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LOW-FIELD AND HIGH-FIELD CHARACTERIZATION OF THUNDER ACTUATORS*

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Abstract. THUNDER (THin UNimorph DrivER) actuators are pre-stressed piezoelectric devices developed at NASA Langley Research Center (LaRC) that exhibit enhanced strain capabilities. As a result, they are of interest in a variety of aerospace applications. Characterization of their performance as a function of electric field, temperature and frequency is needed in order to optimize their operation. Towards that end, a number of THUNDER devices were obtained from FACE International Co. with a stainless steel substrate varying in thickness from 1 mil to 20 mils. The various devices were evaluated to determine low-field and high-field displacement as well as the polarization hysteresis loops. The thermal stability of these drivers was evaluated by two different methods. First, the samples were thermally cycled under electric field by systematically increasing the maximum temperature from 25°C to 200°C while the displacement was being measured. Second, the samples were isothermally aged at 0°C, 50°C, 100°C, and 150°C in air, and the isothermal decay of the displacement was measured at room temperature as a function of time.

Key words. piezoelectric, pre-stressed ceramic, hysteresis, temperature effect, isothermal aging

Subject classification. Materials

1. Introduction. This work describes the results of a characterization study of THin UNimorph-like DrivER (THUNDER) actuators to determine the effects of metal thickness on free displacement at both sub-switching and switching field levels. The actuators were supplied by FACE International, Norfolk, VA. Research on THUNDER has focused on qualitative displacement measurements using different loads, voltages, and frequencies for different geometries and boundary conditions [1-4]. Some applications targeted by NASA require additional studies into the effect of temperature on the material as well as high fields for a rectangular geometry and fixed-free boundary conditions. The lack of a reliable study on temperature effects coupled with a need by FACE International, which possesses a commercial license from NASA for THUNDER manufacturing, for the same information led to further studies of THUNDER. The ultimate goal is to gain an understanding of its performance over a range of voltages, frequencies, and temperatures.

2. Procedure. The THUNDER devices were fabricated from 0.008" thick PZT5a piezoelectric ceramic plates, supplied by CTS wireless. To produce the THUNDER actuators, the ceramic materials were coated on both surfaces with a solution of LaRC-SI polyimide (0.001" thickness) and stacked on top of a metal sheet. In this study, stainless steel (0.003" and 0.020") was used as the metal layer to determine the effect of metal thickness on actuator displacement. The stacked ceramic and metal layer were then autoclaved at 300°C to cure the LaRC-SI polyimide.

During cooling, the differences in thermal expansion between the ceramic and metal layer induced internal stresses within the THUNDER structure, which resulted in curvature along the length of the device (Figure 1).

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THUNDER performance is therefore controlled by two phenomena: a stress-bias due to mismatched coefficients of thermal expansion as well as moduli, and a restricted lateral motion or d_{31} -effect arising from geometry.

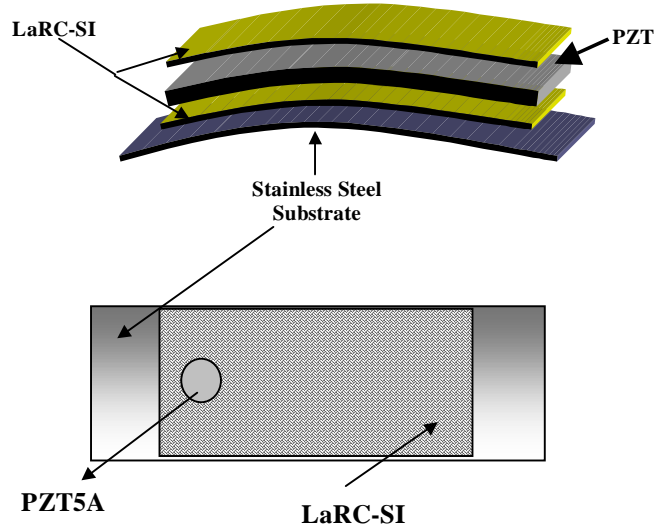


FIG. 1. THUNDER actuator lay-up.

Once fabricated, leads were soldered to the top and bottom surfaces of each THUNDER actuator. Table 1 lists the various cases considered for this study. We are adopting a convention used by Haertling and his group [5] where the metal thicknesses are displayed as thickness ratios (ratio of metal thickness to total device thickness).

TABLE 1.
Ceramic and metal thicknesses used.

PZT thickness (mils)	Steel thickness (mils)	Thickness ratio
8	3	0.230
8	4	0.286
8	5	0.333
8	6	0.375
8	8	0.444
8	20	0.667

The capacitance of each THUNDER actuator was then measured at 1 kHz using a Hewlett-Packard 4284A LCR meter and recorded. Next, the dome height was measured at the center of each THUNDER using a non-contact laser technique (NAIS micro Laser Sensor LM10). The sample was attached to a linear ball motion-bearing slide from one end only. Three different locations along the length of the device were measured for the highest point on each element and the results were averaged.

To ensure repeatability of the displacement measurements, a careful design of the boundary conditions was undertaken. The actuators were mounted into a test fixture designed to allow frictionless lateral translation of the THUNDER actuators while the other end was held constant (fixed-free boundary conditions). The mounting configuration is illustrated in Figure 2. This freedom for lateral movement ensured the least possible interference with sample movement while still holding the sample steady to record displacement data. The properties reported are averages of several samples for each of the test procedures below.

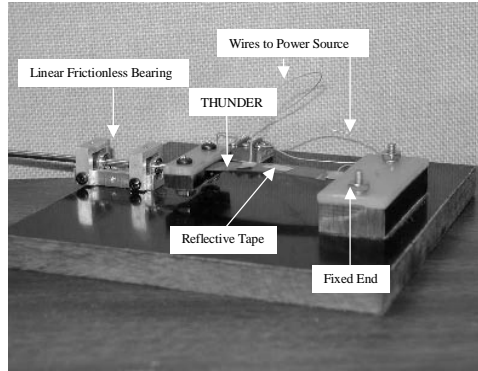


FIG. 2. Clamping configuration for THUNDER actuators tested.

2.1. Low-field to moderate-field displacement. Displacement measurements were performed using a non-contacting fiber optic sensor manufactured by Opto-Acoustic Sensors. An extended working range adapter was added to the tip of the fiber optic cable increasing the maximum measurable displacement to 0.12". Measurements were made from $\pm 2.5\text{V}/\text{mil}$ to $\pm 25\text{V}/\text{mil}$ at 1 Hz, 10 Hz, 100 Hz, 200 Hz, and 300 Hz. A reflective tape was placed on the top surface of the THUNDER device, which was clamped in the sample holder described above.

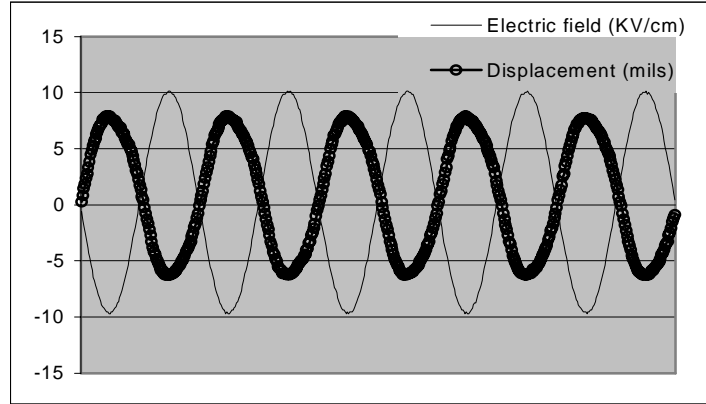
2.2. Temperature effects. To assess the effects of temperature on displacement, measurements were performed from room temperature to 200°C. When heating the samples, two Watlow 0.5" x 1.5" Kapton Flexible Heaters were used in parallel to heat the THUNDER samples between 25 and 200°C. An Omega CN4400 control and HP6024A DC power supply were used to control the temperature. The heaters were taped to the steel on the bottom of the sample while a K-type thermocouple was affixed to the ceramic on top to ensure uniform heating throughout. Wire leads were affixed to the samples using copper wire tape and, at high temperatures, Kapton tape was used to ensure a good connection. Isothermal aging was studied on selected steel thicknesses. Samples were fully characterized (dome heights, low-field displacement) before placed in an oven at a constant temperature. After a time t , samples are taken out and displacement is measured again to evaluate the percent reduction in performance due to thermal aging.

2.3. High-field effects. The displacement hysteresis loops were measured using the non-contacting fiber optic method described above. Polarization hysteresis loops were measured using a Sawyer-Tower circuit.

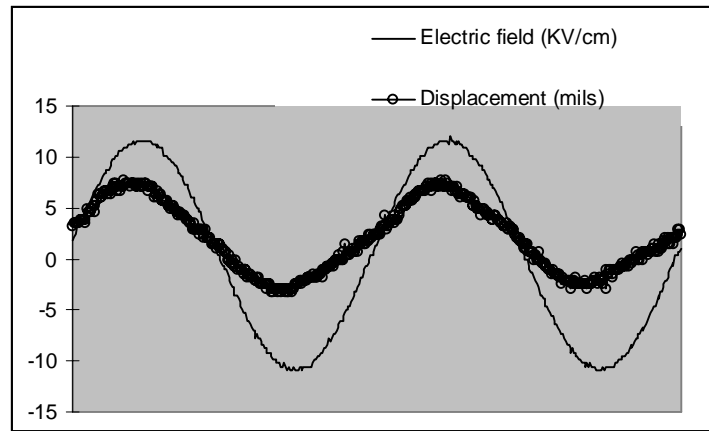
3. Results.

3.1. Low to moderate field displacement. A typical response of THUNDER actuators is shown in Figure 3a. A negative driving field increases the curvature of the THUNDER actuators, whereas a positive field causes the actuator to flatten (displacement is 180° out of phase with respect to electric field). This observation is in contrast to a bulk piezoelectric ceramic, which expands through the thickness when subjected to a positive field (same direction

as poling field) as shown in Figure 3b (displacement and electric field are both in phase). In the case of THUNDER, as a positive field is applied, the piezoelectric ceramic in the sample expands in a direction perpendicular to the surface and contracts in the direction parallel to the surface, therefore flattening the THUNDER device.



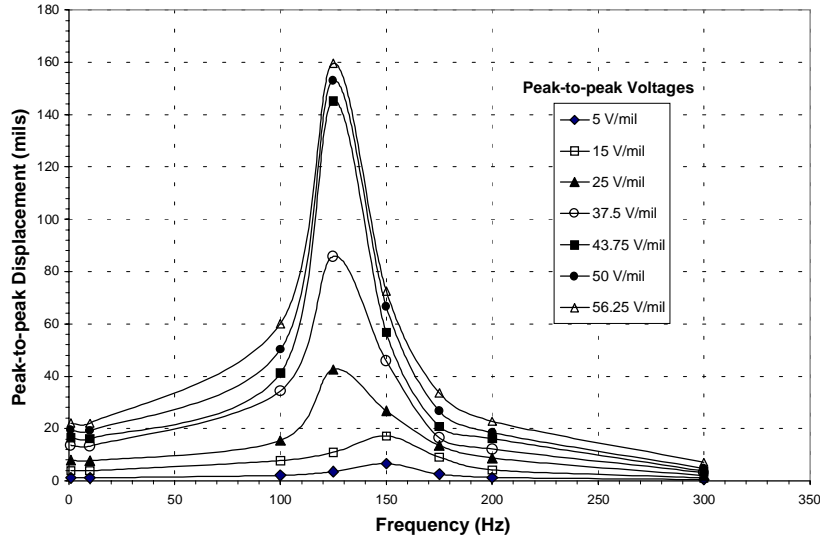
(a)



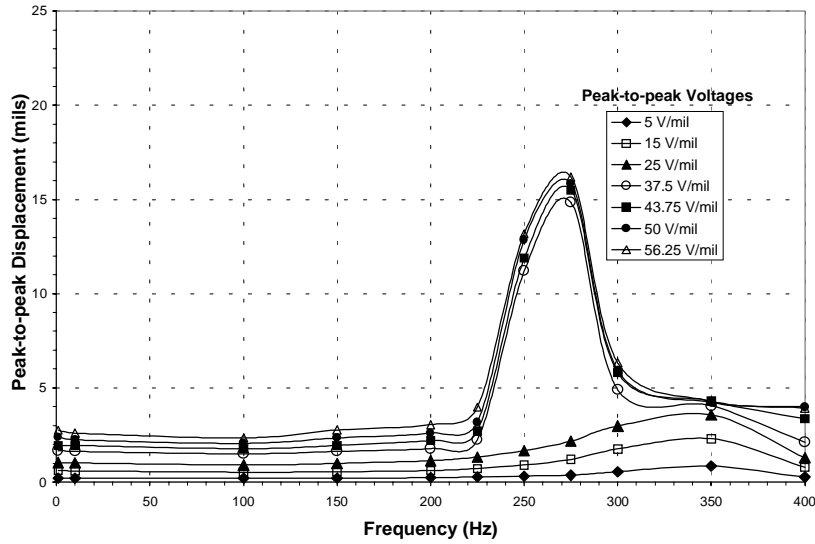
(b)

FIG. 3. Time response of (a) THUNDER actuators and (b) bulk PZT5a.

Measurements of displacement under different voltages and frequencies are illustrated in Figure 4 for two different steel thickness ratios. Between 1 and 100 Hz, the maximum displacement increases as frequency increases. Between 100 and 300 Hz, however, a large drop in displacement occurs, consistent with the observation of resonance peaks in that range. At resonance, accurate measurements of displacement are difficult because of larger, at times unstable deflections in the material. Further inspection of Figures 4a and 4b shows that for both thickness ratios, the resonant frequency decreased as the driving field increased. This seems to indicate that the THUNDER material is softening as voltage increases; it is well known that the piezoelectric coefficients change with applied voltage, Figure 4 indicates that the compliance of the THUNDER increases with applied field.



(a)



(b)

FIG. 4. Displacement as a function of frequency and driving field for (a) 0.286 thickness ratio, and (b) 0.667 thickness ratio.

Displacement measurements at 1 Hz as a function of steel thickness are shown in Figure 5. Results are summarized as maximum (peak-to-peak) displacement for each steel thickness ratio at the peak-to-peak driving fields. Each data point is an average of multiple samples. The steel thickness ratios of 0.280 to 0.375 seem to give the largest, most reliable displacements for any given voltage. As the steel thickness increased above 50% of the total thickness, performance decreased significantly. Dome height measurements are shown in the same figure (Figure 5) and the trend follows that of the displacement, in other words, the THUNDER samples with the highest

dome heights had the highest displacements. Li et al. [5] investigated the effects of internal stresses on field-induced displacements of RAINBOW devices (also a stress-biased piezoelectric actuator). They showed that RAINBOW actuators with maximum tensile stresses also had maximum displacements. They concluded that the influence of the internal stresses on the displacement was a combination of stress-enhanced domain reorientation and non-uniform distribution of the piezoelectric coefficient d_{31} . The same phenomena would apply in our case. The stresses on the ceramic lead to preferential domain orientation, most likely a domination of a-domains (parallel to the surface). When the electric field is applied, the 90° domain reorientation induces large displacements. As the applied field is reduced, the domains switch back to their original direction in the presence of the stresses. In order to fully verify this, we are developing a model to fully understand the effects of thermal stresses, repoling, and d_{31} effects on THUNDER performance. So far, by incorporating effects of thermal stresses and repoling, we have successfully estimated the dome heights for various thickness ratios [6] (Figure 6). Modeling of the THUNDER devices to quantify stress distribution and levels through the thickness for a series of thickness ratios is underway.

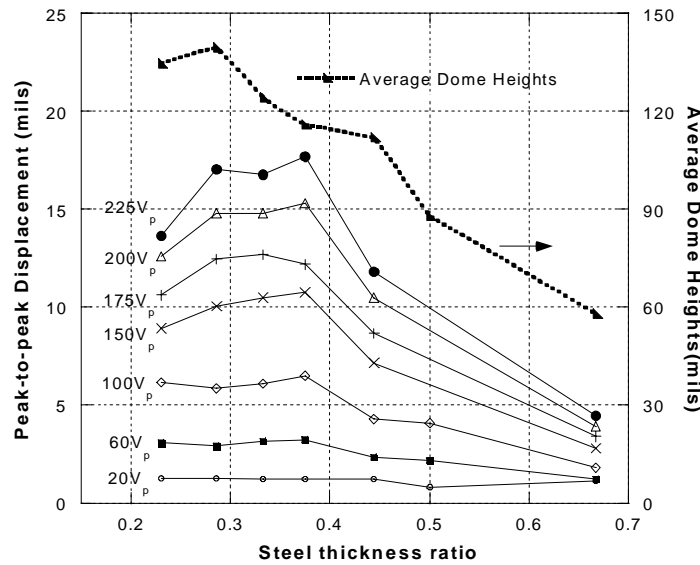


FIG. 5. Change in maximum displacement for the various thickness ratios (at 1 Hz).

3.2. Temperature displacement. After analyzing THUNDER under varying voltages and varying frequencies, temperature was then added as a variable. As can be seen in Figure 7, for all temperatures, displacement increased as voltage increased. Displacement increased with temperature as well until 150°C , above which the displacement decreased slightly. Many commercial vendors report this temperature as the maximum operating temperature for PZT5a. However, it is most likely that, up to 150°C , the performance of THUNDER devices is dominated by extrinsic effects (stress-bias and non-uniform d_{31}) [7]. Conversely, as the temperature increases, the stress domains are changing and relaxing, eventually resulting in a decrease in the overall performance.

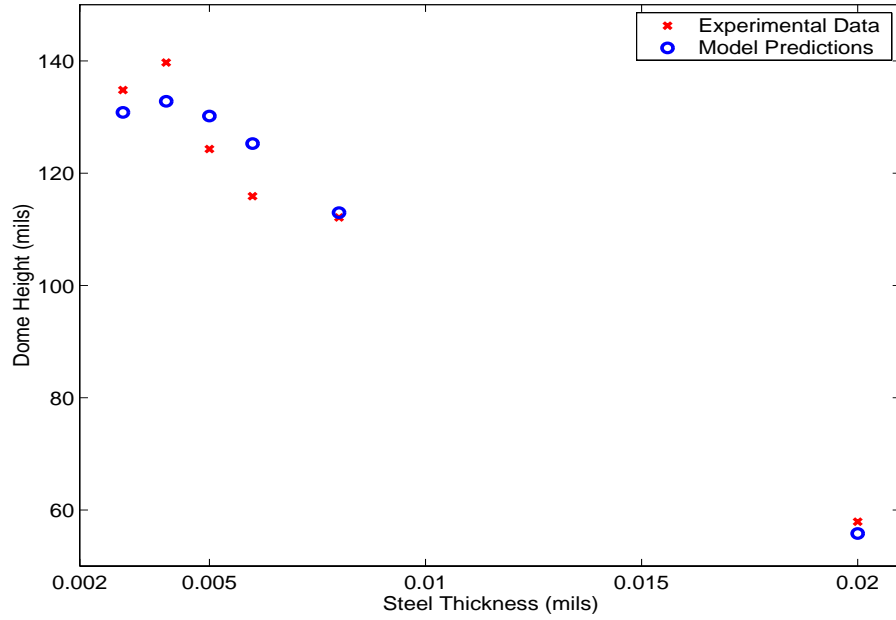


FIG. 6. Comparison of experimental dome heights vs. model predictions.

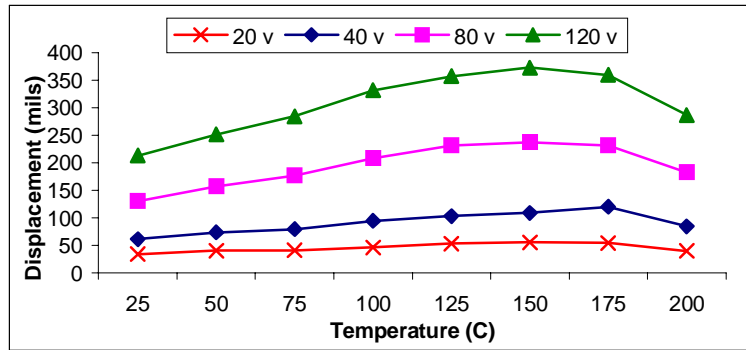


FIG. 7. Change in maximum displacement with temperature.

Isothermal aging data is reported in Figure 8. Samples aged at 50°C retained their initial displacements, however as the aging temperature was increased to 100°C and 150°C, a linear decrease of the performance is observed. At 150°C, after 400 hours, as much as 40% of the performance is lost. The aging at 0°C does not seem to fit the same trend. We believe that stress relaxation is again the cause for the decrease in performance.

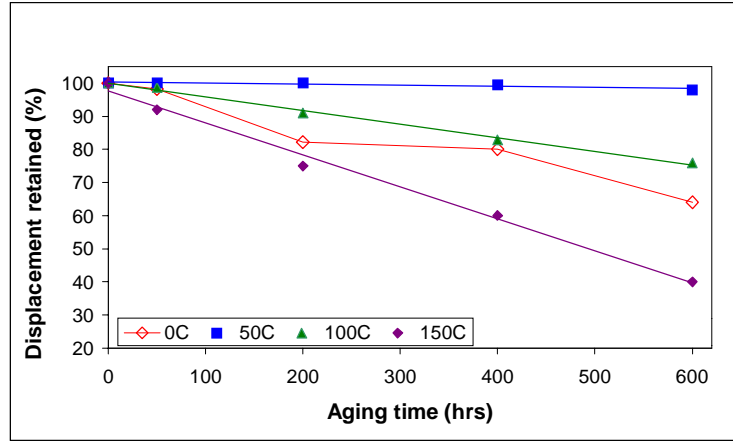
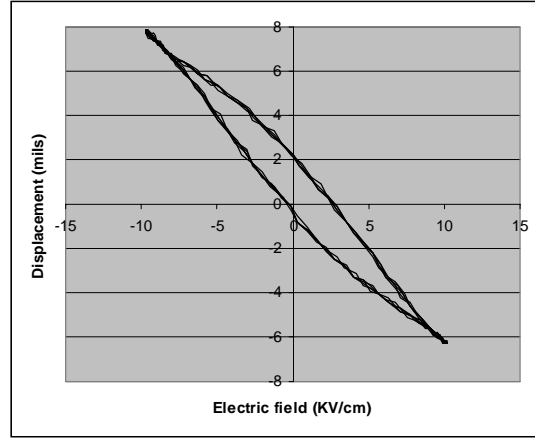
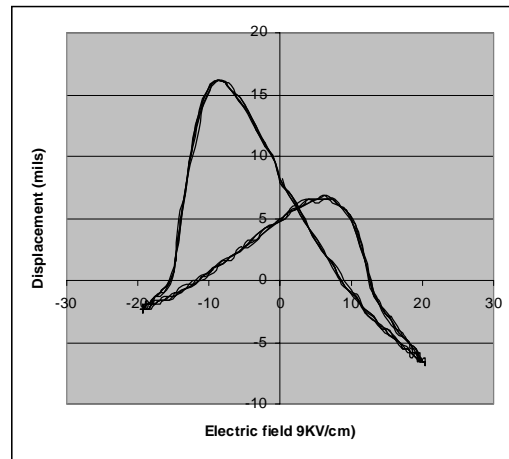


FIG. 8. Isothermal aging.



(a)



(b)

FIG. 9. Electromechanical displacement loops of THUNDER actuators measured at 1 Hz and two electric field levels: (a) $\pm 25\text{V/mil}$, and (b) $\pm 50\text{V/mil}$.

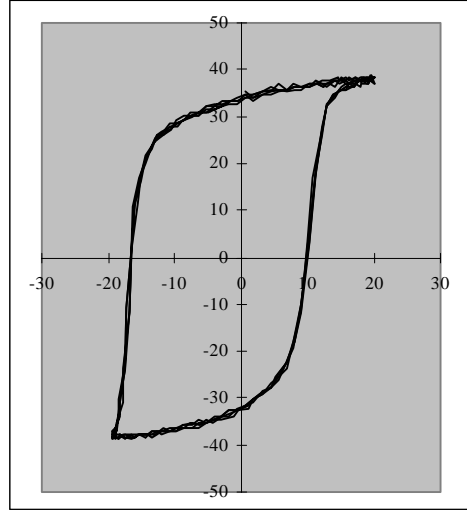


FIG. 10. Typical polarization hysteresis loop for THUNDER actuator.

3.3. High-field effects. As mentioned earlier, THUNDER actuators possess an inverted loop when compared to bulk piezoelectric ceramics. This negative slope is shown in Figure 9a. As the electric field is increased, switching finally occurs and a highly asymmetric “butterfly” loop is obtained. THUNDER flattened more when a maximum positive field was applied than a negative one, indicating enhanced domain alignment for a positive field compared to a negative one. Another aspect of Figure 9b is that after switching, THUNDER actuators flattened under both negative and positive maximum fields. Coercive fields caused the THUNDERS to curve more. This same behavior was observed by Dausch [8] for RAINBOW actuators. Inspection of Figure 10 further confirms these findings; as the polarization hysteresis loop is also highly asymmetric with respect to both axes, and a better saturation is observed for a positive field than a negative one.

TABLE 2.
Comparison of hysteresis loop properties between a bulk PZT5a and the THUNDER actuators at $\pm 50\text{V/mil}$.

	$+ E_c \text{ (KV/cm)}$	$- E_c \text{ (KV/cm)}$	$+ P_r \text{ (}\mu\text{C/cm}^2\text{)}$	$- P_r \text{ (}\mu\text{C/cm}^2\text{)}$
Bulk PZT5a	13.8	-14	34	34
3-mil steel	11	-14.5	34.5	33
4-mil steel	10	-15.5	34	-32.5
5-mil steel	11	-14.5	35	-33
6-mil steel	11	-14	34	-33
8-mil steel	10	-14.5	34	-33
20-mil steel	9.5	-14	34	-34

Table 2 further compares the various THUNDER actuators considered in this study to a bulk PZT5a. A bulk PZT5a possessed equal positive and negative E_c and P_r . The THUNDER actuators on the other hand had much higher negative E_c than positive ones, indicating that it is much easier to switch the domains from negative to positive than the other way around.

4. Conclusion. In this study, we have investigated the low field and high field characteristics of a number of THUNDER actuators having several thickness ratios. The highest displacements were observed for steel thickness ratios between 0.286 and 0.375. It is believed that the stresses vary across the thickness of the actuator; the ceramic layer is in a state of tension on its top surface, and compression towards the bottom. These internal stresses, combined with restricted lateral motion, enhanced the axial displacement and caused large asymmetry in the domain switching at high fields. Asymmetry of the hysteresis is most likely due to stress domains facilitating switching and alignment with positive fields and impeding alignment with negative fields. To quantify the exact relationship between the state of stress in the ceramic and the overall performance, we are pursuing modeling of these devices incorporating both thermoelastic relations and ferroelectric domain theory.

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