Cryogenic Piezoelectric Actuator

Xiaoning Jiang [a], William B. Cook [b] and Wesley S. Hackenberger [a]

[a] TRS Technologies, Inc., 2820 East College Avenue, Suite J., State College, PA 16801
[b] NASA Langley Research Center, Hampton, VA 23681-2199

ABSTRACT

In this paper, PMN-PT single crystal piezoelectric stack actuators and flextensional actuators were designed, prototyped and characterized for space optics applications. Single crystal stack actuators with footprint of 10 mm x10 mm and the height of 50 mm were assembled using 10 mm x10mm x0.15mm PMN-PT plates. These actuators showed stroke > 65 – 85 μm at 150 V at room temperature, and > 30 μm stroke at 77 K. Flextensional actuators with dimension of 10mm x 5 mm x 7.6 mm showed stroke of >50 μm at room temperature at driving voltage of 150 V. A flextensional stack actuator with dimension of 10 mm x 5 mm x 47 mm showed stroke of ~ 285 μm at 150 V at room temperature and > 100 μm at 77K under driving of 150 V should be expected. The large cryogenic stroke and high precision of these actuators are promising for cryogenic optics applications.

Keywords: single crystal piezoelectrics, piezoelectric actuator, stack actuator, flextensional actuator, cryogenic actuator

1. INTRODUCTION

Electromechanical actuators with large stroke and high precision are important for shape control, precision positioning and force control in various NASA, military and civilian applications. A broad range of actuation approaches have been developed including electro-magnetic, electrostatic, piezoelectric, electrostrictive, magnetostrictive, shape memory alloy, and thermal pneumatic. However, more advances are required for lightweight cryogenic actuation with low power consumption [1]. There are some recent research efforts reported on magnetostrictive cryogenic actuation with superconducting coils by Energen, ferroelectric cryogenic rod (or stack) actuators using ceramics by Xinetics, and single crystal actuators by TRS [2]. Piezoelectric actuation has been applied extensively because of its high precision displacement control, high force output, quick response, and low power consumption. Conventional piezoelectric ceramic actuators lost 75% strain at temperature of 40K comparing with room temperature strain, and the specially modified ceramic actuator can only work at temperature < 70K. Single crystal piezoelectrics exhibit significantly higher piezoelectric performance at both room temperature and cryogenic temperatures [3], e.g. d_{33} of single crystal piezoelectrics (PMN-PT or PZN-PT) at 30K is about equal to the d_{33} of PZT-5A at room temperature, indicating promising cryogenic actuation using single crystal piezoelectrics. Single crystal piezoelectric stack actuators could be used for applications requiring stroke <100 μm at temperatures <20 to 300K. Compared with piezoelectric stack actuators, ceramic-metal composites, or flextensional actuators, have the advantage of lightweight and large stroke (> 100 μm).

In this paper, single crystal stack actuators and single crystal flextensional actuators with large stroke at low driving voltages are presented for NASA passive optics applications.

2. EXPERIMENTAL DESIGN

*xiaoning@trstechnologies.com; phone: 814-238-7485 ext 230; fax: 814-238-7539

PMN-PT single crystal stack actuators and flextensional actuators were designed, prototyped and characterized at room temperature and 77 K. The design goal for stack actuators was to obtain > 60 μm stroke at room temperature and > 25 μm at 77 K from a stack actuator with footprint of 10 mm x10mm and length of 50 mm. For flextensional actuators, the goal was to obtain stroke > 200 μm at room temperature from an actuator with dimension < 10mmx10mmx50mm. The driving voltage of these actuators should be < 150 V.

2.1 Piezoelectric actuator design

A. Stack actuator

Actuator Stroke output of a stack actuator is given by the following equation:

$$\Delta L = d_{33} * \frac{V}{t} * L \qquad (1)$$

Where, ΔL is the stroke, d_{33} is the longitudinal piezoelectric coefficient, V is the driving voltage, t is layer thickness, L is the active length of the stack (the sum of all active layer thickness). In the case of given stack length (L) and driving voltage (V), high $d_{33,}$ thin layer (small t) and a long stack (big L) will contribute directly to larger stroke output.

B. Flextensional actuator

Two different piezoelectric drivers can be used for flextensional actuators (cymbal type). One is piezo plate driven, or called "31" mode flextensional actuator (Figure 1(a)). Electric field is applied to the plate in Z direction, the contraction of the plate in X direction is then amplified into a large displacement in Z direction. This "31" mode flextensional actuator is known for large stroke and low profile, but the blocking force is usually low. The other flextensional actuator utilizes a stack actuator as a driver (Figure 1(b)), which is also called "33" mode flextensional actuator. The force output from "33" mode flextensional actuators is known much higher than that of "31" mode. Therefore, a "33" mode flextensional single crystal actuator design was chosen for further study.

ATILA FEM software was used for flextensional actuator modeling. Stroke at X direction and Z direction was calculated to obtain the stroke amplification factor of flextensional actuators. Frame angles were varied in search of designs with large stroke.

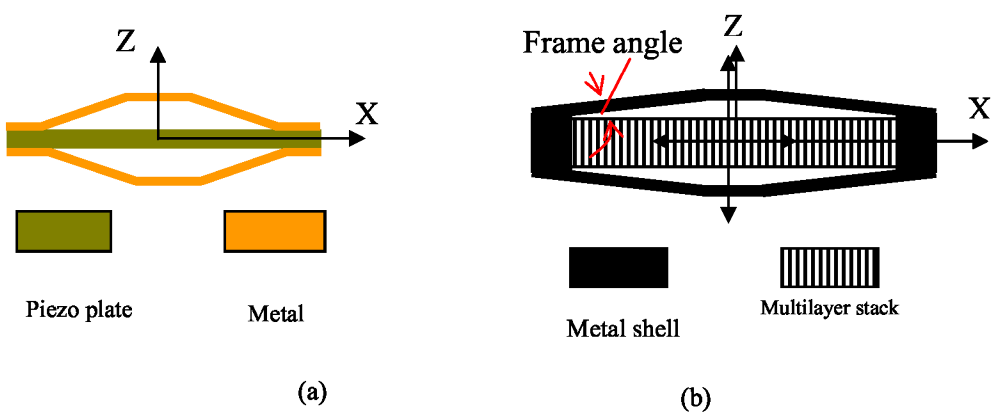


Figure 1. Flextensional actuators (a) "31" mode; (b) "33" mode.

2.2 Actuator prototyping and characterization

Single crystal plates with the designed thickness and lateral dimensions were fabricated with Cr/Au on both sides as electrodes. These plates were poled at 10 KV/cm, followed by capacitance, dielectric loss and piezoelectric coefficient measurements. Capacitance and dielectric loss were measured using an impedance analyzer at 1 KHz. Piezoelectric coefficient was measurement using a d33 meter. PMN-PT plates with acceptable properties were bonded together using cryogenic epoxy to form stack actuators and drivers for flextensional actuators. Stroke of the assembled stacks and flextensional actuators were measured using a LVDT system at room temperature and liquid nitrogen temperature.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Stack actuators

Table 1 shows two designs using PMN-PT single crystal plates with thickness of 0.5 mm thick and 0.14 mm thick, respectively. The design with layer thickness of 0.14 mm was selected in order to further increase stroke at relatively low voltages without bringing significant fabrication difficulty. Plus, the stack capacitance seemed not to be a problem for driving electronics.

Table 1: Single crystal stack actuator designs

Specification	0.5 mm regular plate design	0.14 mm thin plate design
Stroke at room temperature	~ 74.6 μm @ 500 V	~ 76 μm @ 150 V
Stroke at 77K	~ 37 μm @ 500 V	~ 38 μm @ 150 V
Capacitance (nF)	~ 700 nF	~ 9000 nF
Total number of active layers	~93	~ 300

About 2000 pieces of PMN-PT single crystal plates with dimension of 10 mm x 10 mm x 0.14 mm were fabricated and tested. Plates with piezoelectric coefficient d33 of 1600 pC/N – 2300 pC/N, dielectric loss <0.01 were accepted for assembly of stacks. Endcaps were made of non-active ceramic plates with the sizes of 10 mm x 10 mm x 0.14 mm. Thin copper shims with dimension of 9.75 mm x 9. 75 mm x 0.025 mm were used for electrode connection. Cryogenic epoxy (Master Bond) was used to bond PMN-PT plates, shims and end caps together. The stacks were terminated with two lead wires soldered to the shim tabs. **Figure 2** shows the picture of prototyped 6 stacks and each stack consisted of 287-300 layers of 10 mm x 10 mm x 0.14 mm PMN-PT single crystal plates. The final dimension of stacks is about 10 mm x 10 mm x 50 mm. Table 2 summarizes the dimension, dielectric and piezoelectric properties of all 6 stack actuators. The displacement vs. voltage was measured using LVDT system at both room temperature and liquid nitrogen temperature. Figure 3 shows the measurement setup consisted of cryostat, LVDT sensor, power supply, lock-in amplifier and the control computer. Figure (a) shows the stroke of a stack (#2) measured at 77K-298K. Figure 4(b) shows the displacement vs. driving voltage at 77 K, and 298 K respectively. It is noticed that the stroke is about 32.3 μm and 65.8 μm at 77K and room temperature, respectively. About ~ 50% strain retained at 77K comparing with room temperature stroke, and the hysteresis at 77K is found significantly lower than that at room temperature.

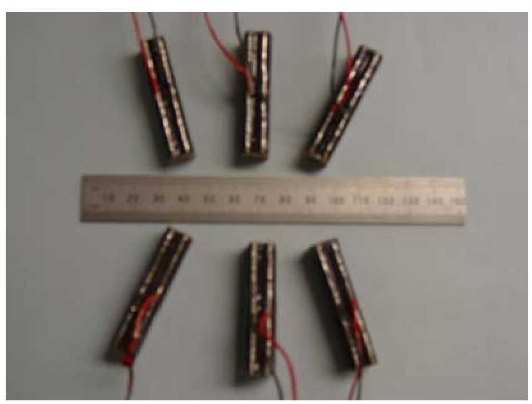


Figure 2. Deliverable PMN-PT single crystal stack actuators.

Table 2: PMN-PT single crystal stack actuators (10mmx10mmx50mm).

Actuator No.	Height (mm)	Total layers	Capacitance (μF)	Dielectric Loss	Effective d33 (pC/N)	Notes
#1	49.95	300	9.37	0.013	1980	Room temperature, @ 150 V
#2	49.9	287	7.78	0.02	1884	
#3	50	287	6.46	0.014	1737	
#4	50	290	7.85	0.014	1858	
#5	50.01	290	7.90	0.017	1889	
#6	49.85	292	8.01	0.017	1973	

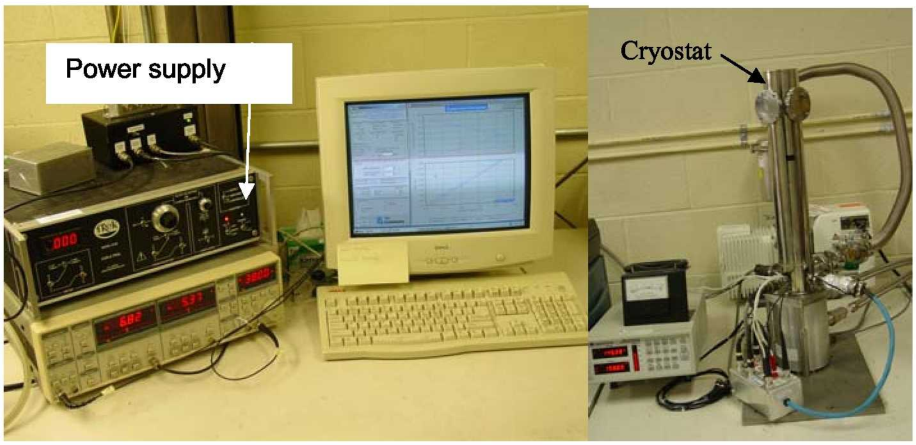


Figure 3. Cryogenic strain measurement system.

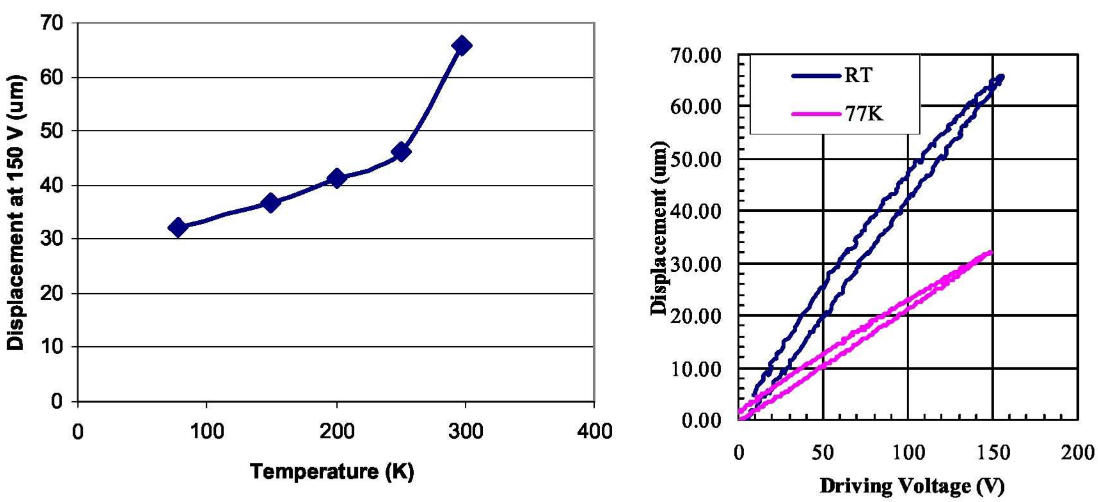


Figure 4. Cryogenic displacement measurement results. (a) actuator displacement at various temperatures at 150 V. (b) displacement vs. voltage at 77K and room temperature.

Figure 5 shows the stroke of 6 actuators at room temperature and at 77 K. The #2 is the only one tested at cryostat and the cryogenic stroke of other actuators was projected from the #2 test. The stroke of actuators varied a little bit because of the materials uniformity as well as the layer thickness variation. All 6 PMN-PT single crystal stack actuators were driven at 150 V to generate stroke at room temperature > 65 μm, and stroke at 77K > 30 μm, both meet the design expectations.

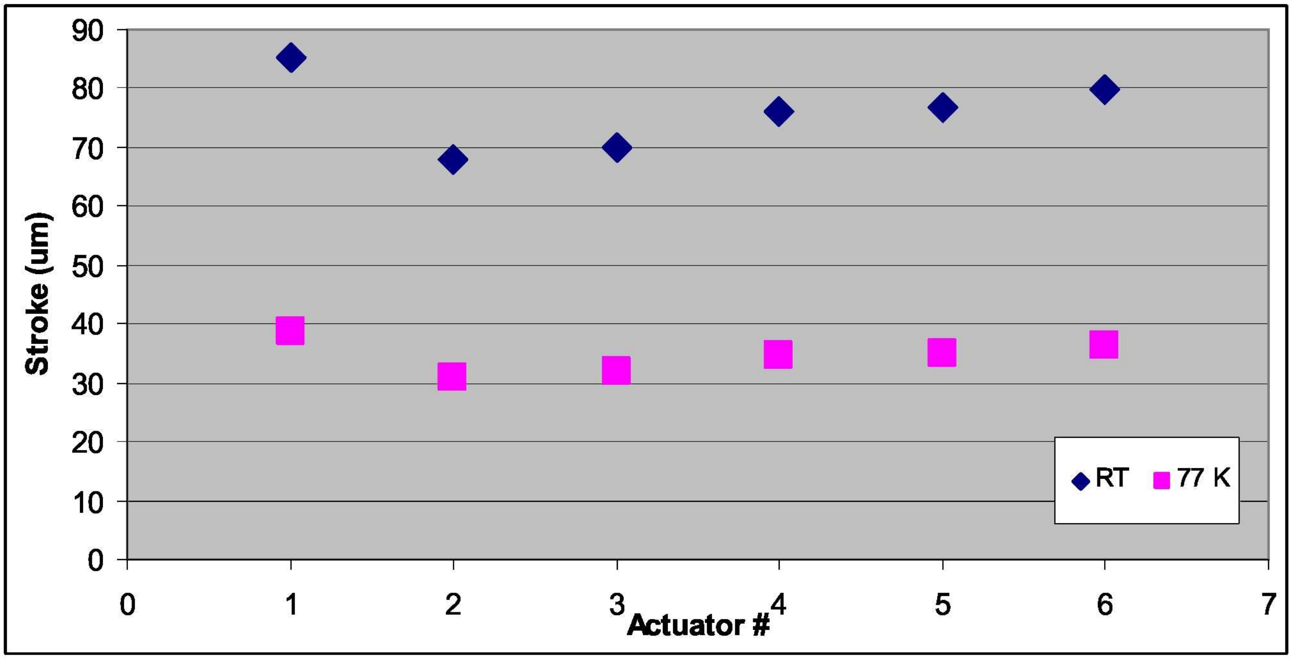
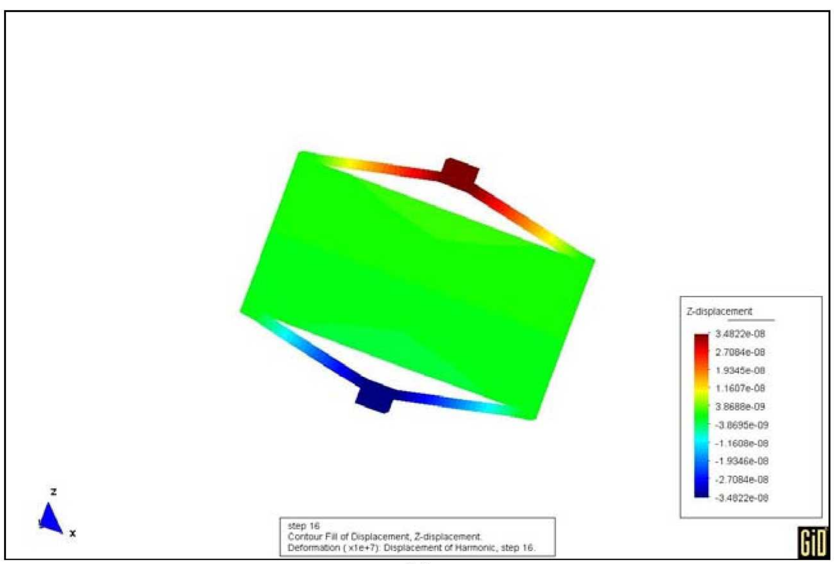


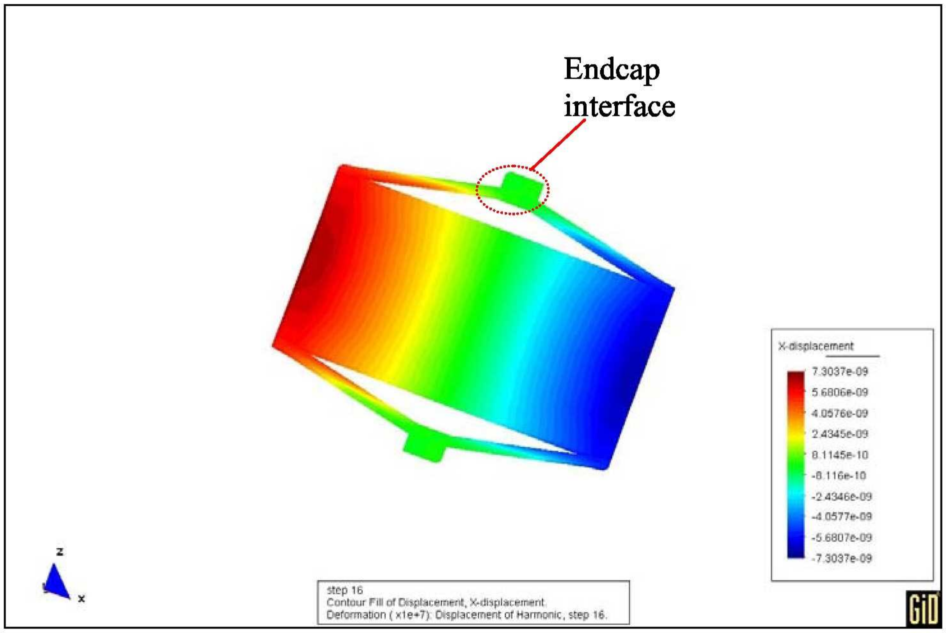
Figure 5. Stroke of actuators at room temperature and 77 K.

3.2 Flextensional actuators

Figure 6 (a) shows the FEM modeling results on stroke profile of a flextensional actuator under 0.01KV/cm (Z direction), and the calculated stroke is about 77.6 μm under 10 KV/cm. If the stack is composed of 5mmx5mmx0.15mm PMN-PT plates, the driving voltage required to achieve this stroke is 150 V. Figure 6 (b) shows stroke at X-direction and the amplification factor is calculated to be about 4.8. More FEM modeling was then focused on varying profile angles to optimize the design with improved stroke and amplification factor.



(a)



(b)

Figure 6. ATILA FEM modeling results for a 10 mm x 5 mm x 7.6 mm flextensional actuator (frame angle of 7.5°): (a) Z-stroke profile under 0.01 KV/cm; (b) X-stroke profile under 0.01 KV/cm.

The peak-to-peak stroke and amplification factors of different designs are presented in Table 3. Among the various designs, the design with frame angle of 5.5 degree and 5mmx1mm interface shows largest stroke and highest amplification factor.

Table 3: Summary on ATILA FEM modeling of flextensional actuators.

Angle (°)	Stroke (μm)	Amplification factor (Z/X)	Endcap interface sizes (mm)	Note
3.5	64	4.97	5mmx2mm	Driving field: 10 KV/cm; frame thickness: 0.25mm.
5.5	67	4.87	5mmx2mm	
5.5	76	5.4	5mmx1mm	
6.5	66	4.7	5mmx2mm	
7.5	63	4.4	5mmx2mm	
7.5	70	4.77	5mmx1mm	
8.5	61	4.1	5mmx2mm	
10	57	3.8	5mmx2mm	

PMN-PT single crystal plates with dimension of 5 mm x 5 mm x 0.1mm were used to assemble stacks as drivers for flextensional actuators. The stack actuators (~ 5mmx5mmx9mm) were then inserted into the metal frames machined using electro-discharge machining (EDM) process. Figure 7 shows pictures of components and assembled flextensional actuators. Stroke of a single crystal stack, stroke at X-direction of the assembled flextensional actuator, and the stroke at Z-direction of the flextensional actuator were measured using LVDT method, and the results are shown in Figure 8(a). The measured stroke of the stack was about 14.8 μm at 150 V without any pre-stress, the stroke at the X-direction of the assembled flextensional actuator was about 12.7 μm at 150 V, which is smaller than that of the free-stress value. The stroke at Z-direction was about 56.1 μm at 150 V (Figure 8 (b)), so the calculated amplification factor of this flextensional actuator is about 4.4, which is close the value (~ 5) from the modeling prediction. Total 6 such flextensional actuators were assembled and tested, the measured stroke of them is presented in Table 4. These 6 flextensional actuators were then assembled in series forming a flextensional stack, as shown in Figure 9 (a). The total height of this stack is about 47 mm, the stroke of this flextensional stack was measured using LVDT at various voltages, as shown in Figure 9(b). The stroke at 150 V is about 285 µm, and the expected stroke at 77K should be > 130 µm at 150 V.

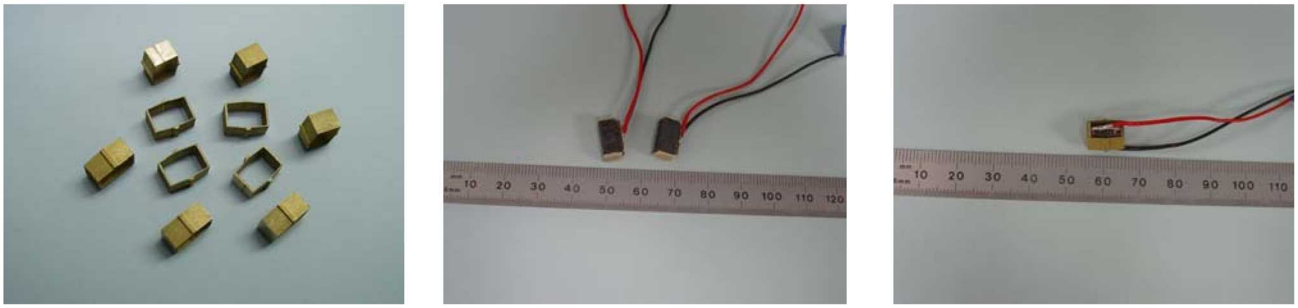


Figure 7. Photograph pictures of flextensional actuator components and assembled actuators. (a) frames; (b) stacks as drivers (5mmx5mmx9mm); (c) assembled flextensional actuator (10mmx5mmx7.6mm).

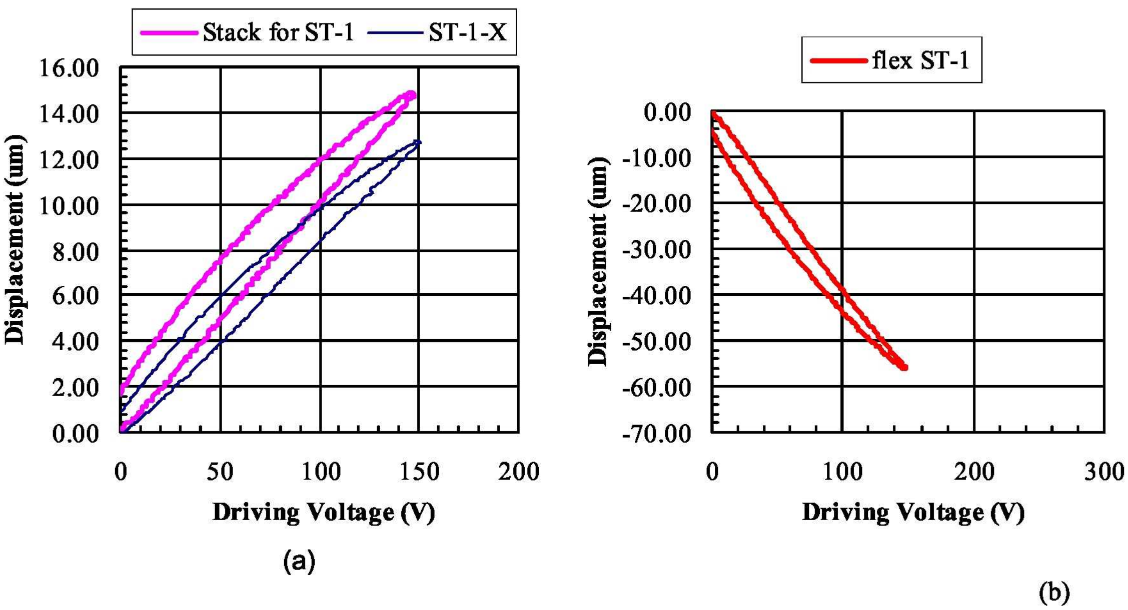
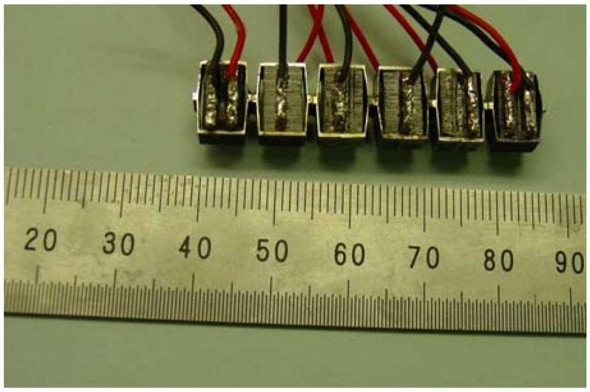
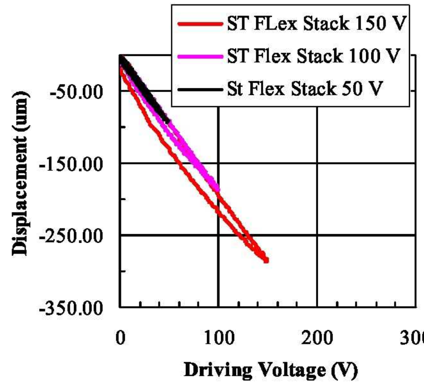


Figure 8. Displacement measurement results for a single crystal stack and a flextensional actuator (steel frame). (a) stack and X-direction stroke; (b) Z-direction stroke.

Table 4: Stroke of flextensional actuators with steel frames (@ 150 V)

Actuator #	ST-1	ST-2	ST-3	ST-4	St-5	ST-6
Stroke (µm)	56.1	46.7	38.5	46.1	45.2	41.4





(a) (b)

Figure 9. Flextensional stack actuators (with steel frames). (a) Photograph picture of a flextensional stack actuator with 6 single crystal flextensional actuators. (b) Stroke of the flextensional stack actuator (Z-direction) at 50V, 100V and 150 V.

4. SUMMARY

PMN-PT single crystal stack actuators and flextensional actuators were designed, fabricated and characterized. The experimental results agree well with the modeling predictions. Stack actuators with dimension of 10 mm x10 mm x50 mm showed stroke > 65 μm at 150 V at room temperature and stroke > 35 μm at 77 K. Flextensional actuators with dimension of 10mm x 5mm x 47 mm showed stroke of 285 μm at 150 V at room temperature. More than 50% of room temperature stroke remained at 77K for PMN-PT single crystal actuators, which is very promising for cryogenic actuation applications.

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