Reliability Testing of NASA Piezocomposite Actuators

W. Wilkie, J. High, J. Bockman
U.S. Army Research Laboratory and NASA Langley Research Center, Hampton, Virginia, USA

Abstract:

NASA Langley Research Center has developed a low-cost piezocomposite actuator which has application for controlling vibrations in large inflatable smart space structures, space telescopes, and high performance aircraft. Tests show the NASA piezocomposite device is capable of producing large, directional, in-plane strains on the order of 2000 parts-per-million peak-to-peak, with no reduction in free-strain performance to 100 million electrical cycles. This paper describes methods, measurements, and preliminary results from our reliability evaluation of the device under externally applied mechanical loads and at various operational temperatures. Tests performed to date show no net reductions in actuation amplitude while the device was moderately loaded through 10 million electrical cycles. Tests were performed at both room temperature and at the maximum operational temperature of the epoxy resin system used in manufacture of the device. Initial indications are that actuator reliability is excellent, with no actuator failures or large net reduction in actuator performance.

Introduction

Piezoelectric fiber composite actuators were originally developed as a means of overcoming many of the practical difficulties associated with using monolithic piezoceramic actuators in structural control applications [1]. Chief among these difficulties were brittleness of piezoceramic materials, poor conformability, particularly when applied to non-planar structures, nondirectional nature of strain actuation, and overall low strain energy density. To increase conformability, first generation piezocomposite actuators were manufactured using a layer of extruded piezoceramic fibers encased in a protective polymer matrix material [2]. Strain energy density was improved by utilizing interdigitated electroding to produce electrical fields in the plane of the actuator [3]. In plane electrical fields allow the piezoceramic elements to produce nearly twice the strain actuation, and four times the strain energy density, of a through-plane poled piezoceramic device. The basic features of the interdigitated electrode piezocomposite concept are illustrated in Figure 1.

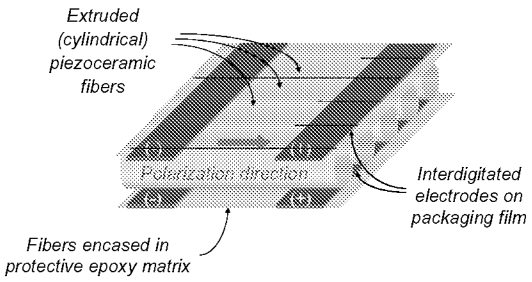

Figure 1. First generation piezocomposite actuator concept.

The two major disadvantages of first generation piezoelectric fiber composite technology were the difficulty of processing and handling expensive piezoceramic fibers during actuator manufacture, and the high actuator voltage requirements [4]. The initial piezoelectric fiber composites typically employed high cost, extruded, round cross-section piezoceramic fibers. Alternative methods of construction using individual square cross-section fibers, diced from lower cost monolithic piezoceramic wafers, were also attempted, although sharp corners and edges of rolled square fibers tended to damage or sever the interdigitated electrode fingers during the final actuator assembly process. Both round and square fiber approaches at the time required individual handling of piezoceramic fibers during the actuator assembly process, resulting in high manufacturing costs. An additional disadvantage associated with early piezoelectric fiber composite technology was high operating voltage requirements. Interdigitated electrode voltages are primarily driven by the spacing, or pitch, of the interdigitated electrode fingers used to produce the actuation electrical field. A problem with early piezocomposites which tended to drive voltages higher was attenuation of the driving electric field by unwanted accumulations of low dielectric matrix material between the electrodes and the piezoceramic elements. This manifested itself most notably as a reduction in the strain-per-volt electrical efficiency of the actuator.

The NASA Langley Research Center Macro-Fiber Composite actuator (LaRC-MFC) was developed to mitigate many of the manufacturing and performance disadvantages associated with early piezocomposites [5]. The LaRC-MFC retains the most advantageous features of the early piezocomposite actuators, namely, high strain energy density, directional actuation, conformability and durability, yet incorporates several new features, chief among these being the use of low-cost fabrication processes that are uniform and repeatable. In this paper, an overview of Langley Macro-Fiber Composite device technology will be presented, including details of actuator manufacturing and basic performance testing. The paper will conclude with a discussion of some results from a recent preliminary endurance test study performed on LaRC-MFC actuators operating under a variety of electrical, mechanical and thermal conditions.

NASA Piezocomposite Actuator Device

The principal components of the LaRC-MFC and their arrangement in the actuator package are illustrated in Figure 2. The LaRC-MFC actuator consists of three primary components: 1) a sheet of aligned rectangular piezoceramic fibers, 2) a pair of thin polymer films etched with a conductive electrode pattern and 3) a structural epoxy adhesive matrix.

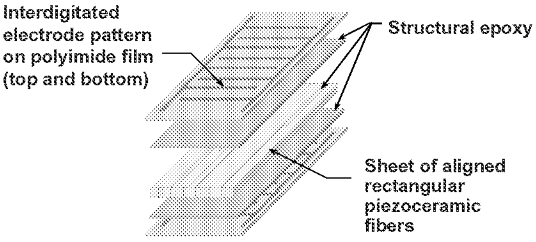

Figure 2. Langley Macro-Fiber Composite actuator components.

The piezoelectric fiber sheets in the LaRC-MFC are machined from low-cost piezoceramic wafers using a computer-controlled dicing saw. These sheets are easily handled and allow the piezoceramic fibers to be precisely aligned within the actuator package. Producing and handling the piezoceramic fibers in precise groups reduces the production cost of the device. This fabrication technique is also precise and repeatable, and easily automated. The electrode pattern used with the LaRC-MFC is supported on a dielectric film, which is used both as an electrode carrier and an insulator. This pattern is typically produced using standard photoresist-and-etch processes on commercially available copper-clad polyimide laminate film. Subsequent assembly consists of the application of an additional coat of adhesive to the fibers, placing the upper electrode film over the lower film, and curing the complete package under heat and pressure. This final consolidation step is typically performed in a vacuum press with heated platens. After assembly, a steady electrical field is applied to the actuator to pole the piezoceramic material. For an electrode finger spacing of 0.021 inches, 1500 volts at room temperature is sufficient to pole the PZT 5A type materials used with the standard MFC actuator, with complete poling achieved in approximately 5 minutes. A completed LaRC-MFC actuator package is shown in Figure 3.

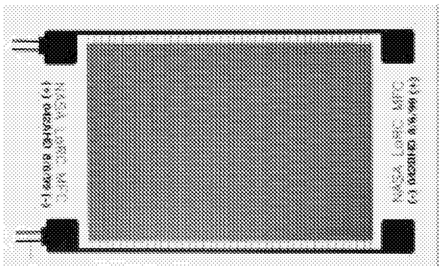

Figure 3. Langley Macro-Fiber Composite actuator device. (Device shown is approximately 3.5 by 2. 5 by 0.010 inches.)

LaRC-MFC Actuator Free Strain Performance

For many smart material devices, strain actuation characteristics under unloaded operating conditions and at low frequencies are typically the easiest measurements to obtain. These free-strain actuation measurements, combined with some knowledge of the actuator elastic properties, are often the best general indicator of overall actuator effectiveness. Maximum free-strain actuation capabilities of a typical LaRC-MFC device are illustrated in Figure 4. Shown are experimentally measured quasistatic actuation strains in the longitudinal (fiber) direction for the highest operational voltage cycle routinely used with the LaRC-MFC. These measurements were obtained using standard electrical resistance foil strain gages bonded to the top and bottom of a mechanically unconstrained actuator. A maximum peak-to-peak actuation strain of approximately 2000 parts-per-million in the longitudinal direction, as shown in the figure, is typical for all NASA LaRC-MFC devices. For comparison, maximum free-strain performance for a typical through-plane poled piezoceramic actuator device is also shown. As seen in the figure, the strain capability of the LaRC-MFC actuator is considerably larger than the through-plane poled "d_{31}" piezoceramic device.

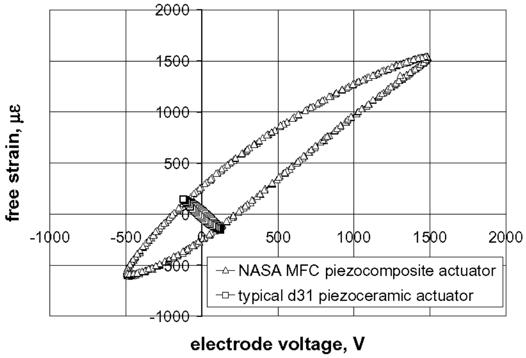

Figure 4. LaRC-MFC piezocomposite longitudinal (fiber-direction) free-strain actuation behavior.

In addition to high strain and stress actuation authority, high endurance under various electrical and mechanical cycling conditions is necessary for use in a practical active structure. The simplest endurance test to conduct again involves the measurement of unloaded actuation trends under repeated electrical cycling. This can be done easily by recording root-mean-squared actuation strains over time for some fixed voltage cycle and frequency condition. These tests are also easily performed at elevated and cryogenic temperatures. An example of typical room-temperature electrical endurance trends of LaRC-MFC devices operating under free strain conditions is shown in Figure 5.

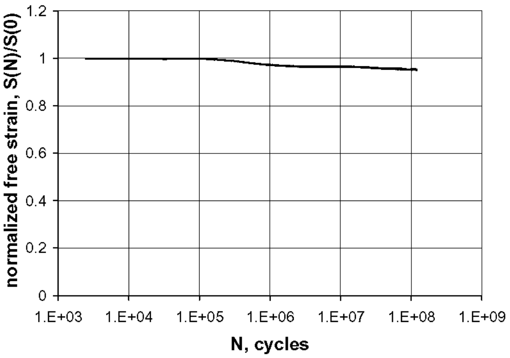

Figure 5. Normalized room temperature free-strain amplitude trend of LaRC-MFC actuator under repeated cycling (1500Vp-p, +300V bias, 500 Hz).

The data shown are from a life cycle test of a specimen operating continuously at 75% of the maximum rated package voltage. Trends in free-strain actuation over 100 million electrical cycles are shown. As seen here, a slight decrease in strain actuation amplitude is seen over the course of the test, although final actuation amplitudes were within 5% of the initial amplitude.

LaRC-MFC Actuator Performance Under Load

The lack of significant performance degradation in free-strain actuation capabilities is a good qualitative indicator of package reliability and endurance. A more interesting, and severe, test of actuator reliability is to conduct a similar test under static or dynamic externally applied mechanical loads. Preliminary results from an initial electromechanical endurance test, including testing at elevated temperatures, of a LaRC-MFC actuator are described below.

Special composite test coupons were fabricated to perform these tests. These coupons consist of a laminate of E-glass cloth on either side of a lengthened LaRC-MFC actuator (Figure 6).

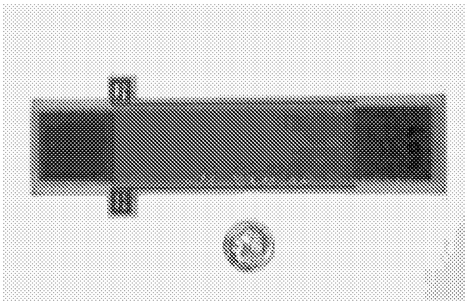

Figure 6. E-glass laminated actuator specimen for electromechanical endurance tests. (Coupon is approximately 5.5 inches long by 1 inch wide.)

Sandpaper tabs, bonded at either end of the laminate, provide a slip-free surface for gripping the test sample in a servo-hydraulic tensile testing system. Electrical resistance foil strain gages are also bonded to the outside of the coupon for monitoring and recording laminate strains during load testing. The hydraulic test system permits static and dynamic tensile loads to be applied to the actuator test coupon. For these initial endurance tests, only static load cases were examined. Once loaded, the LaRC-MFC coupon is electrically cycled while the tensile testing system hydraulic actuator, which grips the test coupon, is held fixed. Resulting changes in the tensile load amplitude, as measured by the test system load cell located beneath the bottom specimen grip, and strain amplitudes, as seen by the specimen strain gages, are then recorded and may be used as measures of actuator performance over time.

For this preliminary study, a moderate static load sufficient to induce a 1000 microstrain displacement in the coupon laminate was applied via the hydraulic tensile testing system. The maximum unbiased operational voltage (1kVp-p) for the LaRC-MFC actuator was also used. A fixed test frequency of 100 Hz was used throughout the endurance test. This frequency was deemed to be high enough to accumulate test cycles in a reasonable period of time, while low enough to avoid exciting resonances in the system. Normalized strain actuation amplitude trends for 10 million electrical cycles at two temperature conditions are presented in Figures 8 and 9.

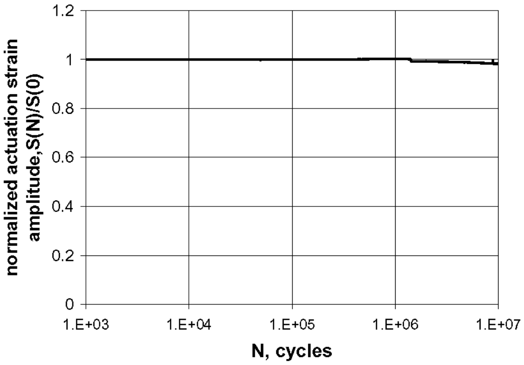

Figure 8. Strain actuation trends under 1000 microstrain static load at room temperature (30C, 1000Vp-p, 100 Hz).

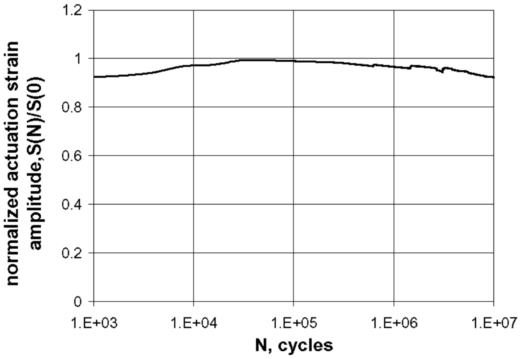

Figure 9. Strain actuation trends under 1000 microstrain static load at elevated temperature (65C, 1000Vp-p, 100 Hz).

Actuation trends at room temperature are shown in Figure 8. Only a slight degradation in amplitude was seen over the test run. Trends at an elevated temperature of 65C are shown in Figure 9. Operation at this temperature is of particular interest as manufacturer provided data indicate a fall-off in shear strength of the epoxy system used in manufacturing the standard LaRC-MFC actuator at temperatures above this point. In contrast to the room temperature case, some variation is seen in the actuation strain amplitude over time, although no net downward trend was observed.

Conclusions

This initial evaluation of the operational endurance of the NASA Langley Macro-Fiber Composite (LaRC-MFC) actuator device indicates that the actuator performs well when subjected to moderate static mechanical loads, including operation at moderately elevated temperatures. Guided by these preliminary results, a more extensive testing program is now underway with the objective of determining load and temperature failure limits for the LaRC-MFC piezocomposite actuator.

References

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