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Solid-State Ceramic Actuator Designs

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Smart electromechanical systems consist mainly of sensors, actuators, and data processing units. Actuators are the responding units of many smart systems including those for active vibration control and noise control. Increased demand for actuators with high-displacement, high generative force, and quick-response time has led to a search for new actuator materials and new designs. The performance of traditional piezoelectric transducers with newly designed flextensional transducers is compared.

I. Introduction

ONE of the qualities that distinguishes living systems from inanimate matter is the ability to adapt to changes in the environment. Smart materials have the ability to perform both sensing and actuating functions and are, therefore, capable of imitating this rudimentary aspect of life. In this review, we focus on actuator materials and solid-state actuator design. The need for high-accuracy displacement elements in such fields as optics, precision machinery, and small motors has led to renewed emphasis on displacement devices.

II. Actuators (Displacement Transducers)

Displacement transducers can be classified into two main groups: conventional displacement transducers and solid-state actuators (Fig. 1). There are three types of conventional displacement transducers: oil pressure cylinders, servo- or step motors, and voice coils. The oil pressure cylinder operates on hydraulic principles, where the displacement piston is driven by oil pressure from another piston. The principal disadvantages are large space requirements and long response times. The servo- or step motor converts the revolutions of an electromagnetic motor into linear movement by using a gear mechanism. Mechanical backlash is a difficult problem for servo-/step motor displacement transducers. The voice coil (speaker) operates through a combination of electromagnetic coils and springs. The generative force of the voice coil is small compared to its input power, and its response time is slow. Each of the conventional displacement devices is capable of generating large displacements in the millimeter to centimeter range, but they are inadequate for precise positioning in the micrometer range. Figure 2 shows the basic designs of conventional actuators.

III. Solid-State Actuators

A second category of displacement transducers consists of a number of different solid-state actuators. The characteristics of the solid-state actuators are summarized in Table 1. This group can be further classified into three categories based on the type of driving mechanism: 1) shape memory effect (thermal drive), 2) magnetostriction (magnetic drive), and 3) piezostriction/electrostriction (electrical drive).

A. Shape Memory Effect

The shape memory effect is a consequence of a crystallographically reversible martensitic phase transformation occurring in the solid state.[1,2] After deformation at low temperature, a shape memory alloy will regain its original shape when heated above the phase transition temperature. The shape memory effect can be classified as either a one-way memory or a two-way memory. For the one-way memory effect, the deformed sample recovers its undeformed shape on heating in a one-time only operation. This undeformed shape then remains constant when the sample is subjected to thermal cycling. In the two-way memory, the shape memory effect is tied to the occurrence of a martensitic phase transformation during cooling and its subsequent reversal during heating. Thermal cycling can be repeated indefinitely. A schematic comparing one-way with two-way memory is shown in Fig. 3.

Shape memory alloys can exhibit large recoverable strains as large as 7%. Because of these large recoverable strains, shape memory alloys have been proposed as alternatives for solenoids, motors, and bimorph-type actuators, as well as for use in flexible robot structures.[3] However, the large thermal energy requirements for martensitic phase transformation together with large hysteresis and long response times are important drawbacks for shape memory alloys. Some of the important shape memory materials are Nitinol, a Ni–Ti alloy, as well as alloys of Cu–Zn–Al and Cu–Al–Ni.

B. Magnetostriction

Magnetostriction is defined as the change in dimension of a magnetic material caused by a change in its magnetic state.[4] Magnetostrictive materials can be used as both sensors and actuators. The magnetostrictive strain arises from a reorientation of the atomic magnetic moments. High-power magnetostrictive actuators can produce forces exceeding 50 MPa with strains on the order of 0.6% (Ref. 5). High reliability, ruggedness, and imperviousness to adverse environmental conditions are the advantages of magnetostrictive materials. However, magnetostrictive materials have the problems of requiring a coil to create the necessary magnetic field. This, in turn, induces noise into adjacent electronic circuits and devices. The most important commercial room temperature magnetostrictive material is Terfenol-D, a $Tb_xDy_{1-x}Fe_2$ alloy. The strain vs magnetic field curves for Terfenol-D rods under various conditions of prestress are shown in Fig. 4 (Ref. 6).

C. Piezoelectricity

Piezoelectricity is the phenomenon whereby electric polarization is generated in certain acentric crystals when they are subjected to mechanical stress, that is, the direct effect. Materials showing this phenomenon must also show a geometrical strain x, which is proportional to the applied electric field E, which is known as the converse effect, that is, $x = \mathrm{d}E$. Natural crystals such as quartz, tourmaline, and zincblende are the classical piezoelectric materials. For many years, these materials have served as transducers for converting mechanical energy into electrical energy and vice versa.[7] In general, natural crystals have rather low piezoelectric coefficients. Ceramic piezoelectric materials were developed in the second half of the 20th

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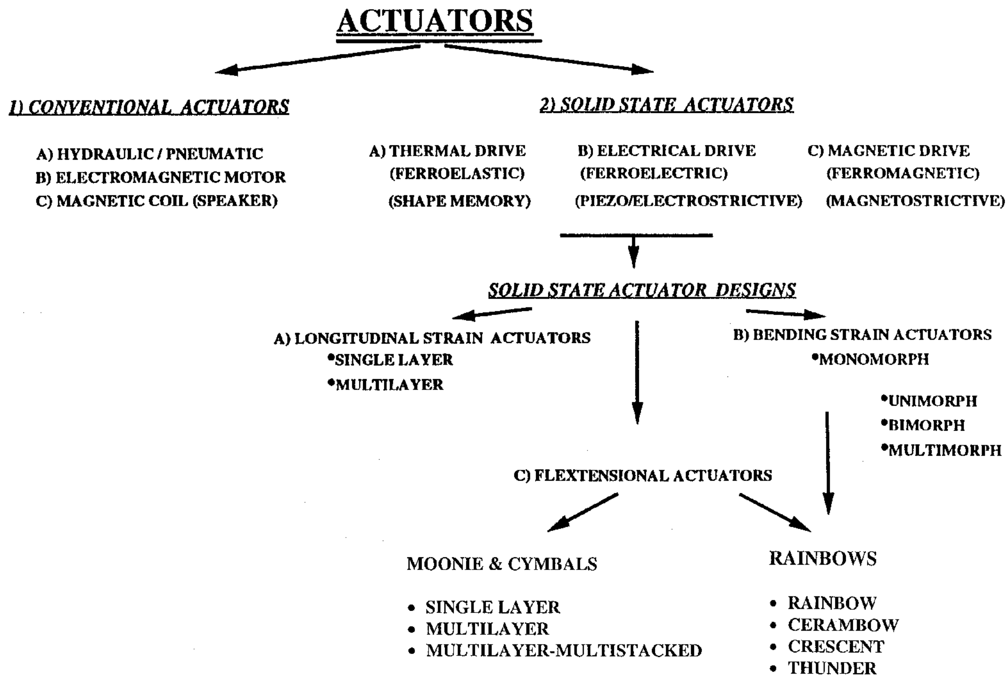


Fig. 1 Classification of actuators.

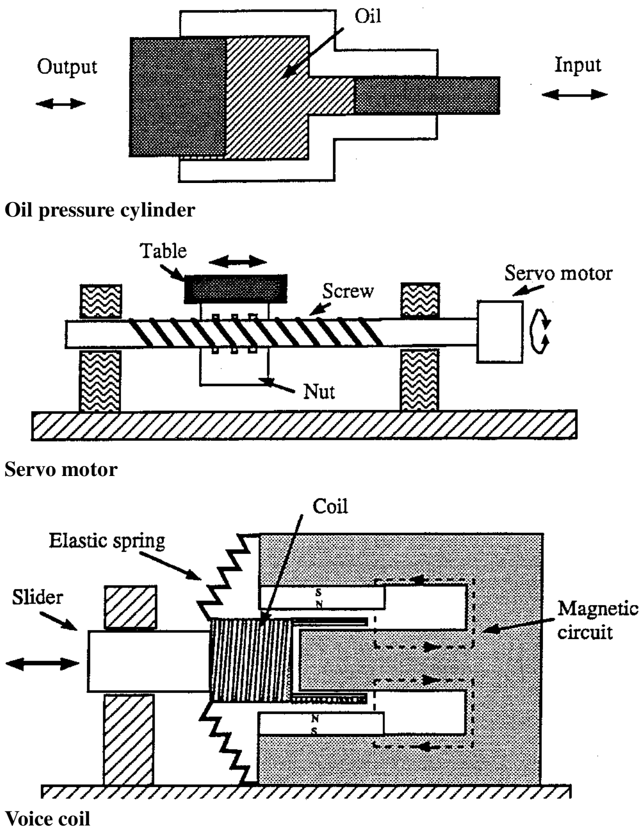


Fig. 2 Structure of the conventional actuators.

century and have been constantly improved since then. Modified lead zirconate titanate [Pb(Zr, Ti)O_3] ceramics (commonly known as PZT) are the leading materials for piezoelectric applications.[8]

The strain curve of a lanthanum-modified lead zirconate titanate, PLZT [(Pb, La)(Zr, Ti)O_3] (7/62/38), is shown in Fig. 5a (Refs. 9 and 10). The induced strain is nearly proportional to the applied field for low field levels. However, the strain curve deviates from this linear trend, and significant hysteresis is exhibited due to domain reorientation as the field becomes larger.

The magnitude of the piezoelectric coefficients depend markedly on dopants and defect structure because of their influence on domain wall motion. This in turn controls the nature of the hysteresis loop in the piezoelectric ceramic. The interaction of the domains and defects leads to so-called soft and hard piezoelectric compositions. Piezoelectrically soft materials are characterized by high piezoelectric constants and high hysteresis as a result of relatively mobile domain walls. In hard piezoelectric ceramics, the domain wall motion is inhibited, resulting in lower piezoelectric constants and reduced hysteresis. Soft piezoelectric materials are preferred for most multilayer and bimorph actuator application because of their high strain. For some actuator applications, which require nonhysteretic response, hard piezoelectric ceramic can be preferable.

Solid solutions of barium tin titanate [Ba(Sn, Ti)O_3] are an interesting new family for actuator applications.[11] Because of its small coercive field, the composition [$Ba(Sn_{0.15}Ti_{0.85})O_3$] exhibits an unusual strain curve, in which domain reorientation occurs only at low fields. This is followed by a long linear range at higher fields (Fig. 5b).

D. Electrostriction

When an electric field is applied to a centrosymmetric dielectric material, it produces a strain proportional to the square of the field. This phenomenon is called the electrostrictive effect. The strain x is approximately equal to ME^2, where M is the field electrostrictive coefficient and E is the electric field. For high-permittivity solids, however, electrostrictive strain is proportional to the square of the polarization, that is, $x = QP^2$, where Q is the electrostriction coefficient and P is the polarization. Because electrostriction is a result of the polarization induced by the applied field, electrostriction may occur in all crystals whether or not the crystals have polarity.

Electrostriction in PMN [$Pb(Mg_{1/3}Nb_{2/3})O_3$] ceramics is extraordinarily large, with strains exceeding 0.1% (Ref. 12). An interesting feature of these materials is the near absence of hysteresis. Figure 6 shows the strain hysteresis of a PMN–PT [($Pb(Mg_{1/3}Nb_{2/3}O_3)$–($PbTiO_3$)] ceramics. Displacement of the piezoelectric ceramics can be positive or negative depending on applied electric field. Electrostrictive oxide ceramics generally elongate parallel to the applied field and contract perpendicular to the field, but polymers such as PVDF contract in the field direction.

E. Phase-Transition Related Strain

The phase transition from an antiferroelectric to a ferroelectric phase can induce larger strains than those found in either piezoelectric or electrostrictive materials.[13,14] A unique characteristic of the phase transition-induced strain in the antiferroelectric phase is its

Table 1 Comparison of solid-state actuators

Characteristic	Piezoelectric	Electrostrictive	Magnetostrictive	Shape memory
Ferroic class	Ferroelectric	Ferroelectric	Ferromagnetic	Ferroelastic
Switching force	Electric field	Electric field	Magnetic field	Thermal stress
Maximum strain, % (Ref.)	0.1 (8 and 10)	0.1–0.2 (12 and 15)	0.1–0.2 (5)	7–10 (1)
Fastest response	μs	μs	μs	s
Generative force, N/cm^2	3,500	5,000	3,500	20,000
Efficiency, %	50	50	80–90	3
Example	Pb(Zr, Ti)O_3	Pb($Mg_{1/3}$,$Nb_{2/3}$)O_3	Terfenol D (Tb, Dy)Fe_2	Nitinol $Ni_{1-x}Ti_x$

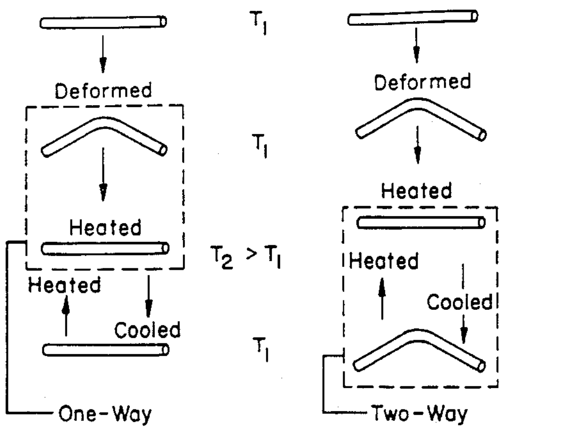


Fig. 3 Schematic comparing one-way and two-way shape memory effects.[1]

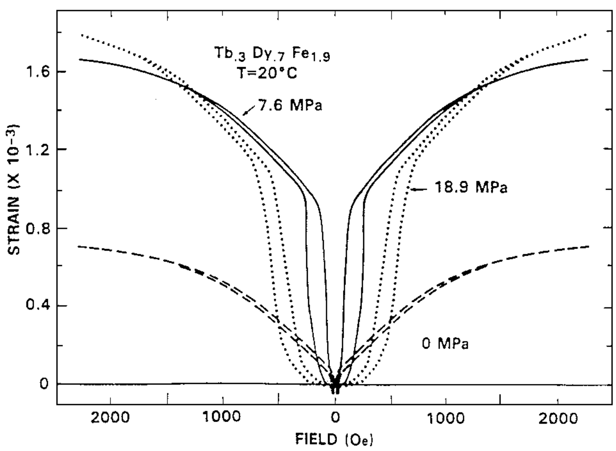
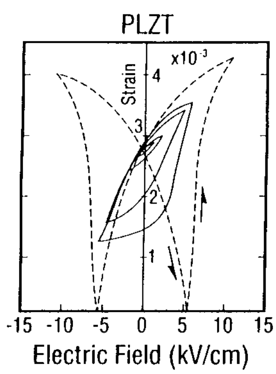
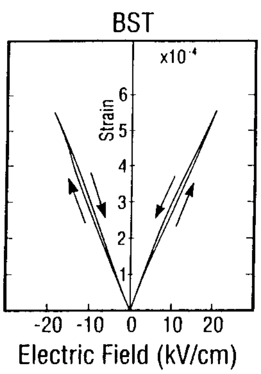


Fig. 4 Strain hysteresis of a magnetostrictor (Terfonal D) under varying compressive stress.[5]



a) (Pb, La)(Zr, Ti)O_3 (Refs. 9 and 10)



b) Ba(Sn, Ti)O_3 (Ref. 11).

Fig. 5 Electric field-induced strain hysteresis of piezostrictors.

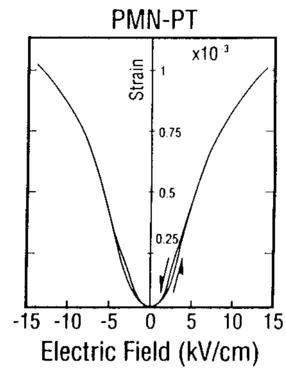
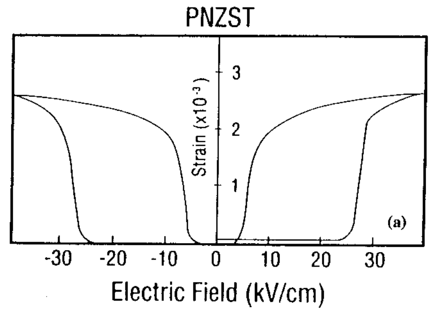
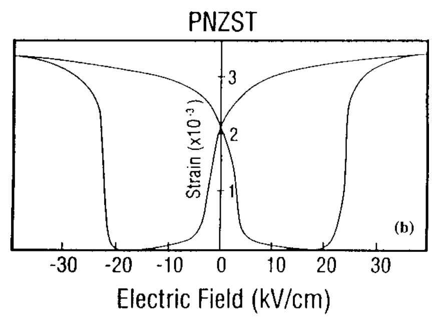


Fig. 6 Electric field-induced strain hysteresis of electrostrictor Pb($Mg_{1/3}$ $Nb_{2/3}$Ti)O_3 (Refs. 12 and 15).



a) DIGITAL DISPLACEMENT



b) SHAPE MEMORY

Fig. 7 Phase transition related strain in Nb-doped Pb(Zr, Sn, Ti)O_3 (Refs. 14 and 17).

isotropic volume expansion, similar to thermal expansion.[15,16] With appropriate compositions, piezoelectric/electrostrictive materials can exhibit two kinds of phase transitions related to strain: a shape memory effect and digital displacement.

Figure 7a shows the strain hysteresis of $Pb_{0.99}Nb_{0.02}[(Zr_{0.6}Sn_{0.4})_{1-y}Ti_y]_{0.98}O_3$ (also known as PNZST), which exhibits a shape memory effect.[17] Once the ferroelectric phase has been induced, it is retained even at zero electric field. It can, however, be erased with the application of small reverse bias fields. This shape memory ceramic is used in energy-saving actuators.[18]

On the other hand, for the phase transition-related digital displacement, two well-defined (on/off) strain states can be achieved. A rectangular-shape hysteresis for a digital displacement transducer is shown in Fig. 7b. The longitudinally induced strain approaches

0.1%, which is rather large when compared to the normal piezostrictors and electrostrictors.

The fundamental characteristics of solid-state ceramic actuators can be summarized as follows: There are displacements of up to several tens of micrometers that can be controlled with a precision of 0.01 μm. Response speeds are on the order of 1–5 μs. Generative forces are as large as 3500 N. Driving power is an order of magnitude smaller than electromagnetic motors.

IV. Solid-State Ceramic Actuator Designs

Standard ceramic actuators are classified into two groups based on their displacement mechanism: linear or bending.[19] A linear type exhibits longitudinal displacement. On the other hand, a bending type exhibits bending displacement and reaches the highest value at the tip of the free end of the actuator. Multilayer actuators and single plates are linear displacement transducers. Monomorphs, unimorphs, bimorphs, and multimorphs are examples of bending displacement transducers (Table 1).

The most common examples of these two classes of actuators are multilayers and bimorphs. Figure 8 shows the structure of multilayer actuators and bimorphs, respectively. The multilayer actuator is composed of a number of ceramic layers alternating with internal electrodes. Individual internal electrodes are electrically connected in parallel with two external electrodes attached to the sides. When an electric field is applied to the element, the element expands along the longitudinal direction in accordance with the converse piezoelectric effect. Important features of multilayer ceramic actuators are low driving voltage (100 V), quick response (10 μs), high generative force (3.0 kN), and high electromechanical coupling.[18–20] However, they only exhibit displacements in the range of 10 μm, which may not be sufficient for some applications.

Bimorphs usually consist of two thin ceramic sheets bonded together with their poling directions opposed and normal to the interface. When an electric field is applied to a bimorph, one of the plates expands while the other contracts. This mechanism creates a bending displacement. In contrast to the multilayer actuator, bimorphs are capable of generating large bending displacements of several hundred micrometers, but the response time (1 ms) and the generative force (1.0 N) are low.

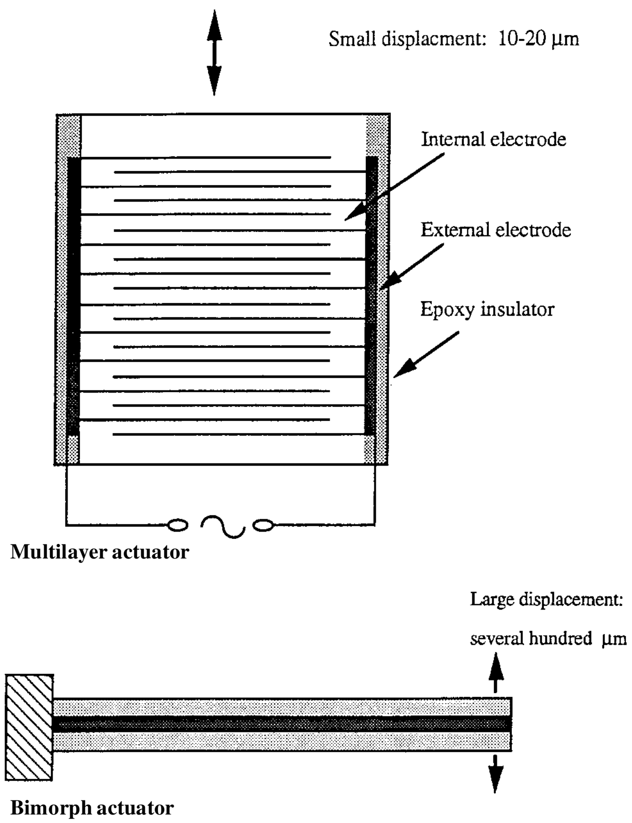


Fig. 8 Two common types of ceramic actuator designs.

When we compare multilayer and bimorph actuators based on three important characteristics (displacement, generative force, and response time), there is a sizeable gap between them with respect to performance. Neither provides both a relatively large displacement coupled with an intermediate level of generative force, but recently there has been extensive effort to design new actuators to fill this gap. The moonie, the cymbal, the reduced and internally biased dome-shaped oxide wafer (RAINBOW), the thin-layer composite unimorph ferroelectric driver and sensor (THUNDER), and the cerambow are new designs developed within the past 10 years. These new designs provide moderate displacements in conjunction with moderate generative force. Basically all of the new designs exhibit bending or flextensional displacements (Fig. 9).

V. Flextensional Transducers

Flextensional transducers are mechanical amplifiers that couple the longitudinal strains in a ceramic bar or disk to the radial flexure of a metal or ceramic shell. The concept of the flextensional transducer originated from the electroacoustic foghorn used for ship navigation in the early 1920s.[21] The theory and design of flextensional transducers was explained by Hayes in 1936 (Ref. 22). Hayes used magnetostrictive materials as the drive element in the foghorn design. Toulis applied this concept to the underwater electroacoustic transducer.[23] Flextensional transducers were classified into five different classes based on their shapes and mode of operation.[21,24] Class IV transducers are the most intensively studied, best understood, and most widely used underwater transducers. Class V flextensional transducers contain two spherical cap shells joined to a radially vibrating ring or dish.

A simplified version of the flextensional or bending transducer emerged in the early 1990s. The basic idea behind the flexural transducer is to convert some of the lateral dilation in the planar direction to the longitudinal direction and thereby increase the longitudinal displacement. Newnham et al.[25] devised a simple, compact type of flextensional transducer, the moonie. With its unique properties the moonie has been investigated for many potential applications. The cymbal is the improved version of the moonie transducer, with higher efficiency, displacement, and generative force.[26] RAINBOW is another new type of transducer.[27] Flextensional designs referred to as cerambow, THUNDER, and crescent are the latest generation transducers derived from RAINBOW structure.[28]

A. Flextensional Moonie Transducer

A moonie consists of a piezoelectric or electrostrictive ceramic disk sandwiched between two metal endcaps, each having a crescent-moon-shaped cavity on its inner surface (hence the name moonie) (Fig. 10). These metal endcaps serve as mechanical transformers for converting and amplifying the lateral displacement of the ceramic into an axial motion normal to the endcaps. Both the d_{33} and d_{31} piezoelectric coefficients contribute to the axial displacement of the composite.[29,30] The design is analogous to a continuous ring of bimorphs whose free ends merge at the center of a circle. Furthermore, because the structure is three dimensional, generative forces larger than those produced by a bimorph alone are generated. Thus, the moonie actuator shows higher generative forces than a bimorph and higher displacements than a multilayer actuator.

The geometry of the endcap affects the displacement characteristics of the moonie actuator. Cavity diameter, cavity depth, and endcap thickness are the main geometrical parameters that play important roles in moonie actuator performance. The displacement of a moonie actuator increases rapidly with increasing cavity diameter.[31] Displacement of the moonie actuator is inversely proportional to the endcap thickness. A maximum displacement of 22 μm can be obtained at a center of the moonie actuator 12.7 mm in diameter and 1.7 mm in total thickness. Incorporating a multilayer ceramic in the moonie design reduces the drive voltage to a more practical 100 V (Fig. 11). By stacking the multilayer moonie actuators together, higher displacement values can be obtained, for example, for five-multilayer moonie stacks, it was 105 μm. Displacement also increased with increasing compliance of the endcap material.[32]

Generative force and displacement values of the moonie actuator are position dependent. Generative force increases when moving

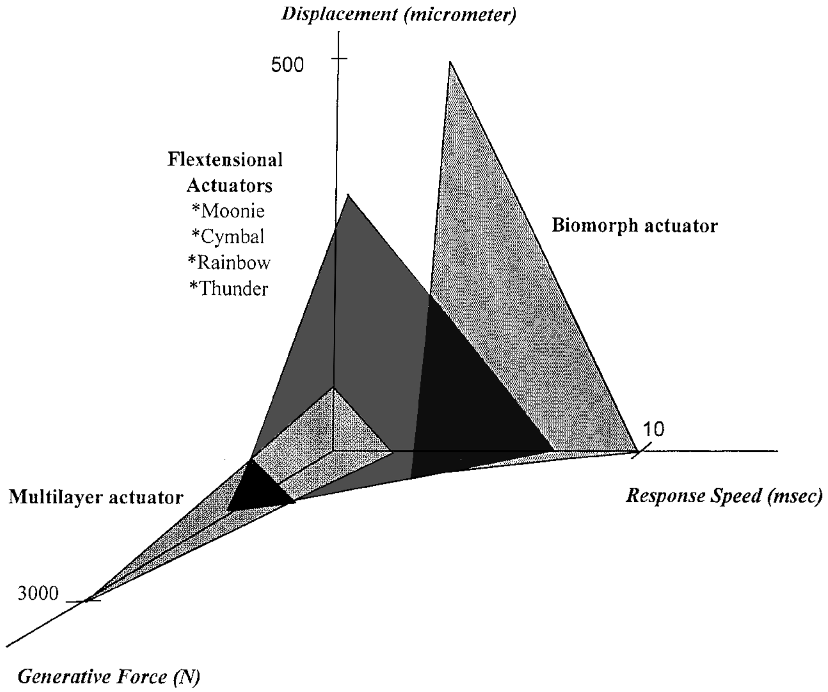


Fig. 9 Comparison of the features of several solid-state actuator designs (approximate values).

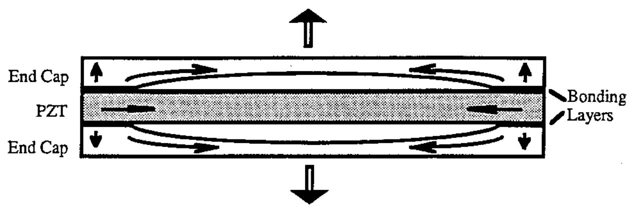


Fig. 10 Schematic of moonie actuator; arrows shows displacement directions.

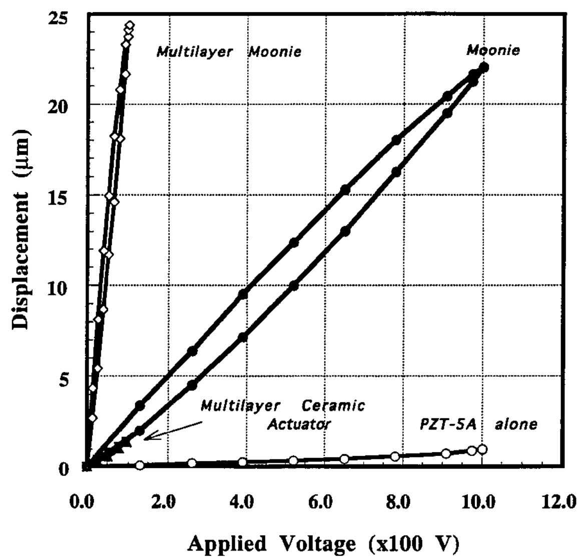


Fig. 11 Displacement characteristic of moonie actuator with multilayer and single-layer ceramic driving elements.

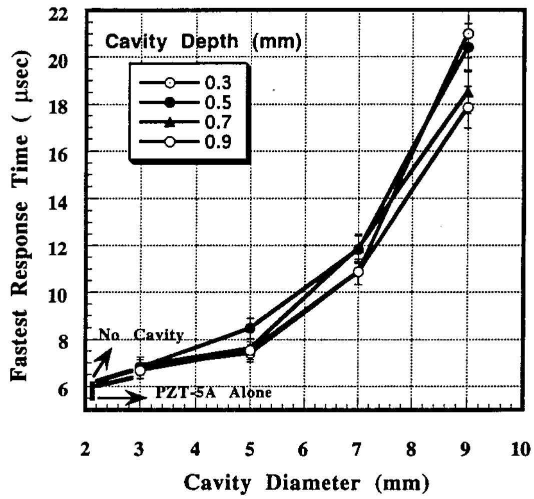


Fig. 12 Effect of cavity diameter on the fastest response time of the moonie transducers at various cavity depths.

from the center to the edge, where it approaches that of the PZT itself. Conversely, the displacement value decreases when moving from center to the edge of the endcap.

The fastest response time of the moonie actuator is in the range of 5–50 μs depending on the cavity size and endcap thickness. The response time of the moonie actuator increases with increasing endcap compliance and increased cavity diameter but changes only slightly with increasing cavity depth (Fig. 12). The fastest response time is inversely proportional to the endcap thickness.

The bonding layer between the metal endcaps and ceramic driving element is a critical region in moonie structure because it is under severe shear stresses. Despite this concern, reliability test results show that there is no degradation of the displacement and resonance spectrum of the moonie transducers.[32] Temperature-dependence and cyclic fatigue tests were performed to investigate the reliability of moonie transducer for long-term usage. Less than $\pm 0.1\%$ deviations were observed on displacement during the fatigue test up to 10^7 cycles under applied field of 1 kV/mm at 100-Hz sinusoidal waveform (Fig. 13). Destructive (peel tests) and nondestructive (scanning acoustic microscopy and resonance spectroscopy) techniques were used to investigate the reliability and strength of the moonie actuator. Eccobond and indium alloy gave the best performance. For the moonie actuators fabricated with brass endcaps and Eccobond epoxy, rather good temperature characteristics were obtained between -20 and $+70$°C. However, because of the coefficient of thermal expansion difference between brass endcaps and ceramic element, thermally induced displacement was observed. This problem has been solved by using caps with similar thermal expansion coefficients to PZT, such as Kovar or tungsten.

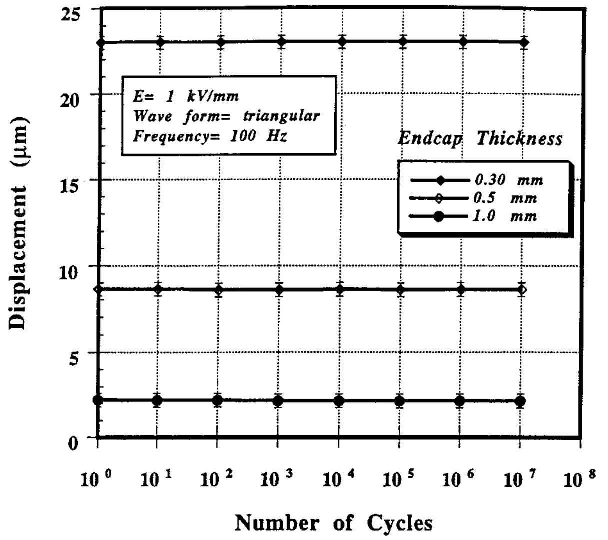


Fig. 13 Fatigue characteristics of moonie actuators.

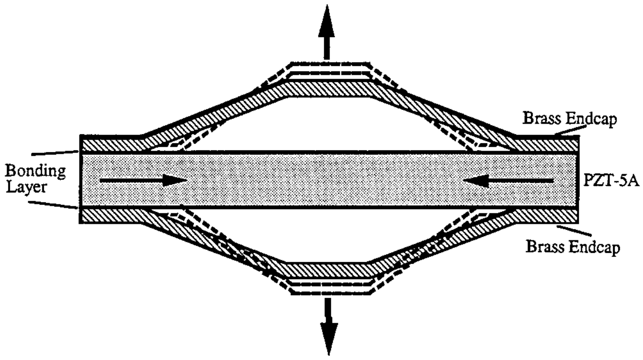


Fig. 14 Schematic of cymbal actuator; arrows shows displacement directions.

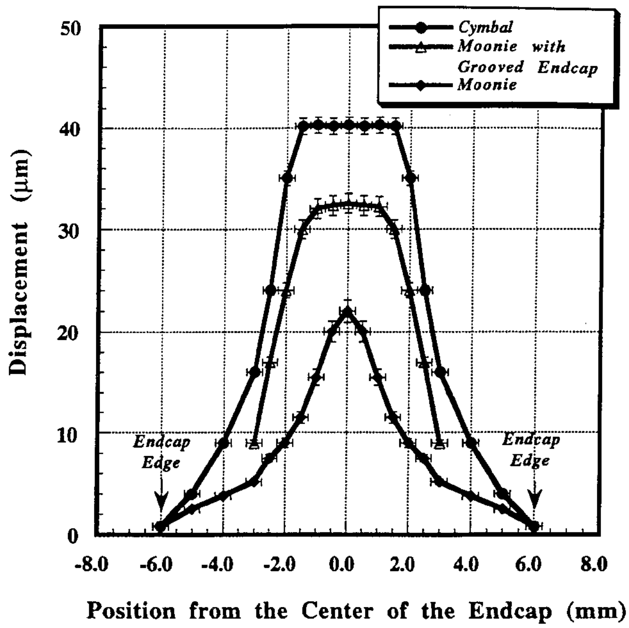


Fig. 15 Displacement characteristics of moonie and cymbal actuators.

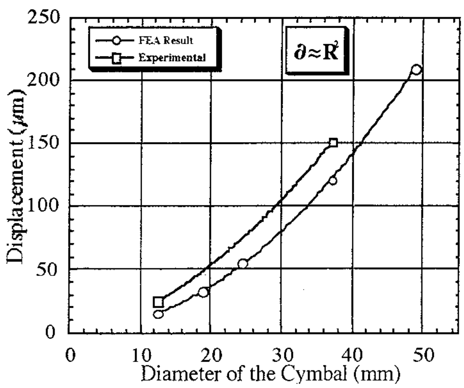


Fig. 16 Size dependence of the displacement performance of the cymbal actuator.

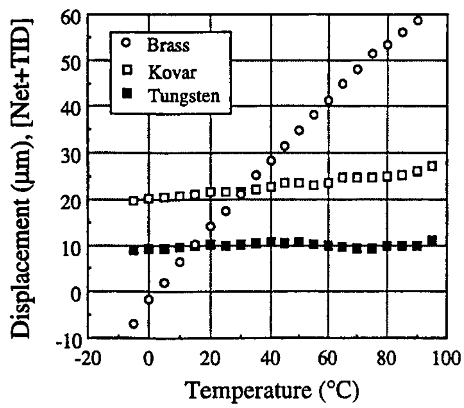


Fig. 17 Temperature dependence of the cymbal actuator with various metal endcaps.

B. Rotoflextensional Cymbal Transducer

From finite element analysis, it was found that a large stress concentration is developed in the thick moonie endcaps in the region above the bonding layer.[33] A new endcap design, cymbal, has subsequently been developed to eliminate this stress concentration and the position-dependent displacement behavior of the moonie.[26] This new endcap is referred to as the cymbal due to its similarity in shape to the musical instrument of the same name. The cymbal cap is thinner than the moonie cap and has the added advantage of being able to be mass produced because it is simultaneously cut, pressed, and shaped from a punch/die assembly. The cymbal transducer operates on the same principle as the moonie with one exception. Whereas the displacement of the moonie is generated solely from a flexural motion of the caps, the cymbal has an added contribution from rotational motion (Fig. 14). The cymbal also exhibits less position-dependent behavior with a more homogeneous displacement and generative force characteristics across the top of the cap (Fig. 15). A 12.7-mm-diam cymbal transducer with brass caps 0.20 mm thick and a cavity depth of 200 μm exhibits a displacement of 40 μm (under a drive field of 1 kV/mm) and a maximum generative force of 15 N (Ref. 26).

The shape and mechanical behavior of the cymbal resembles the Bellville washer (spring). The modulus of elasticity of the endcap material plays an important role on the performance of the cymbal transducer. Displacement, generative force, and response time can be tailored by altering the endcap metal. Cymbal actuator can easily be built in 3–50 mm (even higher) diameters with displacement values of one micrometer to several hundred micrometers, respectively (Fig. 16). Cymbal actuators also have higher generative force than moonie actuators because of the enlarged active surface on endcap. By choosing stiffer material and thicker endcaps, very high generative forces can be achieved while sacrificing some of the displacement. Thermally induced displacement on cymbal actuator can also be diminished by using low thermal expansion materials, such as tungsten, Kovar, and titanium[34] (Fig. 17). The thermal expansion coefficient of tungsten is closer to the ceramic than that of titanium or Kovar. However, titanium and Kovar are more commercialized and cheaper.

In the moonie and cymbal designs, ceramic materials are used as driving elements and metals or polymer as endcaps. The ceramic

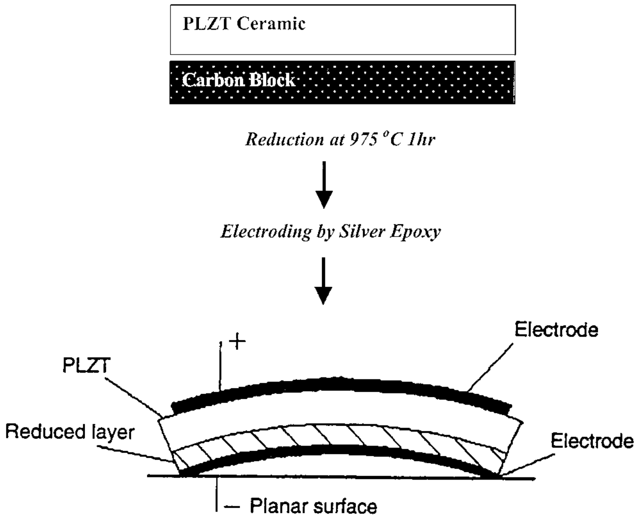


Fig. 18 Fabrication of the RAINBOW actuator.

elements in both designs are mainly under compressive stress. As is well known, the tensile strength of ceramics is much lower than their compressive strength due to their brittle nature. They are not reliable under tensile stress. Metal endcaps can withstand both tensile and compressive forces. For this reason the ceramic driving element in the moonie and cymbal designs are kept flat and under compressive stress as much as possible.

C. RAINBOW

The RAINBOW consists of an electromechanically active layer, such as PZT, PMN, PLZT (lead lanthanum zirconate titanate), PBZT (lead barium zirconate titanate), or PSZT (lead stannate zirconate titanate), in direct contact with a lead-rich constraining layer.[9] This constraining layer is formed by exposing one side of a lead-containing ceramic to a reducing atmosphere at high temperature produced by placing a ceramic in contact with a carbon block. The reduction of the active layer occurs as a result of oxidation of the solid carbon block, first to CO(g) then to CO_2(g). This reduced layer is no longer piezoelectric and is, in fact, a good electrical conductor. Because of the thermal expansion mismatch between the reduced and oxide layer, a curvature develops in the structure, giving it a dome shape, with the oxide layer in compression throughout its volume (Fig. 18). RAINBOW actuators consist of an electromechanical active layer and a constraining layer, similar to the conventional unimorphs. Unlike the unimorph, however, the RAINBOW is a monolithic structure. The RAINBOW disks are typically 0.5 mm thick or less and can range in diameter from 1 to 10 cm. Displacement performance of the RAINBOW depends highly on the composition of ceramic material (Fig. 19).[35,36] Even though it shows flexural motion, the RAINBOW can also be categorized as a monomorph type of actuator (Fig. 1).

RAINBOWs are stress-biased structures. One section of the structure is under high compressive stress and the other under high tensile forces. Hence, they may have long-term stability problems. RAINBOWs of PZT-5H, PZT-5A, and PLZT 9/65/35 compositions exhibit polarization fatigue under cycling loading. A 53% decrease in remnant polarization has been observed after 10^8 cycles under 1 kV/mm in the PZT-5A RAINBOW.[37] The resonance spectrum revealed a significant decrease in the mechanical coupling factor as well. This behavior may be caused by degradation of the interface between the oxide and reduced layer. Depolarization will lead to a decrease in electromechanical coupling and create displacements in the lateral and longitudinal directions.

Long-term tests of displacement show that the under cyclic load RAINBOW actuators lose performance significantly.[35] RAINBOWs made of soft piezoelectric ceramics lose between 10 and 20% of their original displacement value after 10^7 cycles under an applied field of 0.5 kV/mm at 20 Hz and zero force conditions (Fig. 20). Fatigue tests under applied force of 3 N show even more catastrophic results. After 10^4 cycles, most of the displacement disappears. Repoling the samples recovers around 90% of the displacement value of virgin samples. However, the RAINBOW actuator made of electrostrictive materials could not be restored by repoling.[35]

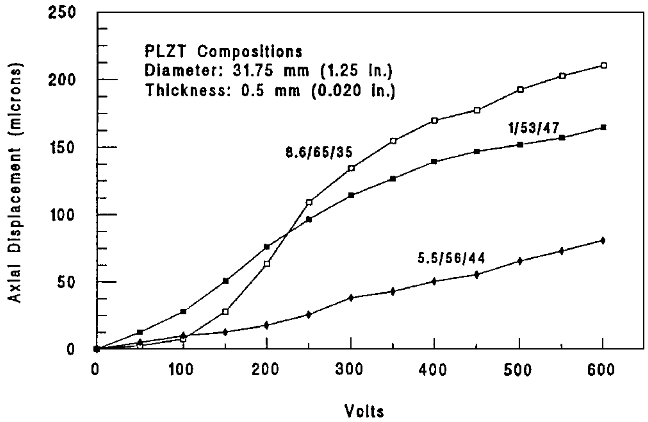


Fig. 19 Displacement characteristics of the RAINBOW actuator in various sizes.[36]

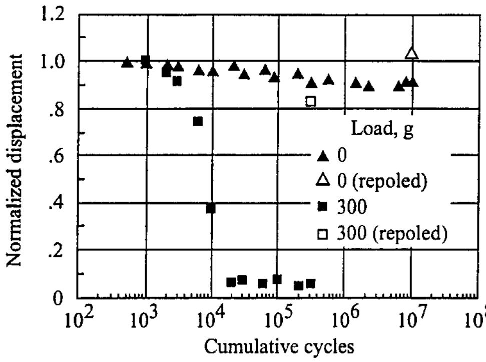


Fig. 20 Displacement fatigue of PZT-5H RAINBOWs under various loads.[35]

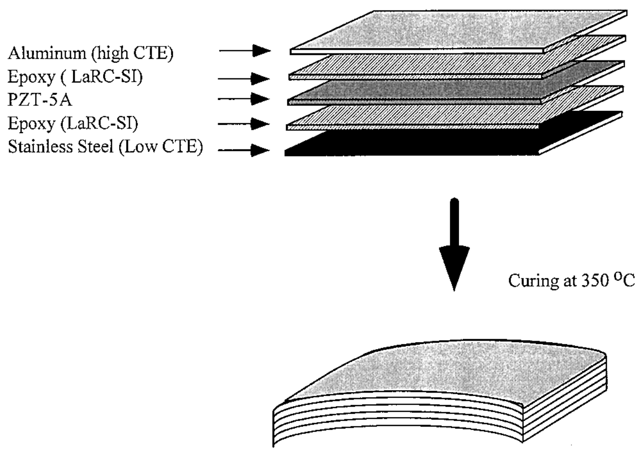


Fig. 21 Schematic of THUNDER actuator.[38]

D. THUNDER

THUNDER, which was developed at NASA Langley Research Center, is an improved version of RAINBOW actuator and based on coefficient of thermal expansion mismatch between materials.[35] The mechanical advantage of the THUNDER or RAINBOW design is due to the flexibility of the device and the radial expansion created by the pairing of preselected thermally mismatched materials. THUNDER transducers consist of an integrated sandwich of three layers. The first and third layers are the prestressed metal layers that sandwich the piezoelectric layer with epoxy bonding between layers. A schematic of the THUNDER is shown in Fig. 21.

THUNDER actuators can be fabricated in virtually any size and thickness.[35,38] Initially, electrical contacts are deposited or plated

Table 2 Comparison of the solid-state actuator designs[a]

Features	Multilayer[42]	Bimorph[42]	RAINBOW[41]	Cymbal	Moonie
Dimensions	$5 \times 5 \times 12.7$ $(L \times W \times T)$	$12.7 \times 10 \times 1$ $(L \times W \times T)$	Ø = 12.7 mm $T = 0.5$ mm	Ø = 12.7 mm $T = 1.7$ mm	Ø = 12.7 mm $T = 1.7$ mm
Driving voltage, V	100	100	450	100	100
Displacement, μm	10	35	20	40	20
Displacement direction	Positive	Positive	Negative	Positive	Positive
Contact surface, mm^2	25	1	1	3	1
Generative force, N	900	0.5–1	1–3	15–100	3
Position dependent of displacement	No	Maximum at the tip	Maximum at the center	Maximum at the center but more diffuse	Maximum at the center
Stability under loading	Very high	Very low	Low	High	Low
Fastest response, μs	1–5	100	100	5–50	5–50
Fabrication method	Type casting and cofiring at 1200°C	Bonding ceramic element with metal shim	Reducing ceramic element at 950°C	Bonding ceramic element with metal endcaps	Bonding ceramic element with metal endcaps
Cost	High	Medium	Medium	Low	Low

[a] L, length; W, width; T, thickness; Ø, diameter.

Table 3 Displacement performance various flextensional composite actuators

Feature	Moonie	Cymbal	RAINBOW[37]	THUNDER[39]
Dimensions, mm	25.4 Ø[a] Disk	25.4 Ø Disk	25.4 Ø Disk	25.4 mm^2 Square
PZT	PZT-5A	PZT-5A	PZT-5A	PZT-5A
Applied field, kV/mm	Unipolar 1.0	Unipolar 1.0	Bipolar ±0.65	Unipolar 1.0
Thickness of PZT, mm	0.500	0.500	380	0.325
Displacement, μm	50	80	88	60

[a] Diameter.

on the active areas of conventional piezoelectric wafers. Next, alternating layers of adhesive and aluminum foil are placed on one side of the piezoelectric wafer. The package is vacuum bagged on a flat fixture and placed in an oven for processing at around 325°C with a pressure of 100 psi. After removal from the oven, the wafers are domed or curved during the cool-down process utilizing the difference in thermal expansion rates of the various materials (layers). Even though it has been claimed that it can go beyond a billion cycles without failure, no experimental data have been published for the dynamic performance and reliability. On the contrary, it has been reported that, after a two-week testing period, the overall displacement performance of the THUNDER wafer began to noticeably degrade. A 33% drop on the capacitance has been observed.[39]

A prototype THUNDER actuator measuring 25.4×25.4 mm^2, which consists of a 170-μm-thick PZT layer (0.325 total thickness), exhibits 60-μm displacement in its center position under an applied electrical field of 1 kV/mm (Ref. 40). Both RAINBOW and THUNDER are highly position-dependent actuators. They exhibit highest displacement at the center of the dome, and displacement decreases drastically toward the age of the actuators.

VI. Comparison of the Solid-State Actuator Designs

Several features of the various solid-state actuator designs are listed in Table 2. Because of insufficient data, THUNDER does not appear in Table 2. It is rather difficult to compare different actuators because of different geometry and various operating conditions for specific applications. To make a fair comparison, similar dimensions for each actuator were selected, and the measurement conditions are those specified in Table 2.

Displacement mechanisms of cymbal, moonie, and RAINBOW class transducers are based on same physical principle: converting the radial displacement to the axial displacement by flexing or bending the structure. In principle, moonie, cymbal, and the rainbows can exhibit comparatively high displacement if an appropriate diameter R to thickness t ratio is chosen. So far RAINBOWs have achieved higher axial displacement than the moonie or cymbal because of differences in the R/t ratio. Scaling analysis show that, being fair in comparison and choosing the same size, moonie and RAINBOW will exhibit similar displacements.[41]

To exhibit a positive displacement, the applied field is in the opposite direction to the polarization in the RAINBOWs but in the same direction as the polarization for the moonie and cymbal designs. For flexural actuators the displacement is given by a simple formula:

$$\delta \approx \pm\left(d_{31} E l^2 \big/ 2t\right) \tag{1}$$

where l is length or diameter and t is thickness for the RAINBOW or THUNDER designs and is cavity height for the cymbal and moonie. The sign is (+) for rainbows and (−) for the moonie and cymbal. Displacement performances of the flexural transducers are compared in Table 3. For a fair comparison, similar actuator dimensions (25.4 mm diam or side length) were chosen and identical electric field (1 kV/mm).

VII. Applications of the Solid-State Ceramic Actuators

Multilayer actuators and bimorphs are used extensively in applications such as precision machining, dot matrix printers, active vibration control, deformable mirrors, optical choppers, electroacoustic transducers, and ultrasonic motors.[20,42,43]

Moonie and cymbal actuators have great potential in the automotive and aviation industries. They can be utilized as sensing and vibration suppression elements and as switching elements in valve designs.[44] RAINBOWs can be used for air acoustic cancellation and pumps and as switches.[36]

The moonie and cymbal actuator can also be used as a micropositioner for applications requiring small size and quick response time but only for modest loads. The Omron Corporation has already succeeded in using the multilayer moonie actuator for an optical scanner.[45,46] A high-density memory storage drivers such as a CD-ROM driver and magneto-optic memory storage driver are some other possible applications for moonie or cymbal actuators capable of delivering precise positioning.[47]

VIII. Summary

Ceramic materials are not strong under tensile forces due to their structure but are rather good under compressive forces. In the moonie and cymbal structures, electroactive ceramic elements are kept flat and sandwiched between two metal endcaps, which clamp the ceramic on the rim. Consequently, there are compressive forces over the bonding layer and small tensile forces under the cavity beneath the endcaps. On the other hand, RAINBOWs and THUNDER are stress-biased structures. Part of the structure is under high compressive forces, and others are under high tensile forces. RAINBOW and THUNDER are based on coefficient of thermal expansion differences between different parts of the actuator, and the displacement is highly temperature dependent. By double layering and using different ceramic compositions, temperature-dependent behavior can be eliminated to a certain extent.[36]

Flextensional moonie, cymbal, RAINBOW, and THUNDER actuators all give moderate generative forces and displacement values that fill the gap between multilayer and bimorph actuators. Each solid-state actuator design has attractive features that can be exploited for certain applications. Advantages of the moonie and cymbal actuators are the easy tailoring of the desired actuator properties by altering the cavity size and endcap dimensions. Easy fabrication is another advantage. The RAINBOW actuator also partially covers this gap. For that type of actuator a reduction step during the processing of the ceramic element at high temperature results in a semiconducting layer and stress bias, which is a potential problem for long-term usage.

The fatigue behavior of the actuators depends markedly on the driving conditions. Dynamical studies under uniaxial prestress under a cycling electric field should be performed on all flexural transducers for aerospace and automobile applications. Thermal cycling tests under various humidity levels will also be very useful, particularly for aerospace applications.

The real concern now is not how high the displacements flextensional actuators can exhibit but their reliability for long-term usage. More experiments must be done on these flexural structures under severe environmental conditions.

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