RECENT DEVELOPMENTS IN NASA PIEZOCOMPOSITE ACTUATOR TECHNOLOGY

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Abstract:
In this paper, we present an overview of recent progress in the development of the NASA Macro-Fiber Composite (MFC) piezocomposite actuator device. This will include a brief history of the development of the MFC, a description of the standard manufacturing process used to fabricate MFC actuators, and a summary of ongoing MFC electromechanical characterization testing. In addition, we describe the development of a prototype single-crystal piezoelectric MFC device, and compare its performance with MFC actuator specimens utilizing conventional piezoceramic materials.

Keywords: piezoelectric actuators, piezoelectric fiber composites

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. Strain energy density was improved by utilizing interdigitated electrodes to produce electrical fields in the plane of the actuator. 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 NASA Langley Research Center Macro-Fiber Composite (MFC) actuator [2] was developed to alleviate many of the manufacturing and performance disadvantages associated with early piezocomposites [3]. The MFC (see Fig. 1) 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 [4, 5].

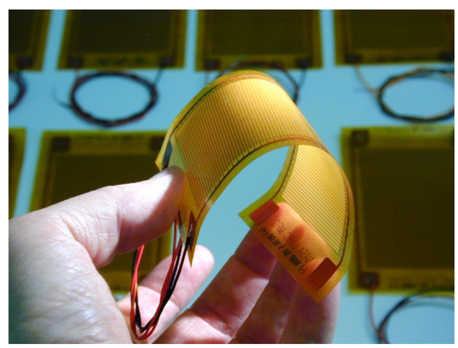

Fig. 1: *NASA Macro-Fiber Composite actuator.*

The principal components of the MFC and their arrangement in the actuator package are illustrated in Fig. 2. The piezoelectric fiber sheets used in assembling the MFC are machined from low-cost piezoceramic wafers using a computer-controlled dicing saw. The sheets are easily handled and allow the piezoceramic fibers to be precisely aligned within the actuator package. Producing and handling piezoceramic fibers in precision groups, versus individual pieces, minimizes variations in the active and passive properties of the actuator

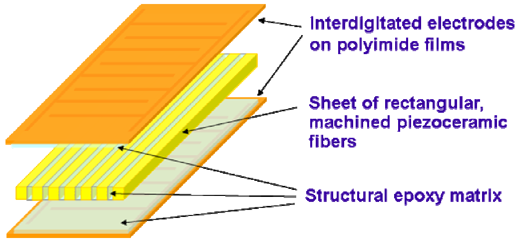

Fig. 2: *General arrangement of Macro-Fiber Composite actuator components.*

package. Production costs associated with handling and manufacturing of individual piezoceramic fibers are also reduced. The flat surfaces of the piezoceramic fiber elements also permit direct contact with the interdigitated electrodes, which minimizes electric field attenuation by the low dielectric epoxy matrix. As a result, actuation performance of MFC piezocomposites tends to be greater (150%) than the earlier round piezoceramic fiber piezocomposites, which often suffer from poor or inconsistent electrode contact.

The MFC has proven to be particularly useful in a variety of rotary-wing and fixed-wing aeronautical applications, ultra-lightweight spacecraft structures applications, and several recent automotive applications. In this paper, we present an overview of our most recent work in the development of the NASA MFC actuator device. In particular, we detail results from an extensive engineering properties characterization effort on laboratory reference MFC specimens, and describe our experiences in developing a single-crystal piezoelectric MFC actuator device.

Engineering properties of MFC devices

While some MFC engineering properties, either estimated, or experimentally measured, have existed for some time, a complete and experimentally validated set of orthotropic mechanical properties, including low-field to high-field piezoelectric constants, has only recently become available [6]. These properties, which are summarized here, were determined by measurements performed on laboratory reference MFC devices (see Fig. 3). The reference MFC differs from typical MFC geometries in that piezoceramic fibers extend longitudinally beyond the edges of the active electrode field region. This is done to provide areas for bonding grip tabs to the specimens when conducting tensile mechanical tests. The reference MFC device is otherwise constructed using the standard MFC manufacturing method and materials.

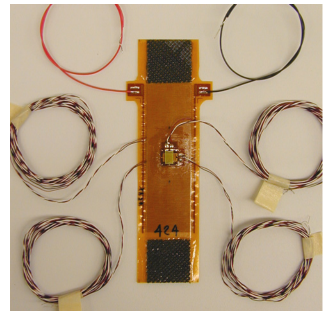

Fig. 3: *Typical reference MFC device used for electro-mechanical properties testing. Specimen is 140 mm x 25 mm x 0.3 mm, approx., including tabs.*

Measured maximum free-strain actuation capabilities of a typical reference MFC device are illustrated in Fig 4. This maximum peak-to-peak actuation strain of approximately 2000 parts-per-million in the longitudinal direction is typical for all NASA-standard MFC devices. The free-strain output of the MFC, as with most piezoceramic devices, varies considerably with the driving electric field amplitude. This variability in effective piezoelectric constants (d_{33}, d_{31}) is nonlinear, but repeatable as seen in Fig. 5.

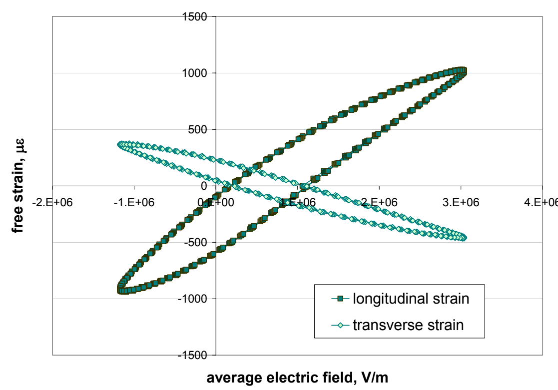

Fig. 4: *Maximum free-strain response of reference MFC device.*

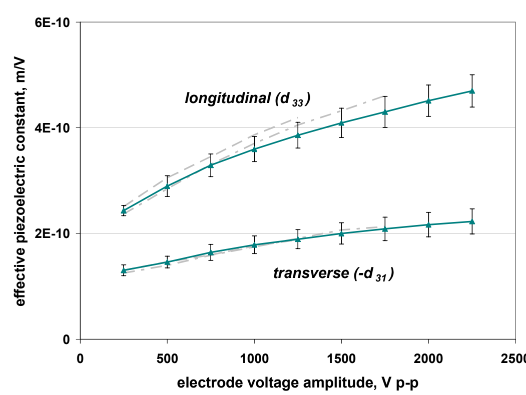

Fig. 5: *Field amplitude dependence and repeatability of reference MFC piezoelectric constants; 1-σ error bars shown.*

Short-circuit stress-strain characteristics of the reference MFC under tensile loading conditions are shown in Fig. 6. In all cases, coupon-to-coupon variations in the elastic properties were small, indicating a high degree of repeatability in the MFC manufacturing process. This experimental program has allowed us to develop and validate several useful analytical micromechanics models for predicting MFC elastic properties [6]. These models most recently have been used to design application-specific MFC laminates, and perform parameter variations studies on the standard MFC package geometry.

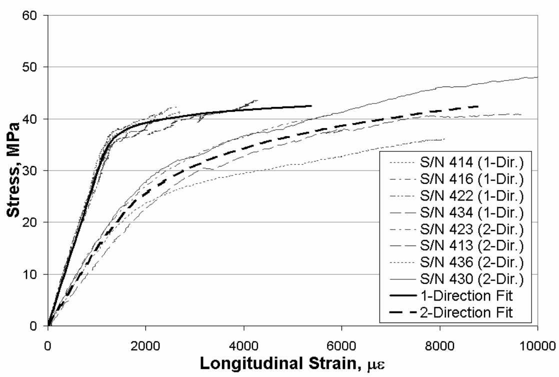

Fig. 6: *Short-circuit tensile properties of reference MFC actuators.*

Single-crystal MFC piezocomposites

Single crystal piezoelectric materials have been the subject of much recent attention due to their promising high-performance piezoelectric properties [7]. Only in the past several years have these materials become commercially available in sizes and quantities suitable for constructing large-scale actuator devices [8]. The authors have successfully constructed and tested one such single-crystal piezoelectric actuator utilizing standard MFC fabrication techniques [9]. A photograph of the prototype single-crystal MFC, which utilizes machined PMN-PT single-crystal fibers in place of conventional piezoceramic fibers, is shown in Fig. 7.

Free strain performance of the prototype single crystal device was measured under quasistatic conditions and compared with geometrically identical devices which use conventional piezoceramic materials. Free-strain response of the PMN-PT specimen is compared with that of a reference specimen constructed with the MFC baseline PZT-5A material and a specimen utilizing an alternative PZT-5H ceramic material. Typical unipolar high-field quasistatic response is shown in Fig. 8.

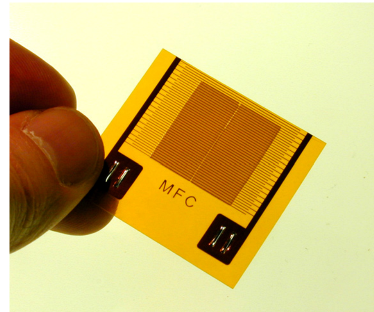

Fig. 7: *Prototype PMN-PT single-crystal MFC piezocomposite actuator. Active area is 20 mm x 20 mm.*

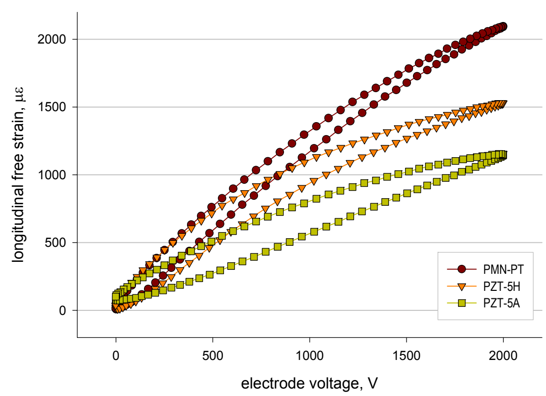

Fig. 8: *Free-strain performance of single-crystal and piezoceramic MFC devices under quasistatic unipolar operation.*

The free-strain of the single-crystal piezocomposite was significantly greater than both of the piezoceramic reference specimens under all voltage conditions. This is qualitatively consistent with expectations based upon the bulk material piezoelectric d_{33} constants of the three specimens, although a large electric field amplitude dependence in effective d constants was observed (see Fig. 9), with a greater relative benefit realized with the single crystal material at lower driving electric fields.

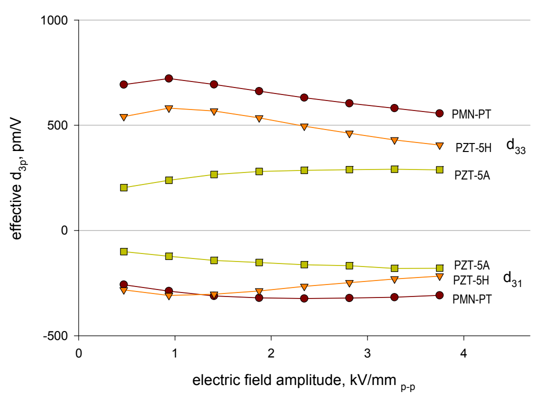

Fig. 9: *Electric field amplitude dependence of piezoelectric constants for single crystal and standard piezoceramic MFC devices.*

Using the micromechanics models developed for the conventional MFC, and bulk material data for the PMN-PT single crystal materials, elastic properties of the single-crystal MFC device were estimated. These calculated properties, taken with the measured free-strain actuation behavior, allow us to estimate the useful working range of a single-crystal MFC when operating against an elastic constraint, e.g., when bonded to, or imbedded within, a non-active material host structure (see Fig. 10).

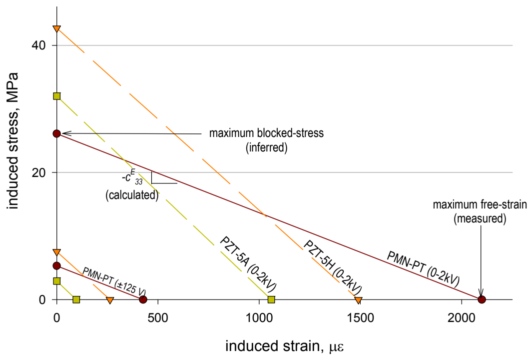

Fig. 10: *Estimated stress and strain actuation envelope of single-crystal and piezoceramic MFC devices.*

The triangular areas indicate the regions of induced stress and strain actuation producible for bipolar, low-voltage operation and unipolar, high-voltage operation. Dashed lines indicate the corresponding operational envelopes of the PZT-5A reference MFC and the PZT-5H alternate MFC device. This diagram suggests that the low stiffness (estimated) and high strain properties of the PMN-PT single crystal MFC make it best suited to low-stress, high strain applications. In particular, if only very low driving are available, vis, the smaller triangle region, the PMN-PT device can outperform the reference PZT-5A device under all circumstances. For higher induced stress applications, the piezoceramic devices, with their higher stiffness properties, will be preferred to the single-crystal MFC device studied here.

Conclusions

Our extensive electromechanical characterization effort of the NASA Macro-Fiber Composite actuator has shown that it has predictable and repeatable linear elastic properties, and repeatable non-linear actuation properties. The successful initial tests of a prototype single-crystal MFC device indicate that the manufacturing methods used to construct standard piezoceramic MFC actuators may be used without modification to construct practical single-crystal piezoelectric composite actuators with actuation properties superior to the conventional piezoceramic-based piezocomposite actuators.

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