PIEZO MOTOR/ACTUATOR KIT MANUAL

KMA-005

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PIEZOELECTRIC MOTOR / ACTUATOR KIT MANUAL

INTRODUCTION TO PIEZOELECTRICITY

MOTOR/ACTUATOR KIT

PURPOSE OF THE KIT

The Motor / Actuator Kit is a development tool for those who wish to rapidly prove the feasibility of a piezoelectric approach to a specialized application. This self contained package makes it possible to establish and verify the performance specifications (i.e. total motion, force, response time, etc.) necessary for a successful actuator. Once performance is defined, the number of material and construction options available for production are considerable. However, the advantages of these options lie primarily in cost at this point.

Piezo Systems recognizes that prototyping material and practical technical information pertaining to piezoceramic motor applications are difficult to obtain. The piezoelectric transducers provided in this kit represent the basic building blocks employed in many piezoelectric systems. The stock supplied is easy to cut to size, center access, and voltage, temperature, and stress limitations are minimal.

The literature will inform the user of basic principles, terminology, actuator design and fabrication techniques, and point out certain practical limitations .

CONTENTS OF THE KIT

Piezoceramic Single Sheets; PSI-5A-S4-ENH

Poled through the thickness; (Red stripe-on one side only)

2.5" x 1.25" x .0075" (63 mm x 31.8 mm x 0.19 mm); 2 pieces

2-Layer Piezoelectric Motor Elements; PSI-5A-S4-ENH

Poled for Series Operation (Red stripe-both sides)

2.50" x 1.250" x .020"	(63 mm x 31.8 mm x 0.51 mm)	1 piece
1.25" x 0.500" x .020"	(31.8 mm x 12.7 mm x 0.51 mm)	1 piece
1.25" x 0.250" x .020"	(31.8 mm x 6.35 mm x 0.51 mm)	1 piece
1.25" x 0.125" x .020"	(31.8 mm x 3.18 mm x 0.51 mm)	1 piece

Poled for Parallel Operation (Red stripe-on one side only)

2.50" x 1.250" x .020"	(63 mm x 31.8 mm x 0.51 mm)	1 piece;
1.25" x 0.500" x .020"	(31.8 mm x 12.7 mm x 0.51 mm)	1 piece
1.25" x 0.250" x .020"	(31.8 mm x 6.35 mm x 0.51 mm)	1 piece
1.25" x 0.125" x .020"	(31.8 mm x 3.18 mm x 0.51 mm)	1 piece

Piezoelectric Motor/Actuator Kit Manual

Solder & Flux

Wires (5 Red & 5 Black; 30 gauge)

PIEZOELECTRIC PHENOMENON

Piezoelectricity is a property of certain materials to physically deform in the presence of an electric field, or conversely, to produce an electrical charge when mechanically deformed. There are a wide variety of materials which exhibit this phenomena to some degree, including natural quartz crystals, semi-crystalline polyvinylidene polymer, polycrystalline piezoceramic, and even human bone.

Piezoelectricity is due to the spontaneous separation of charge within certain crystal structures under the right conditions. This phenomenon, referred to as spontaneous polarization, is caused by a displacement of the electron clouds relative to their individual atomic centers, i.e. a displacement of the positive ions relative to the negative ions within their crystal cells. Such a situation produces an electric dipole.

Polycrystalline ceramic, one of the most active piezoelectric materials known, is composed of randomly oriented minute crystallites. Each crystallite is further divided into tiny "domains", or regions having similar dipole arrangements. The overall effect of randomly oriented polar domains is an initial lack of piezoelectric behavior. However, the material may be induced to exhibit macroscopic polarization in any given direction by subjecting it to a strong electric field, as shown in Figure-1. Such induced materials are termed ferroelectric. Polarization is accomplished by applying a field of ~2350 volts/mm (60 V/mil) across electrodes deposited on outer surfaces.

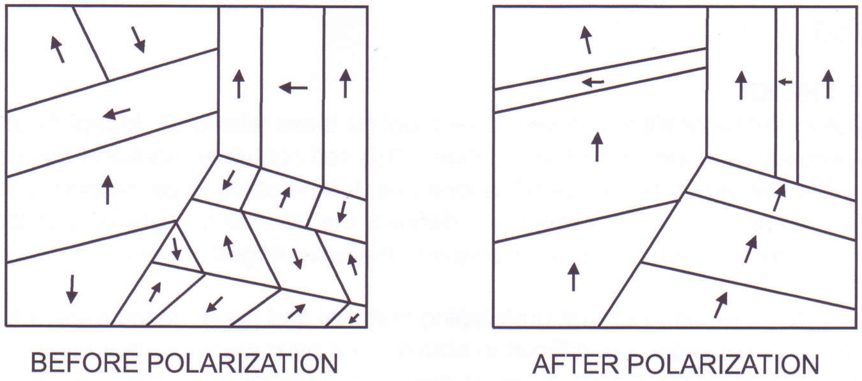


Figure-1. Inducing macroscopic polarization in a polycrystalline piezoceramic by applying a strong electric field across randomly oriented microscopic polar domains.

During electrical polarization the material becomes permanently elongated in the direction of the poling field (polar axis) and reduced in the transverse direction. When voltage is subsequently applied in the same direction as the poling voltage, the piece experiences further elongation along the polar axis and transverse contraction as stipulated by Poisson's ratio. When the voltage is removed, the piece reverts to its original poled dimensions. When voltage is applied opposite to the poled direction (depoling direction), the piece contracts along the polar axis and expands in the transverse direction. Again, it reverts to its original poled dimensions after removing the voltage. These distortions are illustrated in Figure-2 for a rectangularly shaped piece. If too large a voltage is applied in the depoling direction, the original polarization will be degraded (partially or fully depolarized). Or, the electric dipoles may be partially or completely flipped around 180°, causing the piece to be repoled in the opposite direction. The maximum depoling field a piece can withstand without experiencing depolarization is its coercive field, Ec.

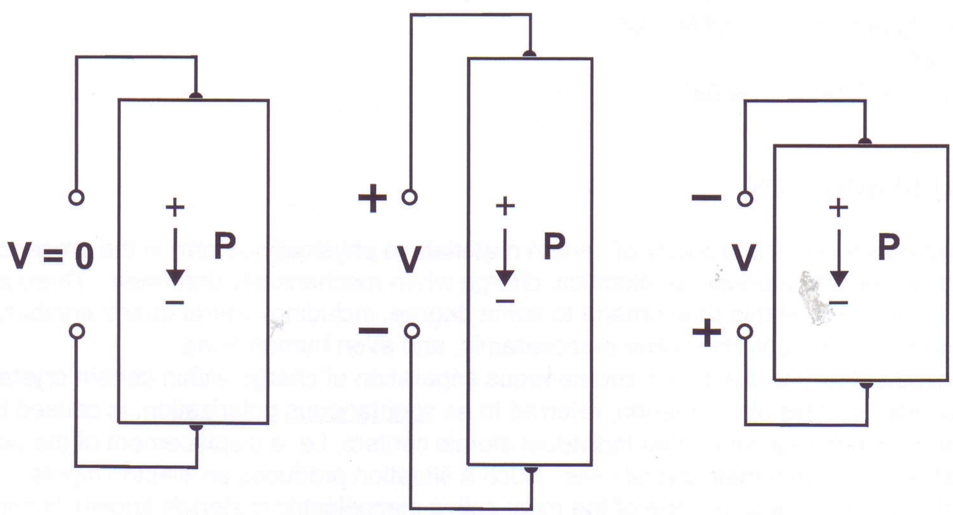


Figure-2. Physical deformation of a rectangular piezoelectric body under the influence of an applied electric field.

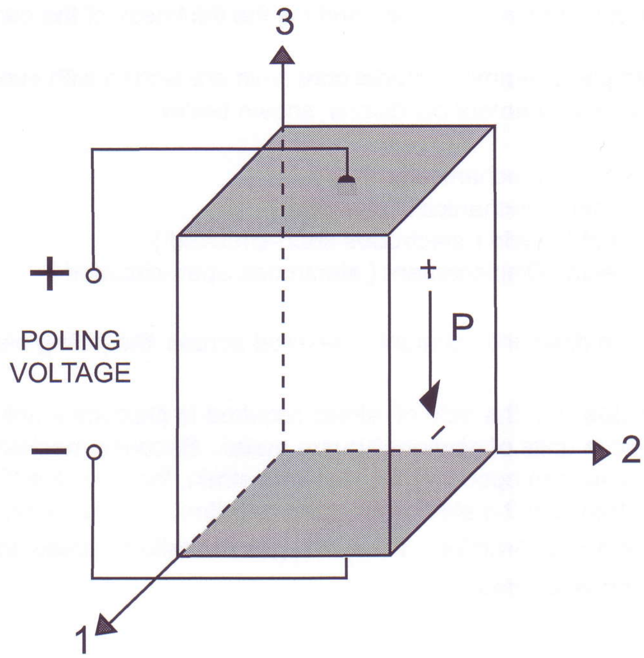
PIEZOELECTRIC AND MATERIAL PROPERTIES OF PIEZOCERAMIC

TERMINOLOGY AND RELATIONS

This section describes the terminology commonly used in the discussion of piezoceramics and notes the fundamental relationships useful in motor applications. It also defines commonly used notations and sign conventions.

Relationships between applied electric fields and the resultant responses depend upon the piezoelectric properties of the ceramic, the geometry of the piece, and the direction of electrical excitation. The properties of piezoceramic vary as a function of both strain and temperature. It should be recognized that the data commonly presented represent values measured at very low strain levels at ~20° C.

Directions are identified using the three axes, labeled 1, 2, and 3, shown in Figure-3. The



"polar" or 3-axis is chosen parallel to the direction of polarization.

Figure-3. Definition of axes for a rectangular piezoelectric body showing the polar or 3-axis, and the transverse or 1 and 2- axes.

The **polarization vector**, established during manufacture by a high DC voltage applied to the electrodes, is represented by an arrow pointing from the positive to the negative poling electrode. This information is conveyed by a dot or stripe on the electrode surface held at high voltage during the poling process.

Piezoelectric coefficients, used to relate input parameters to output parameters, use double subscripts. The **piezoelectric strain coefficients**, d_{ij} , correlate the strain produced by an applied electric field according to the relation:

$$S = d\,E$$

where d_{ij} is expressed in meters/volt. The first subscript gives the direction of the electric field associated with the applied voltage. The second subscript gives the direction of mechanical strain. d_{33} relates the ratio of the the strain along the 3-axis to the electric field applied along the 3-axis, assuming the piece is free to distort in any direction. d_{31} relates the strain along the 1-axis (or 2-axis) to the excitation along the 3-axis under similar conditions.

The **coupling coefficient**, k (lower case), is an indication of the materials ability to convert electrical energy to mechanical energy. Specifically, the square of the coupling coefficient equals the ratio of mechanical energy output to the electrical energy input. It is more relevant to the maximum work output of solid ceramic devices than to bending elements because a practical bending element stores a portion of its mechanical energy in the mount and metal shim center layer. For a bending element, $k_{effective} \sim 3/4\, k_{31}$.

The **relative dielectric constant**, K (upper case), is the ratio of the permitivity of piezoceramic to that of empty space, ε_o ($\varepsilon_o = 8.85 \times 10^{-12}$ farads/meter). K_3 , the relative dielectric constant between the poling electrodes, determines the capacitance of the piece according to the relationship,

$$C = K_3\, \varepsilon_o\, A / t$$

where A is the area of the surface electrode , and t is the thickness of the ceramic layer or layers between electrodes.

Certain piezoceramic material constants are written with superscripts to specify the mechanical or electrical measurement conditions shown below:

T = Constant Stress (mechanically free)
S = Constant Strain (mechanically clamped)
E = Constant Electric Field (electrodes short-circuited)
D = Constant Electric Displacement (electrodes open-circuited)

For example, $K^T{}_3$, is the dielectric constant measured across the poling electrodes of a mechanically free piece.

Young's Modulus, Y , the ratio of stress required to produce a unit of strain, describes the material stiffness of piezoceramic in units of newtons/square meter. Because mechanical stressing of the ceramic produces an electrical response opposing the resultant strain, the effective Young's Modulus with electrodes short circuited is lower than with the electrodes open circuited. Furthermore, the stiffness differs in the 3 direction from that of the 1 or 2 direction. Thus, $Y^E{}_{11}$, is the ratio of stress in the 1 direction to strain in the 1 direction with the electrodes shorted.

PIEZOELECTRIC AND MATERIAL PROPERTIES FOR PSI-5A-S4-ENH PIEZOCERAMIC

The piezoelectric and material properties of PSI-5A-S4-ENH piezoceramic are listed in Table-1 on page 22.

DESIGNING PIEZOELECTRIC ACTUATORS

THE SPECTRUM OF PIEZOELECTRIC MOTOR TRANSDUCERS

Transducers which convert electrical energy to mechanical energy (i.e. motors) come in a wide range of shapes and sizes, each having their own characteristic force-displacement capabilities. Stiff (low compliance) transducers provide tremendous force but tiny motion. On the other hand, highly compliant transducers provide substantial motion but small force.

As a general purpose reference guide,Table-2 shows the spectrum of motor transducers commonly considered in piezoelectric applications. The equations for displacement, force, and resonant frequency, are based on linear relationships and low signal values of their piezoelectric strain coefficients.

BASIC ENGINEERING CONSIDERATIONS

PERFORMANCE

DEFLECTION AND FORCE: Piezoelectric actuators are usually specified in terms of their free deflection and blocked force. Free deflection, X_f, refers to displacement attained at the maximum recommended voltage level when the actuator is completely free to move and is not asked to exert any force. Blocked force, F_b, refers to the force exerted at the maximum recommended voltage level when the actuator is totally blocked and not allowed to move. Deflection is at a maximum when the force is zero, and force is at a maximum when the deflection is zero. All other values of simultaneous displacement and force are determined by a line drawn between these points on a force versus deflection line, as shown in Figure-4. Generally, a piezo motor must move a specified amount and exert a specified force, which determines its operating point on the force vs. deflection line. Work is maximized when the deflection performed permits one half the blocked force to be developed. This occurs when the deflection equals one half the free deflection.

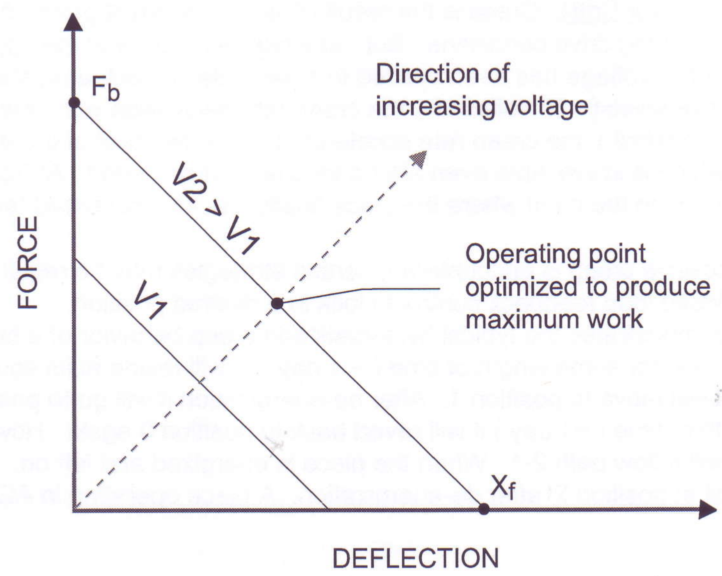


Figure-4. The force versus displacement diagram for a piezoelectric motor element.

For cantilevered bending motors, X_f and F_b are approximated by observing the the tip deflection after energizing, and by holding a force gauge against the tip during energization.

RESPONSE TIME**:** Typically, it is useful to know how fast an actuator will operate. The fundamental resonant frequency, F_r, is a guide post towards answering this question. A piezo actuator can follow a sinusoidal signal up to its resonant frequency. Beyond this point, its inertia inhibits it from keeping up with electrical excitation. From a practical standpoint, it's a good idea to limit operation to ~ 3/4 F_r. The response time, t_r, for an actuator to travel through its full range, for bipolar operation (from 0 to positive voltage, then to negative voltage, and back to 0) is 1/4 cycle. Thus,

$$t_r \text{ (bipolar operation)} = \frac{1}{4 \times (.75\, F_r)}$$

For example, an actuator driven by a bipolar power supply, and having a resonant frequency of 500 Hertz, has a response time of 0.67 milliseconds. Any mass added to the end of the actuator will lengthen the response time.

STABILITY: For those applications which require the piezo actuator to hold its position accurately for a long time, an understanding of hysteresis and creep is important. For dynamic applications, where position is changing continuously, these issues are less critical.

Hysteresis: When a polycrystalline piezoelectric body is deformed, part of the mechanical energy is stored as elastic strain energy, and part is dissipated as heat during small internal sliding events. Hysteresis appears as an offset between the the position path traveled during the application and removal of the excitation field. The size of the offset depends on the field level, the cycle time, and the materials used. It is often specified as a percentage of the total deflection achieved, and ranges from .1% to 10%. Hysteresis is a consideration wherever high frequencies (> 1 KHz) are concerned because of heat accumulation within the piece after each cycle of operation. This is especially the case for low voltage piezo stacks made of high strain material. This can lead to excessive temperatures if care is not taken in the design. Other portions of the piezoelectric system also contribute to losses, such as adhesive bonds, mounts, and attachments. These show up in ultrasonic designs.

Creep (or Drift): Creep is the result of time dependent plastic deformation. Usually it is not a concern under oscillating drive conditions. But, any high level DC voltage application should pay close attention to creep . After voltage has been applied to a piezoelectric actuator, the deflection increases with time. For moderate drive levels(<10 volts/mil), the creep rate decreases with time. However, as the drive level increases (>20 volts/mil), the creep rate accelerates. Upon removal of the drive voltage, the piece retains a set, a portion of which is irreversible even after a long relaxation period. At high drive levels (>30 volts/mil), creep may proceed to the point where the piece finally cracks. Increased temperature exacerbates creep.

When excessive creep is encountered, certain strategies may be required, such as stops to limit excessive travel, or closed loop feedback control to lock in a desired position.

Figure-5 demonstrates the typical hysteresis and creep behavior of a bending element. When a piece has been at rest for some length of time (~ 1 day), it will reside at its equilibrium position, 0. Upon initial energization, it will move to position 1. After de-energization it will go to position 2. If it is allowed to rest for a sufficient length of time (~1 day) it will revert back to position 0 again. However, if it is re-energized immediately, it will follow path 2-1. When the piece is energized and left on, it will creep along the path 1-1', and come to rest at position 2' after de-energization. A piece operating in AC mode will follow path 1-2-3-4-1.

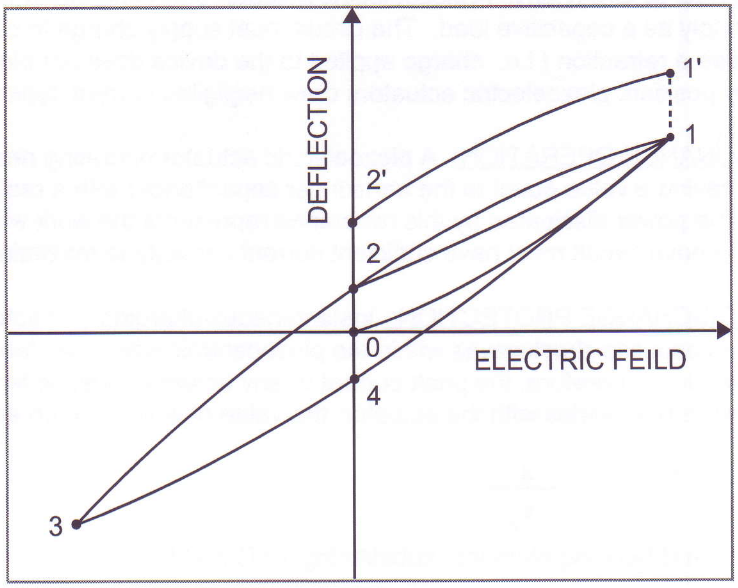


Figure-5. Typical hysteresis and creep behavior of a single bending element.

MECHANICAL CONSIDERATIONS

MOUNTING: An ideal mount permits the normal distortion of the entire active portion of the motor element, while at the same time preventing motion in certain directions at the mounting point or points. Generally piezo motors are either bonded, clamped, or spring loaded to their mounting points. Mounts introduce some mechanical damping into the system since some of the energy from the motor distorts the mount itself. This may or may not be desirable.

RESONANCE: Mechanical resonance is a manifestation of the trading back and forth of kinetic energy (moving mass) and potential energy (elasticity) in an oscillating body. At certain frequencies, known as resonances, the amount of stored enery becomes very large compared to the excitation energy. This phenomena can be useful for achieving large deflections at low voltages, and for obtaining high efficiency. Piezo fans and ultrasonic devices utilize this property. Because of the high amplitudes exhibited at resonance, care must be taken not to overstrain and crack the actuator.

The resonant frequencies of a piezo motor depend on its dimensions, material properties, and the manner of mounting. The cantilever beam element has the lowest fundamental (first) resonant frequency per unit length of all configurations and mounting schemes. Equations for determining the fundamental resonant frequencies for several motor configurations are shown in Table-2. These frequencies apply to unloaded elements only. Attachments to the element will add to the resonating mass and lower the resonant frequency.

OPERATING FREQUENCY BAND: Up to resonant frequency, the deflection of a piezoelectric bending element is nearly independent of frequency and proportional to the operating voltage. Around the resonant frequency, deflection rises rapidly to a multiple of its normal value. The amplitude and narrowness of the resonance depend on the internal and external losses acting on the actuator. Above resonance, deflection decreases steadily with the square of the frequency. First resonance marks the limit of the usable frequency band for quasi-static actuators. For resonant applications, the useable frequency range is limited to a small band around the useful resonant modes.

STRENGTH LIMITATIONS: Piezoceramic is very strong in compression but weak in tension. Bending elements always have one side in compression and the other side in tension, where the magnitude of stress increases linearly from the midplane to the outside surface. Therefore, the element is always limited by the maximum recommended tensile strength, generally considered to be in the range of 20-35 x 10^6 Newtons/meter^2. From a strain point of view, the ceramic should not be allowed to strain more than 500x10^{-6} meter/meter.

DRIVE CIRCUIT CONSIDERATIONS

QUASI-STATIC OPERATION: A piezoelectric actuator operating below its fundamental resonance can be treated simply as a capacitive load. The circuit must supply charge to cause a motion, and must withdraw charge to cause a retraction (i.e. charge applied to the device does not bleed off internally). When held motionless in any position, piezoelectric actuators draw negligible current, typically much less than a microamp.

NEAR RESONANCE OPERATION: A piezoelectric actuator operating near resonance can be modeled as a capacitor (having a value equal to the transducer capacitance) with a resistor in parallel (typically 10 to 100 ohms). The power dissipated by this resistance represents the work which the actuator does on its environment. The drive circuit must have sufficient current capacity to maintain the desired voltage on the resistor.

CHARGE / DISCHARGE PROTECTION: Instantaneous charging or discharging of piezoelectric actuators causes acoustic shockwaves within the piezoceramic which can lead to localized stress concentrations and fracture. Therefore, the peak current to any actuator must be limited. One simple method places a protection resistor in series with the actuator, the value of which can be estimated using the following relation:

$$5 R_p C \geq \frac{4}{F_r}$$

For a series operated cantilevered bending element, substituting for C and Fr:

$$R_p = (5 L / \varepsilon_o K_3 b) (\rho / Y_{11})^{1/2}$$

This essentially limits operation to a frequency region below the fundamental resonance.

OUTPUT STAGE PROTECTION: Piezoelectric bending elements can generate high voltages (>100 volts) under external vibration, shock, or temperature shifts. If these conditions are expected, the drive circuitry of the output stage must be protected against transient voltages of all polarities.

ELECTRICAL ISOLATION: The outer electrode surfaces of certain motor elements are electrically "live" in many configurations. For product or experimental safety, consideration should be given to insulating or sheilding the electrodes, mount, and power take-off sections of the motor element.

ELECTRICAL BREAKDOWN: The highest value of applied electric field is determined by electrical breakdown occurring either through the body of the piezoceramic sheet or over the its edges. Pieces of dust and debris adhering to edges can initialize edge discharge at fields as low as 400-800 volts/mm. However, the discharge arc vaporizes the debris, thereby cleaning itself. A number of these edge-debris arcs may occur during the initial energization of the bending motor, but they will not occur again. Continuous breakdown occurs around 3,000-4,000 volts/mm, usually at impurity or defect regions within the bulk of the material. This can lead to a short circuit across the sheet due to vapor deposition of electrode or shim material near the site of arcing. A current limiting resistor or in-line fuse is recommended when excessive electric fields are used.

ELECTRICAL LOSSES: The bulk resistivity of piezoceramic is $\sim 10^{12}$ Ω-cm. Therefore, electrical losses are minimal under static or low frequency operation. However, dielectric losses are significant under cycled operation and can lead to heating under high frequency /high power operation. The loss tangent, the ratio of series resistance to series reactance, for PSI-5A-S4-ENH is ~0.015.

THERMAL CONSIDERATIONS

CURIE TEMPERATURE: For each piezoceramic material there is a critical temperature, known as its Curie point, which represents its maximum operating temperature before suffering a permanent and complete loss of piezoelectric activity. In practice, the operating temperature must be limited to some value substantially below the Curie point because at elevated temperatures depoling is greatly facilitated, the aging process is accelerated, electrical and mechanical losses increase, and the maximum safe stress is reduced. As a rule of thumb, a temperature equal to one half the Curie temperature is considered the maximum safe operating temperature.

PIEZOELECTRIC AND MATERIAL PROPERTIES AS A FUNCTION OF TEMPERATURE: Piezoceramic properties are strongly temperature dependent, and thermal dependence varies markedly from one material to the next. Figure-6 demonstrates the temperature dependence of K_3 and d_{31} for PSI-5A-S4-ENH.

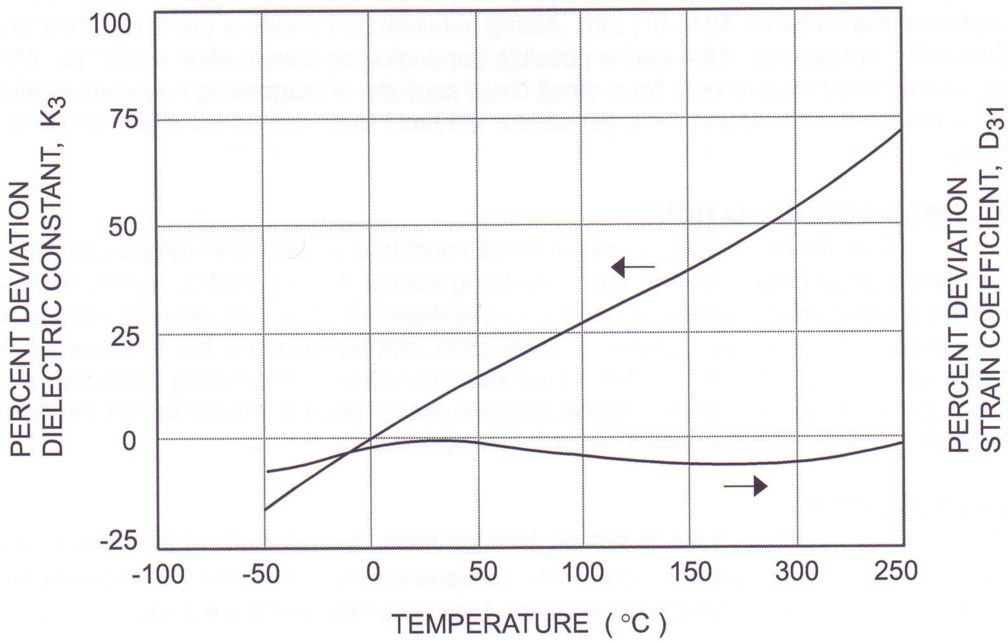


Figure-6. The relative dielectric constant and transverse strain coefficient as a function of temperature.

PYROELECTRIC EFFECTS: An electric field is induced on the electrodes of a piezo motor when it is exposed to a thermal change. The induced field is

$$E = \frac{\alpha (\Delta T)}{\varepsilon_o K_3}$$

where α is the pyroelectric coefficient in units of coulombs / M^2 °C, ΔT is the temperature change, K_3 is the relative dielectric constant in the poling direction, and ε_o is the permitivity of free space. It should be noted that a depoling voltage will be developed across a layer of piezoceramic when the temperature drops. This can happen during processing, testing, or normal useage. If a temperature drop is sufficient, over a time interval which is too short to allow charge to leak away, a voltage greater than the coercive field can result. This can degrade the original polarization causing reduced performance. It is always good practice to short circuit the electrodes of any piezo device during a cool down procedure.

THERMAL EXPANSION: One must account for thermal displacements over the temperature range anticipated. The actuator must be capable of compensating for thermal displacements and still have a useful motion range.

In addition, differential thermal expansions of adjacent assembly parts will cause moments and warping. The standard bending motor element has a symmetrical construction. Distortion due to thermal excursion should be negligible. However, care should be taken in the design of the mount or any other attachments not to introduce thermal distortion. This is facilitated by properly matching the thermal expansion coefficients of adjacent members to that of the ceramic element. The coefficient of thermal expansion of PSI-5A-S4-ENH is ~ 4 μM / M °C.

CRYOGENIC OPERATION: The low signal values of the strain coefficients for operation at 4.2 °K are reduced by a factor of 5-7 times. The value of the coercive field increases substantially however. Cycling the transducer between these temperature extremes does not seem to affect them adversely.

VACUUM CONSIDERATIONS

Because piezo actuators are solid state devices, they lend themselves to high vacuum operation. However, several issues should be understood. First, voltage should not be applied to the electrodes during the vacuum pump-down process because of the low insulation resistance of air and nitrogen between the range of 10 to 0.1 torr. Arcing between electrodes is possible within this pressure range. Secondly, outgassing of the part is possible depending on construction materials. Motors to be used in high vacuum environments should have small cross sections of outgassing materials (primarily the adhesive). If bake-out is necessary, the transducer will have to be built to withstand solvents and bake-out temperatures.

ELECTRIC FIELD CONSIDERATIONS

As mentioned earlier, under adverse conditions piezoelectric properties may degrade, vanish completely, or be flipped around 180°. A strong electric field applied to a piezoceramic in a sense opposite to the original poling voltage will tend to cause depoling. The field strength necessary to initiate depoling depends on the material, duration of application, and temperature, but is typically in the range of 475 volts/mm at 20° C for PSI-5A-S4-ENH under static conditions. Alternating fields may also degrade the piezoceramic, but the peak field level is higher because the duration is shorter before the field is reversed. A peak field of 600 volts/mm may be tolerated for 60 Hz operation at 20° C.

STRESS CONSIDERATIONS

When the mechanical stress on a piezoceramic element becomes too high, again there is a danger of degrading the piezoelectric properties. Generally, compressive or hydrostatic stress levels of ~50×10^6 N/M^2 are required to degrade PSI-5A-S4-ENH if no other degrading influences are present.

AGING

Piezoelectric properties change gradually with time. The changes tend to be logarithmic with time after the original polarization. Therefore, the rate reduces rapidly with time. Aging depends on the ceramic material, manufacturing process, and ambient conditions such as temperature, vibration or shock. Pieces may be heated for a specified time to accelerate the aging process.

PIEZOELECTRIC BENDING MOTORS

PRINCIPLES OF OPERATION

The most common type of piezoelectric bending motor is composed of two layers of piezoceramic bonded to a thin metal shim sandwiched in the middle. The construction and typical dimensions of the 2-layer elements provided in this kit are shown in Figure-7.

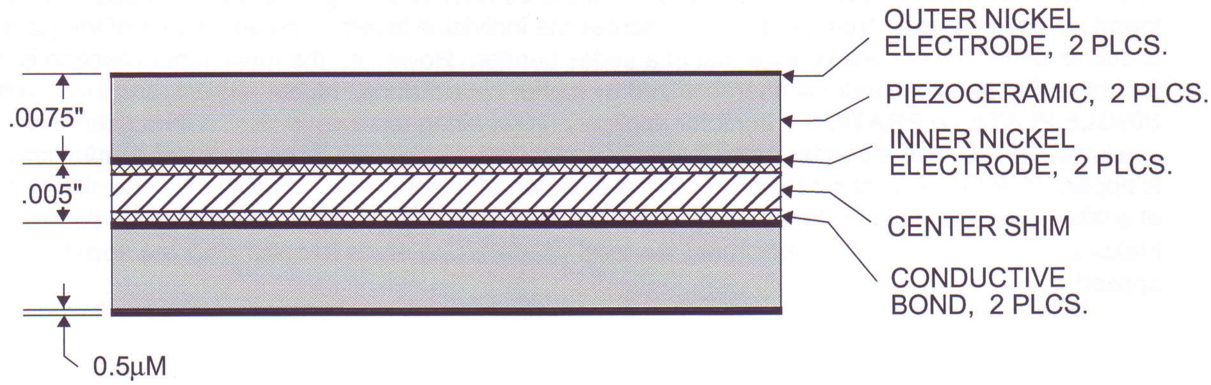


Figure-7. Construction of laminated 2-layer motor element.

The application of voltage to the element is analogous to the application of heat to a bimetallic strip. The voltage across the bender element forces one layer to expand, while the other contracts, as depicted in Figure-8. The result of these physical changes is a strong curvature and large deflection at the tip when the other end is clamped. The tip deflection is much greater than the change in length of either ceramic layer.

Bending motors exhibit unique properties. They may be energized proportionately and be held in the energized position with negligible consumption of energy or generation of heat. They may be operated over billions of cycles without wear or deterioration. Their low profile allows their use in very restricted locations.

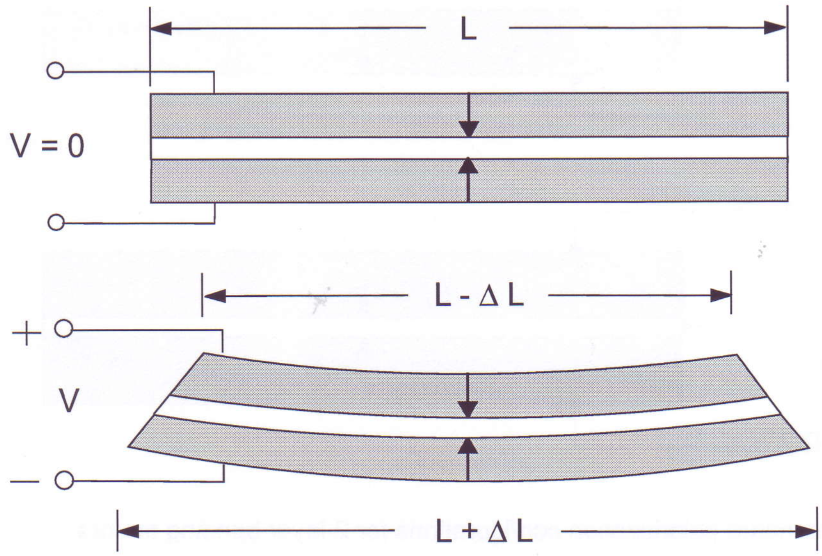


Figure-8. The curvature of a bending motor is due to the expansion of one layer and contraction of the other.

STANDARD POLARIZATION CONFIGURATIONS

There are three standard polarization configurations for the two layer bender construction: series, parallel, and single plate (monomorph). These are illustrated in Figure-9. Both the series and parallel elements are limited to electric fields below the coercive field (~ 475 V/mm for PSI-5A-S4-ENH).

SERIES OPERATION The bender poled for series operation is the simplest and most economical. It requires two connections to the outside surfaces of the piezoceramic layers which are electrically in series. It is characterized by a lower capacitance, lower current, and higher voltage.

PARALLEL OPERATION The bender poled for parallel operation requires three electrical connections. The third connection accesses the center shim of the bender, requiring an extra manufacturing step and therefore a higher cost. Voltage is applied across the individual layers. The advantage of the parallel bender is that its deflection per volt is twice that of a series bender. However, the maximum deflection is the same for both. The parallel bender is characterized by higher capacitance, higher current, and lower voltage.

SINGLE PLATE OPERATION In motor applications requiring extra deflection, a third alternative is available. In this case a bender poled for series operation is used with three electrical connections. Voltage is applied to either layer of piezoceramic in the direction of polarization. Usually only one side is energized at a time. The excitation field may exceed the coercive field since there is no concern for depolarization. Fields as high as 1,500-2,000 volts/mm (the level where arcing starts to occur near the edges) may be applied.

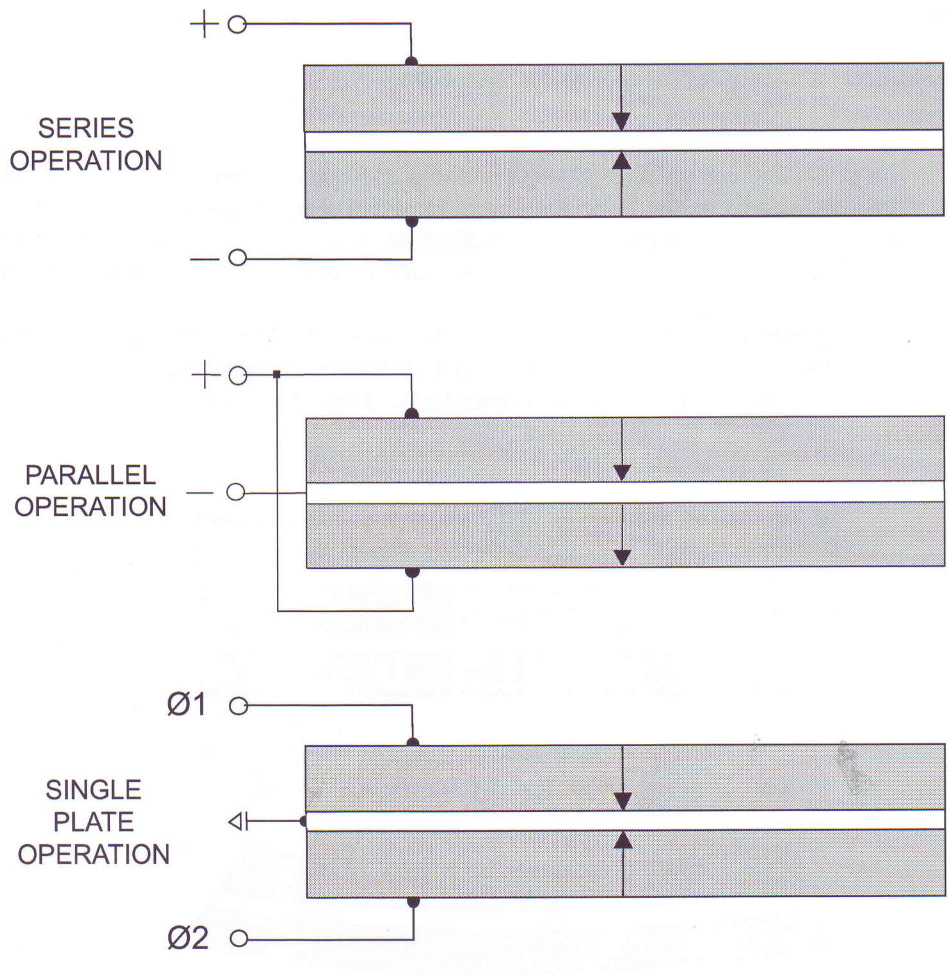


Figure-9. The three standard polariazation configurations for 2-layer bending motors

STANDARD MOUNTS FOR BENDING MOTORS

Standard mounts for bending motors are illustrated in Figure-10 and fall into two general categories. The first category has power taken off at one end and is mounted at the other. Known as the cantilever mount, it provides maximum compliance and deflection. The second category has power taken off at the center and is mounted at the ends. The simple beam mount allows the ends to move in and out as well as rotate, but fixes their vertical position. Compared to the cantilever mount, the simple beam mount produces reduced deflections, increased forces, and increased frequency. For high frequency-resonant applications, power dissipation at the mounts can be minimized by using nodal mounts. The nodes are evenly spaced, .55L apart, where L is the length of the beam. The beam may also be rigidly clamped at both ends, although this results in a significant proportion of the beam being constrained.

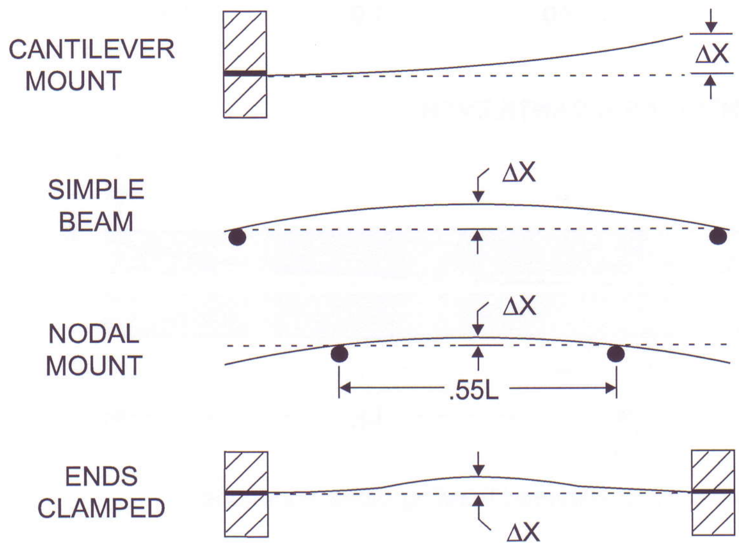


Figure-10. Standard mounting techniques for bending motors.

BENDING MOTOR EQUATIONS

The "Bending Motor Equations" describe non-linear behavior and take into account the center shim. They can be used to: 1.) verify that the bending motor is operating properly, and 2.) scale the dimensions of the experimental actuator to define the dimensions of the final design, or vice versa. The relations below were developed by C. P, Germano of Vernitron Piezoelectric, with minor modifications by Piezo Systems.

Definition of terms:

- L = Total length of the bending motor (M)
- L_c = Cantilever length (M)
- T = Total thickness of bending motor (M)
- d = Thickness of center shim and adhesive layers (M)
- t_c = Thickness of a single layer of piezoceramic (M)
- b = Width of bending motor (M)
- d_{31} = Piezoelectric transverse strain coefficient (M/V)
- E = Electric field strength (V/M)
  - E (series operation) = Voltage / 2 t_c
  - E (parallel operation) = Voltage / t_c
- Y = Young's modulus of elasticity (N/M^2)
- K = Relative dielectric constant of piezoceramic
- ε_o = Permitivity of free space (8.85×10^{-12} Farads / Meter)

ρ = Average density of bending motor
β = A non-linearity constant related to the electric field strength
γ = A non-linearity constant related to the electric field strength

E (V/mm)	E(V/mil)	β	γ
0	0	1.0	1.0
200	5	1.5	1.2
400	10	1.8	1.3
800	20	2.0	1.4
1200	30	2.1	1.3
1600	40	2.0	1.3
2000	50	1.9	1.3

BENDING MOTOR MOUNTED AS A CANTILEVER

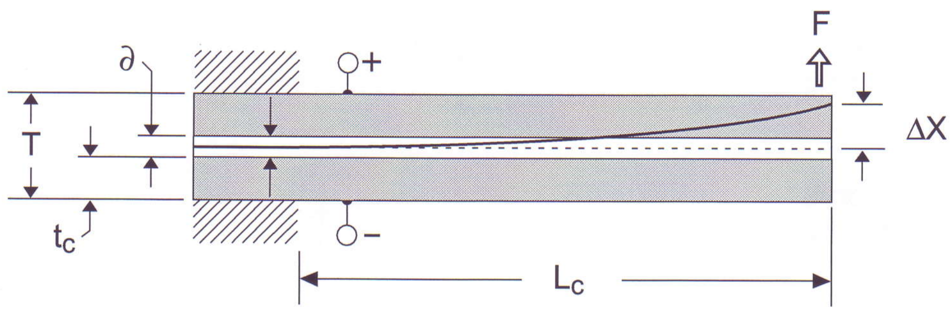


Figure-11. Terminology used for cantilevered bending motor equations

FREE DEFLECTION: The free deflection, X_f, is usually twice the required operating deflection.

$$X_f = 3 \beta d_{31} (L_c^2 / T^2)(1 + \delta / T) t_c E$$

where $t_c > \delta \quad 0$

BLOCKED FORCE: The blocked force, F_b, is usually twice the required operating force.

$$F_b = (3/4) \gamma Y_{11} d_{31} (b T / L_c)(1 + \delta / T) t_c E$$

where $tc \geq \delta > 0$

RESONANT FREQUENCY: $F_r = (.16 T / L_c^2)(Y_{11} / \rho)^{1/2}$

MAXIMUM SURFACE STRAIN: ~ 500×10^{-6} is the maximum recommended strain limit in tension.

$$S = X_f T / L_c^2$$

CAPACITANCE: C (series operation) = $K_3 \varepsilon_o L b / 2 t_c$
C (parallel operation) = 4 x series operation

BENDING MOTOR MOUNTED AS A SIMPLE BEAM

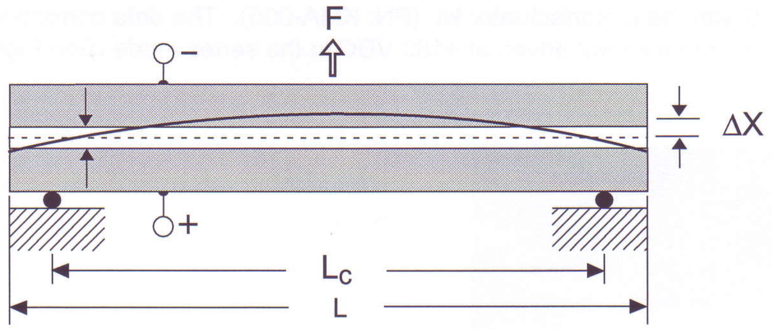
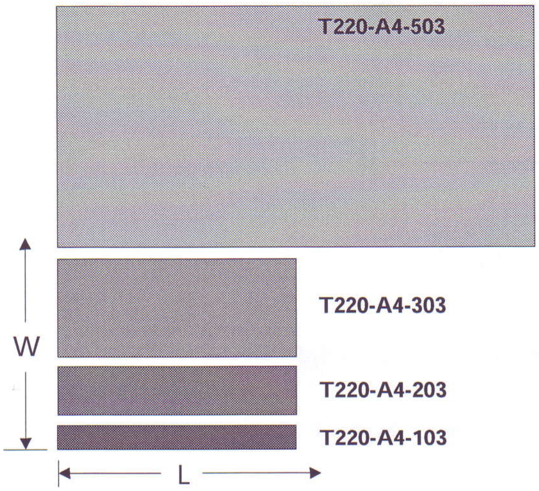


Figure-12. Terminology used for simple beam bending motor equations

FREE DEFLECTION:	Multiply the cantilever X_f by 1/4
BLOCKED FORCE:	Multiply the cantilever F_b by 4
RESONANT FREQUENCY:	Multiply the cantilever F_r by $\sqrt{8}$
SURFACE STRAIN:	Multiply the cantilever S by 4
CAPACITANCE:	Same as cantilever for both series and parallel operation

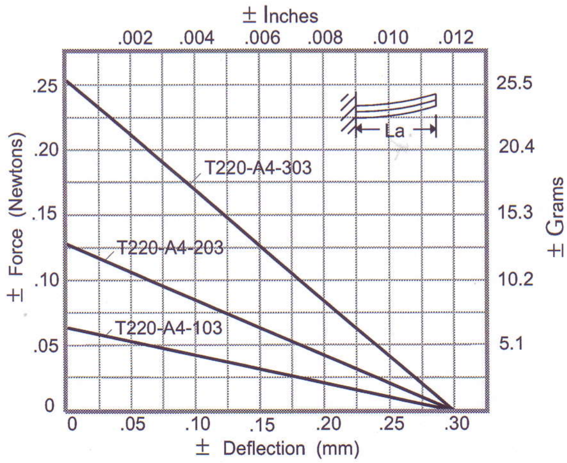
MEASURED BENDING MOTOR PERFORMANCE OF 2-LAYER KIT ELEMENTS

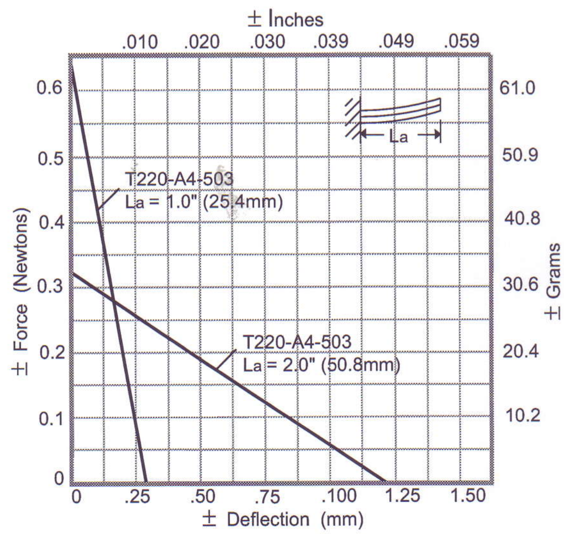
As a reference point, the chart below provides measured bender performance for the 2-layer elements supplied with the motor/actuator kit (PN: KMA-005). The data corresponds to the performance at the tip of a cantilevered element driven at ±180 VDC in the series mode (See Figure-9).



SPECIFICATIONS & BENDING MOTOR PERFORMANCE (In the cantilever configuration)

Part Number	Weight	Capacitance		Rated Voltage		Response Time (Full Amplitude)		Free Deflection		Blocked Force	
		Series Operation	Parallel Operation	Series Operation	Parallel Operation	Active Length, mm					
						25.4	50.8	25.4	50.8	25.4	50.8
	grams	nF	nF	±Vp	±Vp	ms	ms	±mm	±mm	±N	±N
T220-A4-103	.40	3.6	14.	±180	±90	1.2	-	±.25	-	±.07	-
T220-A4-203	.80	7.4	29.	±180	±90	1.2	-	±.25	-	±.14	-
T220-A4-303	1.6	14.5	58.	±180	±90	1.2	-	± .25	-	±.28	-
T220-A4-503	8.0	72.5	290.	±180	±90	1.2	4.8	± .25	±1.0	±.70	±.35





BUILDING PIEZOELECTRIC ACTUATORS

WORKING WITH PIEZOCERAMIC

THIN-SHEET PIEZOCERAMIC STOCK

Unlike laminated bending motor stock, thin sheet piezoceramic is extremely fragile and difficult to handle. However, with proper care and practice it can be manipulated quite easily. Rough cutting is accomplished by lightly scribing a ruled line along it's surface with a sharp razor blade until the piece cracks. It should then be picked up by inserting the razor blade under one edge and lifting until it can easily be grasped with one's fingers. Subsequent operations should not be performed until after the piece has been bonded to its intended surface.

2-LAYER MOTOR STOCK

DURABILITY: The two layer motor stock is much more rugged than generally assumed. It can be handled without special care and oftentimes dropped without damage. The ceramic is non porous and is impervious to moisture as well as chemically inert with acids and solids. The adhesives used for lamination, the center shim, and the nickel electrodes, however, are susceptible to particular solvents and acids.

CUTTING AND SHAPING: For prototyping purposes, the motor stock can be rough cut on a band saw (having ~14 teeth/inch or more) as long as it is supported underneath by a back-up plate (plexiglass, metal, etc.). This is not recommended for dimensions less than 1/4". Rough cutting usually produces burrs at the center shim which may make electrical contact to one of the outer electrodes. The burrs can be removed by filing or sanding the edge. Chipping will occur along the edge, but this is seldom great enough to affect performance. With some practice, the motor stock can be trimmed with scissors when one wants to remove thin slivers.

High quality cuts, necessary for long term stable performance, require the use of a high speed diamond wheel saw.

ACCESSING THE CENTER SHIM: A milling machine can be used to remove ceramic in order to access the center shim electrode. Removal of ~1 mil per pass is recommended. A hand held grinding tool (i.e. Dremel Tool) is suitable for quick center shim access.

It is also possible to contact the center shim with a razor blade or push pin when only temporary access is needed (for example, repoling).

BONDING AND ATTACHING TO PIEZOCERAMIC

Attachments for power take off or mechanical grounding are usually accomplished by bonding to the piezoceramic at its ends or middle. Holes or fasteners are put in these secondary members. Almost any adhesive bonds well to the piezoceramic nickel surface. These include epoxies, anaerobics, and cyanoacrylates. For quick mounting, the bending element is often clamped between two surfaces.

SOLDERING & ATTACHING LEADS TO THE ELECTRODES & CENTER SHIM

Piezoceramic electrodes will be either fired silver or nickel. Silver electrodes are flat white in color while nickel electrodes are grey. Electrical connections are usually made to these electrodes by soldering, but one may also use conductive adhesive, or clips to attach wires. **Soldering materials in the Motor/Actuator Kit are for soldering to nickel electrodes unless specifically requested otherwise.** Silver electrodes are not recommended for high electric field DC applications where the silver is likely to migrate and bridge the two electrodes. It is often used in AC applications. Silver used as an electrode is in the form of flakes suspended in a glass frit. It is generally screened onto the ceramic and fired. The glass makes the bond between the ceramic and the silver particles. Silver is soluble in tin and a silver loaded solder should be used to prevent scavenging of silver in the electrode. Nickel has good corrosion resistance and is a good choice for both AC and DC applications. It can usually be soldered to easily with tin/lead solder. Electroless nickel, used for plating piezoceramic, contains phosphor. Sometimes the phosphor content in a plating run can make it hard to solder. Vacuum deposited nickel electrodes are usually very thin, making soldering tricky.

Choice of the correct flux (to remove surface oxidation) makes soldering to electrode surfaces easy even under adverse conditions.

A wire is attached to the center shim if the element is used in parallel operation. Generally, the center shim layer of a 2-Layer piezoelectric bending elements is either brass or stainless steel. Shims are soldered to in the same way as the nickel electrode.

Tools & Materials For Soldering
- Soldering iron set ~ 550°-600° F
- 60 Sn / 40 Pb Solder
- Supersafe # 67 DSA Liquid Flux
- Wires (preferably #30 gauge or smaller)
- Pencil eraser and paper clip

Procedure For Soldering
- Clean surface to be soldered with an abrasive (pencil eraser) and wipe with alcohol. This step can usually be skipped when using the proper flux.
- Dip the tip of a paper clip into the flux and apply a small dot of Supersafe Liquid Flux to the electrode area to be soldered.
- Apply small amount of solder to iron tip and transfer solder to the piezoceramic electrode by touching iron tip to flux dot. A good solder joint should flow rapidly (≤ 1 second) and look shiny. Metal shims take longer due to the increased thermal mass (~2 seonds).
- Apply another small dot of Supersafe Liquid Flux to the solder dot on electrode.
- Position pre-tinned wire on solder dot and apply soldering iron to the wire until the solder melts. Remove iron quickly after the solder melts and hold the wire still until the solder solidifies. A 30 gauge wire or smaller is recommended to minimize strain on the solder joint during wire handling.
- Remove Supersafe Liquid Flux residue with clean running water. This flux residue is electrically conductive and must be removed for proper functioning of a piezo device. Any rosin residue may be removed with alcohol.
- Wherever feasible, the wire-solder joint should be strain relieved with a drop of adhesive.

PERFORMANCE TESTING

Generally, measurements of free deflection, blocked force, resonant frequency, and capacitance are easy to make and should be recorded for each design configuration explored. Capacitance is a good measure of the health of the element. If the capacitance of the piece decreases during operation or testing, from that of the its initial value, then the element has probably depoled, cracked, or lost electrical contact during operation.

For fundamental performance testing, a power supply and switching box with an adequate series protection resistor are suggested. Any frequency generator can be used to measure resonant frequency. The resonance patterns may be observed by sprinkling sugar on the piece and sweeping through the frequency band. At resonance, sugar will be tossed off the anti-nodes and collect at the nodes. Suitable means for measuring force and deflection, such as an X-Y table and high compliance force gage, are needed. Such a system is shown in Figure-13.

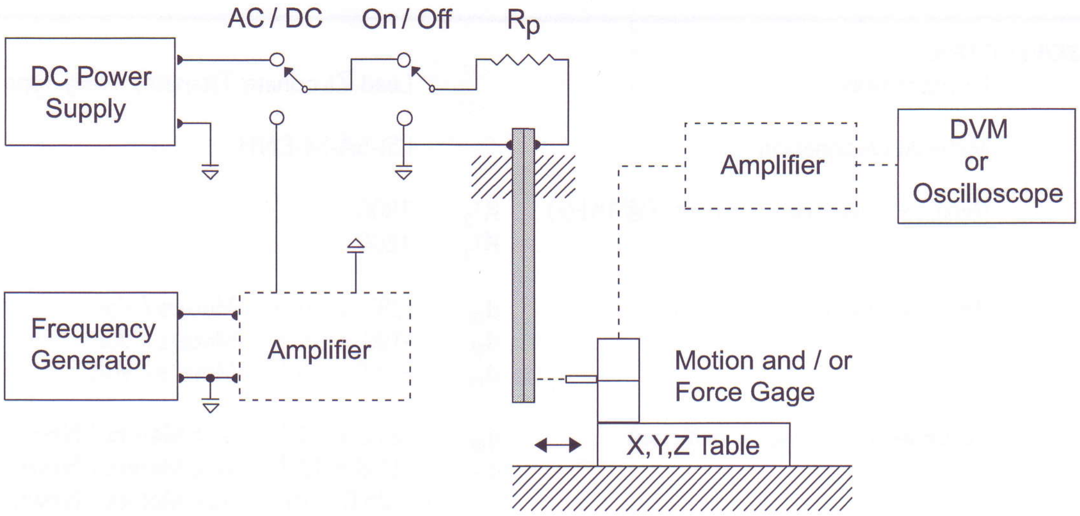


Figure-13. System for measuring output performance (free deflection, blocked force, and resonant frequency) of a bending motor element.

PROFESSIONAL ENGINEERING SERVICES

Piezo Systems Inc. (PSI) recognizes that in many instances, after the principles and feasibility of a piezoelectric approach have been demonstrated, timely and professional development is essential. PSI offers the support services listed below.

CUSTOM PIEZOELECTRIC DESIGN AND DEVELOPMENT ENGINEERING

For customers who have demanding long-term projects employing piezoelectric motor or generator technology, PSI offers a phased program for custom device and product development. The program enhances development success and product reliability by eliminating potential design flaws which might plague those unfamiliar with piezoelectric technology, especially in the areas of: lamination bonding, hinge/flexure design, ceramic stress and fatigue criteria, high temperature stability and performance, mounting and power take-off attachment, drive circuit design, testing, and evaluation. Using extensive in-house software, PSI can move directly from your requirements to a completed actuator or system design. Development time is reduced from years to months and incorporates realistic economic and processing assumptions.

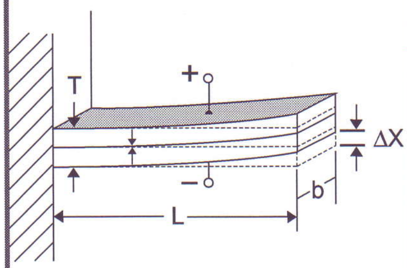
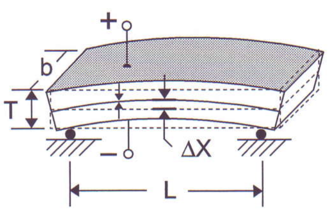
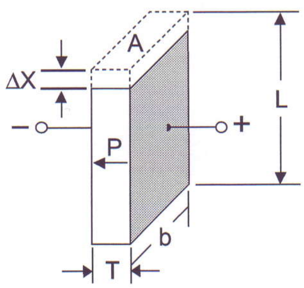
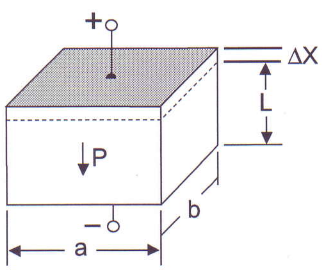
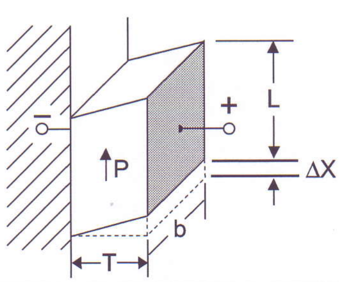
CONSULTING SERVICES

Discussions with the Piezo System's technical staff concerning a wide range of technical and economic issues are available.

TABLE-1. PIEZOELECTRIC AND MATERIAL PROPERTIES FOR PSI-5A-S4-STD PIEZOCERAMIC

PIEZOELECTRIC				
Composition			Lead Zirconate Titanate, Navy Type-II	
Material Designation			PSI-5A-S4-ENH	
Relative Dielectric Constant	(@1KHz)	K^T_3	1800	
		K^T_1	1800	
Piezoelectric Strain Coefficient		d_{33}	390×10^{-12}	Meters / Volt
		d_{31}	-190×10^{-12}	Meters / Volt
		d_{15}	$\sim 550 \times 10^{-12}$	Meters / Volt
Piezoelectric Voltage Coefficient		g_{33}	24.0×10^{-3}	Volt Meters / Newton
		g_{31}	-11.8×10^{-3}	Volt Meters / Newton
		g_{15}	$\sim 26.0 \times 10^{-3}$	Volt Meters / Newton
Coupling Coefficient		k_{33}	0.72	
		k_{31}	0.32	
		k_{15}	0.59	
Polarization Field		Ep	2×10^6	Volts / Meter
Coercive Field	(DC)	Ec	5×10^5	Volts / Meter
	(@ 60 Hz)		6×10^5	Volts / Meter
MECHANICAL				
Density		ρ	7750	Kg / Meter^3
Elastic Modulus		Y^E_{33}	4.9×10^{10}	Newtons / Meter^2
		Y^E_{11}	6.2×10^{10}	Newtons / Meter^2
Poisson' Ratio		υ	0.31	
Compressive Strength			5.2×10^8	Newtons / Meter^2
Tensile Strength	(Static)		7.5×10^7	Newtons / Meter^2
	(Dynamic)		2.0×10^7	Newtons / Meter^2
Mechanical Q			80	
THERMAL				
Curie Temperature			350	°C
Pyroelectric Coefficient			$\sim 420 \times 10^{-6}$	Coulombs / Meter^2 °C
Thermal Expansion Coefficient			$\sim 4 \times 10^{-6}$	Meters / Meter °C
Specific Heat		Cp	440	Joules / Kg °C

TABLE-2. SPECTRUM OF COMMON PIEZOELECTRIC TRANSDUCERS

PIEZOELECTRIC CONFIGURATION	FREE DEFLECTION	BLOCKED FORCE	RESONANT FREQUENCY	GENERAL FEATURES
	CANTILEVER BENDING MOTOR			\$1 - \$100 10 - 500 Hz 10 - 500 grams 5 mm
	$\frac{3 d_{31} L^2 E}{2 T}$	$\frac{3 d_{31} Y b T^2 E}{8 L}$	$\frac{.16 T}{L^2}\sqrt{\frac{Y_{11}}{\rho}}$	
	SIMPLE BENDING MOTOR			INCREASING COST ↓ INCREASING RESONANT FREQUENCY ↓ INCREASING FORCE ↓ INCREASING DISPLACEMENT ↑
	$\frac{3 d_{31} L^2 E}{8 T}$	$\frac{3 d_{31} Y b T^2 E}{2 L}$	$\frac{.48 T}{L^2}\sqrt{\frac{Y_{11}}{\rho}}$	
	TRANSVERSE (D31) CONTRACTION MOTOR			
	$d_{31} L E$	$d_{31} Y A E$ where $A = b T$	$\frac{1}{2 L}\sqrt{\frac{Y_{11}}{\rho}}$	
	LONGITUDINAL (D33) EXTENSION MOTOR			
	$d_{33} L E$	$d_{33} Y A E$ where $A = a b$	$\frac{1}{2 L}\sqrt{\frac{Y_{33}}{\rho}}$	
	SHEAR MODE MOTOR			\$100 1 MHz 10^3 Kg µM
	$d_{15} T E$	$d_{15} G A E$ where $A = b L$	$\frac{1}{2 T}\sqrt{\frac{Y_{55}}{\rho}}$	