PIEZO GENERATOR/SENSOR KIT MANUAL

KGS-006

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PIEZOELECTRIC GENERATOR / SENSOR KIT MANUAL

1. INTRODUCTION TO PIEZOELECTRICITY

GENERATOR / SENSOR KIT

PURPOSE OF THE KIT

The Generator / Sensor 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. charge, voltage, response time, etc.) necessary for a successful transducer. 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 generator 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 and center access. Voltage, temperature, and stress limitations are minimal.

The literature informs the user of basic principles, terminology, generator design and fabrication techniques, and point out certain practical limitations .

CONTENTS OF THE KIT

Piezoceramic Single Sheets; PSI-5A4E

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 Generator Elements; PSI-5A4E

Poled for Series Operation (Red stripe-both sides or no stripes on either side)

2.50" x 1.250" x .020"	(63 mm x 31.8 mm x 0.51 mm)	1 piece	PN: T220-A4-503X
1.25" x 0.500" x .020"	(31.8 mm x 12.7 mm x 0.51 mm)	1 piece	PN: T220-A4-303X
1.25" x 0.250" x .020"	(31.8 mm x 6.35 mm x 0.51 mm)	1 piece	PN: T220-A4-203X
1.25" x 0.125" x .020"	(31.8 mm x 3.18 mm x 0.51 mm)	1 piece	PN: T220-A4-103X

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;	PN: T220-A4-503Y
1.25" x 0.500" x .020"	(31.8 mm x 12.7 mm x 0.51 mm)	1 piece	PN: T220-A4-303Y
1.25" x 0.250" x .020"	(31.8 mm x 6.35 mm x 0.51 mm)	1 piece	PN: T220-A4-203Y
1.25" x 0.125" x .020"	(31.8 mm x 3.18 mm x 0.51 mm)	1 piece	PN: T220-A4-103Y

Piezoelectric Generator/Sensor Kit Manual

Solder & Flux

Wires (5 Red & 5 Black; 30 gauge; Stripped and Tinned)

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.

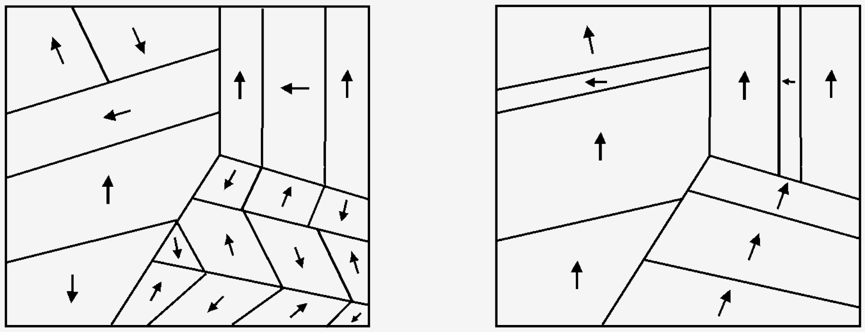


Figure-1. Inducing macroscopic polarization in a polycrystalline piezoceramic by applying a strong electric field across randomly oriented microscopic polar domains.

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 effects is its coercive field, Ec.

When stress is applied along the poling axis, an electric field arises within the body which tends to oppose the force acting upon it. Compressive stress generates an electric field with the same orientation as the original poling field, trying to induce the piece to elongate in opposition to the compressive forces. The piece reverts to its original poled dimensions after removing the stress. Tensile stress generates an electric field with an orientation opposite to that of the original poling field. These electric fields are illustrated in Figure-3 for a rectangularly shaped piece.

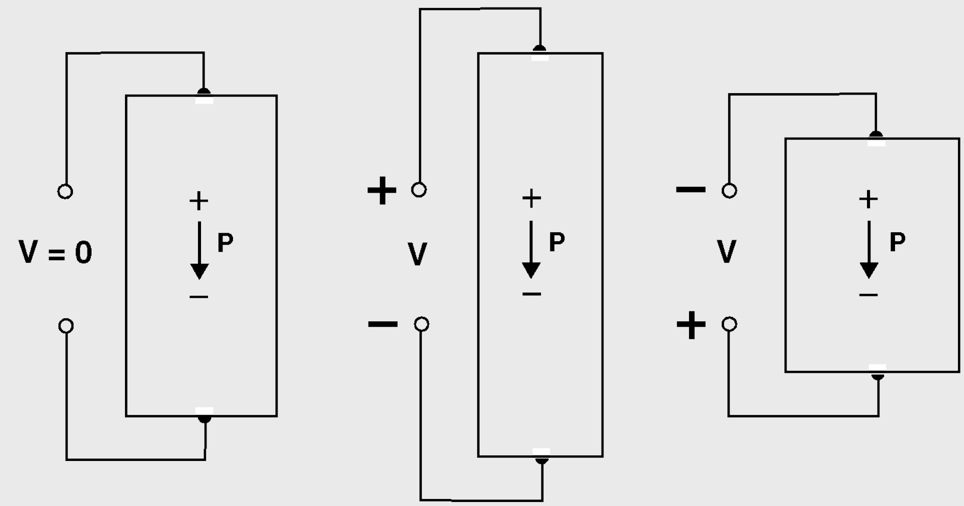


Figure-2. Physical deformation of a rectangular piezoelectric body due to an applied electric field.

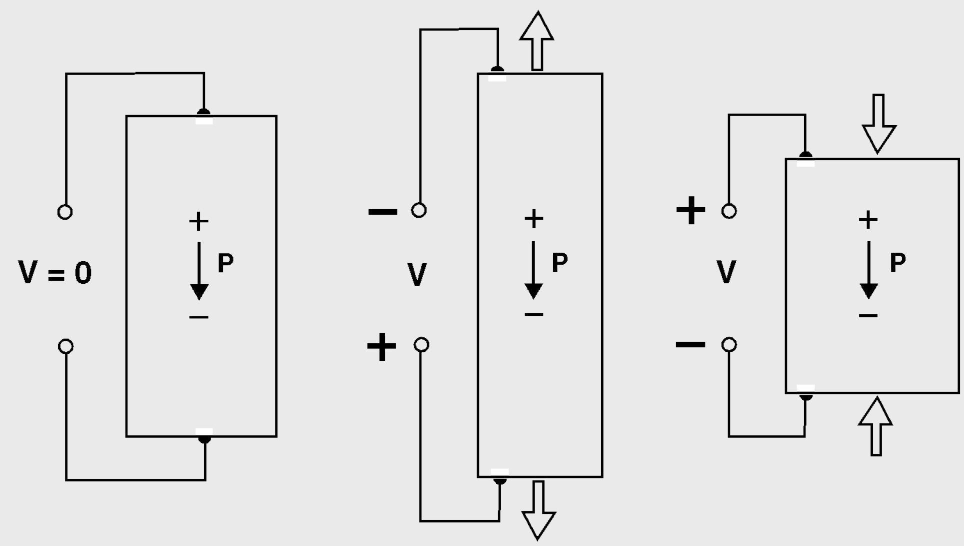


Figure-3. Electric field developed by a rectangular piezoelectric body due to an applied stress.

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 generator 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 or mechanical 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-4.

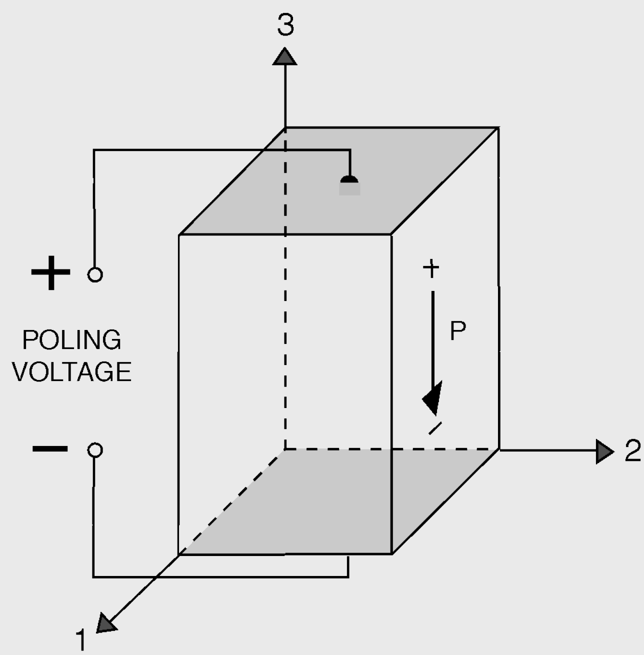


Figure-4. Definition of axes for a rectangular piezoelectric body showing the polar or 3-axis, and the transverse or 1 and 2- axes.

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 positive potential during the poling process. It is helpful to remember that the polarization arrow represents the force exerted on a positive charge by a positive potential field. Thus, it signifies the direction a positively charged particle would displace when influenced by a nearby positive charge. “Conventional” (positive) current flow moves in this direction. It should be kept in mind that electron flow moves in the opposite direction.

Piezoelectric coefficients, relating input parameters to output parameters, use double subscripts. The first subscript denotes the direction of the electric field E or dielectric displacement D, and the second subscript refers to the direction of mechanical stress T or strain S.

The **piezoelectric charge coefficients**, d_{ij} , comprise a 3 x 6 matrix and correlate the charge displaced per unit area (with electrodes short circuited), associated with an applied stress, according to the relation:

$$D = d\,T$$

where d_{ij} is expressed in coulombs / meter^2 per Newton / meter^2. The first subscript gives the direction of the charge motion associated with the applied stress. The second subscript gives the direction of mechanical stress. d_{33} relates the ratio of charge motion along the 3-axis to the stress applied along the 3-axis, assuming the electrodes are shorted and no other stresses are present. d_{31} relates the charge flow along the 3-axis to the stress along the 1-axis (or 2-axis) under similar conditions.

The **piezoelectric field coefficients**, g_{ij} , comprise a 3 x 6 matrix and correlate the electric field, E, developed (with electrodes open circuited), associated with an applied stress, T, according to the relation:

$$E = - g\,T$$

Tensile stress is positive, compressive stress is negative, and g_{ij} is expressed in units of volts / meter per Newton / meter^2. The first subscript gives the direction of the electric field associated with the applied stress. The second subscript gives the direction of mechanical stress. g_{33} relates the ratio of the the electric field developed along the 3-axis to the stress applied along the 3-axis, assuming the electrodes are open circuited and no other stresses are present. g_{31} relates the ratio of the electric field along the 3-axis to the stress along the 1-axis (or 2-axis) under similar conditions.

The **coupling coefficient**, k (lower case), is an indication of the piezo materials ability to convert mechanical energy to electrical energy. Specifically, at frequencies well below the resonant frequency, the square of the coupling coefficient equals the ratio of stored electrical energy output to the stored mechanical 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 its 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 permittivity of piezoceramic to that of empty space, ε_o ($\varepsilon_o = 8.85 \times 10^{-12}$ farads/meter). K_{33}, the relative dielectric constant between the poling electrodes, determines the capacitance of the piece according to the relationship,

$$C = K_{33}\, \varepsilon_o\, A / t$$

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_{33} , 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 per 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.

It is common to describe this property with a 6 x 6 elastic stiffness matrix, c_{ij}, or its reciprocal, a 6 x 6 elastic compliance matrix, s_{ij}.

PIEZOELECTRIC AND MATERIAL PROPERTIES FOR PSI-5A4E PIEZOCERAMIC

The piezoelectric and material properties of PSI-5A4E piezoceramic are listed in Table-2 on page 31. This is the piezoceramic used to make the elements supplied in this kit.

2. DESIGN CONSIDERATIONS FOR PIEZOELECTRIC GENERATORS

ELECTRICAL OUTPUTS

CHARGE AND VOLTAGE

Piezoelectric generators are usually specified in terms of their short-circuit charge and open-circuit voltage. Short-circuit charge, Qs, refers to the total charge developed, at the maximum recommended stress level, when the charge is completely free to travel from one electrode to the other, and is not asked to build up any voltage. Open-circuit voltage, Vo, refers to the voltage developed, at the maximum recommended stress level, when charge is prohibited from traveling from one electrode to the other. Charge is at a maximum when the voltage is zero, and voltage is at a maximum when the charge transfer is zero. All other values of simultaneous charge and voltage levels are determined by a line drawn between these points on a voltage versus charge line, as shown in Figure-5. Generally, a piezo generator must move a specified amount of charge and supply a specified voltage, which determines its operating point on the voltage vs. charge line. Work is maximized when the charge moved permits one half the open circuit voltage to be developed. This occurs when the charge equals one half the short-circuit charge.

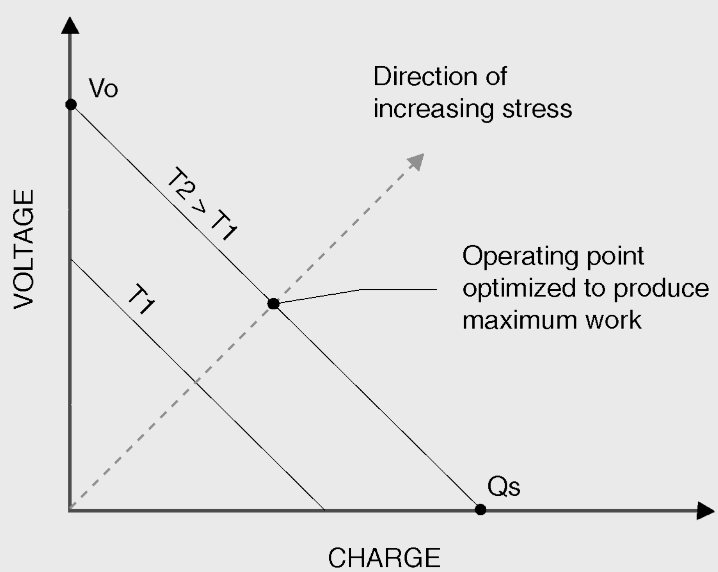


Figure-5. The voltage versus charge diagram for a piezoelectric generator element.

MECHANICAL INPUTS

Mechanical inputs can be described as either forces or displacements acting on a specific point or area of the generator body. These forces may be either static or dynamic, low power (typically sensing) or high power (typically generating). If the force is oscillating and continuous, then the generator may be driven either at resonance or off- resonance (typically below resonance)

STATIC INPUT FORCES OR DISPLACEMENTS

For long duration static forces acting on a piezo generator, such as a static pressure measurement, an understanding of creep, hysteresis and electrical leakage is useful.

<u>Creep & Relaxation</u>: Creep and relaxation are time dependent plastic phenomena resulting from piezoceramic grains slipping within the polycrystalline material upon application or removal of a load. When a constant load is applied and maintained on a piezo body, it will initially deform and then continue to deform (creep) over a period of time. There are three levels of creep: transient creep occurring immediately after load application; steady state creep characterized by a decreasing creep rate; and accelerating creep. At high drive levels, accelerated creep may proceed to the point where the piece finally cracks.Creep rates vary based on load level, temperature, and time. Upon removal of the load, the piece may slowly relax to its original equilibrium condition or retain a set.

<u>Mechanical Hysteresis</u>: Hysteresis is a lagging of strain values during stress cycling. When a polycrystalline piezoelectric body is deformed, part of the input energy is stored as elastic strain energy, and part is dissipated as heat due to small internal slippage mechanisms. Hysteresis appears as an offset in the strain level between the application and removal portions of a stress load. The size of the offset depends on the force level, cycle time, temperature, and materials used. For low stress levels encountered in small signal sensing, hysteresis is inconsequential, but for moderate and high stress levels it may be significant. Hysteresis is described as a percentage of the total strain and ranges around 15% for high stress levels. Voltage or charge production, which is strain dependent, is influenced by the mechanical hysteresis behavior. Hysteresis leads to non-linearity in transducer output.

Figure-6 demonstrates the typical mechanical hysteresis and creep behavior of a piezoelectric element such as a bender. Imagine a force applied to the tip of a cantilevered bending element. When the element has been at rest for some length of time (~ 1 day), it will reside at its equilibrium position, 0. Upon initial energization, the tip 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 forced again immediately, it will follow path 2-1. If the force is left on, it will creep along the path 1-1', and come to rest at position 2' after de-energization. A piece experiencing a full bipolar cycle will follow path 1-2-3-4-1. The size of the loop is time dependent and the area inside the loop represents the energy dissipation occurring during the cycle.

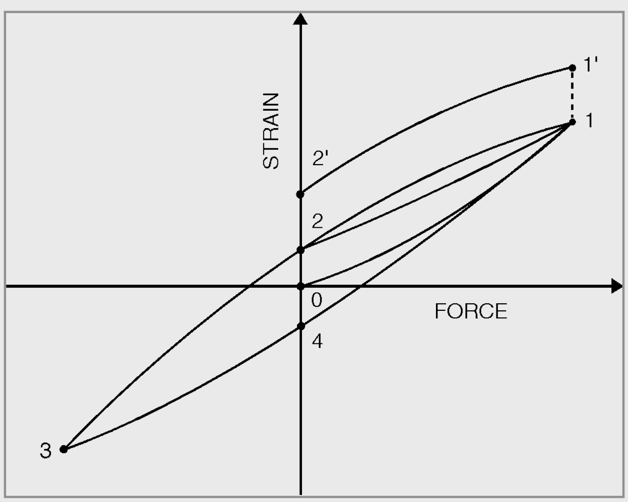


Figure-6. Typical mechanical hysteresis and creep behavior of a piezoelectric element.

Electrical Leakage: After charge has been established on the electrodes of a piezo generator, it will immediately begin to leak away even though the insulation resistance is large. It will leak through the bulk of the piezo slab according to the relation for bulk resistance:

$$R = \frac{\rho t}{A}$$

where ρ is the bulk resistivity of the piezo material in ohm-meters, t is the thickness between electrodes, and A is the electrode area. The value of resistivity for PSI-5A4E is $\sim 10^{10}$ ohm-meters. Charge will travel along surfaces and over edges from one electrode to the other. Surface contaminants exacerbate this problem. Charge also drains through the input circuit. Lastly, charge may drain through the bleed resistor often placed across the electrodes to limit voltage swings due to pyroelectric (thermal) sources, triboelectric (surface friction) sources, and transient circuit currents. Eventually, the electrostatic charge will leak back to zero.

Overall, the behavior described above indicates why it is so difficult to design statically driven piezo sensing devices and why only dynamic force is generally measured.

DYNAMIC INPUT FORCES OR DISPLACEMENTS

Piezo is much more friendly to dynamic applications. Dynamic inputs may either be pulsed or continuous.

Pulsed Input Forces: For a short duration transient force, issues of creep and electrical leakage are insignificant since there is insufficient time for their behavior to occur. However, hysteresis still applies.

Continuously Alternating Input Forces: When the generator will be excited by an oscillating force, it is useful to be familiar with the following concepts.

Hysteresis: Hysteresis is a concern with oscillating forces because heat accumulates within the element for each cycle of operation. Heat accumulates from contributions due to mechanical losses described earlier and dielectric losses attributed to the phase lag between charge displacement and electric field. Low voltage piezo stacks are generally limited to < 1Khz operation at full loading due to heat build up. Care should be taken in the design to account for heating caused by internal piezo losses as well as external system losses, such as strains within adhesive bonds, and friction at the mount or other points of attachment.

Mechanical Resonance: When a piezo body is acted upon by a periodic series of impulses, it will be set into relatively large amplitude vibration if the frequency of those impulses correspond to the natural or resonant frequency of the device. This resonance is a manifestation of the trading back and forth of kinetic energy (moving mass) and potential energy (elasticity) in the oscillating body. At resonance, the amount of stored energy becomes very large compared to the excitation energy. For this reason it is useful for achieving large voltages at low stress levels, and thus, for obtaining high efficiency. Because of the high amplitudes exhibited, care must be taken not to overstrain and crack the generator.

The resonant frequencies of a piezo generator depend on its dimensions, material properties, and the manner of mounting. The cantilevered piezo bending element, being very compliant, has the lowest fundamental (first) resonant frequency per unit length of all configurations and mounting schemes. The piezo stack, being very stiff, has a high resonant frequency. Equations for determining the fundamental resonant frequencies for several generator 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: Below resonant frequency, the strain of a piezoelectric transducer is nearly independent of frequency and proportional to the applied stress. Around the resonant frequency, strain 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 generator. Above resonance, strain decreases steadily with the square of the frequency. Generally, for quasi-static transducers, a value of about 2/3 of the fundamental resonance marks the limit of the usable frequency band. For resonant applications, the useable frequency range is limited to a small band around the useful resonant modes. Figure-7 shows strain as a function of operating frequency.

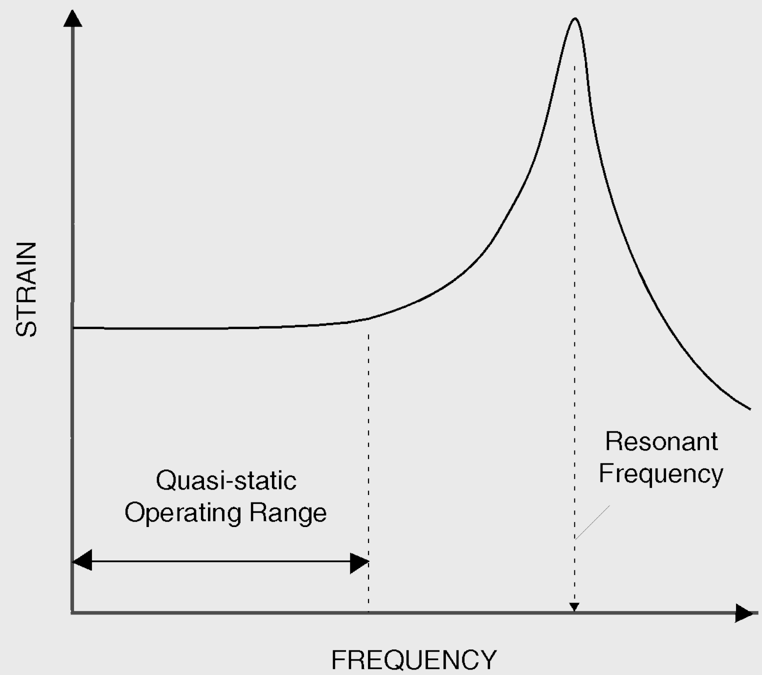


Figure-7 . Strain as a function of operating frequency.

MECHANICAL CONSIDERATIONS

MECHANICAL RESPONSE TIME

It is useful to know how fast a generator element can respond to a force input . The fundamental resonant frequency, F_r, helps answer this question. A piezo transducer can follow a sinusoidal input up to its resonant frequency. Beyond this point, inertia prevents the transducer from keeping up with excitation. The time it takes a generator to travel from it's zero position to full positive amplitude at its resonant frequency, is its response time, tr. This is 1/4 the time it takes the transducer to travel a full bipolar cycle (from zero to peak positive amplitude to 0 to peak negative amplitude back to zero). Thus,

$$tr \sim \frac{1}{4 \times F_r}$$

The response time of a generator may be measured by driving it as an actuator with a low level sinusoidal signal at resonance. For example, a generator having a resonant frequency of 500 Hertz, has a response time of 0.5 milliseconds. Any mass added to the end of the generator will increase the response time.

MOUNTING

An ideal mount permits the normal distortion of the entire active portion of the generator element, while at the same time preventing motion in certain directions at the mounting point or points. Generally piezo generators 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 generator distorts the mount itself. This may or may not be desirable.

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 piezoceramic should not be allowed to strain more than 500x10^{-6} meter/meter in tension.

STRESS DEPOLING

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 x 10^6 N/m^2 are required to degrade PSI-5A-S4-ENH if no other degrading influences are present.

ELECTRICAL CONSIDERATIONS

QUASI-STATIC OPERATION

A piezoelectric generator operating below its fundamental resonance can be treated simply as a capacitive element. It supplies, withdraws or stores charge. Ideally, this charge does not leak away. However, in practice charge may leak through the bulk material, over its edges, or through external circuitry.

NEAR RESONANCE OPERATION

A piezoelectric generator operating at resonance can be treated as a capacitor (having a value equal to the transducer capacitance) with a resistor in parallel. The power dissipated by this resistance represents the work which the transducer does on its environment or the internal loss occurring within the transducer.

ELECTRICAL ISOLATION

The outer electrode surfaces of certain generator elements are electrically "live" in many configurations. For product or experimental safety, consideration should be given to insulating or shielding the electrodes, mount, and power input sections of the generator element.

ELECTRICAL BREAKDOWN

The highest value of generated electric field is determined by electrical breakdown occurring either through the body of the piezoceramic sheet or over the its edges. Debris adhering to edges can initialize edge discharge at fields as low as 400-800 volts/mm. 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.

ELECTRICAL LOSSES

The bulk resistivity of piezoceramic is ~ 10^{12} | -cm. Therefore, electrical losses are minimal under static or low frequency operation. However, dielectric losses are significant at high frequency, under high load, and can lead to heating under high frequency /high power operation. The loss tangent, the ratio of series resistance to series reactance, for PSI-5A4E is ~0.015.

ELECTRICAL DEPOLARIZATION

As mentioned earlier, under adverse conditions piezoelectric polarization 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-5A4E 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.

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 temperature dependent, and thermal dependence varies markedly from one material to the next. Figure-8, Figure-9 and Figure-10 demonstrate the temperature dependence of d_{31}, g_{31}, and K^T_{33} for PSI-5A4E, respectively.

PYROELECTRIC EFFECTS

An electric field is induced across the electrodes of a piezo generator when it is exposed to a thermal change. The induced field, E (volts/meter), is

$$E = \frac{V}{t} = \frac{p(\Delta T)}{\varepsilon_o K^T_{33}}$$

where p is the pyroelectric coefficient in units of coulombs / m^2 °C, ΔT is the temperature change, K^T_{33} is the relative dielectric constant in the poling direction, and ε_o is the permittivity of free space. It is important in the design of a sensor to maximize the ratio of mechanical effect to pyroelectric effect.

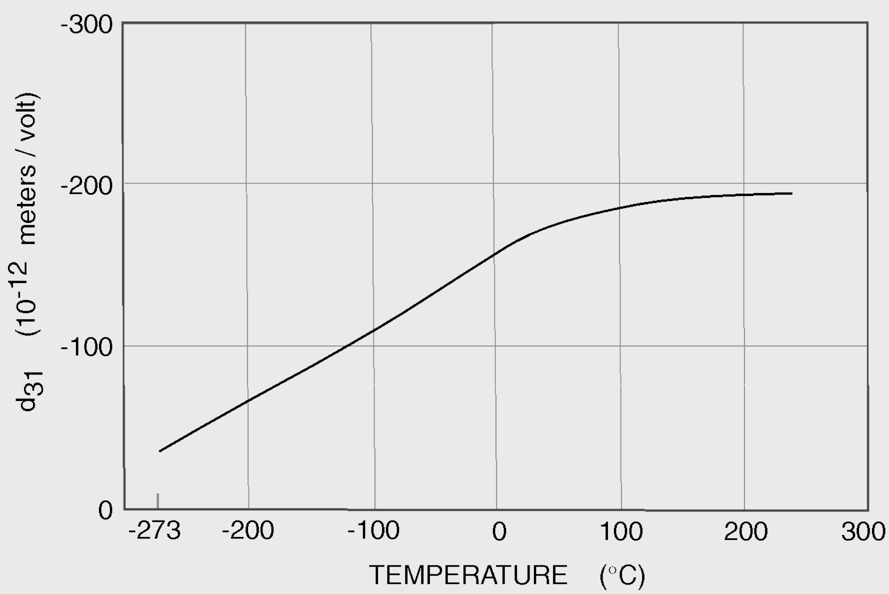


Figure-8. Typical temperature dependence of d31 for PSI-5A-S4-ENH.

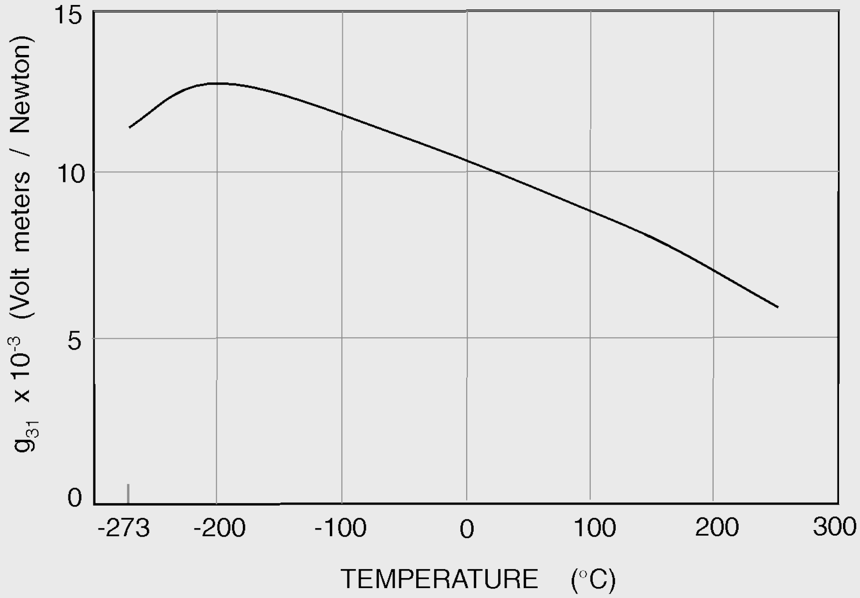


Figure-9. Typical temperature dependence of g_{31} for PSI-5A-S4-ENH.

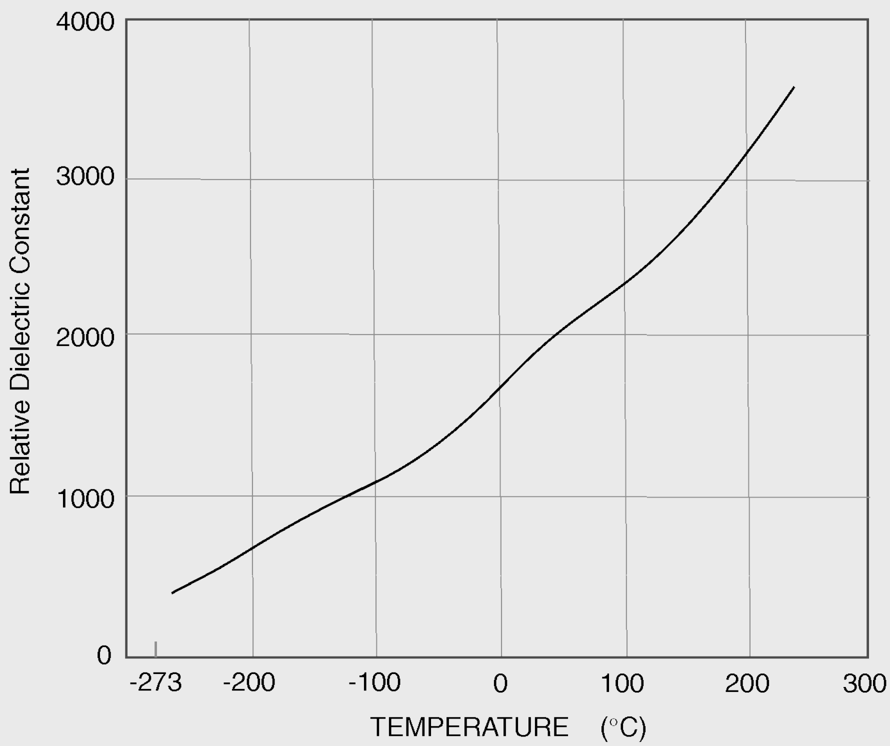


Figure-10. Typical temperature dependence of K_{33} for PSI-5A-S4-ENH.

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, shipping, or normal usage. 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

Thermal expansion, ΔL, results in a dimensional change due to a thermal change, ΔT, according to the relation:

$$\Delta L / L = \alpha^E \Delta T$$

The coefficient of thermal expansion (at constant electric field), α^E, of PSI-5A4E is ~ 4 µm / m °C. If positional stability is important, one must account for thermal expansion / contraction displacements over the temperature range anticipated.

Differential thermal expansions of adjacent assembly materials will cause moments, warping, and shifting. The standard 2-layer bending generator element has a symmetrical construction. Distortion due to thermal excursion should be slight. 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.

CRYOGENIC OPERATION

The low signal values of the charge coefficients for operation at 4.2 °K are reduced by a factor of 5-7 times. The value of the dielectric constant decreases and the value of the coercive field increases however. In general, piezo sensors work quite well at cryogenic temperatures were they have been used to monitor magnetic flux motions in superconducting magnets bathed in liquid helium. Cycling the transducer between these temperature extremes does not affect them adversely.

THERMAL DEPOLARIZATION

Thermal agitation can reduce the number of electric dipoles aligned during the original poling process. The higher the temperature, the greater the effect. Eventually, at the Curie temperature, the piezoceramic suffers a complete loss of piezoelectric properties and repoling becomes necessary.

VACUUM CONSIDERATIONS

Because piezo generators are solid state devices, they lend themselves to high vacuum operation. However, several issues should be understood. First, high voltage should not be generated across 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. Generators 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.

TEMPORAL CONSIDERATIONS

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.

CIRCUIT CONSIDERATIONS

It is common practice to model piezoelectric devices electrically to describe their piezoelectric, dielectric and electric properties.

PIEZO CHARGE GENERATOR
Figure-11 shows the equivalent circuit for a piezo charge generator where Cp is the piezo capacitance and Rp is the internal (or bulk) resistance of the piezo device. Since the resistivity of piezoceramic is of the order of ~10^{12} ohm-cm, Rc is generally neglected.

PIEZO VOLTAGE GENERATOR

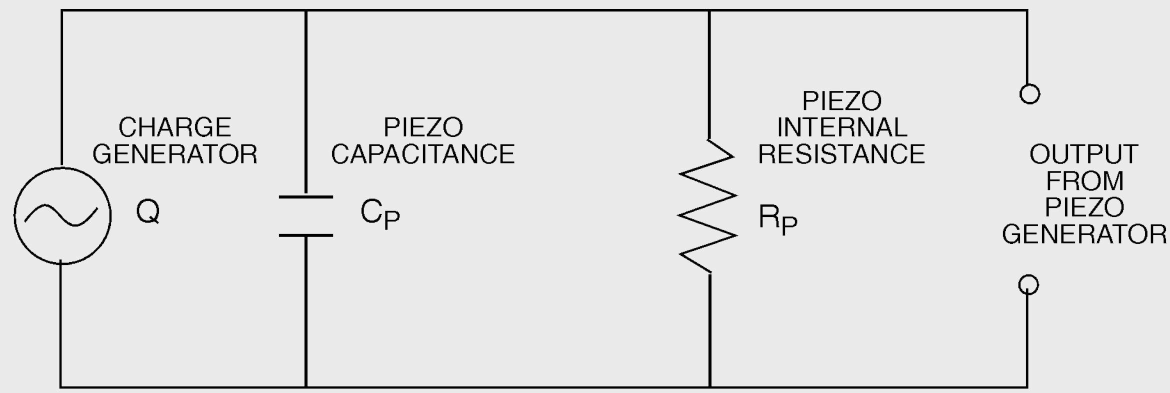


Figure-11. Piezo transducer modeled as a charge generator.

Since voltage can be calculated from the charge delivered by a piezo device according to the relationship that V = Q / Cp, Figure12 shows a piezo device modeled as a voltage generator. Voltage output, proportional to the stress or strain of the piezo device, provides a sensing function.

ELECTRICAL TIME CONSTANT

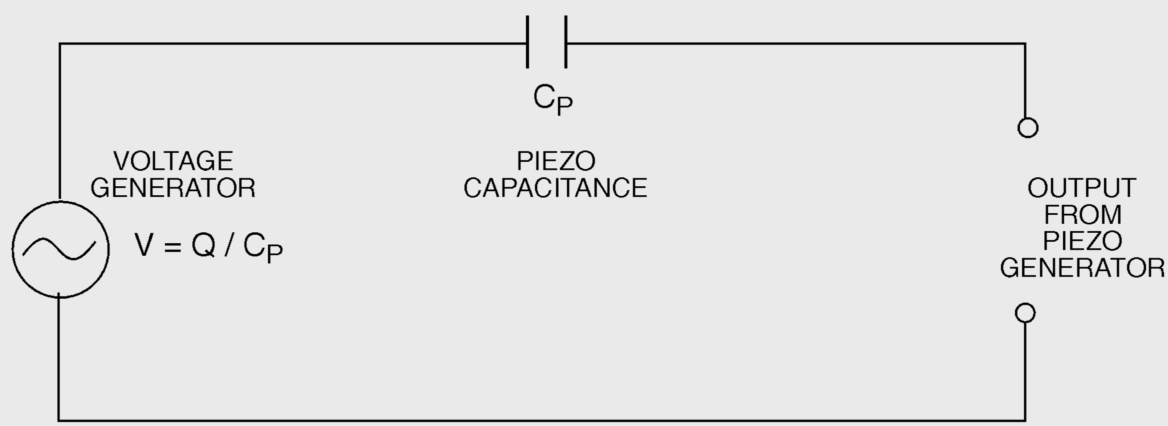


Figure-12. Piezo transducer modeled as a voltage generator.

The charge on a piezo sensor decays with time at a rate determined by its RC time constant. An RC circuit exhibits the exponential decay. Typically, charge is generated quickly. If the discharge time constant is large, it will not decay faster than the charging rate. Clearly, a long time constant is necessary if low frequencies need to be monitored.

INPUT SIGNAL CIRCUITS

The signals from piezo sensors can be fed to meters, oscilloscopes, and circuits. The circuits are numerous, ranging from simple to complex, whose purpose is to filter or cancel unwanted portions of the signal, to amplify or switch the signal (transistors and operational amplifiers), or to make decisions based on information from signals (digital logic).

INPUT STAGE PROTECTION

Piezoelectric elements can generate high voltages (>>100 volts) under external vibration, shock, or temperature shifts. If these conditions are expected, the circuitry of the input stage must be protected against transient voltages of all polarities. This is commonly accomplished with a high resistance bleed resistor placed in parallel with the piezo element.

CABLES

An op amp should be kept as close to the piezo sensor as possible. Shielded coax cable should be used when possible, although this can add leakage and capacitance to the circuit. Motion of the cable is another source of noise. The cable should be held down firmly to eliminate any movement or vibration. Polar plastic materials, used for cable insulation, can generate charge. Teflon is a good choice of material to minimize this problem.

3. CALCULATING GENERATOR OUTPUTS

THE SPECTRUM OF PIEZOELECTRIC GENERATOR TRANSDUCERS

Transducers which convert mechanical energy to electrical energy (i.e. generators) come in a wide range of shapes and sizes, each having their own characteristic voltage-charge output capabilities as well as input force - displacement characteristics. The design process involves correctly matching the volume and stiffness of the generator to the input force in such a way as to produce sufficient strain to generate the required amount of electrical energy. The electrical energy must also be matched to the load it will drive. Electrically "stiff" (low capacitance) transducers typically provide higher voltage and lower charge production. Electrically "compliant" (high capacitance) transducers provide higher charge production and lower voltage.

As a general purpose reference guide,Table-1 shows the spectrum of generator transducers commonly considered in piezoelectric applications.

CHARGE AND VOLTAGE CALCULATIONS

The equations for charge and voltage as functions of either input force or displacement shown in Table-1 are based on linear relationships and low signal values for their piezoelectric coefficients.

RESONANT FREQUENCY CALCULATIONS

Table-1 also provides the equations for determining the fundamental resonant frequency. The expression

$$(Y / \rho)^{1/2}$$

common to all calculations of frequency represents the velocity of sound in piezoceramic along the associated axis of interest. The time it takes for an element to actuate is related to how quickly a pressure wave can travel through the medium.

For devices which may be constructed of multiple material layers (such as benders), the modulus, Y, and density, ρ, are determined by be following relations:

$$Y = \frac{T1\,Y1 + T2\,Y2 + \ldots}{T_{total}}$$

$$\rho = \frac{T1\,\rho 1 + T2\,\rho 2 + \ldots}{T_{total}}$$

BASIC ENERGY CALCULATIONS

STORED MECHANICAL ENERGY
The mechanical energy stored by a piezo device acted upon by a force is:

$$E_m \text{ (Stored mechanical energy) } = (1/2)\, Y\, S^2\, V$$

where E_m is the stored mechanical energy in Joules, Y is Young's modulus in N / m^2, S is the induced strain in m / m, and V is the volume of piezoceramic in m^3.

STORED ELECTRICAL ENERGY
The electrical energy stored by a piezo device is:
The mechanical energy stored by a piezo device acted upon by a force is:

$$E_e \text{ (Stored electrical energy) } = (1/2)\, C\, V_0^2$$

where Ee is the stored electrical energy in Joules, C is the capacitance in Farads, and Vo is the open circuit voltage.

TABLE-1. SPECTRUM OF COMMON PIEZOELECTRIC GENERATORS

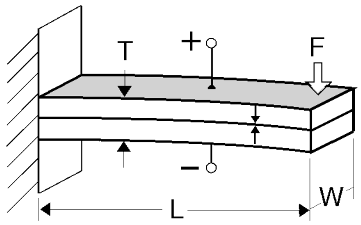
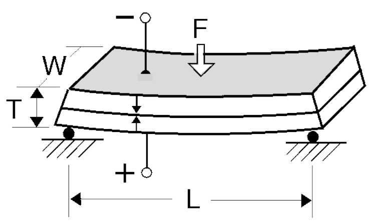
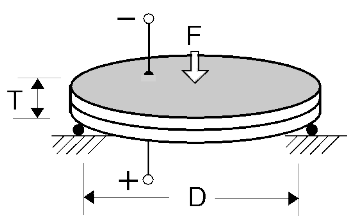
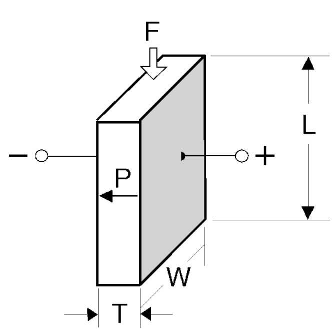
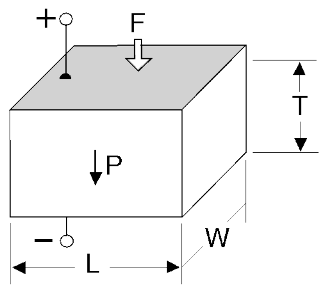
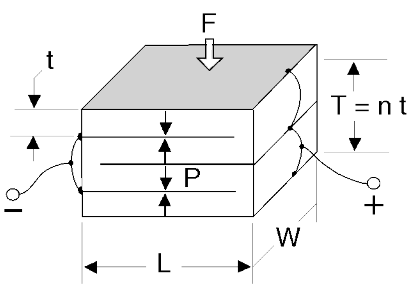
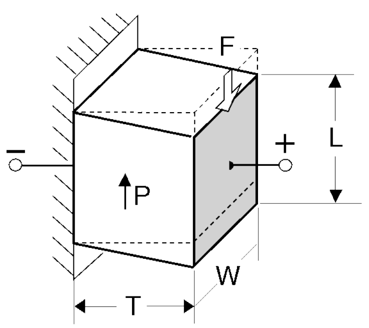
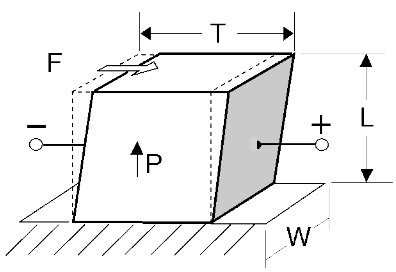
PIEZOELECTRIC CONFIGURATION	SHORT CIRCUIT CHARGE	OPEN CIRCUIT VOLTAGE	RESONANT FREQUENCY
	CANTILEVERED BENDING (D31) GENERATOR		
	$\frac{3\,L^2}{2\,T^2}\, d_{31}\, F$	$\frac{3\,L}{2\,W\,T}\, g_{31}\, F$	$\frac{.16\,T}{L^2}\sqrt{\frac{Y_{11}}{\rho}}$
	$\frac{3\,T\,W}{8\,L}\, Y\, d_{31}\, \Delta X$	$\frac{3\,T^2}{8\,L^2}\, Y\, g_{31}\, \Delta X$	
	SIMPLY SUPPORTED BENDING (D31) GENERATOR		
	$\frac{3\,L^2}{8\,T^2}\, d_{31}\, F$	$\frac{3\,L}{8\,W\,T}\, g_{31}\, F$	$\frac{.48\,T}{L^2}\sqrt{\frac{Y_{11}}{\rho}}$
	$\frac{3\,T\,W}{2\,L}\, Y\, d_{31}\, \Delta X$	$\frac{3\,T^2}{2\,L^2}\, Y\, g_{31}\, \Delta X$	
	SIMPLY SUPPORTED DISK BENDING (D31) GENERATOR		
	$\frac{.42\,D^2}{T^2}\, d_{31}\, F$	$\frac{.56}{T}\, g_{31}\, F$	$\frac{T}{D^2}\sqrt{\frac{Y_{11}}{\rho}}$
	$3.1\,T\,Y\, d_{31}\, \Delta X$	$\frac{4.1\,T^2}{D^2}\, Y\, g_{31}\, \Delta X$	
	TRANSVERSE (D31) GENERATOR		
	$\frac{L}{T}\, d_{31}\, F$	$\frac{1}{W}\, g_{31}\, F$	$\frac{1}{2\,L}\sqrt{\frac{Y_{11}}{\rho}}$
	$W\,Y\, d_{31}\, \Delta X$	$\frac{T}{L}\, Y\, g_{31}\, \Delta X$	

TABLE-1. SPECTRUM OF COMMON PIEZOELECTRIC GENERATORS

PIEZOELECTRIC CONFIGURATION	SHORT CIRCUIT CHARGE	OPEN CIRCUIT VOLTAGE	RESONANT FREQUENCY
	LONGITUDINAL (D33) GENERATOR		
	$d_{33} F$	$\frac{T}{L W} g_{33} F$	$\frac{1}{2 T}\sqrt{\frac{Y_{33}}{\rho}}$
	$\frac{L W}{T} Y d_{33} \Delta X$	$Y g_{31} \Delta X$	
	MULTI-LAYER LONGITUDINAL (D33) GENERATOR		
	$n d_{33} F$	$\frac{T}{n L W} g_{33} F$	$\frac{1}{2 T}\sqrt{\frac{Y_{33}}{\rho}}$
	$\frac{L W}{T} Y d_{33} \Delta X$	$\frac{Y g_{31} \Delta X}{n^2}$	
	PARALLEL SHEAR (D15) GENERATOR		
	$d_{15} F$	$\frac{T}{L W} g_{15} F$	$\frac{1}{2 T}\sqrt{\frac{Y_{55}}{\rho}}$
	$\frac{L W}{T} G d_{15} \Delta X$	$L W G g_{15} \Delta X$	
	TRANSVERSE SHEAR (D15) GENERATOR		
	$\frac{L}{T} d_{15} F$	$\frac{g_{15} F}{W}$	$\frac{1}{2 L}\sqrt{\frac{Y_{55}}{\rho}}$
	$W G d_{15} \Delta X$	$\frac{T}{L} G g_{15} \Delta X$	

PIEZOELECTRIC BENDING GENERATORS

Although the mechanical stress and electric field are uniformly distributed for most transducers, this is not the case for bending transducers. In addition, there are various combinations with regard to their construction and operation. For this reason they are discussed in greater detail.

PRINCIPLES OF OPERATION

The most common type of piezoelectric bending generator is composed of two layers of piezoceramic bonded to a thin metal shim sandwiched in the middle. This is sometimes referred to as a “bimorph” element. The construction and typical dimensions of the 2-layer elements provided in this kit are shown in Figure-13.

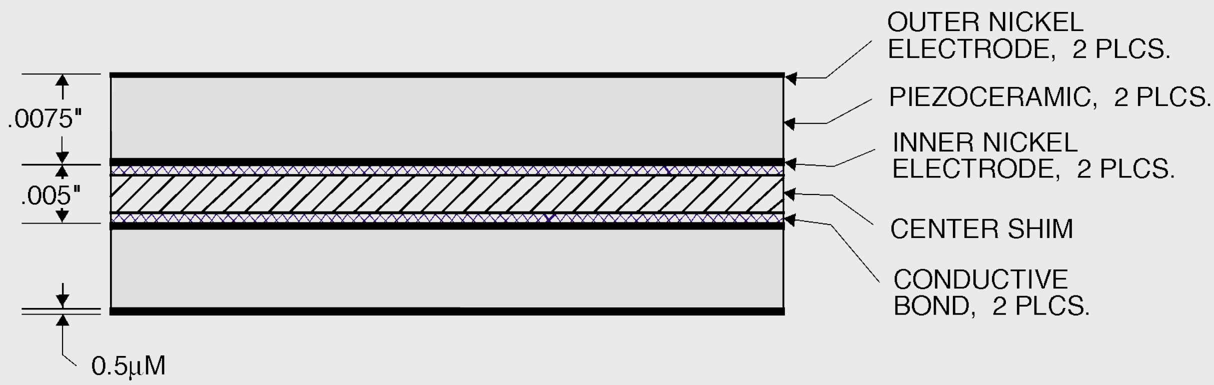


Figure-13. Construction of laminated 2-layer generator element.

As an actuator, the application of voltage across the bender element forces one layer to expand, while the other contracts, as depicted in Figure-14. 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. A similar effect, to a lesser extent, may be obtained by bonding one piezoceramic layer to a passive non-piezoceramic layer. This is sometimes referred to as a a “monomorph” construction.

As a generator, when the bender is forced to flex, one layer will be in tension while the other is in compression. The stresses in each layer will produce electrical outputs. Based on the orientation of polarization discussed next (series or parallel), the electrical output of the bender will then be the summation of the outputs of each layer. This is depicted in Figure-15.

Bending generators exhibit unique properties. They require no outside energy source to produce a signal. They may be operated over billions of cycles without wear or deterioration. Their low profile allows their use in very restricted locations.

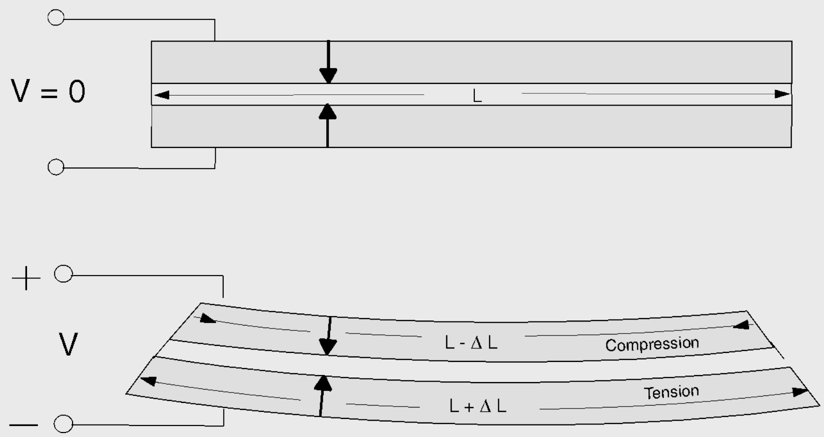


Figure-14. The curvature of a bending motor is due to the expansion of one layer and contraction of the other.

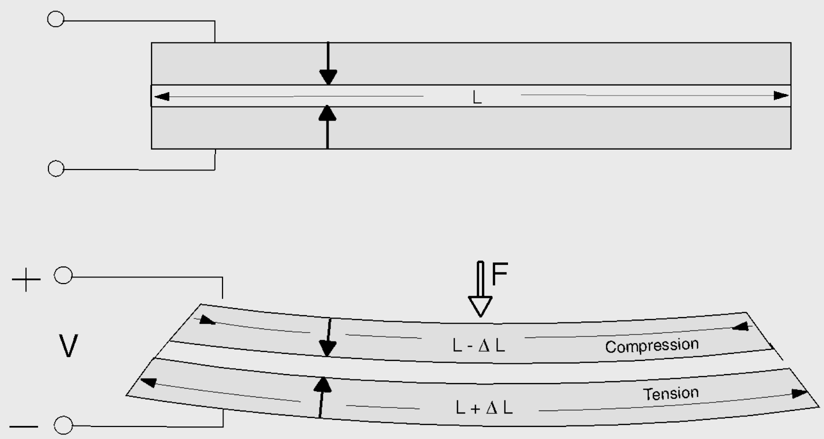


Figure-15. Charge is produced by a bending generator due to the expansion of one layer and contraction of the other when forced to flex.

STANDARD POLARIZATION CONFIGURATIONS

There are two standard polarization configurations for the two layer bending generator construction: series and parallel. 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-5A4E).

SERIES OPERATION The bender poled for series operation is the simplest and most economical. As depicted in Figure-16, 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.

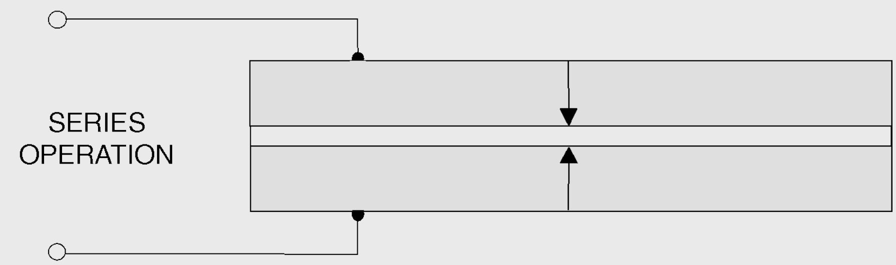


Figure-16. Bending generator poled for series operation.

PARALLEL OPERATION As depicted in Figure-17, 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 developed across the individual layers. The parallel bender is characterized by higher capacitance, higher current, and lower voltage.

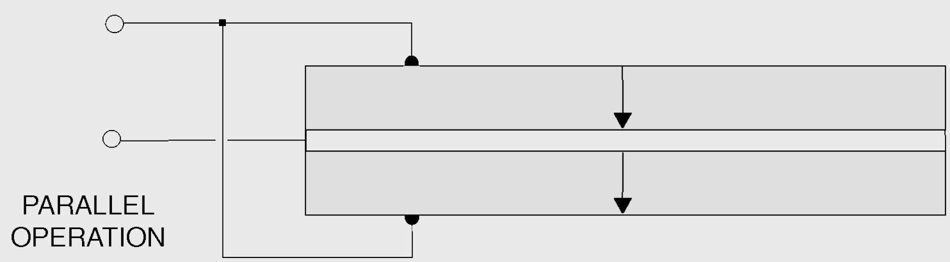


Figure-17. Bending generator poled for parallel operation

STANDARD MOUNTS FOR BENDING GENERATORS

Standard mounts for bending generators are illustrated in Figure-18 and fall into two general categories. The first category has power input at one end and is mounted at the other. Known as the cantilever mount, it provides maximum compliance. The second category has power input 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 provides increased compliance and 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 portion of the beam being constrained.

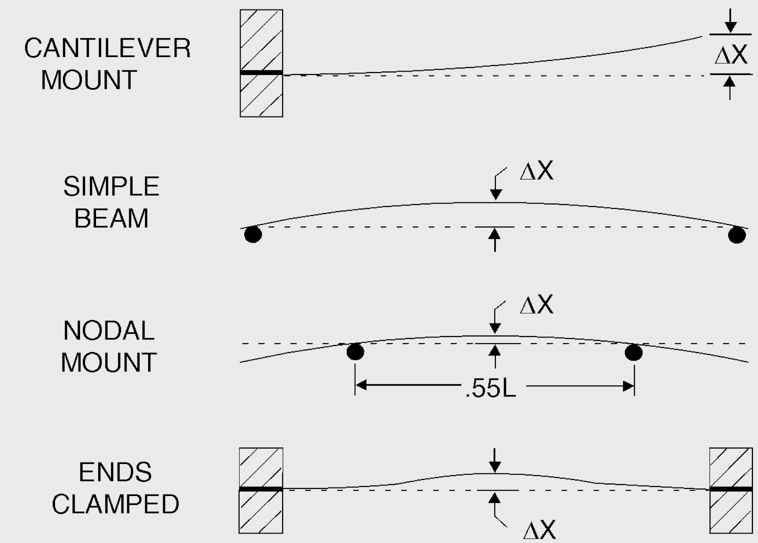


Figure-18. Standard mounting techniques for bending generators.

BENDING GENERATOR EQUATIONS

The following equations for bending generators are more accurate than those in Table-1 in so far as they take into account the center shim. They can be used to: 1.) verify that the bending generator is operating properly, and 2.) scale the dimensions of the experimental generator to define the dimensions of the final design, or vice versa. The relations below were taken from an article titled “Flexure Mode Piezoelectric Transducers” by Carmen Germano, published in *IEE Transactions on Audio and Electroacoustics*, Volume AU-19, No.1, March 1971.

Definition of terms:

L = Total length of the bending generator (Meters)
L_c = Active length of the bending generator (Meters)
T = Total thickness of bending generator (Meters)
δ = Thickness of center shim and adhesive layers (Meters)
t_c = Thickness of a single layer of piezoceramic (Meters)
b = Width of bending generator (Meters)
d_{31} = Piezoelectric transverse charge coefficient (Meters / Volt)
g_{31} = Piezoelectric transverse voltage coefficient (Volt Meters / Newton)
Y = Average Young's modulus of elasticity (Newtons / Meter^2)
K_3 = Relative dielectric constant of piezoceramic
ε_o = Permitivity of free space (8.85×10^{-12} Farads / Meter)
ρ = Average density of bending generator (Kilograms / Meter^3)
V = Voltage output from the piezo generator (Volts)
Q = Charge output from the piezo generator (Coulombs)
F = A force applied to the piezo generator (Newtons)
Δx = A displacement applied to the piezo generator (Meters)

BENDING GENERATOR MOUNTED AS A CANTILEVER

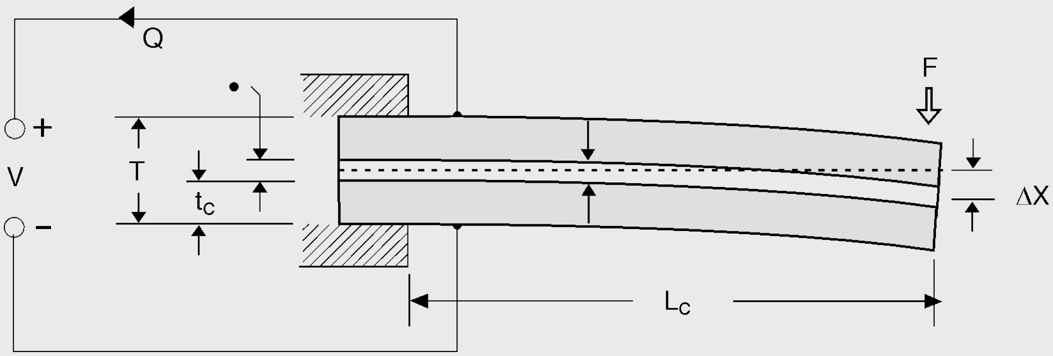


Figure-19 . Terminology used for cantilevered bending generator equations.

Short Circuit Charge: The short-circuit charge, Q_s, is usually twice the required operating charge.

$$Q_s\,(F) = (3/2)\,(1+\delta/T)\,(L_c^2/T^2)\,d_{31}\,F$$

$$Qs\,(X) = (3/8)\,(1+\delta/T)\,(b\,T/L_c)\,Y\,d_{31}\,\Delta X$$

where $t_c > \delta > 0$

Open Circuit Voltage: The open circuit voltage, Vo, is usually twice the required operating voltage.

$$V_o\,(F) = (3/2)\,(1-\delta^2/T^2)\,(L_c/b\,T)\,g_{31}\,F$$

$$V_o\,(X) = (3/8)\,(1-\delta^2/T^2)\,(T^2/L_c^2)\,Y\,g_{31}\,\Delta X$$

where $tc > \delta > 0$

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

Maximum Surface Strain: $S_{max} \sim (T/L_c^2)\,\Delta X$
where ~ 500 X 10 $^{-6}$ is the maximum recommended strain limit in tension.

Capacitance: C (series operation) = $K^T_{33}\,\varepsilon_o\,(L\,b/2\,t_c)$
C (parallel operation) = $2\,K^T_{33}\,\varepsilon_o\,(L\,b/\,t_c)$

BENDING GENERATOR MOUNTED AS A SIMPLE BEAM

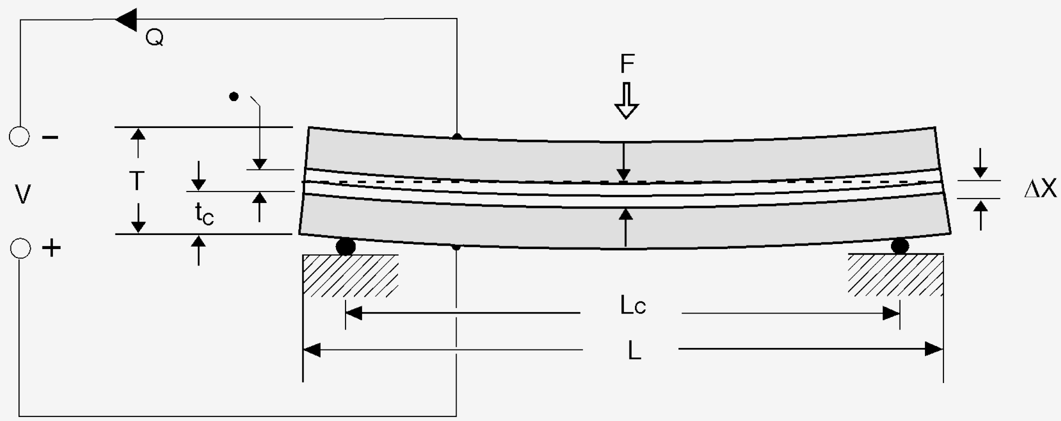


Figure-20. Terminology used for simple beam bending generator equations.

Short Circuit Charge: The short-circuit charge, Q_s, is usually twice the required operating charge.

$$Q_s(F) = (3/8)(1+\delta/T)(L_c^2/T^2)\, d_{31}\, F$$

$$Q_s(X) = (3/2)(1+\delta/T)(b\,T/L_c)\, Y\, d_{31}\, \Delta X$$

where $t_c > \delta > 0$

Open Circuit Voltage: The open circuit voltage, Vo, is usually twice the required operating voltage.

$$V_o(F) = (3/8)(1-\delta^2/T^2)(L_c/b\,T)\, g_{31}\, F$$

$$V_o(X) = (3/2)(1-\delta^2/T^2)(T^2/L_c^2)\, Y\, g_{31}\, \Delta X$$

where $tc > \delta > 0$

Resonant Frequency: $F_r = (.48\, T/L_c^2)(Y_{11}/\rho)^{1/2}$

Maximum Surface Strain: $S_{max} \sim (4T/L_c^2)\,\Delta X$

where ~ 500×10^{-6} is the maximum recommended strain limit in tension.

Capacitance: C (series operation) = $K^T_{33}\,\varepsilon_o\,(L\,b/2\,t_c)$

C (parallel operation) = $2\,K^T_{33}\,\varepsilon_o\,(L\,b/\,t_c)$

BUILDING PIEZOELECTRIC GENERATORS

WORKING WITH PIEZOCERAMIC

THIN-SHEET (SINGLE LAYER) PIEZOCERAMIC STOCK

Unlike laminated bending generator 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. This technique can be used for sheets up to ~ .0105” thick. Thicker sheets should be cut using a dicing saw with a composite diamond blade.

2-LAYER GENERATOR STOCK

DURABILITY: The two layer generator 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 generator 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 generator 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 input 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, silicones, 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 Generator/Sensor 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 .004" (.1mm) thick brass or stainless steel. Shims are soldered to in the same way as the nickel electrode.

Tools & Materials For Soldering

- Soldering iron set ~ 660°-650° F
- 60 Sn / 40 Pb Solder
- Supersafe # 67 DSA Liquid Flux
- Wires (preferably #32 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 seconds).
- 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 #32 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.

TABLE-2 PIEZOELECTRIC AND MATERIAL PROPERTIES FOR PSI-5A4E PIEZOCERAMIC

PIEZOELECTRIC				
Composition			Lead Zirconate Titanate, Navy Type-II	
Material Designation			PSI-5A4E	
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}	-11.6×10^{-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}	~0.55	
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	7800	Kg / Meter^3
Elastic Modulus		Y^E_{33}	5.2×10^{10}	Newtons / Meter^2
		Y^E_{11}	6.6×10^{10}	Newtons / Meter^2
Poisson's 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-3 LIST OF SYMBOLS

Symbol	Name	Unit
A	Area	m^2
C	Capacitance	F
D	Diameter	m
Di (i=1 to 3)	Dielectric displacement	C / m^2
d_{ij} (i=1 to 3) (j=1 to 6)	Piezoelectric charge constants	C / N
E_i (i=1 to 3)	Electric field components	V / m
E_c	Coercive field	V / m
F_r	Resonant frequency	Hz
F	Force	N
F_b	Blocking Force	N
g_{ij} (i=1 to 3) (j=1 to 6)	Piezoelectric voltage constants	V m / N
G	Shear modulus	N / m^2
k	Electromechanical coupling coefficient	
k_{33}	Longitudinal coupling coefficient	
k_{31}	Transverse coupling coefficient	
k_{15}	Shear coupling coefficient	
k_p	Planar coupling coefficient	
k_t	Thickness coupling coefficient	
k_{eff}	Effective coupling coefficient	
K_{ij}^S (i=1 to 3) (j=1 to 3)	Relative dielectric constant at constant strain	
K_{ij}^T (i=1 to 3) (j=1 to 3)	Relative dielectric constant at constant stress	
L	Length	m
p	Pressure	N / m^2
p	Pyroelectric coefficient	$C / m^2 K$
Pi (i=1 to 3)	Polarization components	C / m^2
P	Power	W
Q	Mechanical quality factor	

Symbol	Name	Unit
Q	Electric charge	C
Q_s	Short circuit charge	C
R	Electrical resistance	Ω
s_{ij}^E (i=1 to 6) (j=1 to 6)	Elastic compliance at constant E	m^2 / N
s_{ij}^D (i=1 to 6) (j=1 to 6)	Elastic compliance at constant D	m^2 / N
S_i (i=1 to 6)	Strain components	
S_{max}	Maximum recommended strain	
t	Time	s
t	Thickness	m
tr	Response time	s
T	Thickness	m
T_i (i=1 to 6)	Stress components	N / m^2
V	Volume	m^3
V	Electrical voltage	V
V_o	Open circuit voltage	V
v_s	Velocity of sound	m / s
x	Deflection	m
x_o	Free deflection	m
α	Thermal expansion coefficient	1 / K
ε_o	Dielectric constant of free space	F / m
ρ	Density	kg / m^3
ρ	Electrical bulk resistivity	Ω m