Evaluation Criteria for THUNDER™ Actuators

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ABSTRACT

THUNDER™ (thin-layer composite unimorph ferroelectric driver and sensor) represents a new class of piezoceramic-based actuators capable of generating significant displacements and forces in response to input voltages. The performance capabilities of THUNDER™ actuators are due to the component materials and process used in their construction. A typical THUNDER™ actuator is composed of metallic backing materials (e.g., aluminum or stainless steel), a piezoceramic wafer, and adhesive in spray or film form. The materials are bonded under high pressures and temperatures and then cooled to room temperature after the adhesive has solidified. Due to the prestresses which result from the differing thermal properties of the component materials under cooling, the actuator is highly durable with respect to mechanical impacts and voltage levels. As a result of this construction, voltages in excess of 800 V can be applied to new actuator models without causing damage. This provides the actuators with significant displacement and force capabilities. In this paper, we discuss the development of evaluation criteria which are suitable for characterizing the actuator capabilities and provide a legitimate methodology for comparing THUNDER™ properties with those of other smart material actuators. For example, the concept of blocked force is often used to quantify the force capabilities of an actuator. However, due to the inherent curvature and mode of operation, standard techniques for measuring blocked forces are inappropriate for THUNDER™ actuators. Furthermore, changing operating conditions, frequency, etc., often make blocked force measurements ambiguous. We will discuss techniques for evaluating THUNDER™ properties in a manner which limits such ambiguities when comparing with other smart materials. We note that the evaluation issues discussed here are germane to a variety of high performance smart material transducers.

Keywords: THUNDER™ actuators, evaluation criteria

1. Introduction

Piezoelectric actuator technology has evolved greatly on the last decade. There are a variety of actuators available on the market today ranging from benders to stacks with different properties which make them unique. Actuators can be divided in categories depending on their construction (stacks), and their function (benders). It has been demonstrated that due to the wide range of the possible applications of piezoelectric actuators, their proper selection and implementation is a key factor in developing an appropriate configuration[1]. Some of the most common actuators available on the market today include bimorphs, RAINBOW, patches, tubular, multilayer, mechanically amplified, CERAMBOW, CRESCENT, and THUNDER™ actuators. Each one of these actuators has properties which make them more readily usable in a particular application than others. Because of the wide range of actuator configurations, as well as the variety of means to mount them and measure their performance, direct comparisons can sometimes be misinterpreted and can be difficult to accomplish in a meaningful way. The issue of determining accurate comparison criteria is further complicated when trying to quantify the performance relative to other smart material systems such as magnetostrictive transducers.

When attempting to measure the relationships between force, displacement and voltage of piezoelectric actuators, especially those designed to emphasize displacement at the expense of force, the experimental setup has a major effect on the accuracy and interpretation of results. This is especially true at high frequencies, but must be considered even at low frequencies. This paper deals with the effect of the selection of measurement apparatus on the results, and how these choices can vary depending upon how the measured variables are defined.

This paper also describes different evaluation criteria for THUNDER™ (thin-layer composite unimorph ferroelectric driver and sensor) actuators in such a manner so as to facilitate comparison with other actuators of this type. THUNDER™ consists of a laminate composed of metallic layers and a piezoelectric wafer bonded with a thermoplastic material (LaRC-SI) at high temperatures. The fabrication process of a THUNDER™ device makes this particular actuator very flexible in its properties[2]. A THUNDER™ actuator can be made with many combination of metals such as aluminum, steel, brass, titanium, beryllium copper, copper, etc. as well as several types of PZT (PZT4, PZT5, PZT8, etc.) making its properties difficult to classify. Due to the variety of THUNDER™ products, this paper will present in Section 2 typical configurations of THUNDER™ devices and their different properties. In Section 3, measurement techniques for free displacement in configurations such as cantilever and simply supported; while force measurements are summarized in Section 4.

2. Typical THUNDER™ Configurations

The manufacturing of THUNDER™ devices is easy and very flexible. Since the process is easy and very flexible, a wide range of possibilities is available. The most commonly used configuration includes a top metallic layer, an adhesive layer, a PZT wafer, an adhesive layer, and backing metallic layers (either one or several with adhesive in between)[2, 3, 4, 5]. As seen in references 2, 3, and 4, the number of layers also plays a significant role in the performance (i.e., displacement, and force) within the particular set of devices. THUNDER™ devices also vary in shape (circular, squares, rectangular, See Figure 1), and thickness, which may produce different results depending on the boundary conditions that are used. Common boundary conditions include simply-supported (pin-pin, pin-free, pin-guided), and cantilever (pinned from the ceramic itself, or only the backing metallic layer, etc.). The type of mounting conditions also has a significant effect on resonant frequency [6].

Another important characteristic of THUNDER™ pieces is the curvature. Depending on the width to length ratio, or thickness to diameter ratio, two modes of curvature can be observed, namely, saddle, domed, and sometimes even slightly curved across the width[7]. These shapes produce different performance characteristics as well as require specially built mechanisms so that the pieces can be used at their optimum mode. The curvature of the THUNDER™ devices has advantages in some applications such as the matching of wing or antenna contours [8, 9]. Details concerning the modeling of the final actuator shape as a function of manufacturing conditions is summarized in reference 10.

Figure 1. Typical THUNDER shapes and sizes

3. Displacement Measurements

By definition "free stroke" is the actuator displacement under zero external load[11]. Measurements of "free stroke" actuators are the most elementary of the characteristics of an actuator. However, depending on the boundary conditions results may vary greatly. Cantilever measurements under no load present no difficulty, but especially for THUNDER™ actuators and bimorphs, several factors need to be taken into account. Holding the "active" parts of the actuator or the "inactive" part will produce slightly different results especially depending on where and how it is held. For instance, for unimorphs, it is normally specified that they should be held a particular distance from the edge of the actuator. Some recommended methods for clamping THUNDER™ devices are shown in Figure 2.

The displacement of a piezoelectric actuator depends upon the applied voltage, frequency, and force. While force can be considered to be a dependent variable, which is developed by an actuator, it is more helpful to consider it to be independent, where the force is applied to the actuator. In this way, confusion between external and inertial forces and between static and dynamic forces is minimized. The problem is clarified when the consideration is one of determining how forces are to be applied rather than how they are to be measured. The measurement problem is still present, and apparatus is still needed, but the system and its interactions are easier to understand. Details concerning the issues associated with force measurements for THUNDER™actuators and relevant comparisons with other high performance actuators are discussed in the next section.

Displacement measurement is quite simple. Whether the instrument is a non-contact type such as a laser-based device, or whether it is a contacting type such as an LVDT, the problem is simply one of accurately measuring the motion of a specified point on the actuator. Transducer accuracy can vary from quite coarse (mechanical dial gauges, for example, with 0.025 mm precision) to extremely fine (laser interferometers can resolve fractions of a micron) and the choice is largely dependent on experimental needs and cost. The instrument must be mounted to limit vibration and minimize interference with actuator motion, but these are mechanical limitations that are readily overcome. If a contact-type instrument is chosen it is more important, and more difficult, to avoid inertial effects that may distort measurements by changing the applied forces. It is easier to compensate for this aspect of experimental design when force is treated as an independent variable; the applied force can be adjusted as needed to take into account the inertial effects. It is much more difficult to try to calculate how developed forces are changed by the presence of a mass when amplitude can vary. The situation becomes even more complex when frequency is varied also.

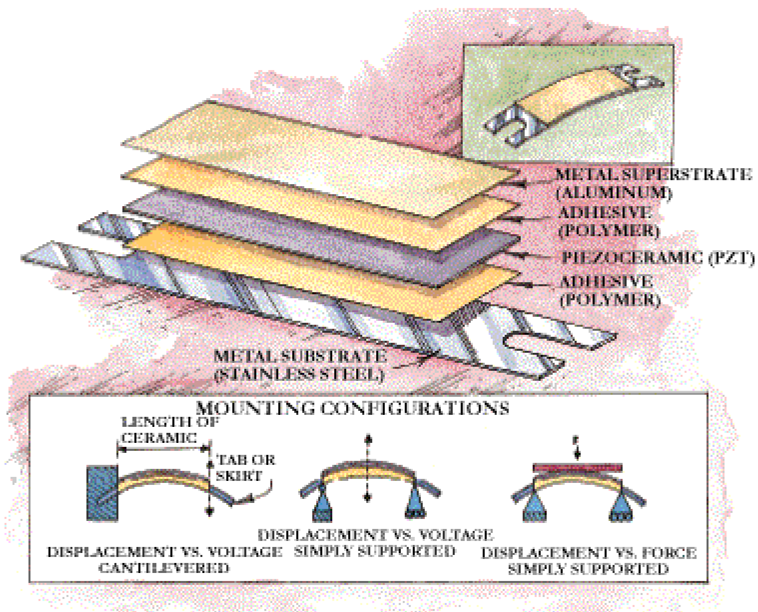


Figure 2. Typical THUNDER™ Device and its different clamping mechanisms[13]

4. Force Measurements

Due to its interpretation and variability, the reliable measurement of blocked force is often controversial. Giurgiutiu defines blocked force *as the point where the external load is such that the resulting output displacement is zero*[10]. This definition does not address the boundary conditions at which the actuator is subjected, i.e., simply supported or cantilevered, as well as a variety of other operating conditions.

The most difficult variable to measure is cantilevered blocked force. Assuming the mounting type is appropriate, several different techniques may be used. The most commonly used technique is through the use of load cells. Load cells come in a variety of ranges which make their selection difficult and cumbersome. Both the type selected and the manner in which the cell is placed over the actuator can produce different results. Therefore, when selecting an actuator, the manner through which force is measured becomes an issue. For instance, another definition of cantilevered blocked force is given as *the force observed on a gauge when holding the tip of the actuator during energization*[9].

Inertial effects are minimized when the system is operated at very low frequencies. If the operating frequency is selected so that inertial forces are much lower than the forces developed by the actuator, the interpretation of the results is greatly simplified. This is fine for low-frequency measurements, and it is the method used for developing force-displacement curves for THUNDER™. These curves are completely valid, as long as the absence of inertial factors is recognized. In

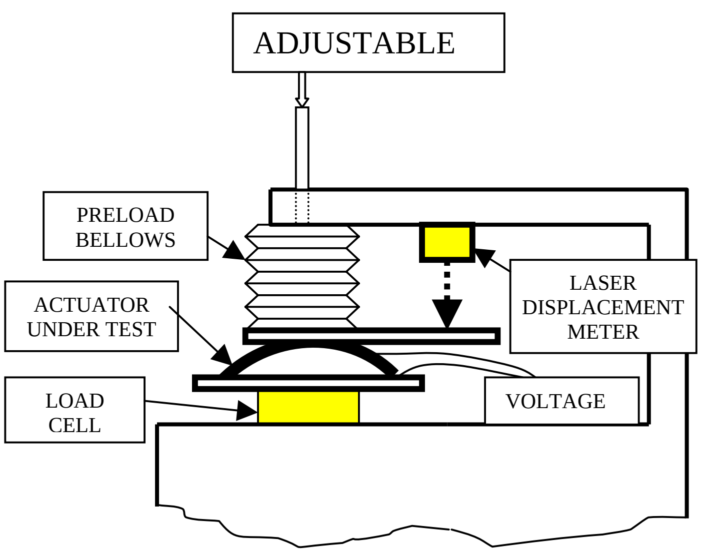
THUNDER™ actuators, it has been demonstrated that the generated force is independent of frequency when inertial forces are negligible.

When inertia cannot be ignored, whether because the frequency or the masses involved are too high, more care must be taken. The applied force must have minimal inertial components so that the use of a mass to develop the force is not acceptable. A hydraulic force must be used with care, since hydraulic fluids have significant mass. Forces generated by pneumatic means are useful, since air has a low mass; however, the piston or other pneumatic device may have too much mass or the resistance to fluid flow may be too high to be neglected. A bellows developing force from air pressure with an adequate reservoir and large tubing sizes seems an ideal low-inertia force generator but it too can cause serious problems since a bellows can have a significant spring force. Whether within the force generator or within a force measuring device, the presence of spring effects can cause even more difficult problems than inertial effects. If a bellows is used, it must have a very low spring constant. Such bellows are available, and they make very satisfactory force generators. Made from metal foils or polymer films, pneumatic bellows can combine the desired combination of low inertia and low spring constant.

Since force generators having the required properties are difficult to obtain, one might consider measuring the resultant forces rather than control the applied force. The difficulty is that most force measuring devices are unable to operate without restricting the motion of the actuator. A load cell can only move a very short distance over its full measuring range. A typical load cell only moves from 0.0254 to 0.10-mm[14]. Hence, the measuring device must be able to measure the force developed by the actuator over the full range of displacement without biasing the result with the force needed to move the device itself. Specifically, when measuring a curved structure such as THUNDER™ difficulties arise when attempting to use a load cell having a flat surface[15]. Using the method described by Kugel, et al., a significant scattering in the measuring of blocking force is obtained.

For that reason, a spring type force gauge is not satisfactory either. It measures force by compressing a spring and measuring the distance that the spring contracts or expands under the influence of the applied force. As the gauge moves, the exerted force changes. Only at the portion of the range where incremental changes in force result in very small gauge displacements can this method produce accurate results.

Design of an experiment that measures the force-displacement performance of an actuator requires careful selection of adequate equipment and instruments which this is not a trivial problem. Care and a complete understanding of the interactions between components of the system are essential to the success of the experiment. An example of a well-designed experimental setup used to measure simply supported piezoelectric actuator performance is provided by Marco Industries [16]. Figure 3 shows the essential components of the apparatus in which the actuator to be tested is positioned between a load cell having very low displacement under load and a constant force piston. (Since the original experiment was a test of a stacked piezoelectric actuator, developed forces are very high and inertial forces could be nominal without introducing significant errors. In that case a piston was acceptable as a driver). The displacement transducers are fixed to the upper end of the actuator, which is co-located with the force piston, and measure the motion of the platform supporting the lower end of the load cell. Thus, the displacement of the actuator plus that of the load cell is the measured variable. Since the load cell has minimal displacement, that of the actuator is the measured variable. Other variations of force measurement devices can be seen in Figure 4. This particular measurement technique is used for measuring piezostacks[17].



Notes:

- The force required to extend the bellows must be much less than the forces being measured.
- The load cell displacement under load must be much less than the displacements being measured.
- The supporting framework must not distort under load.
- The inertial loads at the test frequencies must be much lower than the forces being measured.
- The plate supporting the actuator must be rigid and must have a low coefficient of friction.
- The pneumatic pressure is adjusted to provide the desired preload force, measured by the load cell.
- Displacement is measured with reference to the displacement at zero preload and zero voltage.
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Figure 3. Recommended piezoelectric actuator force measurement apparatus

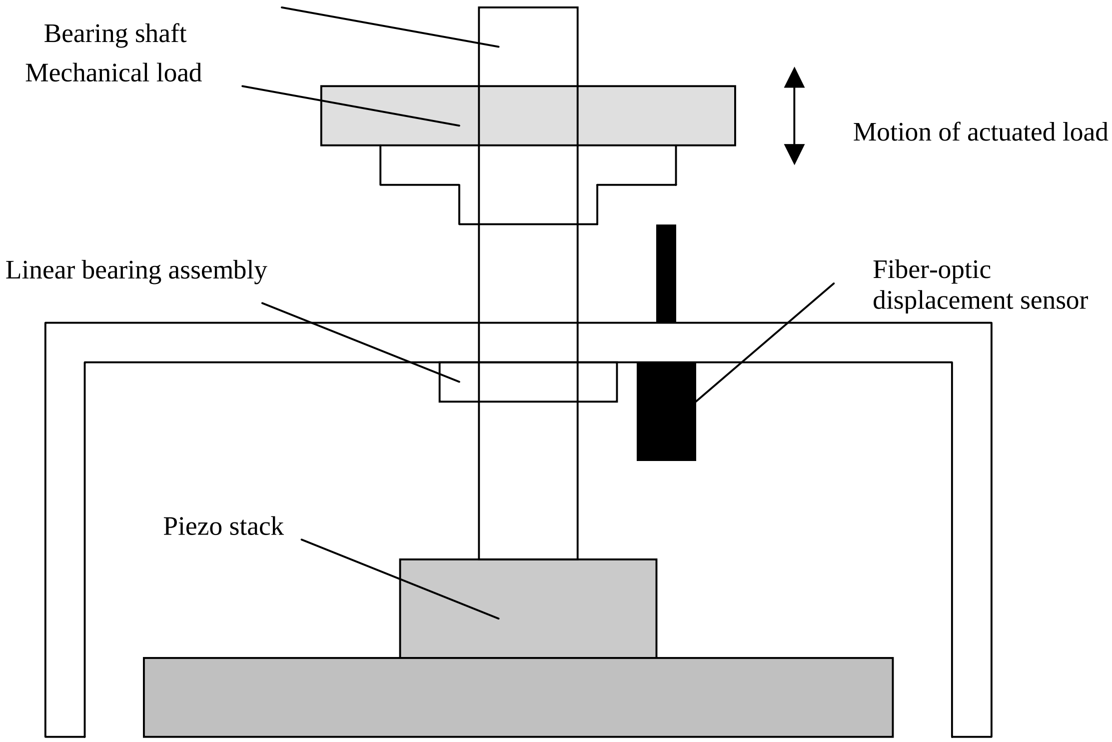

Figure 4. Test Configuration for measuring displacement properties of piezoelectric actuators under load [16]

The data obtained from the test apparatus shown in Figure 3 contains complete information on the performance of the actuator. The values of displacement versus force at zero applied voltage represent the static spring behavior of the actuator. Hysteresis values are obtained in complete detail for the representative THUNDER simulation depicted in Figure 5. The difference in displacement between the zero volt level and those values above zero voltage are the dynamic displacements.

In this experiment, all forces are static - that is, there are no inertial forces intentionally applied. To obtain dynamic forces, the frequencies applied or the masses moved must be high enough to bring inertial forces into play.

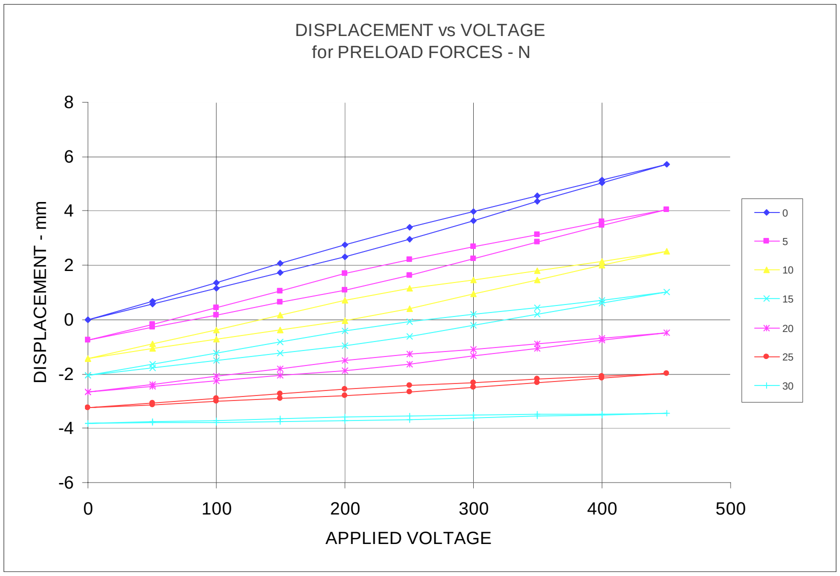

Figure 5. Representative THUNDER™ simulation of displacement vs voltage and preload force

5. Conclusions

This paper summarizes issues pertinent to the design of measurement criteria appropriate for high performance smart material transducers such as THUNDER™ actuators. Such criteria are necessary both to quantify the outputs of the transducers and to provide unambiguous methods for comparing these outputs to those generated by other smart material systems. The difficulties associated with force and displacement measurements for THUNDER™ actuators are compounded by the inherent curvature of the actuators as well as varying boundary conditions, frequency dependence and inertial effects. The advantages and disadvantages of various techniques for quantifying blocked forces are discussed and an appropriate setup employed by Marco Industries is described. In contrast, this provides an overview of issues which must be considered when characterizing certain high performance actuators or determining the optimal actuator for a given application.

References

1. C. D. Near, "Piezoelectric Actuator Technology," SPIE Conference, Vol. 2717, pp. 246-258
2. K. M. Mossi, G. V. Selby, and R. G. Bryant, "Thin-layer composite unimorph ferroelectric driver and sensor properties," *Materials Letters*, 35, pp. 39-49, 1998.
3. K. Mossi, G. Selby, and R. Bryant, "Electromechanical Characterization of a new class of piezoelectric devices," SAA No.326, April 8, 1997.
4. K. Mossi, R. Bryant, D. Bishop, "THUNDER™ - a New Family of High Performance Piezoelectric Devices to Enable Advanced Automation, Drive, Sensor and Motion Systems," AMD&C'98 proceedings, pp. 18–35, November 7-13, 1998.
5. Michael G. Gilbert, and Garnett C. Horner, "Actuator concepts and mechatronics," Proceedings of SPIE, Vol. 3326, pp. 214-222.
6. J. O. Simpson, S. A. Wise, R. G. Bryant, R. J. Cano, T. S. Gates, "Innovative Materials for Aircraft Morphing," Proceedings of SPIE, Vol. 3326, pp. 240-249.
7. M. W. Hyer, and A. Jilani, "Predicting the deformation characteristics of rectangular unsymmetrically laminated piezoelectric materials," *Smart Materials and Structures*, 7, pp. 1-8, 1998.
8. J. L. Pinkerton, A.R. McGowan, R.W. Moses, R. C. Scott, J. Heeg, "Controlled aerolastic response and airfoil shapping using adaptive materials and integrated systems," Proceeding of SPIE, Vol. 2717, pp. 166-177.
9. Paul Proctor, "Multifunction Antennas," *Aviation Week and Space Technology*, January 4, 1999.
10. M. Capozzoli, J. Gopalakrisnan, K. Hogan, J. Massad, T. Tokarchik, S. Wilmarth, H. T. Banks, K. M. Mossi, R. C. Smith, "Modeling Aspects Concerning THUNDER Actuators," CRSC Technical Report CRSC-TR99-06 ; Proceeding of the SPIE to appear on March 1999.
11. Victor Giurgiutiu, Zaffir Chaundhry, and Craig A. Rogers, "Energy-Based Comparison of Solid-State Actuators," Report No. CIMSS95-101, September 1995.
12. Piezo systems, Inc., Interim Catalog 2B, pp. 45, 1997.
13. Designer's Corver, "Extreme Effecter," *Design News*, July 20, 1998
14. Omega Catalog 99, Volume F, pp. F-10 – F-14, 1999.
15. V. D. Kugel, Sanjay Chandran, and L. E. Cross, "A comparative analysis of piezoelectric bending-mode actuators," SPIE Vol. 3040, pp. 70-80, 1997.
16. *marco: Quasimonolithic low-voltage actuator QNA*, www.marco.de/E/D/pa/qna/003.html.
17. Stephanie A. Wise, and Matthew W. Hooker, " Characterization of Multilayer Piezoelectric Actuators for use in Active Isolation Mouns," NASA Technical Memorandum 4742, March 1997.