High Displacement Piezoelectric Actuators: Characterization at High Load with Controlled End Conditions

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Abstract -- Piezoelectric ceramic transducers are characterized by relatively small strains on the order of 0.1%. Methods of achieving larger displacements include mechanical amplifiers and flexural mode actuators, such as unimorphs or bimorphs. A particular type of stressed unimorph flexural actuator, the "THUNDER" actuator, provides enhanced flexural strain. (THUNDER™ is a trademark of FACE International Corporation). However, displacement has generally not been characterized as a function of load, which was needed for our application. We found that load and displacement were very sensitive to end conditions, which has also not been reported in the literature. The commercially available THUNDER™ model 8-R rectangular actuators were chosen for the research presented here. They were operated in a flexural mode, and used to characterize displacement as a function of load under well-controlled end conditions. Our experimental results show that progressively restrictive end conditions increased the stiffness, ranging from 2.5N/m to 23N/m, which increased the load capabilities of the actuator. In some cases, displacement actually increased as a function of load as well. This enhanced stiffness was obtained at a cost of reduced no-load flexural strain (defined as the ratio of flexural displacement and ceramic length), ranging from 1.08% for free end conditions to 0.2% for highly restricted end conditions. The load bearing capabilities were tested out to 10N for most end conditions.

INTRODUCTION

Piezoelectric actuators are manufactured in many forms. Simple devices include disc multilayers (also known as stacks), and simple cylinders [1]. More complex devices include unimorphs, bimorphs, moonies, hinged levers and inchworms [2]. Typical piezoelectric actuators have strains on the order of 0.1%, which severely limits their applicability. Traditionally, this problem has been addressed by utilizing the high force capabilities of piezoelectrics, coupled with a mechanical advantage mechanism to produce larger displacements. More recently, composite structures have been produced. The first structure of this type was called RAINBOW. A subsequent structure is known as THUNDER™. These materials can have flexural strains on the order of 1%, a substantial improvement. (Flexural strain is defined as the flexural displacement divided by the length of the ceramic.) However, these high displacement actuators are compliant structures. Consequently, their performance is strongly dependent on physical boundary conditions. The current literature contains virtually no information on this dependency. A thorough investigation of load capabilities is also absent from the literature.

The RAINBOW (Reduced And Internally Biased Oxide Wafer) transducer / actuator was introduced by Haertling [3] in 1994. It is formed by reducing one side of a PLZT (lead lanthanum zirconate titanate) disk at high temperature, thereby transforming a surface layer from ceramic to a nearly metallic composition. Upon cooling, the disk deforms to a characteristic, shallow dome shape due to a difference in coefficients of expansion between the reduced layer and the bulk of the ceramic. Actuator fabrication is completed by poling perpendicular to the piezoelectric/metallic interface. These actuators produced flexural strains of 0.5%. (Displacement was divided by the 22.4cm-diameter of the disk actuators.)

The THUNDER™ (Thin-layer composite unimorph ferroelectric driver and sensor) actuator [4], developed under grants from NASA, achieves deformation and pre-stress by a different route. A PZT (lead zirconate titanate) ceramic thin sheet is bonded under hydrostatic pressure to a metal substrate *while at* elevated temperature. Upon cooling, the laminate develops curvature and consequent internal stresses due to differences in coefficients of expansion between the metal layer and ceramic layer. As with RAINBOWs, actuator fabrication is completed by poling perpendicular to the piezoelectric/metal interface.

It is important to realize that when compared to more traditional piezoelectric actuators, these high displacement actuators operate very differently. The actuators can operate in different modes, but an "indirect" or two-step mode of operation was most useful for our application. As explained above, the manufacturing process results in an arced or domed shape that introduces asymmetry. Consider an actuator placed on a horizontal surface such that its convex side is facing upward. If a mass is placed at the apex of the arc or dome the loaded actuator tends to

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flatten. Actuator *displacement* is taken as displacement of the apex relative to its zero voltage initial position at equilibrium under a particular load. (Actuator *position*, on the other hand, is measured relative to the zero voltage initial position of the apex *at zero load*.) If a voltage is applied across the thin dimension of the ceramic such that the top is positive relative to bottom, the ceramic tends to contract because of the negative d_{31} transverse coupling. As a result, the actuator apex displaces even further downward. Remove the voltage and the actuator returns to its equilibrium level under load. It is actually the mechanical restitution (elastic rebound) that performs work on the load. (Throughout this article, the downward displacement of load and actuator is taken as a positive y direction.) So, free displacement involves two steps. When voltage is applied, ceramic contraction works in parallel with the load to store additional elastic energy in the composite structure, which is then recovered during elastic rebound when the voltage is off. It may be useful to think of this type of actuator as a spring in which the stiffness can be altered with an external voltage. Although it is possible to drive the THUNDER™ actuator under reversed polarity, voltage must be limited to avoid damage to the actuator. This limits the usefulness of reversed polarity operation.

Although displacement data and limited force data are available in the literature [5,6], reported results generally assume that the THUNDER™ actuators are "simply supported," that is, resting on a pair of knife edges, or attached to supports by flexible media such as duct tape or modeling clay. This article reports results obtained by controlling boundary conditions more carefully, so that the effects of hindered or allowed rotation or translation on one or both ends of a THUNDER™ actuator can be examined.

PROCEDURE

Commercially available THUNDER™ model 8-R actuators [7] were used in this investigation. They were constructed by bonding thin PZT ceramics (0.152mm thick by 1.37cm wide by 3.81cm long) to stainless steel sheets (0.20mm thick by 1.27cm wide by 6.35cm long). The actuators were installed in a fixture designed to control specifically whether actuator ends were free to rotate or translate in various combinations of end conditions. This fixture, and accompanying apparatus, is shown in Figure 1. Each end of an actuator was clamped into an axle. An LVDT (Linear Variable Differential Transformer) for measuring changes in actuator position was mounted on a steel shaft running through linear bearings in a frame positioned above the actuator fixture. Slotted weights could be stacked onto the steel shaft for loading the actuator. As designed, the test fixture blocks or allows rotation in the left axle, right axle, or both axles. The means for allowing or blocking translation was available only in the right axle.

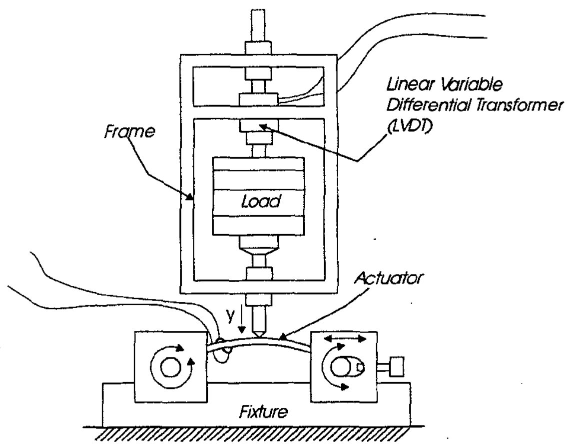


Figure 1: Test apparatus for measuring actuator positions under various loads at a range of applied voltages and various end conditions.

Each end condition shown in Table I constituted a "test," which was conducted. In each test, five data sets were gathered repetitively without changing the test arrangement in any way. A LabVIEW™ computer program was used to conduct tests and acquire data. It determined measurement range, then automatically acquired and averaged 20,000 data point at each of 17 loads and 10 voltages in each of the five data sets. Of the eight possible permutations of blocking or allowing right axle rotation, left axle rotation, or translation, two were omitted because blocking *rotation* of the right axle of the actuator fixture effectively blocked translation. (However, blocking *translation* of the right axle did not block its rotation.)

To calibrate the relationship between LVDT signal and actuator position, a scaling factor (in μm/mV or equivalently, mm/V) was determined, using a number of reference thicknesses. For THUNDER™ 8-R actuators, typical free displacements range from 300μm to 400μm for an applied voltage of 450V and free end conditions.

End Condition	Rotation		Translation
	Right	Left	
A	Y	Y	Y
B	Y	N	Y
C	Y	Y	N
D	N	Y	N
E	Y	N	N
F	N	N	N
Omit	(N)	(Y)	(Y)
Omit	(N)	(N)	(Y)

Table I: Table of six end conditions for all the allowed combinations. Two end conditions were omitted due to the fact that blocking rotation of the right axle of the actuator fixture effectively blocked translation.

RESULTS

Figure 2 shows a plot of *position* vs. load for end condition A, in which translation and rotation of each end is allowed (see Table I). The lower line is drawn through zero voltage data points, and shows the inherent stiffness of the actuator as a passive beam. The upper line is drawn through the highest voltage (480 V) data points. The difference in slopes between these two lines demonstrates a voltage-dependent stiffness

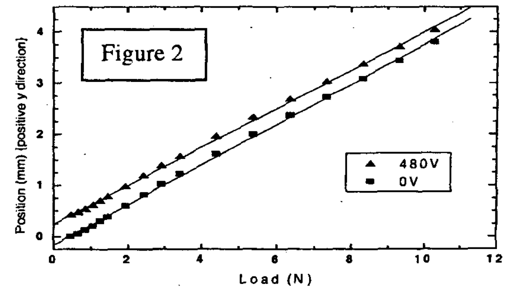


Figure 2

Figure 3 shows a plot of *displacement* vs. load data for the same end condition as in Figure 2. Each plotted position or displacement value represents the average of values (for the particular load and voltage) from the five data sets generated under each end condition.

Figure 3

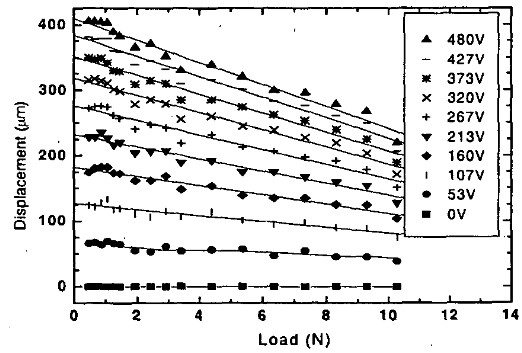
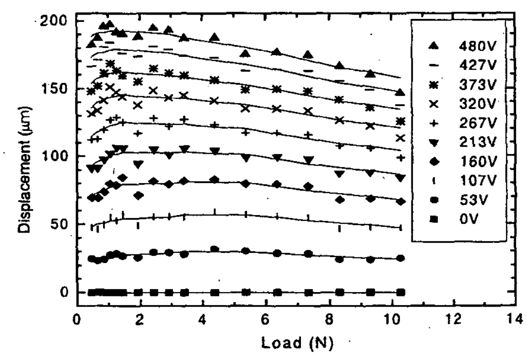


Figure 4 shows the effect of introducing even a small end constraint (end condition B). Only rotation on one axle has been blocked, but no-load displacement has fallen to approximately half that for the unconstrained end condition. This represents increased structural stiffness. Note, however, that the negative slope of fitted lines in Figures 3 and 4 indicates that displacement decreases with increasing load under the relatively free end conditions. As actuator ends are further constrained, the reduction of displacement in return for increased stiffness continues, but successive constraints have diminishing effect.

Figure 4



When translation is blocked (rotation might also be blocked), an *increase* in displacement is observed with increasing load. (Figure 5 shows data measured under end condition F.) Eventually, a point of instability is reached and the actuator buckles. The buckling phenomenon is an abrupt transition or collapse from negative curvature (concave downward) to positive curvature (concave upward). Even an unconstrained actuator may flatten under high loads and then sag into a positive curvature as additional load is applied. However, the transition is a gradual settling, not a sudden and abrupt collapse. Figure 5 has been truncated beyond an applied load of 7.0 N and does not show data through the buckling transition. However, a non-linearity at the high-load ends of the fitted lines indicates that buckling is imminent.

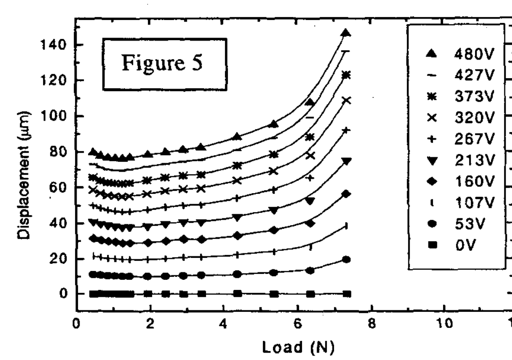


Figure 5

Finally, a summary is presented in Figure 6, which maps measurements taken at each end condition on a stiffness vs. displacement plane. Measurements on unconstrained actuators (end condition A) map to a zone of high displacement and low stiffness. With only rotation blocked (end condition B), plotted measurements fall at approximately half the displacement and twice the stiffness of unconstrained actuator data. Several points characterized by blocked translation fall in the zone of high stiffness and low displacement. The plotted points tend to follow a hyperbolic trace: that is, the product of stiffness and displacement remains approximately constant when end conditions are modified.

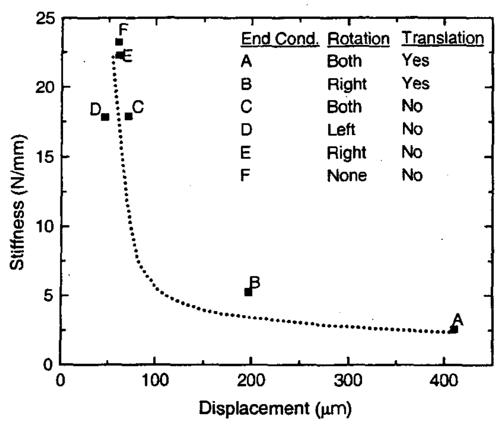


Figure 6: Measurements at controlled end conditions mapped onto stiffness vs. displacement plane

In summary, end conditions involving blocked translation or higher degrees of constraint tended to result in increased stiffness (lower downward displacement) with applied voltage and with increasing displacement with increasing load. The last aspect suggests that constrained actuators do more work as load increases. Calculations of load / displacement work performed support this, although other experiments have shown that the actuators must operate in a continuously loaded state, as in these tests, rather than seeing their load intermittently, as in inchworm devices, for higher work output to occur.

CONCLUSIONS

Load and end conditions are interdependent properties. Our results show that if maximum free displacements are desired, freedom of rotation and translation must be allowed as much as possible. In the case of loaded actuation, constrained end conditions result in a stiffer actuator, and therefore enhanced load capabilities, but at the cost of reducing displacement. In particular, blocking end translation substantially reduces free displacement and increases stiffness, more so than blocking end rotation. The buckling phenomenon is also favored more by blocking translation than rotation. Thus, boundary conditions have a huge impact on actuator stiffness and displacement.

Restrictive end conditions can substitute for or combine with the stiffness of the metal substrate in the laminate as an option for increasing actuator stiffness.

Since work is actually performed against a load when voltage is removed rather than when it is applied, these high-displacement actuators can be thought of as springs with a voltage-controlled stiffness. Electrical excitation has the effect of suddenly changing the stiffness of the actuator. With constant load and changing stiffness, a displacement must occur.

This introduces the interesting possibility of designing resonant mechanical systems, automotive suspensions for example, with a tunable resonant frequency. In mechanical systems the stiffness and the mass determine the resonant frequency. In direct analogy, the capacitance and the inductance determine the resonant frequency of a tank circuit. In electrical circuits the capacitance and/or the inductance can easily be changed, resulting in a multitude of useful tuned circuit designs. In mechanical systems the spring stiffness and mass are not easily changed. This type of actuator or "voltage controlled spring" provides some control over the stiffness, therefore control over the resonant frequency.

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