

A Comparison of Packaged Piezoactuators for Industrial Applications

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ABSTRACT

A comparison of different commercially available packaged piezoelectric actuators is presented. The comparisons are based on force, stress and strain performance at similar field densities. A new metric of comparison, based on energy efficiency, is introduced. This paper provides designers with useful information on actuators and actuator performance for industrial applications. The QuickPack® and PowerAct™ actuators remain the only packaged piezoelectric actuators to be produced in high volume and to feature in commercial applications.

Keywords: Actuators. Piezoelectric. Comparison. Force. Strain. Stress. Cost. Packaged Piezoelectric.

INTRODUCTION

Piezoceramic wafers were first used as strain actuators in the early 1980s, in research on the control of structural shape and vibration. Early work at the Massachusetts Institute of Technology (MIT) considered both surface-bonded and embedded elements¹. In both cases, the difficulty of handling the brittle ceramics was evident from the outset. Soldering wires to the electroded piezoceramics required special materials and skill, and often resulted in broken elements, unreliable connections, or localized thermal depoling of the elements. Embedding the piezoceramics in carbon fiber composites proved very difficult, due to the conductivity of the fibers, conclusively demonstrating the need for reliable, electrically insulating packaging, capable of withstanding high temperatures and large mechanical stresses.

In the early 1990s, Active Control eXperts, Inc. (ACX) developed a packaging technology in which one or more electro-active elements are laminated between sheets of polymer flexible printed circuitry^{2,3,4,5,6}. This technology provided the needed robustness, reliability, and ease of use to strain actuation, and was a key breakthrough enabling strain actuators to move out of the laboratory and into real-world industrial and commercial applications⁷. ACX packaged piezoceramic devices first reached the market in volume as vibration dampers in sporting goods applications in 1995^{8,9,10}. Since then, these QuickPack® strain actuators also have been used by manufacturers of automotive and medical products, as buzzer alerts and drivers for flat speakers.

Meanwhile, R&D involving packaged strain actuators has continued in industries such as aerospace^{11,12,13} and automotive¹⁴, which have much longer design cycles and correspondingly more stringent requirements on component cost and reliability. Industrial and commercial applications such as these have driven the need for higher performance, lower cost, and increased flexibility in the packaged strain actuator (see, e.g., Ref. 15). Some newer versions of the packaged strain actuator have been developed in response to these needs. ACX developed the QuickPack IDE™ actuator^{5,16,17}, using the same packaging but reorienting the poling (3-direction) into the plane of the actuator to improve performance. ACX also developed a number of proprietary high-volume manufacturing processes to reduce unit costs. In response to the need for greater flexibility, Midé Technology Corporation substituted a laser-machined piezoceramic element for the monolithic wafer in the QuickPack packaging. This PowerAct™ actuator¹⁸ can be bonded to curved surfaces without a loss in performance. Finally, NASA's Langley Research Center developed the Macro Fiber Composite (MFC)¹⁹ in which a diced piezoceramic element is substituted for the monolithic wafer in a flexible packaged device.

The objective of this paper is to compare the current commercially available packaged strain actuators – QuickPack, QuickPack IDE, PowerAct and MFC – in terms of performance, reliability, manufacturability and cost. Section 2 provides a brief technical description of these four products. Sections 0 and 0 describe the experimental setup and procedures, and discuss the results of performance and lifetime testing conducted for this study. Cost, reliability and manufacturability are compared, using a combination of quantitative data and qualitative information, in Section 0. The paper concludes with Section 0.

STRAIN ACTUATOR TECHNOLOGIES

By convention, the direction of polarization in a piezoceramic defines the “3-axis”. Traditional strain actuators like the QuickPack and PowerAct use piezoceramic wafers poled through their thickness, with voltage applied also through the thickness. When these devices are bonded to a surface, actuation is in the plane of the wafer through the so-called “ d_{31} ” effect. In this case, the applied electric field couples equally to piezo actuation in both in-plane directions ($d_{31} = d_{32}$).

The second type of actuator has inter-digitized electrodes (IDE) so that both the poling (3-axis) and the applied electric field are oriented down the length of the piezoelectric wafer. In this case, the applied electric field couples to piezo actuation along the length of the device according to d_{33} , and transversely according to d_{31} . For typical ceramics, $d_{33} \approx -3d_{31}$. These actuators, including the QuickPack IDE and the MFC, take advantage of the more efficient electromechanical coupling in the 3-axis to provide greater actuation performance along their length.

The second metric of distinction between the four actuators considered here is their conformability. Piezoelectric wafers are brittle and break easily when bent. Packaging the monolithic piezoceramic element protects it from damage and crack propagation, but it still impractical to bond such an actuator to a curved surface. Removing some of the piezoceramic material in the actuator and replacing it with softer epoxy can form a composite material that has the ability to absorb more strain than the piezoceramic alone. This type of actuator can then be bonded to curved surfaces because it has the ability to conform to the shape of the surface. This type of composite actuator, including the PowerAct and MFC, will be referred to as a “conformable actuator” in this paper.

Experiment design

This paper compares the performance of different actuators with two sets of tests. The first was a simple force-deflection test and the second a lifetime test. Both these test attempted to simulate actual environments that packaged piezoelectric actuators will experience when fixed to a structure in an industrial application.

Force – Deflection Test

To determine and compare the actual performance of a number of different packaged piezoelectric actuators a standard force and deflection test was devised. This test involved sandwiching the packaged actuator between two aluminum 6061-T6 sheets as indicated in Figure 1. A strain gauge was attached to the aluminum sheets as shown.

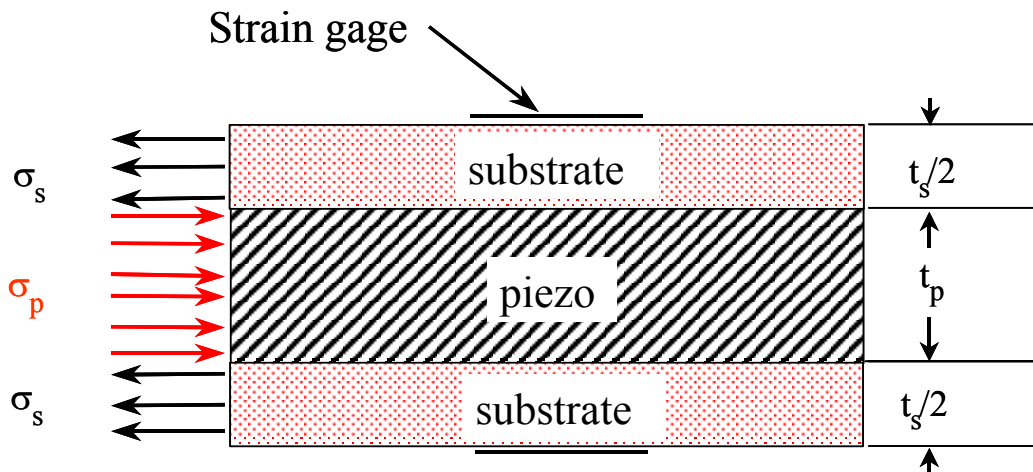


Figure 1: The packed piezoelectric actuator is sandwiched between two aluminum substrates. A strain gauge on each side measures the strain that the actuator induces in the substrate. Varying the thickness of the aluminum substrate varies the stiffness and the stress on the piezo as shown by this sectional view.

By varying the stiffness (thickness) of the aluminum, a different load condition could be achieved for each actuator. The only other variable in the tests was the actuation electric field.

Four different actuators were tested. These included all the types that were described in the previous section. The actuators, with their substrates and strain gauges are shown in Figure 2.

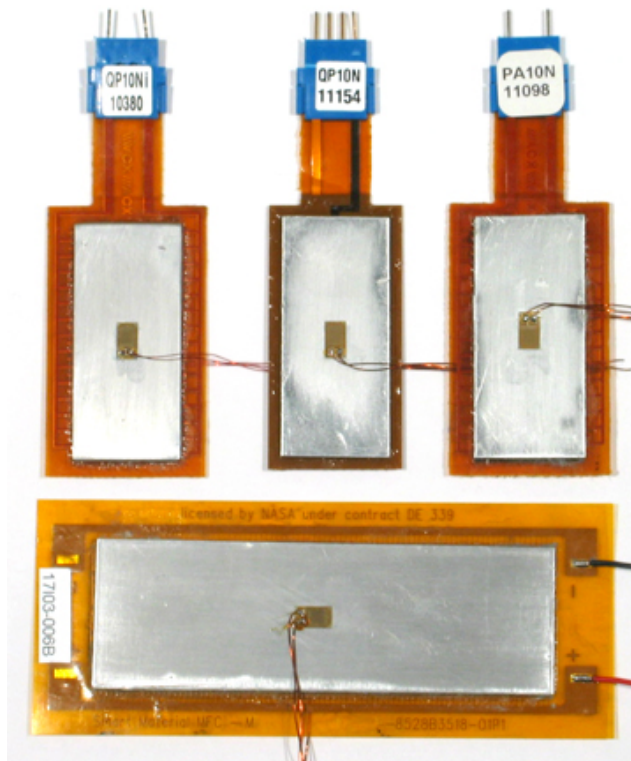


Figure 2: The actuators that were tested. From left to right, top to bottom: QP10Ni, QP10N, PA10N, MFC8528

Table 1 lists the different actuators, their characteristics and the type of substrates used for each actuator test.

Table 1: Actuators used for comparative tests

Actuator	Aluminum substrate total thickness (in.)	Size of active area (in.)	Thickness of active material (in.)	Active material of frontal area	IDE / Traditional	Conformability
QP10Ni	0.002 0.060	1.81 × 0.81	0.010	100%	IDE	None
QP10N	0.002 0.060	1.81 × 0.81	0.010	100%	Trad.	None
PA10N	0.002 0.060	1.81 × 0.81	0.010	88%	Trad.	Yes
MFC 8528	0.002 0.060	3.4 × 1.1	0.007	90%	IDE	Yes

The test setup is shown in Figure 3. The actuator-aluminum combination was placed on a Teflon sheet for minimum frictional interference. The strain gauge was connected to a standard Wheatstone bridge. The output of the bridge was amplified and fed into a voltmeter from where it was manually recorded. Two different amplifiers were used for the two different classes of actuators that were tested. The first type was a standard Midé Amplifier capable of delivering ± 200V for use in with traditional actuators. For the IDE products an amplifier capable of delivering 2 kV was required. The test equipment is listed in Table 2.

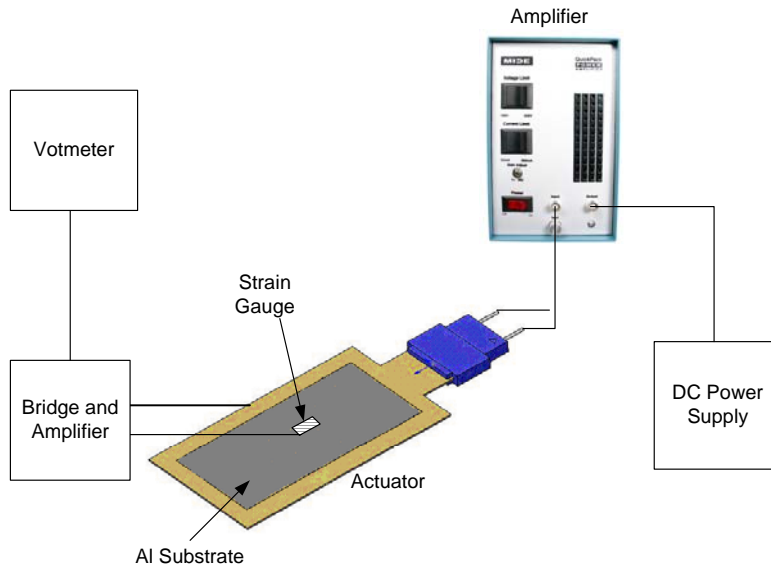


Figure 3: The force deflection test setup. Varying the output from the power supply varies the output from the amplifier. This resulted in a change in the substrate strain and output from the strain gauge that resulted in a change in amplifier output.

Table 2: Test equipment for the stress strain test.

Equipment	Manufacturer	Model
Low Voltage Amplifier	Midé Technology Corp.	EL-1224
High Voltage Amplifier	Bertan Associates Inc.	Series 230 High Voltage Power Supply
Power Supply	Global Specialties	1310
Strain Gauge	Micro Measurements	J2A-06-S033P-350
Strain Gauge Amplifier	Inline	Signal Conditioner / Amplifier

The test procedure was as follows:

1. Connect strain gauges to bridge an amplifier
2. Connect actuator to driving amplifier.
3. Connect actuator to driving amplifier.
4. Slowly increase driving voltage to the desired level.
5. Decrease driving voltage to zero
6. Continue cycling for ten times.
7. Slowly increase voltage to desired level.
8. Record strain gauge reading from Voltmeter
9. Decrease voltage to zero.
10. Repeat from step 4 ten times
11. Repeat from step 4 for next voltage level
12. Repeat from step 1 for next actuator-substrate set.

Lifetime Tests

The lifetime test was performed by expanding and contracting the actuators, bonded to the thick aluminum, at an elevated frequency. This condition is more representative of an actual industrial application, in which the actuator works against a load, than the often-cited stress-free case.

The test setup is shown in Figure 4. Table 3 lists the equipment used for the test. In order to simulate the most realistic conditions, the 60 mil aluminum substrates were used. The actuators were driven as close to maximum field density specified by the manufacturer. The actuators, their respective substrates and test field densities and frequencies as well as the manufacturer’s specified field densities are shown in Table 4.

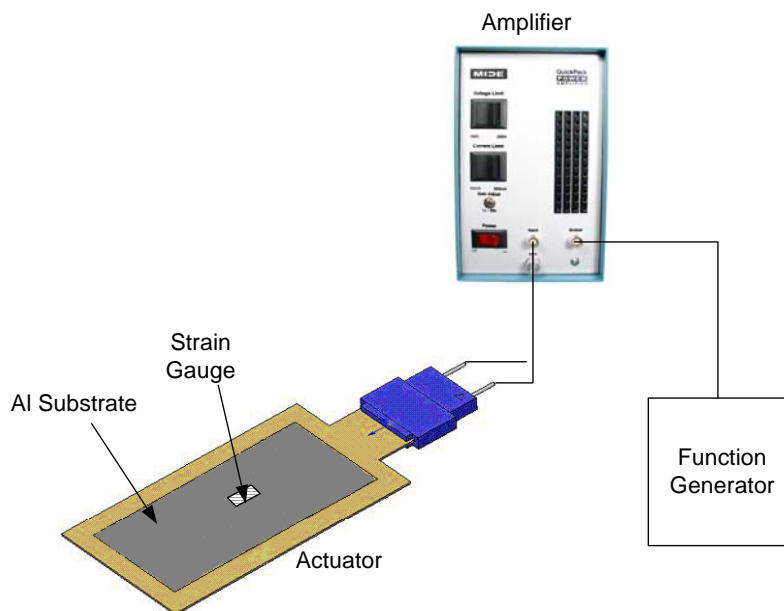


Figure 4: Test setup for lifetime tests.

Table 3: Equipment used for the lifetime tests.

Equipment	Manufacturer	Model
Amplifier	KEPCO	BOP 1000M, Bipolar Operational Power Supply/Amplifier
Function Generator	BK Precision	4017A 10MHz Sweep/Function Generator

Table 4: Test articles and conditions for the lifetime tests.

Actuator	PA10Ni	MFC 8528
Substrate	60 mil Al	60 mil Al
Manufacturer's Specified Field Density	± 20 V/mil	-25 to +75 V/mil
Test Field Density	± 20 V/mil	-25 to +75 V/mil
Actuation Frequency	1 kHz	1 kHz

The methodology of the lifetime tests was to run the actuators for a specified time at the specified frequency and field density. After a certain amount of cycles have been performed, the cycling was stopped and the actuator removed. The actuator was then subjected to the standard force and deflection test of the previous section. After its performance was measured, the actuator was coupled to the cycling equipment and cycled for the next interval.

RESULTS

4.1 Force Deflection Test Results

Each load condition and field density was tested at least 10 times in order to produce a statistically significant sample. The average of these 10 tests were then calculated and these are the values used in the figures.

The first comparison was based on a constant maximum electric field of ± 20 V/mil, the typical limit used in dynamic applications requiring high reliability and robustness to depoling. (At AC fields exceeding -20 V/mil the probability of depoling the material increases to unacceptable levels.)

Due to the difference in the electrode spacing of the actuators, different peak voltages were applied to the to achieve electric field of 20V/mil. Table 5 lists the actuators, their electrode spacing and driving voltage corresponding to 20V/mil. This table also compiles the resulting free strain and blocked piezo stress that was delivered at 20V/mil.

Table 5: Tested actuators' characteristics and results for the 20V/mil test.

Actuator	Electrode Spacing	Driving Voltage	Free Strain ($\mu\epsilon$)	Blocked Stress (ksi)
QP10Ni	60 mil	1,200V	959	4.98
QP10N	10mil	200V	385	3.08
PA10N	10mil	200V	353	2.69
MFC	20mil	400V	583	4.72

The result of the 20V/mil comparison test is shown in Figure 5. The d_{31} actuators QP10N and PA10N clearly produce less strain and stress with the applied field. The IDE actuators deliver more stress and strain, with the QP10Ni delivering the greatest performance. Note that piezo stress is substituted here for the more conventionally used "blocked force," to account for the different cross-sectional areas of the active elements in the four actuators tested. For example, the QP10Ni is thicker, relative to the constraining aluminum layers, than the MFC is, so all else being equal the QP10Ni would be expected to produce more force and strain at a given electric field.

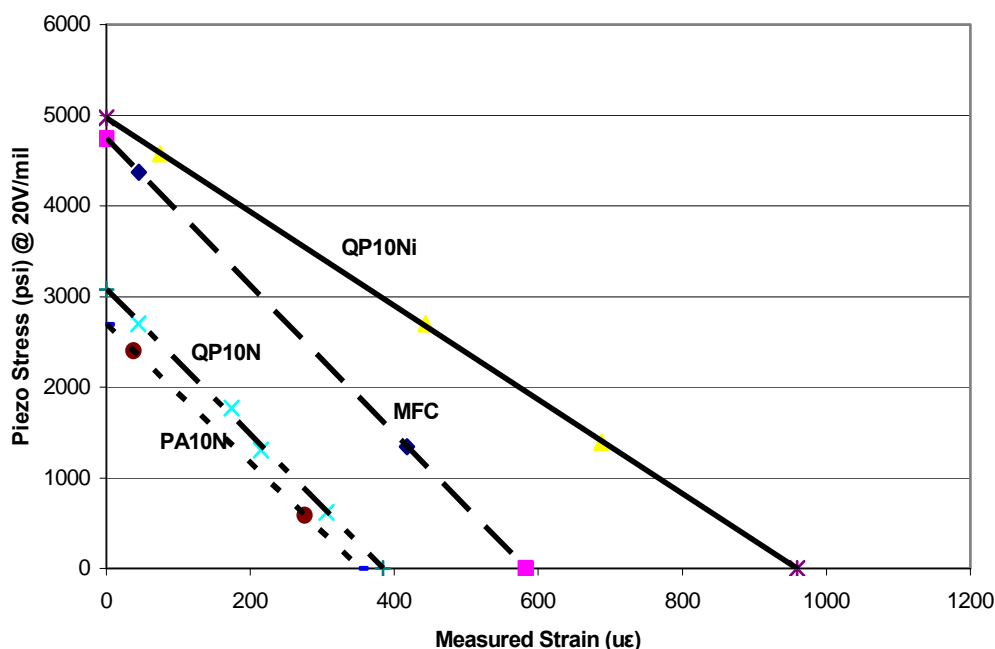


Figure 5: Piezo stress versus measured strain for 20V/mil field.

One explanation for the superior performance of the QP10Ni vs. the MFC is likely found in the electrode spacing used in each. The QP10Ni uses 0.060 inch spacing, or six times the wafer thickness. The MFC uses 0.02 inch spacing, or about three times the wafer thickness. A larger ratio of spacing to thickness generally results in better IDE actuator performance. (The tradeoff is, of course, higher actuation voltages required to achieve a given electric field.)

The comparison on a stress basis can be converted to the amount of blocked force that each actuator, as purchased off the shelf will deliver to an application. In order to obtain the amount of force that a specific actuator will deliver, the stress it produces is multiplied by its frontal area. This comparison is shown in Figure 6. The QP10Ni produces the highest blocked force and free strain for the given electric field.

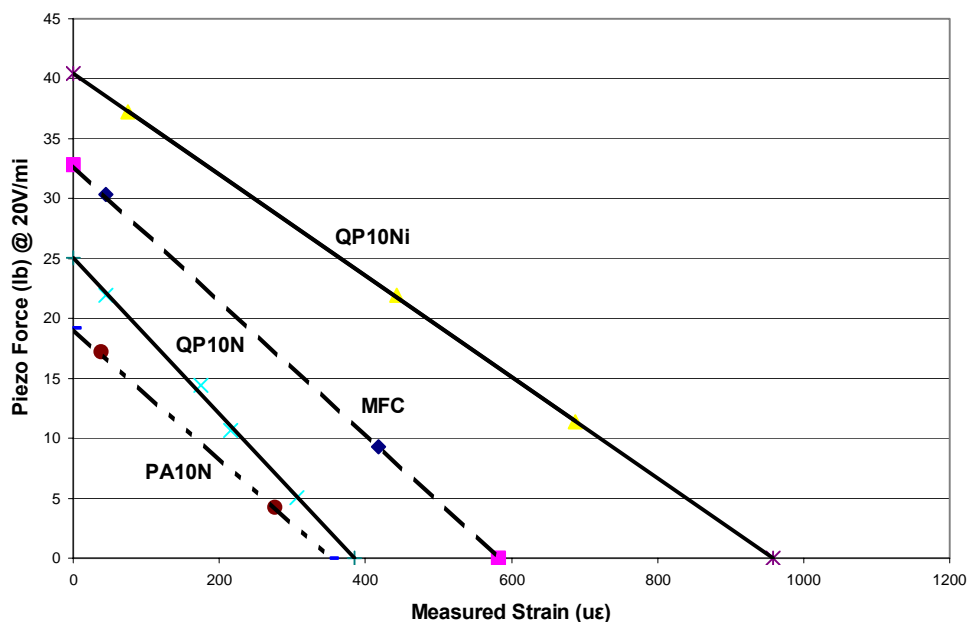


Figure 6: Force versus measured strain for 20V/mil as applied to each specific actuator.

In comparing the performance of d_{31} and d_{33} actuators it is also important to consider their efficiency at converting applied electrical energy into mechanical work. The amount of electrical energy delivered to a piezoelectric actuator is given by $\frac{1}{2}CV^2$, where C is the capacitance of the actuator and V is the voltage applied to the actuator. These values are presented in Table 6. Typically IDE actuators have lower capacitance than traditional d_{31} actuators. By dividing the performance of the actuators in Figure 5 and Figure 6 by the amount of energy (mJ) delivered by the power supply, a comparison on the basis of the amount of energy can be devised. This is a valid comparison if it is assumed that the slope of the load lines do not change with a change in energy / voltage delivered to the actuator. Some actuators do exhibit a change in the load line slope at different actuation field, but this change is usually very small. For this comparison, the energy at the maximum allowable field density (20V/mil) was used.

Table 6: Capacitance, driving voltage and energy delivered to the actuators.

Actuator	Capacitance Max / Min	Pk-Pk Voltage @±20V/mil	Average Energy Delivered
QP10Ni	1.74 / 1.55 nF	1,200V	4.8 mJ
QP10N	44 / 56 nF	200V	4.1 mJ
PA10N	50 / 51 nF	200V	4.0 mJ
MFC	10.2 / 9.8 nF	400V	3.2 mJ

The result of this comparison is shown in Figure 7. MFC performs better than QP10Ni for strains less than 150 µε. The d_{31} actuators continue to perform worse than the d_{33} actuators, as expected. Figure 8 compares force delivered by the various test specimens at constant input energy. In this comparison, MFC provides more force to the substrate up to 200µε, from which point QP10Ni starts to dominate.

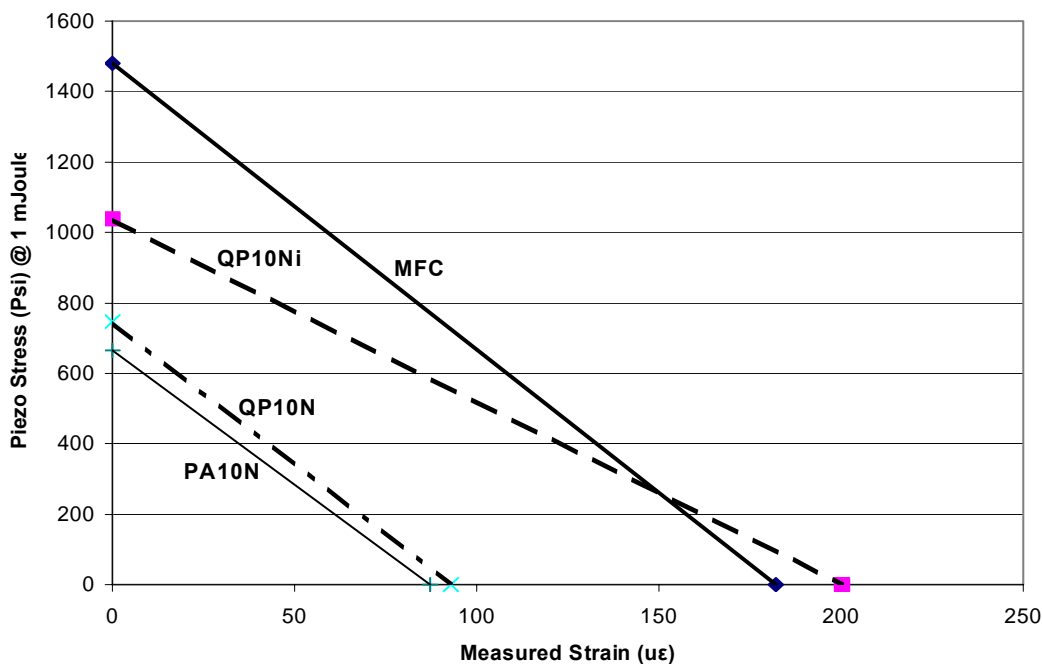


Figure 7: Piezo stress versus measured strain for 1 mJ of energy delivered to the actuator.

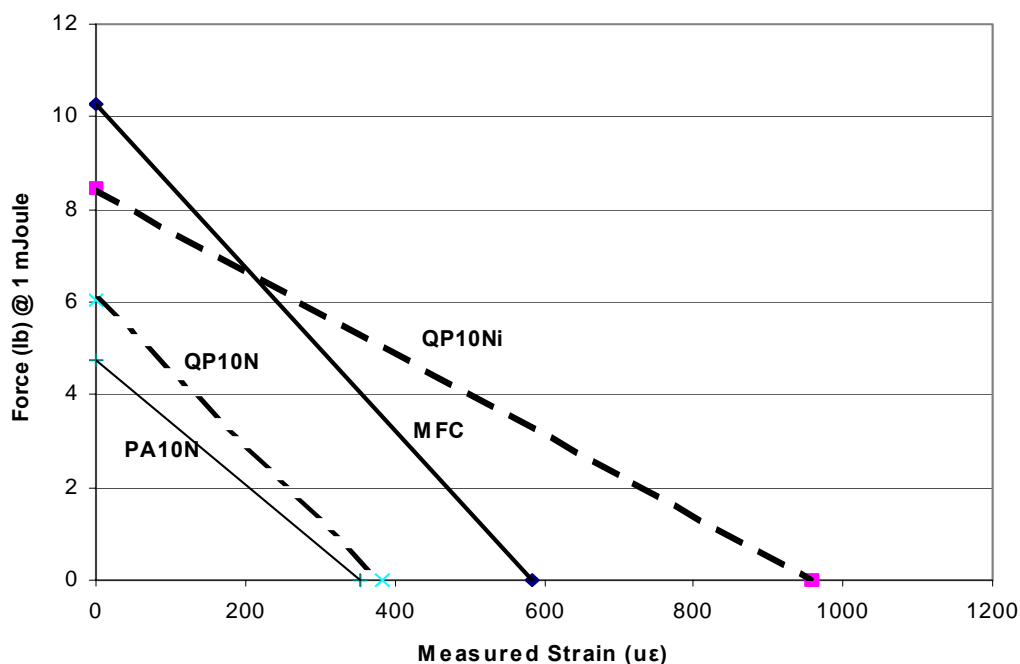


Figure 8: Force versus strain provided by the actuators for 1mJ energy applied.

Lifetime Test Results

The results of the lifetime tests performed on the QuickPack IDE and MFC actuators are shown in Figure 9. The QP10Ni did not show measurable degradation in strain induced in the 60 mil aluminum sheets. The MFC induced strain was seen to decrease by 15% after 8.4 million cycles. By 36 million cycles the MFC stabilized to a level 18%

lower than at the outset of the test. Note that the peak applied field in the life tests equaled the manufacturers' rated maximums (Table 4), which for the MFC is ± 50 V/mil around a +25V/mil DC bias (-25 to +75 V/mil), and for the QP10Ni is ± 20 V/mil unbiased. The "bias and overdrive" scheme used in the MFC is discussed in more detail in the next Section.

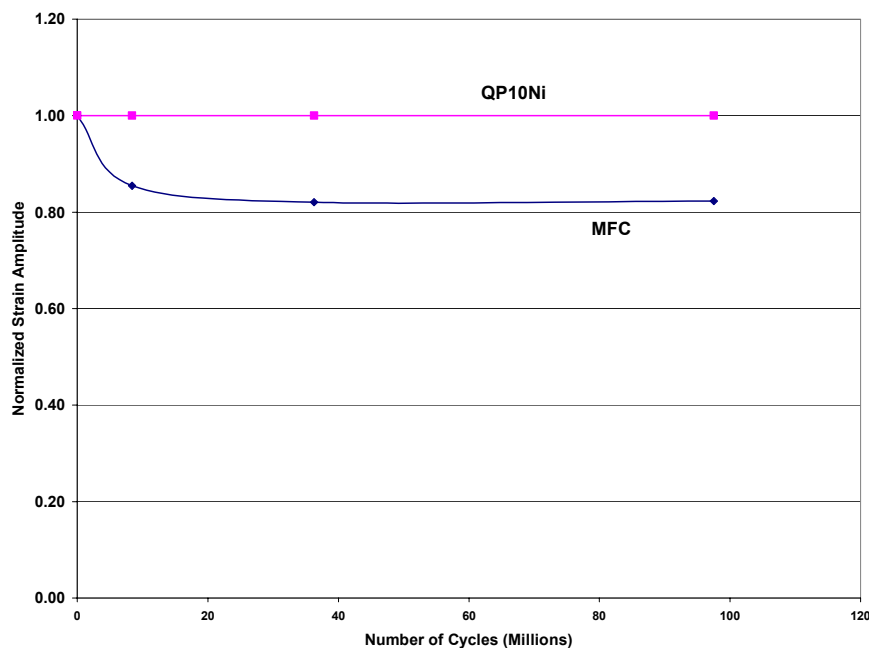


Figure 9: Results of the lifetime tests. The MFC actuator has an approximately 15% reduction in performance after 8.4 million cycles and 18% after 36 million. The QP10Ni shows zero reduction in performance after 100 million cycles.

COST, MANUFACTURABILITY AND RELIABILITY

To this point, we have considered quantitative performance results of two types of experiment using a specific loading condition. Performance and aging properties are very important in industrial applications of packaged strain actuators, but practical considerations almost always necessitate tradeoffs of performance for cost or reliability. Furthermore, the different modes of actuation associated with the d_{31} and d_{33} devices means that application-specific performance comparison is required prior to selecting a particular actuator type. Table 7 contains a qualitative ranking of the four types of packaged strain actuator, with 1 being the best and 4 being the worst.

Table 7: Ranking of Commercial Packaged Strain Actuators

Trade Name:	QuickPack		PowerAct	MFC
PZT Element:	Wafer		Laser-Machined Wafer	Diced Wafer
Actuation Mode:	31	33	31	33
Authority per unit thickness...				
• principal strains in actuated structure having same sign:	1	4	3	2
• principal strains in actuated structure having opposite signs:	4	1	3	2
Feasibility of thick actuator (high force)	1	2	3	4
Conformability	4	4	2	1
Ease of electrical drive	1	4	1	2
Ease of fabrication	1	2	3	4
Overall technical maturity	1	2	3	3

Authority: While d_{33} is significantly larger, in the absolute sense, than d_{31} , real applications of packaged strain actuators involve two in-plane dimensions. In the classic application of controlling bending in a metallic cantilever beam, the desired pattern of the induced strain is very similar to the natural actuation pattern of the d_{33} actuator. The ratio d_{31}/d_{33} is very nearly equal to the Poisson ratio of metals like aluminum, so the IDE actuation couples very well into the strain field of the actuated structure. Traditional actuators, on the other hand, naturally expand in the transverse direction when expanding in the longitudinal axis, working against the natural transverse deformation of the bending beam and reducing the actuation effectiveness. But in more complex structures it is possible that the deformation of interest is associated with in-plane strains that have the same sign. This has been shown to be true, for example, on the vertical tails of the F/A-18 and F-22 aircraft in their first mode of vibration. In this case, d_{31} actuators can be as effective, if not more effective than d_{33} actuators¹³. The rankings in the table for the PowerAct and MFC reflect their relative ineffectiveness at inducing stress and strain in the transverse direction due to the partial or total segmentation of the active element.

Thickness: In applications of packaged strain actuators requiring high forces, the use of d_{33} may not suffice. It may also (or alternatively) be necessary to use a thick PZT wafer. While it is always possible to achieve a given total thickness of PZT by using multiple layers, this is undesirable due to increased cost and loss of strain transfer through intervening packaging layers. In active applications, the increased voltages mitigate against this, but in passive damping applications thicker can be better. (For example. 0.060 inch thick wafers in the d_{31} configuration were used for the ACX ski damper) The traditional monolithic d_{31} configuration used in the QuickPack is most amenable to thick wafers.

Conformability: Conformability is desirable in a number of applications, particularly those involving shafts (like golf clubs). The MFC, with its completely diced elements, is the preferred technology under this criterion. PowerAct, with partially machined elements, follows behind. The QuickPack and QuickPack IDE do not apply well to surfaces with small radii of curvature. Anecdotally, QuickPack actuators were found to be flexible enough to conform to the surface of a full-scale F/A-18 vertical tail.

Electrical Drive: The IDE devices tend to require larger drive voltages to achieve similar electric fields. The QP10Ni uses voltages up to 1,200V, due to the 0.060 inch center-to-center spacing of its electrode lines. (This 6 to 1 ratio of spacing to PZT wafer thickness was chosen to maximize performance at the lowest possible voltage.) The MFC uses up to 1,500V due to the bias-and-overdrive scheme selected, but in the table above we have assumed 20 V/mil peak drive, or 400V. (If the MFC used the more efficient 6 to 1 ratio, 3kV would be required to achieve the maximum +75V/mil field specified for this device.) In any case, the cost, and often the size of electronic components increases when rated for more than 100 to 200 volts. For overall system cost-effectiveness – including actuator and drive electronics – in high volume applications (such as automotive), IDE actuators may not be practical.

Fabrication: The true cost of packaged strain actuators is most likely not reflected in the low-volume sample prices published by the manufacturers. Low volume production can be labor-intensive, and great variability is possible in both the vendor cost agreements negotiated, as well as the amount of profit margin desired or required to achieve a particular business goal. While no self-respecting manufacturer will publicize the costs associated with producing its products, it is possible to analyze qualitatively, in terms of manufacturing steps required, the true costs of the four packaged strain actuators considered here.

- Take the QuickPack as the baseline.
- QuickPack IDE requires the additional step of poling, which takes time and reduces end-to-end manufacturing yield.
- PowerAct requires the extra step of laser machining of the wafer part of the way through its thickness, which is likely slightly more costly (in low volume, at least) than the IDE poling.
- MFC requires a several-step process of dicing, and teardown of the dicing setup, as well as the IDE poling step. The poling yield, however, should be somewhat better than in the QP10Ni due to the reduced poling voltages required due to the smaller electrode spacing.

By this argument, with all else being equal the QuickPack actuator should be the cheapest to produce.

Figure 10 shows the available pricing data on the various technologies. The low-volume (up to 15 units) data points represent the average published “catalog” prices, on a per-unit-area basis. The QP10Ni is included in the QuickPack average, but none of the many 2-layer QuickPack catalog

products are included in that average. By the argument above, the fact that the MFC is slightly less expensive than the QuickPack most likely does not reflect an inherent cost advantage of the MFC technology.

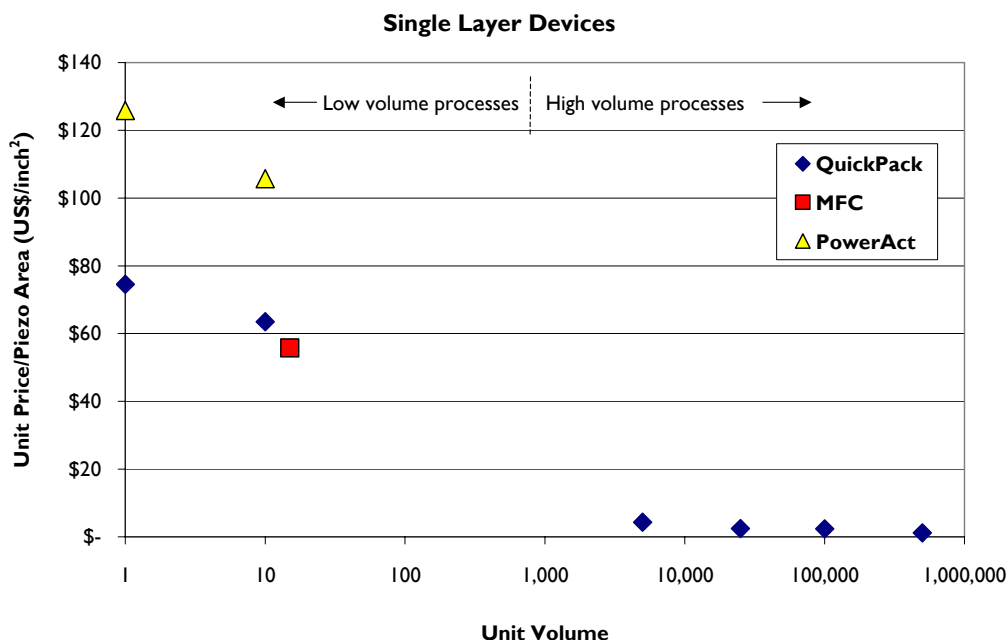


Figure 10. Pricing data for commercially available packaged strain actuators.

At high volumes, with more severe downward pressure on prices, it might be expected that unit prices more accurately reflect the actual costs to produce the product. However, the only product currently used in high volume applications is the QuickPack, so no meaningful quantitative price comparison is possible.

Reliability: As with cost, it is impossible to compare the various devices meaningfully in terms of reliability. Only the QuickPack has been used widely enough to accumulate significant field data. To date, more than one million QuickPack devices have been fielded, with an extremely low rate of field returns. The QuickPack is the most mature of the commercially available packaged strain actuator technologies.

R&D projects concerned with high-performance applications have uncovered certain reliability concerns with packaged strain actuators. In the F/A-18 vertical tail vibration control project referred to above, ACX attempted to increase the performance of d_{31} actuators by using the same bias-and-overdrive scheme as recommended for standard operation of the MFC. Under certain experimental conditions, with maximum drive voltage and maximum external dynamic loading applied to the vertical tail, d_{31} actuators tended to fail^{11,12}. The observed failure mechanism was cracking, followed by electrical arcing through the thickness of the device, along the crack. Subsequent experimental study under controlled conditions identified the cause as a combination of large dynamic (about 20 Hz) mechanical stress (2000 microstrain peak to peak) and high fields (-20 to +60V/mil)²⁰. No failures were encountered when applying unbiased AC voltages in free-free tests.

Published data on MFC²¹ suggest good reliability under 1000 microstrain static loading and ±500V (25V/mil) unbiased drive. These results are consistent with those of the earlier ACX study. In the ACX study, failures did not occur until the bias and overdrive scheme was used, and then only with larger, dynamic stresses applied. Further study is needed to determine the reliability of MFC at these more severe operating conditions.

CONCLUSIONS

The analysis reported in this paper shows that the QuickPack QP10Ni is the best performing commercially available packaged strain actuator. More work is required to establish the reliability of new actuator technologies in industrial applications. Also, the true high volume cost of these new technologies is unknown. By contrast, the QuickPack and PowerAct family of products have a proven track record in industrial applications with more than one million units sold worldwide.

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