_e}{R}. \quad (1)$$

In this case, the curvature is constant over the length and the shape of the bended beam will confirm a circle. Optical image acquisition technology can be used to obtain the data of the beam shape and the averaged curvatures under different applied voltages can be determined by least-square curve fitting method.

Another important character of the cantilever beam actuators is the actuation force. The force can be measured directly by a force sensor. Generally, the force sensor is put at the tip of the beam and constrained the tip displacement. The measured force is so called stall force. However, unlike the actuation of linear extension or contraction, it is not easy to predict the actuation force with a certain displacement by knowing the stall force and the free deformation of the beam actuator due to the geometric nonlinearity. The bending rigidity is a

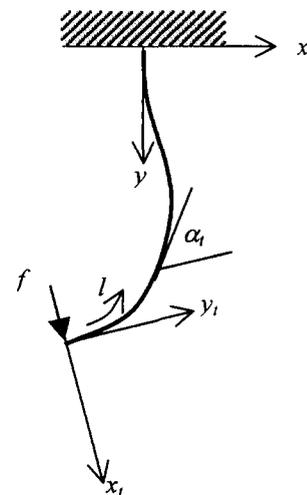


Fig. 2 Beam with tip normal force

more fundamental parameter of the beam that related to the capacity of output force. An analytical model was developed to the actuation force with displacement when the rigidity is known. The model is also used to find the bending rigidity of the beam from the stall force measurement

Consider the case of the cantilever beam with a normal tip force as shown in Fig. 2. There are two external forces applied to the beam, an electrically introduced moment m_e and the tip force f . It is not easy to resolve the beam shape in the ordinary x - y coordinate because the direction of the tip force is varied with the beam shape. The problem can be solved in an alternative coordinate, x_t - y_t , that locates at the tip and takes the force direction as x_t direction. We have a set of integral equations as

$$k(l) = \frac{f}{R} y_t(l) + k_e, \quad (2)$$

$$\alpha_t(l) = \int k(l) dl, \quad (3)$$

$$y_t(l) = \int \cos[\alpha(l)] dl, \quad (4)$$

$$x_t(l) = \int \sin[\alpha(l)] dl, \quad (5)$$

with boundary conditions of

$$\alpha(0) = 0, y_t(0) = 0, \text{ and } x_t(0) = 0, \quad (6)$$

where the l is the length along the beam curve from the tip, k the curvature, and α_t is the angle referred to y_t . The integrals can be calculated numerically. Then, using the coordinate transformation formulas of

$$x = [x_t(L) - x_t(L)] \cos[\alpha_t(L)] - [y_t(L) - y_t(L)] \sin[\alpha_t(L)], \quad (7)$$

$$y = [x_t(L) - x_t(L)] \sin[\alpha_t(L)] + [y_t(L) - y_t(L)] \cos([\alpha_t(L)], \quad (8)$$

to convert the beam curve to x - y coordinate, where L is the length of the beam. The root clamping constrain condition of $\alpha = 0$ at $(x, y) = (0, 0)$ is satisfied automatically.

Actually, the curve in x_t - y_t coordinate is only dependent to k_e and f/R , but the beam length. We can truncate the curve to any length to obtain the beam shape for the beam with that length.

The rigidity of the beam can be determined from the measured stall tip force and the free bending curvature with the help of this developed model. We calculate the beam shapes for different f/R and find the right value that led to a result fit the beam shape in the stall tip force measurement. It should be noticed that, in the measurement, the force sensor contacted and stopped the movement at the point of $(0, Y)$. As shown in the Fig. X, the total length of the effective beam was longer than the distance from the clamped point to the contact point and was varied with the degree of the bending. Instead truncating the beam at fix length, we truncate the beam at the fixed distance in y direction and check the position of contact point in x - y coordinate until the error of x less than a pre-set value. The rigidity is calculated as

$$R = \frac{f_m}{(f/R) \cos[\alpha_t(L)]}, \quad (9)$$

where the f_m is the measured force, which is in the horizontal direction. The effect of the friction force between the force sensor and the beam is assumed neglectable.

3. TEST SETUP

Since EAP is soft, in order to minimize measurement errors, any characterization method that is being considered needs to be of a non-contact type or the effects of mechanical impedance of the probe must be known. An Image

Acquisition and Processing System was developed to allow measurements from EAP beams that are subjected to various load and voltage levels. The image acquisition consists of a digital CCD camera MegaPlus model ES-310 (Redlake MASD, Inc.) with an image acquisition board model NI PCI-1422 (National Instruments Corp.) An LabView software controls the hardware. The data acquisition was constructed with a rate of up to 125 frames of 640x480 pixels per second. The image-processing program written in Matlab tracks the shapes of EAP beams from the recorded images. The processing involves the use of a best-fit edge detection algorithm that enabled more accurate curve description.

4. EXAMPLES OF BENDING ACTUATOR CHARACTERIZATIO

The samples of EAP bending beam actuators are made of electron irradiated P(VDF-TrFE) copolymer (stretched). The modulus is about 1 GPa (at 1 Hz) and the density is about 1.8 g/cc. Each sample consists of two or three polymer layers as shown in Table 1. One of the layers is inactive i.e. without electrode.

Table 1. Dimension and parameters of samples

Sample	T (Micron)	W (mm)	L (mm)	C (nF)	D	ϵ	Tp (Micron)
S1	20	3	30	1.54	0.048	38.7	20
	18	3	30	1.75	0.046	39.5	
2B	26	3	30	0.79	0.066	25.8	20
	26	3	30	0.85	0.06	27.7	
2S	23	5	30	2.34	0.044	40.5	23

Where the T, W and L is the thickness, width and length of the active layer respectively, the C, D and capacitance and loss factor of the active layers, ϵ is calculated dielectric constant, and Tp is the thickness of the passive (inactive) layer.

2. Free bending curvature measurement

The free bending curvature measurement was conducted in the Image Acquisition and Processing System [Bar-Cohen and Leary, 2000]. The actuator samples were clamped at the root of the beam. The active length of the beam is around 30mm. The images of the beam were taken under different applied voltage as shown in Fig. 1. The edges of the beam were extracted and fitted by circle as shown in Fig. 3. The bending curvature of the beam was calculated as one over the radius of the circle.

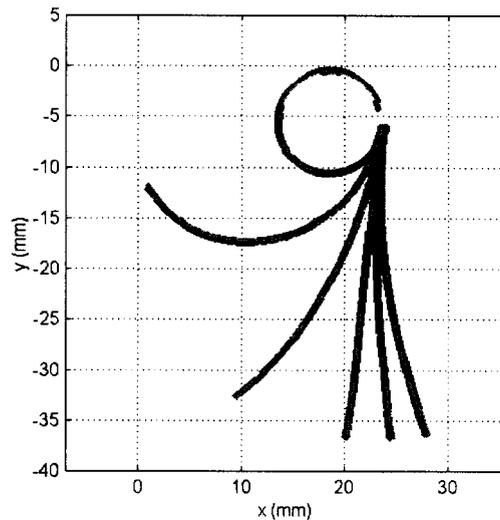


Fig. 1: Circle fitting for sample S1 under 0, 240, 340, 500, 700 and 1000 V. The dark shows the edge of the beam and the gray is the fitted circle.

The bending curvatures were found being proportional to the V^2 in general as predicted (see Fig. 3).

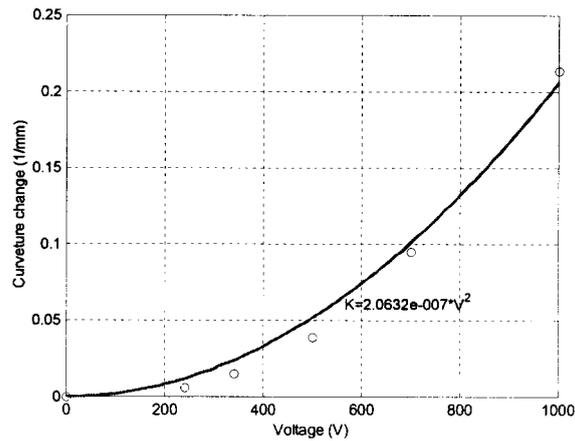


Fig. 3 Curvature change of the sample S1 by applied voltage

2. Stall tip force measurement

The stall tip force was measured by a load cell. The sensitivity of the load cell is 0.5 V/gram-f. The beam was clamped at the position 10.7 mm above the tip of the load cell as shown in Fig. 4. With applied voltage, the beam intended to bend in vertical plan. The force was also found being proportional to V^2 in general (see Fig. 5).

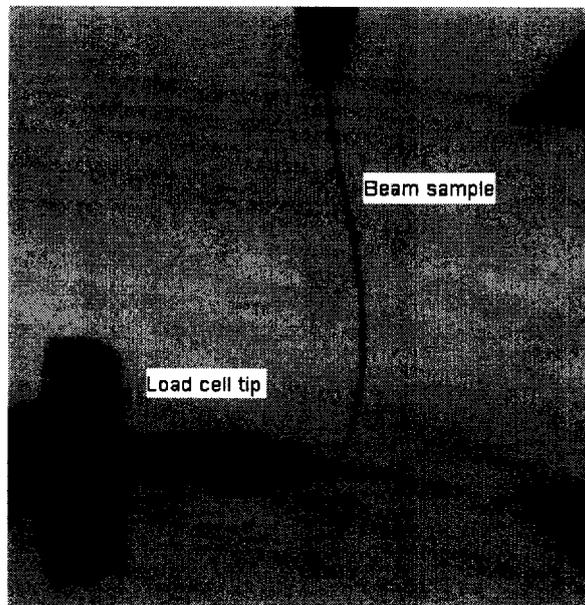


Fig. 2: Stall tip force measurement, S1 under 1000 V

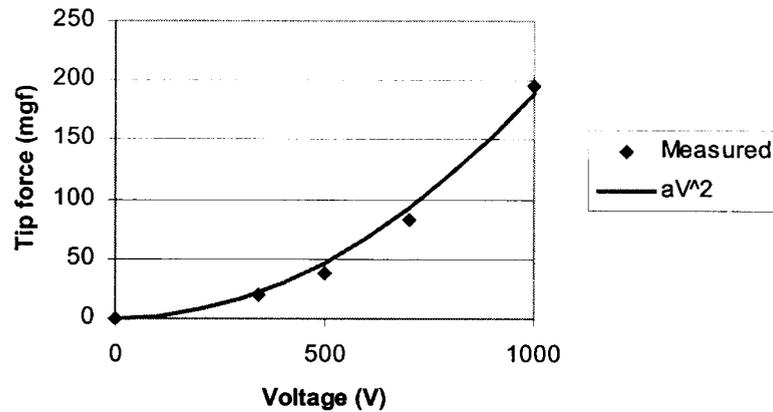


Fig. 3: Stall tip force of sample S1 with 10 mm long

3. Bending rigidity calculation

A computer program was developed to calculate the shape of a pre-bended cantilever beam with a tip force. The pre-bended curvature was determined by the free bending measurement. We found the rigidity R by adjusting it until the position of the contact point of the load cell and the beam in agree with the experiment. An example of the calculated result is shown in Fig. 6.

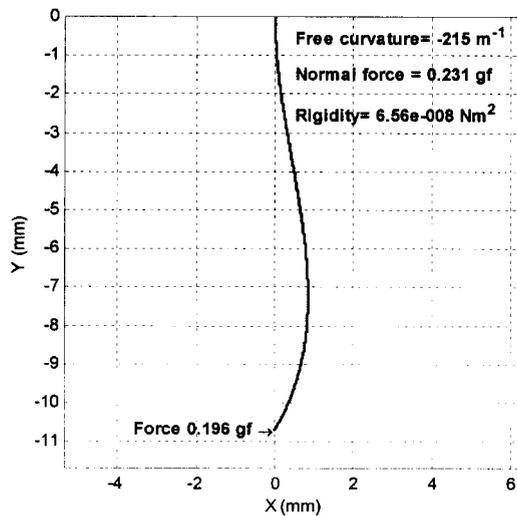


Fig. 4: Calculated result of the sample S1 under 1000 V in tip force measurement

4. Material property estimation

The equivalent Young's modulus E_{eq} was estimated by simple beam theory from the data of the rigidity, total thickness and width, assuming the beam is made of a uniform material. The results for the three samples are summarized in Table2.

Table 2. Summary of the bending actuator performances and estimated active material properties

Sample	T_{total}	W	K @1KV	F@1KV	R	E_{eq}	ε_{@100V/μm}
	μm	mm	m ⁻¹	10 ⁻³ gf	Nm ²	10 ⁹ Pa	%
S1	63	3.9	215	196	6.56E-08	0.808	3.2
2B	79	4	67	136	14.3E-08	0.872	2.8
2S	50	6.95	140	100	5.05E-08	0.698	2.5

Where

T_{total} Total thickness of actuator

W Width of actuator

T_{act} Thickness of active polymer

K @1KV Free bending curvature under 1000 Volt

F@1KV Stall tip force of 10.75 mm long actuator under 1000 Volt

R Calculated bending rigidity of the beam according to the free bending curvature and stall tip force measured at 1000 Volt.

E_{eq} Equivalent Young's modulus estimated by the rigidity, the thickness and width of the actuator using simple beam theory

ε_{@100V/μm} The estimated strain of the active polymer under the electric field of 100V/μm, which is the maximum electric field that may be applied according to the sample provider.

The estimated strain of the active polymer under the electric field of 100V/μm, ε_{@100V/μm}, was calculated by simple beam theory. It is the strain without any load. The electric field of 100V/μm is the maximum electric field that may be applied to the material, according to the sample provider.

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