Basic Introduction to NanoPositioning with Piezoelectric Technology

NOTES

For more detailed information see "Fundamentals of Piezoelectricity and Piezo Actuators", page 4.15.

Basics

The piezoelectric effect is often encountered in daily life. For example, in small butane cigarette or gas grill lighters, a lever applies pressure to a piezoelectric crystal creating an electric field strong enough to produce a spark to ignite the gas. Furthermore, alarm clocks often use a piezoelectric element. When AC voltage is applied, the piezoelectric material moves at the frequency of the applied voltage and the resulting sound is loud enough to wake even the strongest sleeper.

The word "piezo" is derived from the Greek word for pressure. In 1880, Jacques and Pierre Curie discovered that pressure applied to a quartz crystal creates an electrical charge in the crystal; they called this phenomena the piezo effect. Later they also verified that an electrical field applied to the crystal would lead to a deformation of the material. This effect is referred to as the inverse piezo effect. After the discovery it took several decades to utilize the piezoelectric phenomenon. The first commercial applications were ultrasonic submarine detectors developed during World War I and in the 1940's scientists discovered that barium titanate ceramics could be made piezoelectric in an electric field.

As stated above, piezoelectric materials can be used to convert electrical energy into mechanical energy and vice versa. For nanopositioning, the precise motion which results when an electric field is applied to a piezoelectric material is of great value. Actuators using this effect first became available around 20 years ago and have changed the world of precision positioning.

Piezoelectric actuators (PZTs) offer the user several benefits and advantages over other motion techniques:

- **Repeatable nanometer and sub-nanometer sized steps at high frequency can be achieved with PZTs because they derive their motion through solid state crystal effects. There are no moving parts (no "stick-slip" effect).**
- **PZTs can be designed to move heavy loads (several tons) or can be made to move lighter loads at frequencies of several 10 kHz.**
- **PZTs act as capacitive loads and require very little power in static operation, simplifying power supply needs.**
- **PZTs require no maintenance because they are solid state and their motion is based on molecular effects within the ferroelectric crystals.**

With high-reliability PZT materials a strain on the order of 1/1000 (0.1%) can be achieved; this means that a 100 mm long PZT actuator can expand by 100 micrometers when the maximum allowable field is applied.

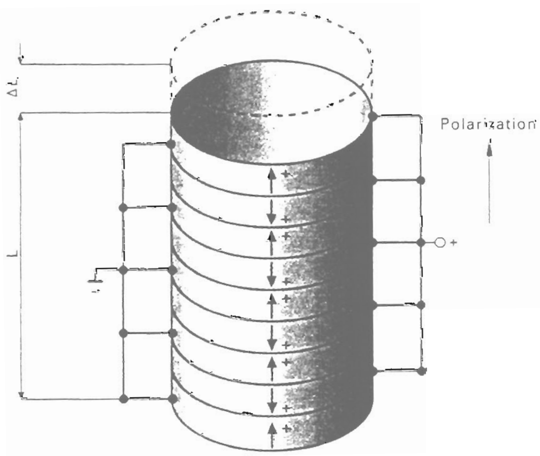
Low Voltage and High Voltage PZTs

Two main types of piezo actuators are available: low voltage (multilayer) devices requiring about 100 volts for full motion and high voltage devices requiring about 1000 volts for full extension. Modern piezo ceramics capable of greater motion replace the natural material used by the Curies, in both types of devices. Lead zirconate titanate (PZT) based ceramic materials are most often used today. Actuators made of this ceramic are often referred to as PZT actuators.

The maximum electrical field PZT ceramics can withstand is on the order of 1 to 2 kV/mm. In order to keep the operating voltage within practical limits, PZT actuators consist of thin layers of electroactive ceramic material electrically connected in parallel (Fig. 4.10/1). The net positive displacement is the sum of the strain of the individual layers. The thickness of the individual layer determines the maximum operating voltage for the actuator (for more information see "Displacement of Piezo Actuators (Stack & Contraction Type)", page 4.19).

High voltage piezo actuators are constructed from 0.5 to 1.0 mm layers while low voltage piezo actuators are monolithic (diffusion bonded) multilayer designs constructed from 20 to 100 µm layers.

Both types of piezo actuators can be used for many applications: Low voltage actuators facilitate drive electronics design, high voltage types operate to higher temperatures (150 °C compared to 80 °C). Due to manufacturing technology high voltage ceramics can be designed with larger cross-sections for higher load applications (up to several tons) than low voltage ceramics.



4.10/1 Electrical connection of disks in a PZT stack actuator.

Resolution

Piezo actuators have no "stick slip" effect and therefore offer theoretically unlimited resolution. This feature is important since PZTs used in atomic force microscopes are often required to move distances less than one atomic diameter. In practice, actual resolution can be limited by a number of factors such as piezo amplifier (electric noise results in unwanted displacement), sensor & control electronics (noise and sensitivity to EMI affect the positional resolution and stability) and mechanical parameters (design and mounting precision of the sensor, actuator and preload influence micro-friction which limits resolution and accuracy). PI Closed Loop PZT Actuators provide sub-nanometer resolution and stability.

Open and Closed Loop Operation

PZT actuators can be operated in open and closed loop. In open loop, displacement roughly corresponds to the drive voltage. This mode is ideal when the absolute position accuracy is not critical or when the position is controlled by data provided by an external sensor (interferometer, CCD chip etc.). Open loop piezo actuators exhibit hysteresis and creep behavior (like other open loop positioning systems).

Closed loop actuators are ideal for applications requiring high linearity, long-term position stability, repeatability and accuracy. PI Closed Loop PZT Actuators & Systems are equipped with position measuring systems providing sub-nanometer resolution and bandwidth up to 10 kHz. A servo controller (digital or analog) determines the output voltage to the PZT by comparing a reference signal (commanded position) to the actual sensor fed back position signal (for more information see page 4.32).

PI has designed multi-axis Closed Loop PZT positioners that offer the possibility of repeatedly locating a point within a 1 x 1 x 1 nanometer cube (see "PZT Flexure NanoPositioners" section for more information). It is important to remember that such accuracy is obtainable only if the surrounding environment is controlled, since temperature changes and vibrations will cause changes in position at the nanometer level.

Dynamic Behavior

A piezo actuator can reach its nominal displacement in approximately 1/3 of the period of the resonant frequency. Rise times on the order of microseconds and accelerations of more than 10,000 g's are possible. This feature permits rapid switching applications. Injector nozzle valves, hydraulic valves, electrical relays, adaptive optics and optical switches are a few examples of fast-switching applications.

Resonant frequencies of industrial reliability piezo actuators range from a few tens of kHz for actuators with total travel of a few microns to a few kHz for actuators with travel more than 100 microns. These figures are valid for the piezo itself; an additional load will decrease the resonant frequency as a function of the square root of the mass (quadrupling the mass will halve the resonant frequency).

Piezo actuators are not designed to be driven at resonant frequency (with full stroke and load), as the resulting high dynamic forces might endanger the structural integrity of the ceramic material.

Mechanical Considerations

Stiffness

In a first approximation, a piezo actuator can be regarded as a spring/mass system. The stiffness or spring constant of a piezo actuator depends on the Young's Modulus of the ceramic (approximately 25 % that of steel), the cross section and length of the active material and a number of other nonlinear parameters (for more information see "Stiffness", page 4.22).

Load Capacity and Force Generation

PZT ceramics can withstand high pushing forces and carry loads to several tons. Even when fully loaded, the PZT will not lose any travel as long as the maximum load capacity is not exceeded.

Load capacity and force generation must be distinguished. The maximum force (blocked force) a piezo can generate is determined by the product of the stiffness and the total travel. A piezo actuator (as most other actuators) pushing against a spring load will not reach its nominal displacement. The reduction in displacement is dependent on the ratio of the piezo stiffness to the spring stiffness. As the spring stiffness increases, the displacement decreases and the generated force increases (for more information see "Stiffness", page 4.22).

Protection from Mechanical Damage

Since PZT ceramics are brittle and cannot withstand high pulling or shear forces, the mechanical actuator design must isolate these undesirable forces from the ceramic. For example, spring preloads can be integrated in the mechanical actuator assembly to compress the ceramic inside and increase the ceramic's pulling capabilities for dynamic push/pull applications (for more information see "Mounting Guidelines", page 4.44).

Power Requirements

Piezo actuators operate as capacitive loads. Since the current leakage rate of the ceramic material is very low (resistance >> 10 MΩ), piezo actuators consume almost no energy in a static application and therefore produce virtually no heat.

In dynamic applications the power consumption increases linearly with frequency and actuator capacitance. High-load actuators with larger ceramic cross sections have higher capacitance than small actuators.

For example, a typical medium load LVPZT actuator with a motion range of 15 microns and 10 kg load capacity requires only five watts to be driven at 1000 Hz while a high load actuator capable of carrying a few tons may require hundreds of watts for the same frequency (for more information see page 4.28).

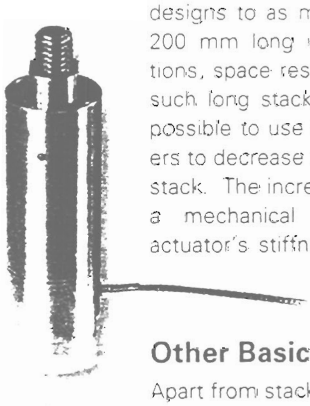
Different Piezo Actuator Designs to Suit Various Applications

Stack Actuators (Translators)

The most common form of piezo actuator is a stack of ceramic layers with two electrical leads. To protect the ceramic against external influences, a metal case is often built around it. This case may also contain built-in springs to compress the ceramic to allow push and pull operation.

The P-845 Closed Loop LVPZT Translator (Fig. 4.13/2) is one example of a low voltage translator with internal spring preload and integrated high-resolution strain gage position sensor. This translator provides displacement to 90 microns and stiffness to 400 N/µm. It can handle loads up to 300 kilograms and withstand pulling forces to 700 N (see "PZT Actuators" section for details). Applications include vibration cancellation, shock wave generation and machine tool positioning for fabrication of non-spherical contact lens surfaces.

PI offers PZT stack translators with travel ranges from a few microns for small designs to as much as 200 microns for 200 mm long units. In some applications, space restrictions do not allow for such long stacks. In these cases, it is possible to use mechanical lever amplifiers to decrease the length of the ceramic stack. The increase in travel gained with a mechanical amplifier reduces the actuator's stiffness and maximum operating frequency.



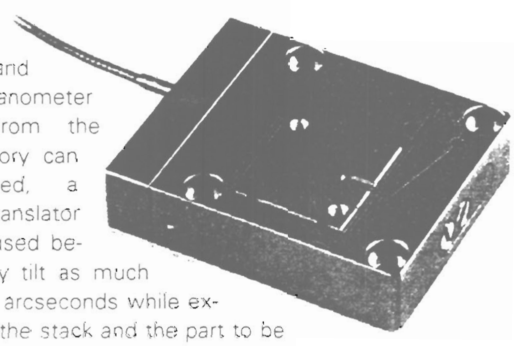
4.13/2 P-845 Closed Loop LVPZT Translator

Other Basic Actuators

Apart from stack translators, a number of other basic PZT actuators are available: bender actuators providing long travel (millimeter range), contraction actuators, tube actuators, shear actuators etc. See page 4.39 for more information.

Actuators with Motion Amplifiers & Trajectory Control

In some applications a stack actuator alone is not enough to perform complex tasks. For example, when straight motion is needed and only nanometer deviation from the ideal trajectory can be tolerated, a stack translator cannot be used because it may tilt as much as a few 10 arcseconds while expanding. If the stack and the part to be moved are decoupled and a precision guiding system is employed, exceptional trajectory control can be achieved. The best guiding precision can be achieved with flexures.



4.13/1 P-780 PZT Flexure NanoPositioner and scannner with integrated motion amplifier.

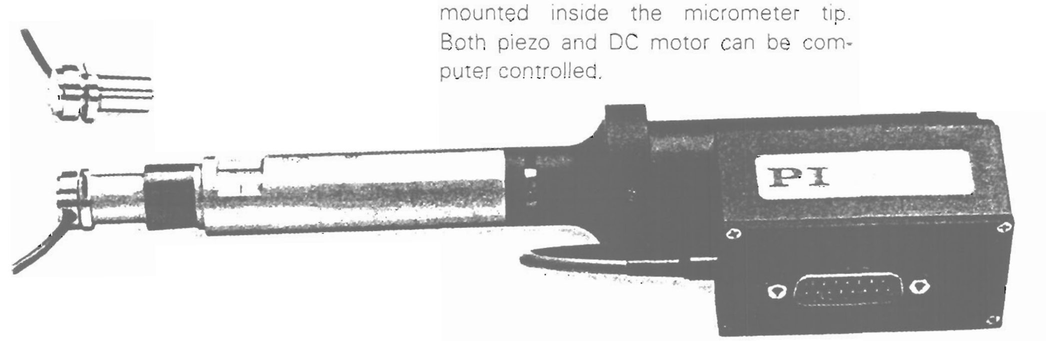
Fig. 4.13/1 shows one example of a piezoelectrically driven miniature flexure stage with integrated flexure guiding system and motion amplifier. The stage is made of stainless steel and all flexures are wire EDM (Electrical Discharge Machining) cut. The flexures are computer designed by an FEA (Finite Element Analysis) program. The central part of the stage can move +/- 40 micrometers along one axis. The movement is accomplished by an integrated 3:1 lever driven by a PZT stack pushing a spherical tip constructed integrally to the lever. The resonant frequency of the unloaded stage is 1 kHz (high when the lever amplification is considered).

The lever is connected to the platform by a flat spring which is very stiff in the push/pull direction but flexible in the lateral direction. This flexibility ensures straight stage motion with minimum tilt and lateral deviation. The system runout and flatness are less than 5 nanometers and even this low figure can be reduced with a larger flexure base (sub-nanometer, sub-microradian flatness can be achieved with actively error compensated multi-axis systems (see "PZT Flexure NanoPositioners" section for details). The flexure design is not limited to single axis stages; systems with up to six degrees of freedom are available.

Single- and multi-axis flexure positioners are used in research, laboratory and industrial applications such as disk drive testing, mask aligners for X-Ray steppers, adaptive optics, precision machining, fiber aligners, scanning microscopy, autofocus systems for surface profilers and hydraulic servo valves.

Piezo Actuators combined with Motorized Long Range Positioning Systems

Piezo actuators can be combined with other actuators to form long range, high resolution systems. A good example is the M-224.50/P-250 combination of a piezo actuator with a motor-driven lead screw (Fig. 4.14/1). This combination provides 25 mm coarse range (versions with 50 mm are available) but preserves the high resolution characteristics intrinsic to PZTs. Coarse motion is provided by a micrometer with a non-rotating tip driven by a DC motor/encoder/gearhead unit capable of < 0.1 µm resolution. A short PZT stack providing sub-nanometer resolution is mounted inside the micrometer tip. Both piezo and DC motor can be computer controlled.



4.14/1 Combination of M-224 DC-Mike Linear Drive and P-250 PZT Translator.

Design Points to Remember

Piezo actuators offer unique and compelling advantages in nanometer resolution and high speed applications. To obtain maximum performance while avoiding problems, however, piezoelectric characteristics need to be considered. Pulling, shear and torsional forces can damage the PZT ceramic. Standard PZT ceramics are limited to a maximum operating temperature of 150 °C. PZT ceramics must be protected from humidity or fluid contamination (like other electric materials and actuators).

Close contact between the PZT user and the manufacturer assures the right actuator design is chosen for your application. PI has 25 years of experience in designing piezoelectric actuators and systems and offers a wide variety of options which can adapt PZTs to various environmental conditions.

Fundamentals of Piezoelectricity and Piezo Actuators

Material Properties

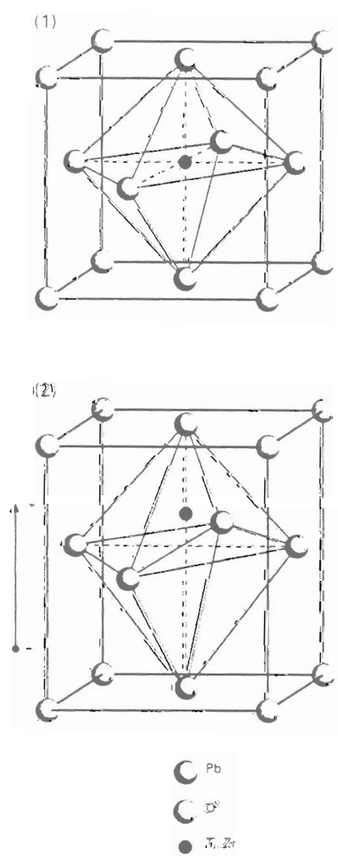
NOTES

The following pages give a detailed overview of piezo actuator theory and their operation. For basic knowledge read "Basic Introduction to NanoPositioning with Piezoelectric Technology". For definition of units, dimensions and terms, see "Glossary" on page 4.7 and "Units and Dimensions" on page 4.8

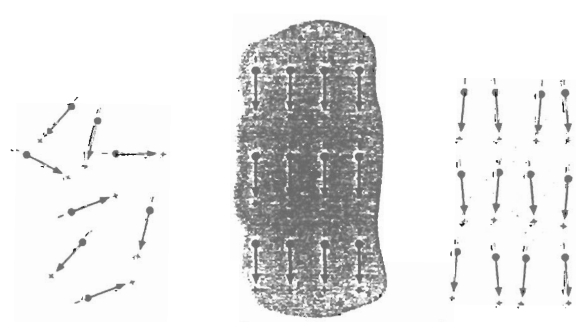
Since the piezo effect exhibited by natural materials such as quartz, tourmaline, Rochelle salt, etc. is very small, polycrystalline ferroelectric ceramic materials such as BaTiO3 and Lead Zirconate Titanate (PZT) have been developed with improved properties. Ferroelectric ceramics become piezoelectric when poled. PZT ceramics are available in many variations and are still the most widely used materials for actuator or sensor applications today. PZT crystallites are centro-symmetric cubic (isotropic) before poling and after poling exhibit tetragonal symmetry (anisotropic structure) below the Curie temperature (see Fig. 4.15/1). Above this temperature they lose the piezoelectric properties.

Charge seperation between the positive and negative ions is the reason for electric dipole behavior. Groups of dipoles with parallel orientation are called Weiss domains. The Weiss domains are randomly oriented in the raw PZT material, before the poling treatment has been finished. For this purpose an electric field (> 2000 V/mm) is applied to the (heated) piezo ceramics. With the field applied, the material expands along the axis of the field and contracts perpendicular to that axis. The electric dipoles align and roughly stay in alignment upon cooling. The material now has a remanent polarization (which can be degraded by exceeding the mechanical, thermal and electrical limits of the material). As a result, there is a distortion that causes growth in the dimension aligned with the field and a contraction along the axes normal to the electric field.

When an electric voltage is applied to a poled piezoelectric material, the Weiss domains increase their alignment proportional to the voltage (see Fig. 4.15/2). The result is a change of the dimensions (expansion, contraction) of the PZT material.



4.15/1
Piezoelectric elementary cell; (1) before poling (2) after poling



4.15/2
Electric dipoles in Weiss domains; (1) unpoled ferroelectric ceramic, (2) during and (3) after poling (piezoelectric ceramic)

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PZT Ceramics Manufacturing Process

PI manufactures its own piezo ceramic materials at the PI Ceramic factory. The process starts with mixing and ball milling of the raw materials. Next, the mixture is heated to 75% of the sintering temperature to accelerate reaction of the components. The polycrystalline, calcinated powder is ball milled again to increase its reactivity. Granulation with the binder is next to improve processing properties. After shaping and pressing the (green) ceramics is heated to 750° to burn out the binder.

The next phase is sintering at temperatures between 1250° C and 1350° C. The ceramic block is cut, ground, polished, lapped, etc., to the desired shape and tolerance. Electrodes are applied by sputtering or screen printing processes. The last step is the poling process which takes place in a heated oil bath at electrical fields up to several kV/mm.

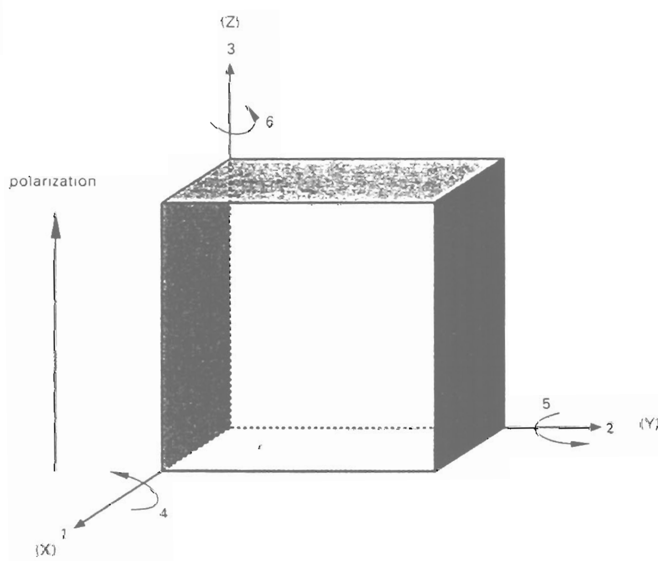
Multilayer PZT actuators require a different manufacturing process. After milling a slurry is prepared. A foil casting process allows layer thickness down to 20 µm. Next, the sheets are screen printed and laminated. A compacting process increases density of the "green" ceramics and removes air trapped between the layers. The final steps are the binder burnout, sintering (co-firing) at temperatures below 1100° C, end termination and poling.

All processes, especially the heating and sintering cycles must be controlled to very tight tolerances. The smallest change affects quality and properties of the PZT material. 100% final testing of the piezo material and components at PI Ceramic guarantees the highest product quality.

Definition of Piezoelectric Coefficients and Directions

Because of the anisotropic nature of PZT ceramics, effects are dependent on direction (see Fig. 4.16/1). To identify directions the axes, termed 1, 2, and 3, are introduced (analogous to X, Y, Z of the classical right hand orthogonal axial set). The axes 4, 5 and 6 identify rotations (shear).

The direction of polarization (3 axis) is established during the poling process by a strong electrical field applied between two electrodes. For actuator applications the piezo properties along the poling axis are most essential (largest deflection).



4.16/1 Orthogonal system describing the properties of a poled piezoelectric ceramic. Axis 3 is the poling direction.

NOTES

It should be clearly understood that the piezoelectric coefficients described here are not independent constants. They vary with temperature, pressure, electric field, form factor, mechanical and electrical boundary conditions etc. The coefficients only describe material properties under small signal conditions. Compound components such as PZT stack actuators, let alone preloaded actuators or lever amplified systems cannot be described sufficiently by these material parameters. This is why each component or system manufactured by PI is characterized by specific data such as stiffness, load capacity, displacement, resonant frequency, etc., acquired by individual measurements.

Piezoelectric materials are characterized by several coefficients:

Examples are:

- **d_{ij}: Strain coefficients [m/V]:**
  strain developed (m/m) per electric field applied (V/m)
  or (due to the sensor / actuator properties of PZT material).
  Charge output coefficients [C/N]:
  charge density developed (C/m²) per given stress (N/m²).
- **g_{ij}: Voltage coefficients or field output coefficients [Vm/N]:**
  open circuit electric field developed (V/m) per applied mechanical stress (N/m²)
  or (due to the sensor / actuator properties of PZT material)
  strain developed (m/m) per applied charge density (C/m²).
- **k_{ij}: Coupling coefficients [no dimensions].**
  The coefficients are energy ratios describing the conversion from mechanical to electrical energy or vice versa.
  k^2 is the ratio of energy stored (mechanical or electrical) to energy (mechanical or electrical) applied.

Other important parameters are the Young's modulus Y (describing the elastic properties of the material) and the relative dielectric coefficients (permittivity) ε (describing the capacitance of the material).

To link electrical and mechanical quantities double subscripts (e.g. d_{ij}) are introduced. The first subscript gives the direction of the excitation, the second describes the direction of the system response.

Example:

d_{33} applies when the electric field is along the polarization axis (direction 3) and the strain (deflection) is along the same axis. d_{31} applies if the electric field is in the same direction as before, but the strain is in the 1 axis (orthogonal to the polarization axis)

In addition the superscripts "S, T, E, D" are introduced. They describe an electrical or mechanical boundary condition.

Definition:

S = strain = constant (mechanically clamped)
T = stress = constant (not clamped)
E = field = constant (short circuit)
D = electrical displacement = constant (open circuit)

The individual piezoelectric parameters are related by several equations that are not explained here because they are not important for the user of piezo actuators.

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Resolution

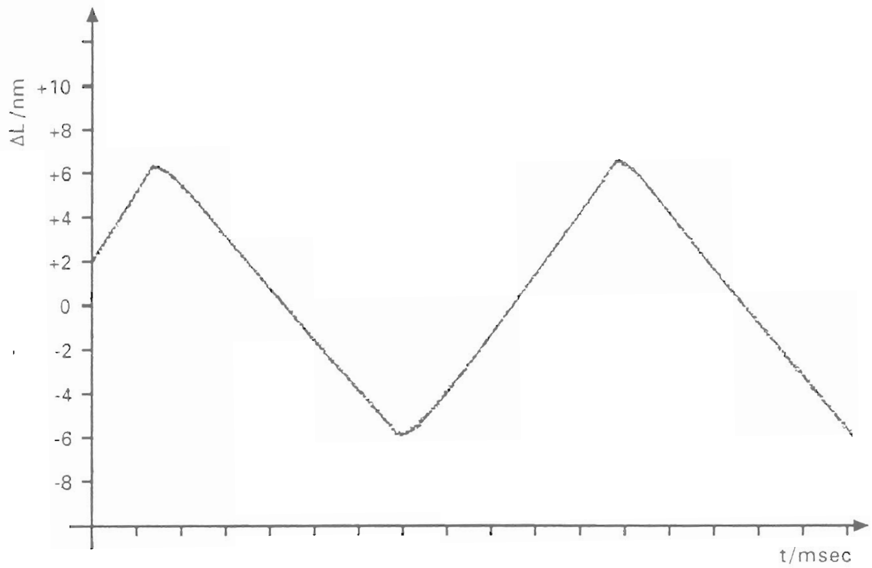
Since the displacement of a piezo actuator is based on the orientation of electrical dipoles in the elementary PZT cells, the resolution depends on the electrical field applied and is theoretically unlimited. Infinitesimally small changes in operating voltage are converted to a smooth linear movement (see Fig. 4.18/1).

No threshold voltages influence the constant motion.

Piezo actuators are used in atomic force microscopes to produce motion less than the diameter of an atom. Since displacement is proportional to the applied voltage, optimum resolution cannot be achieved with noisy, unstable voltage sources.

NOTES

The above presented performance can only be provided by frictionless and stictionless solid state actuators such as PZTs. "Traditional" technologies used in motion positioners (stepper or DC servo motor drives in combination with dovetails, ball bearings, and roller bearings) all have varying degrees of friction and stiction. This fundamental property limits resolution, causes wobble, hysteresis, backlash, and an uncertainty in position repeatability – limiting their practical usefulness to a precision of two orders of magnitude less than with PI PZT NanoPositioners.



4.18/1 Response of a P-170 HVPZT translator to a ± 1V, 200 Hz triangular drive signal. Note that one division is only 2 nanometers.

Amplifier Noise

As stated above, amplifier noise directly influences the position stability (resolution) of a piezo actuator. Some vendors specify the noise value of their PZT driver electronics in millivolts. This information is of little use without spectral information. If the noise occurs in a frequency band far beyond the resonant frequency of the mechanical system, its influence on mechanical resolution and stability can be neglected. If it coincides with the resonant frequency, it will have a more significant influence on the system stability. Therefore, meaningful data can only be acquired if resolution of the complete system – piezo actuator and drive electronics – is measured in terms of nanometers rather than millivolts. For further information see "Position Servo Control (Closed Loop Operation)"

NOTES

PI PZTs are designed for industrial reliability. Displacement, operating voltage range and load capability in the technical data tables are realistic figures with regard to safe operation in conditions not restricted to research labs. Since we manufacture our own ceramics (in contrast to most other PZT vendors) we can easily modify material parameters to trade lifetime for displacement. When you are looking for piezo actuators to be included in your application, "Maximum Displacement" may not be the only important design parameter.

Displacement of Piezo Actuators (Stack & Contraction Type)

Displacement of PZT ceramics is a function of the applied electric field strength E, the piezoelectric material used and the length L of the PZT ceramics. The material properties can be described by the piezoelectric strain coefficients d_{ij}. These coefficients describe the relationship between the applied electrical field and the mechanical strain produced.

The displacement ΔL of an unloaded single layer piezo actuator can be estimated by the equation:

$$\Delta L = S * L_0 \approx \pm E * d_{ij} * L_0 \quad (4\text{-}1)$$

Where

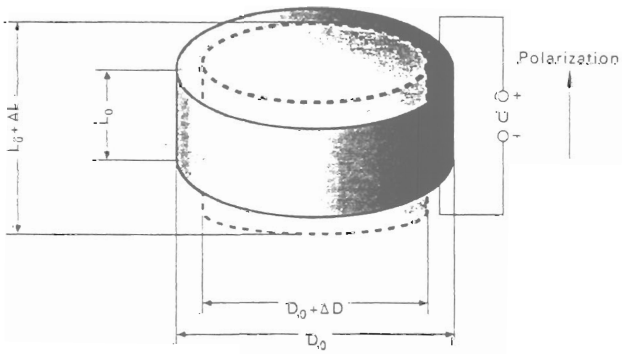
S = strain (relative length change $\Delta L/L$, without dimension)

L_0 = ceramic length [m]

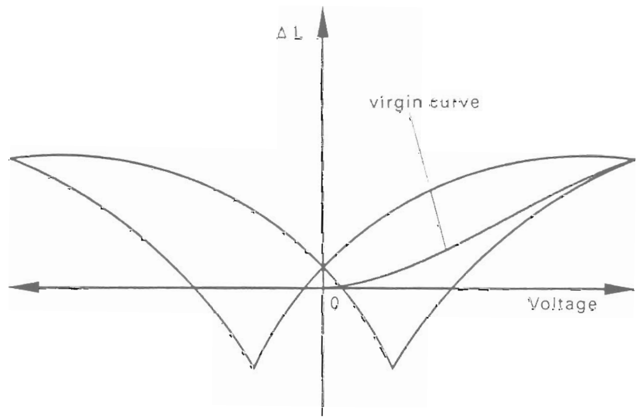
E = electrical field strength [V/m]

d_{ij} = material properties

d_{33} describes the strain parallel to the polarization vector of the ceramics (thickness) and d_{31} the strain orthogonal to the polarization vector (width). d_{33} and d_{31} are sometimes referred to as "piezo gain". See Fig. 4.19/1 for explanation. The strain coefficient d_{33} applies for PZT stack actuators, d_{31} applies for tube and strip actuators.



4.19/1 Elogation and contraction of a PZT disk when a voltage is applied. Note that d_{31} (affects the lateral deformation ΔD) is negative.



4.19/2 Response of a PZT actuator to a bipolar drive voltage. When a certain threshold voltage (negative to the polarization direction) is exceeded, reversion of polarization can occur.

Note:
For the material used in standard PI piezo actuators, d_{33} is on the order of 450 to 650 x 10^{-12} m/V, d_{31} is on the order of -200 to -300 x 10^{-12} m/V. These figures only apply to the raw material at room temperature under small signal conditions.

For standard PI PZTs, the allowable field strength ranges from 1 to 2 kV/mm in the poling direction and up to 300 V/mm inverse to the poling direction (semi-bipolar mode), see Fig. 4.19/2 for details. The maximum voltages depend on the ceramic properties and the insulating materials. **Exceeding the maximum voltage may cause dielectric breakdown and irreversible damage of the PZT.**

With the inverse field, negative expansion (contraction) occurs to yield an additional 20 % of the nominal displacement. If both the regular and inverse electric field are used, a relative expansion (strain) up to 0.2 % is achievable with PZT stack actuators.

Stacks can be built with as aspect ratios up to 12:1 (length:diameter). Maximum travel for medium size stack piezo

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actuators (15 mm diameter), is therefore limited to approximately 200 µm. Longer travel ranges can be achieved by mechanical amplification techniques. See "Piezo Actuators with Integrated Lever Motion Amplifier", page 4.42.

Hysteresis (open loop PZTs)

NOTES

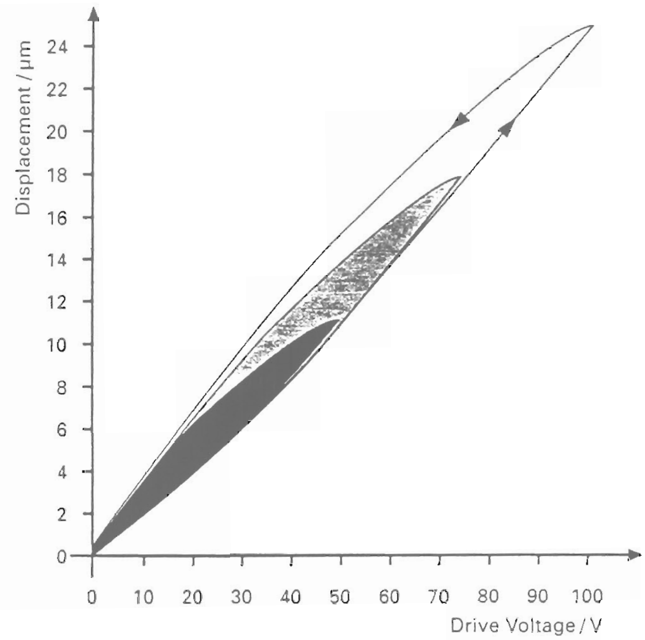
For periodic motion, hysteresis does not affect repeatability.

Hysteresis can be eliminated by closed loop PZT actuators (see page 4.32). Similar to electromagnetic devices, open loop piezo actuators exhibit hysteresis (they are also referred to as ferroelectric actuators). Hysteresis is based on crystalline polarization effects and molecular friction. The absolute displacement generated by an open loop PZT depends on the applied electric field and the piezo gain which is related to the remanent polarization. Since the remanent polarization and therefore the piezo gain is affected by the electric field applied to the piezo, its deflection depends on whether it was previously operated at a higher or a lower voltage (and some other effects). Hysteresis is typically on the order of 10 to 15 % of the **commanded** motion (see Fig. 4.20/1)

E.g. if the drive voltage of a 50 µm piezo actuator is changed by 10 %, (≅ 5 µm motion) the position repeatability is still on the order of only 1 % full travel or better than 1 µm. Classical motor driven leadscrew positioners will hardly beat this repeatability.

PI closed loop piezo actuator systems eliminate hysteresis. PI offers these systems for applications requiring the absolute position information, as well as motion with high linearity, repeatability and accuracy in the nanometer and subnanometer range (see page 4.32).

For positioning where the travel is controlled by an external servo loop (e.g. the eyes and hands of the operator or a sophisticated electronics system), hysteresis behavior and linearity are of secondary importance since they can be compensated for by the external loop.



4.20/1 Hysteresis curves of an open loop piezo actuator for various peak voltages. The hysteresis is related to the distance moved.

Example:

Piezoelectrically driven fiber couplers derive the control signal from the optical power transmitted from one fiber to the other. The goal is to maximize the transmission rate, not to determine the exact position. An open loop PZT system is sufficient for this application offering unlimited resolution, fast response, no backlash and no stick/slip effect.

NOTES

For periodic motion, creep does not affect repeatability.

Creep (Drift) (open loop PZTs)

Creep only occurs with open loop PZTs. Like hysteresis, creep is related to the effect of the applied voltage on the remanent polarization of the piezo ceramics. Creep decreases logarithmically with time. If the operating voltage of a (open loop) PZT is increased (decreased), the remanent polarization (piezo gain) continues to increase (decrease), manifesting itself in a slow creep (positive or negative) after the voltage change is complete. The following equation describes the effect:

$$\Delta L(t) \approx \Delta L(1+\gamma^{*}\lg^{*}(t/0.1)) \qquad (4\text{-}2)$$

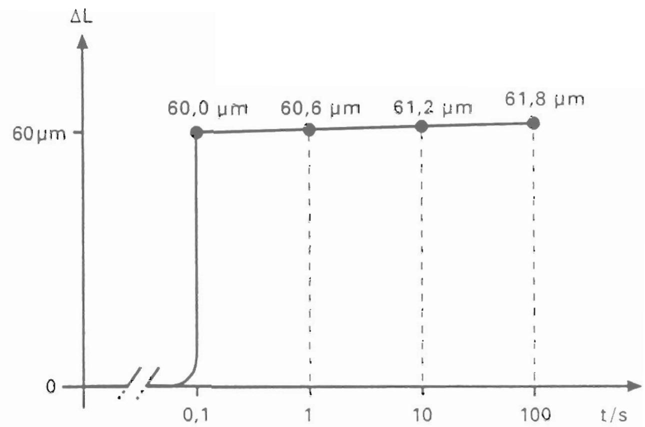
Creep of PZT motion as a function of time.

where

ΔL = displacement 0.1 seconds after the voltage change is complete [m].

γ = creep factor which is dependent on the properties of the actuator (on the order of 0.01 to 0.02).

Maximum creep (after a few hours) can add up to a few % of the commanded motion (see page 4.32 for drift elimination).



4.21/1 Creep of open loop PZT motion after a 60 µm change in length as a function of time. Creep is on the order of 1 % of the last commanded motion per time decade.

Aging

Aging refers to reduced piezo gain as a result of the depoling process. Aging can be an issue for sensor or charge generation applications (direct piezo effect), but with actuator applications it is negligible, because repoling occurs every time a higher electric field (in the poling direction) is applied to the element.

Mechanical Considerations

Maximum Applicable Forces (Compressive Load Limit, Tensile Load Limit)

The mechanical strength values of PZT ceramic material (given in the literature) is often confused with the practical long term load capacity of a PZT actuator. PZT ceramic material can withstand pressures up to 250 MPa (2500 x 10^5 N/m²) before it breaks mechanically. For practical applications, this value must not be approached because depolarization occurs at pressures on the order of 20 to 30 % of the mechanical limit. For actuators (which are a combination of several materials) additional rules apply. Parameters such as aspect ratio, buckling, interaction at the interfaces etc. must be considered. If the maximum compressive force for a PZT is exceeded, damage to the ceramics as well as depolarization may occur.

The load capacity data listed for PI actuators are conservative values which allow long lifetime. Standard PI PZT stack actuators can withstand compressive forces to several 10,000 N (≅ several tons).

Tensile loads of non preloaded PZTs are limited to 5 - 10 % of the compressive load limit. PI offers a variety of piezo actuators with internal spring preload for extended tensile load capacity. Preloaded elements are highly recommended for dynamic applications.

Shear forces must be isolated from the PZT ceramics by external measures (flexure guides, etc.).

Stiffness

When calculating force generation, resonant frequency, system response, etc., piezo stiffness is an important parameter. In solid bodies stiffness depends on the Young's Modulus which is the ratio of stress (force per unit area) to strain (change in length per unit length). It is generally described by the spring constant k_T, relating the influence of an external force to the dimensional change of the body.

This narrow definition does not apply fully for PZT ceramics; large and small signal conditions, static and dynamic operation, open and shorted electrodes must be distinguished. The poling process of PZT ceramics leaves a remanent strain in the material which depends on the magnitude of polarization. The polarization is affected by both the drive voltage and external forces. When an external force is applied to poled PZT ceramics, the dimensional change depends on the stiffness of the ceramic material and the change of the remanent strain (caused by the polarization change). The equation $L_N = F/k_T$ is only valid for small forces and small signal conditions. For larger forces, an additional term describing the influence of the polarization changes, is superimposed on stiffness (k_T).

Since piezo ceramics are active materials, they produce an electrical response (charge) when mechanically stressed (e.g. in dynamic operation). When the electric charge cannot be drained from the PZT, it generates a counter force to the mechanical stress. This is why a PZT element with open electrodes appears stiffer than one with shorted electrodes. With actuators (compound structures of different active and passive materials) the scenario is even more complicated.

The above discussion explains why the (dynamically measured) resonant frequency of a piezo actuator does not necessarily match the results calculated with the "simple harmonic oscillator

NOTES

There is no international standard for measuring piezo actuator stiffness. Therefore stiffness data of different manufacturers cannot be compared without additional information.

equation": $f_0 = (1/2\pi) * \sqrt{(k_T/m_{eff})}$ with statically measured stiffness. (For more details see "Resonant Frequency").

Since stiffness values of PZT actuators are not constants they can only be used to estimate the behavior under certain conditions and to compare different PZT actuators of one manufacturer.

NOTES

It must be understood that a piezo actuator can only generate considerable force if it is directly coupled (no slack!) to an element which is stiff when compared to the PZT.

Force Generation

In most applications, piezo actuators are used to produce displacement. If used in a restraint, they can generate forces. Force generation is always coupled with a reduction in displacement. The maximum force (blocked force) a piezo actuator can generate depends on its stiffness and maximum displacement. See also "Displacement with External Forces", page 4.24.

$F_{max} \approx k_T * \Delta L_0$ (4-3)

Maximum force that can be generated in an infinitely rigid restraint (infinite spring constant). At maximum force generation, displacement is zero.

where

ΔL_0 = max. nominal displacement without external force or restraint [m]

k_T = PZT actuator stiffness [N/m]

In actual applications the load spring constant can be larger or smaller than the PZT spring constant. The force $F_{max\ eff}$ generated by the PZT is:

$F_{max\ eff} \approx k_T * \Delta L_0 (1-k_T/(k_T+k_S))$ (4-4)

Effective force a piezo actuator can generate in a yielding restraint

where

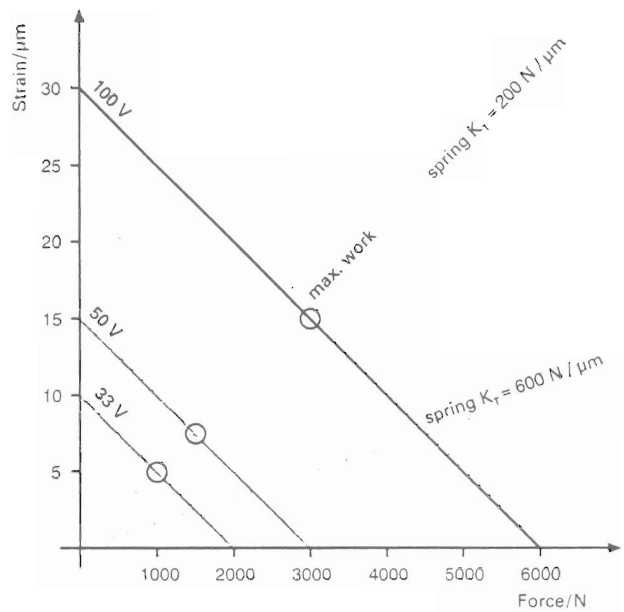
ΔL_0 = displacement (without external force or restraint) [m]

k_T = PZT actuator stiffness [N/m]

k_S = spring stiffness [N/m]

Example:

Force generation of P-845.20 (see page 1.17 in "PZT Actuators" section). The PZT can produce a maximum force of 30 µm * 200 N/µm = 6000 N. When force generation is maximum, displacement is zero. At full displacement no force can be generated (see Fig. 4.23/1 for details).



4.23/1 Force Generation vs. Displacement of a P-845.20 LVPZT actuator at various operating voltages. The points where the dashed lines (external spring curves) intersect the PZT force/displacement curves determine the force and displacement for a given setup with an external spring. Maximum work can be produced when the stiffness of the PZT actuator and external spring are identical.

Example:

A piezo actuator is to be used in a metal sheet embossing application. At rest (zero position) the distance between the PZT tip and the sheet is 30 microns (given by mechanical system tolerances). A force of 500 N is required to emboss the metal.

Q: Can a 60 µm actuator with a stiffness of 100 N/µm be used?

A: Under ideal conditions this actuator can generate a force of 30 x 100 N = 3000 N (30 microns are lost motion due to the distance between the sheet and the PZT tip). In reality the force generation depends on the stiffness of the metal and the support. If the support was a soft material, with a stiffness of 10 N/µm the PZT could only generate a force of 300 N onto the metal when operated at maximum drive voltage. If the support was stiff but the metal itself was very soft (gold, aluminum, etc.) it would yield and the piezo actuator still could not generate the required force. If both the support and the material were stiff enough, but the PZT mount was too soft, the force generated by the PZT would push the actuator away from the material to be embossed. The situation is similar to lifting a car with a jack. If the ground (or the car's body) is too soft, the jack will run out of travel before it generates enough force to lift the wheels off the ground.

Displacement with External Forces

Like any other actuator, a piezo actuator is compressed when a force is applied. Two cases must be considered when operating a PZT with a load:

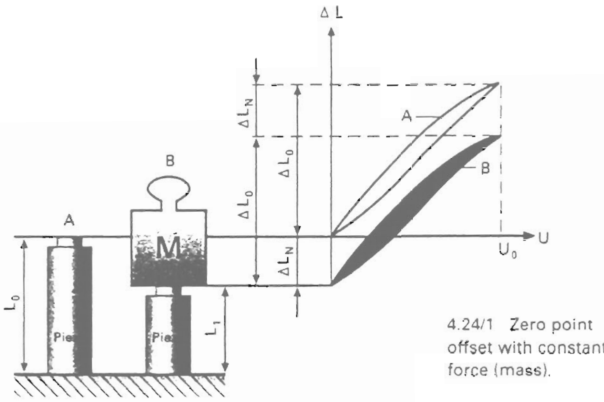
a) the load remains constant during the motion process
b) the load changes during the motion process.

Case a
(Force = constant)
Zero point is offset

A mass is installed on the PZT which applies a force F = M * g (M: mass, g: acceleration due to gravity). The zero point will be offset by an amount $\Delta L_N \approx F/k_T$, where k_T equals the stiffness of the PZT. If this force is within the specified load limit (technical data), full displacement can be obtained at full operating voltage (see Fig. 4.24/1).

$\Delta L_N \approx F/k_T$ (4-5)

Zero point offset with constant force
where
ΔL_N =Zero point offset [m]
F = Force (generated by mass and gravity) [N]
k_T = PZT actuator stiffness [N/m]



4.24/1 Zero point offset with constant force (mass).

Example:
Q: How large is the zero point offset of a 30 µm PZT actuator with a stiffness of 100 N/µm if a load of 20 kg is applied and what is the maximum displacement with this load?

A: The load of 20 kg generates a force of 20 kg * 9.81 m/s² = 196 N. With a stiffness of 100 N/µm, the piezo actuator is compressed slightly less than 2 µm. The maximum displacement of 30 µm is not affected by this constant force.

Case b
(Force on the PZT is a spring)
Force = Function (ΔL):
displacement is reduced
For PZT operation with spring loads different rules apply. The "spring" could be an I-beam or a single fiber each with its characteristic stiffness or spring constant. Part of the displacement generated by the piezo effect is lost due to its elasticity of the piezo element. The total available displacement can be related to the spring stiffness of by the following equations

$\Delta L \approx \Delta L_0 \, (k_T/(k_T+k_S))$ (4-6)

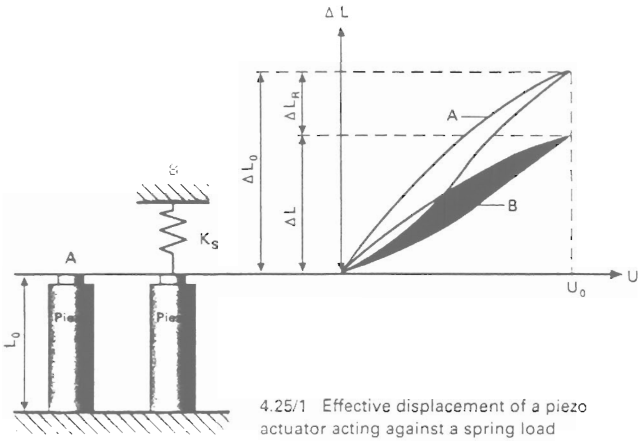
Maximum displacement of a piezo actuator acting against a spring load.

$\Delta L_R \approx \Delta L_0 \, (1- k_T/(k_T+k_S))$ (4-7)

Maximum displacement loss due to external spring force. In the case where the spring stiffness k_s is ∞ (infinitely rigid restraint) the PZT only acts as a force generator.
where
ΔL = displacement with external spring load [m]
ΔL_0 = max. nominal displacement without external force or restraint [m]
ΔL_R = lost displacement caused by the external spring [m]
k_s = spring stiffness [N/m]
k_T = PZT actuator stiffness

NOTES

When designing (internally or externally) preloaded PZT systems, the stiffness of the preload spring should be less than 1/10 of the PZT stiffness. Otherwise too much of the unloaded displacement would be sacrificed. If the preload spring has the same stiffness as the PZT, displacement will be cut in half.



4.25/1 Effective displacement of a piezo actuator acting against a spring load

Example:

Q: What is the maximum displacement of a 15 µm PZT translator with a stiffness of 50 N/µm, mounted in an elastic restraint with spring constant k_s (stiffness) of 100 N/µm ?

A: Equation 4-6 shows that the displacement is reduced in an elastic restraint. The spring constant of the external restraint is twice the value of the piezo translator. The achievable displacement is therefore limited to 5 µm (1/3 of the nominal travel).

Mechanical Considerations for Dynamic Operation of PZTs

Dynamic Forces

Every time the PZT drive voltage changes, the piezo element changes its dimensions (if not blocked). Due to the inertia of the PZT mass (plus any additional mass), a rapid change will generate a force (pushing or pulling) acting on the piezo. The maximum force is equal to the blocked force described by:

$$F_{max} \approx \pm k_T * \Delta L_0 \qquad (4\text{-}8)$$

Maximum force available to accelerate the piezo mass plus any additional mass.

where

ΔL_0 = max. nominal displacement without external force or restraint [m]

k_T = PZT actuator stiffness [N/m]

Tensile forces must be compensated for by a mechanical preload (inside the actuator or external) in order to prevent damage to the ceramics. Preload should be around 20 % of the compressive load limit, with soft preload springs soft compared to the PZT stiffness (1/10 or less).

In sinusoidal operation with frequency f and the amplitude $\Delta L/2$, peak forces can be expressed as

$$F_{dyn} = \pm 4\pi^2 * m_{eff} * (\Delta L/2) * f^2 \qquad (4\text{-}9)$$

Dynamic forces on a PZT in sinusoidal operation with frequency f.

where

F_{dyn} = dynamic force [N]

m_{eff} = effective mass [kg]

ΔL = peak to peak displacement [m]

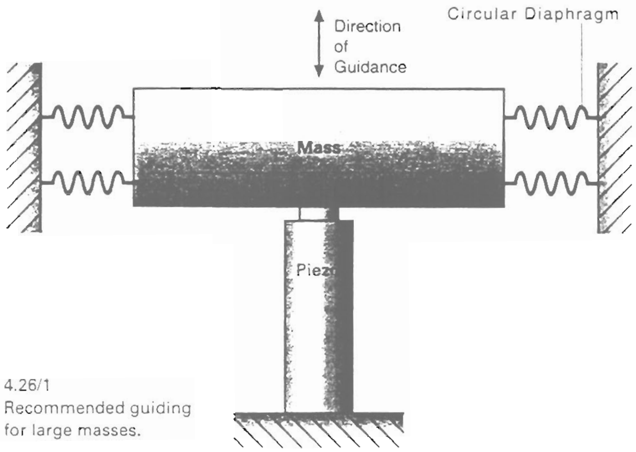
f = frequency [Hz]

The maximum permissible forces must be considered when choosing an operating frequency.

Example:

Dynamic forces at 1000 Hz, 2 µm peak-peak, 1 kg load are approximately ± 40 N.

Note:
A guiding system (e.g. diaphragm type) is recommended when heavy loads or large mechanical parts (compared to the piezo actuator diameter) are moved dynamically. Without a guiding system there is a potential for tilt oscillations and other non-axial forces that may damage the PZT ceramics.



4.26/1 Recommended guiding for large masses.

Resonant Frequency

In general, the resonant frequency of any spring/mass system is a function of its stiffness and effective mass (see Fig. 4.26/2). The resonant frequency given in the technical data tables always refers to the unloaded actuators, rigidly mounted on one end.

$$f_0 = (1/2\pi) * \sqrt{(k_T/m_{eff})} \qquad (4\text{-}10)$$

Resonant frequency of an ideal spring/mass system.

where

f_0 = resonant frequency of the unloaded actuator [Hz]

k_T = actuator stiffness [N/m]

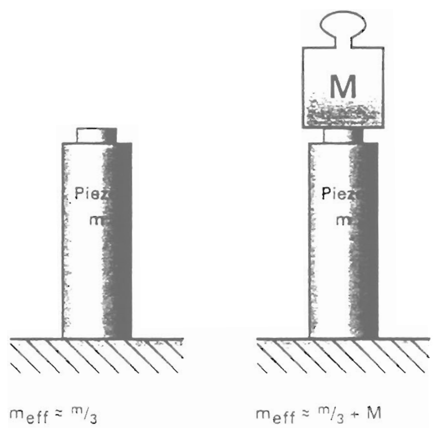
m_{eff} = effective mass (about 1/3 of the mass of the ceramic stack plus any installed end pieces) [kg]

Note:
Due to the non-ideal spring behavior of PZT ceramics, the theoretical result of the above equation does not necessarily match the real-world behavior of a PZT system.

When adding a mass to the actuator the resonant frequency drops according to the following equation:

$$f_0' = f_0 \sqrt{(m_{eff}/(m_{eff}+M))} \qquad (4\text{-}11)$$

Resonant frequency with additional mass M.



4.26/2 Effective mass of an actuator fixed on one end.

The above equations show that increasing the mass on the actuator by a factor of 4 will reduce the response (resonant frequency) by a factor of 2. Increasing the spring preload on the actuator does not significantly affect its resonant frequency.

The phase response of a PZT system can be approximated by a second order system and is described by

$$\varphi \approx 2 * \arctan (f/f_0) \qquad (4\text{-}12)$$

φ = phase angle [deg]
f_0 = resonant frequency [Hz]
f = operating frequency [Hz]

How Fast Can a Piezo Actuator Expand?

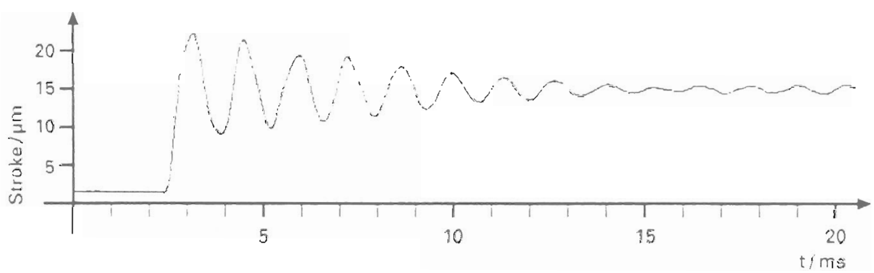
Fast response is one of the desirable features of piezo actuators. A rapid drive voltage change results in a rapid position change. This property is necessary in applications such as switching of valves/shutters, generation of shock-waves, vibration cancellation systems, etc.

A PZT can reach its nominal displacement in approximately 1/3 of the period of the resonant frequency with significant overshoot (see Fig. 4.27/1).

$T_{min} \approx f_0/3$ (4-13)

Shortest rise time of a piezo actuator (requires an amplifier with sufficient output current and rise time).

For example, a piezo translator with a 10 kHz resonant frequency can reach its nominal displacement within 30 µs. For more information see "Dynamic Operation (Switched)", page 4.30.



4.27/1
Response of a lever amplified PZT actuator (low resonant frequency) to a rapid drive voltage change.

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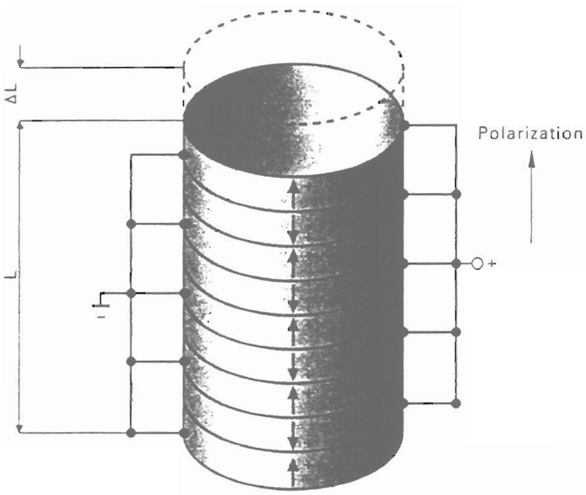
Electrical Requirements for Piezo Operation

General

When operated far below the resonant frequency a PZT behaves as a capacitor where displacement is proportional to charge (first order estimation).

PZT stack actuators are assembled with thin wafers of electroactive ceramic material electrically connected in parallel.



4.28/1 Design of a PZT stack actuator.

The (small signal) capacitance of a stack actuator can be estimated by

$$C \approx n^*\varepsilon_0{}^*\varepsilon_{33}{}^*A/d_s \quad (4\text{-}14)$$

Where

n = number of layers

ε_0 = dielectric constant in vacuum [As/Vm]

ε_{33} = relative dielectric constant [without dimension]

A = electrode surface area [m²]

d_s = distance between the individual electrodes (layer-thickness) [m]

The above equation shows that for a given actuator length l_0 and a given disk thickness d_0 capacitance is a quadratic function of the ratio d_0 / d_1 where $d_1 < d_0$. Therefore, the capacitance of a piezo actuator constructed of 100 µm thick layers is 100 times the capacitance of an actuator with 1 mm thick layers if the two actuators are the same length.

Static Operation

When electrically charged, the energy $E = 1/2\ CU^2$ is stored in a piezo actuator. Every change in the charge (and therefore in the displacement) of the PZT requires a current i:

$$i = dQ/dt = C * (dU/dt) \quad (4\text{-}15)$$

Relationship of current and voltage for the piezo actuator

Where

i = current [A]

Q = charge [Coulomb; As]

C = capacitance [Farad; As/V]

U = voltage [V]

t = time [s]

For static operation only the leakage current has to be supplied. The high internal resistance reduces leakage currents to micro-amp or sub-micro-amp range. Even when disconnected from the electrical source, the charged actuator will not make a sudden move but return to its uncharged dimensions very slowly (> 1 hour).

For slow position changes, very low current is required. For example an amplifier with an output current of 20 µA fully expands a 20 nF actuator within one second. (See section "PZT Control Electronics" section for variety of PZT amplifiers).

PI

NOTES

Low Voltage PZTs (100 µm layers, 100 V operating voltage, high capacitance) require 10 times the driving current of High Voltage PZTs of similar size (1 mm layers, 1000 V operating voltage, low capacitance). Power requirements are similar. PI High/Low Voltage amplifiers are specially designed to meet the different requirements for driving High/Low Voltage actuators.

Dynamic Operation (Analog)

PZTs can provide accelerations of thousands of g's and are perfectly suited for dynamic applications.

Several parameters influence the dynamics of a PZT positioning system:

Mechanical considerations:

- **If the piezo element is installed in a positioning mechanism (and sufficient electrical power from the amplifier is available), the maximum drive frequency can be limited by dynamic forces (see "Dynamic Forces", page 4.25).**
- **The maximum operating frequency is also limited by the phase and amplitude response of the system (especially in closed loop systems). Rule of thumb: the higher the system resonant frequency the better the phase and amplitude response and the higher the usable frequency.**

Electrical considerations:

- **The amplifier output current and rise time determine the maximum operating frequency of a piezoelectric system.**
- **In closed loop operation other parameters such as sensor bandwidth, phase margins and control algorithms determine the performance of a positioning system.**

The following equations describe the relationship between amplifier output current, voltage and operating frequency. They help determine the minimum specifications of a PZT amplifier for dynamic operation.

$$i_a \approx f * C * U_{p\text{-}p} \qquad (4\text{-}16)$$

Average current required for sinusoidal operation

$$i_{max} \approx f * \pi * C * U_{p\text{-}p} \qquad (4\text{-}17)$$

Peak current required for sinusoidal operation

$$f_{max} \approx i_{max}/(2 * C * U_{p\text{-}p}) \qquad (4\text{-}18)$$

Maximum operating frequency with triangular ave form as a function of the amplifier output current limit

Where
i_a = average amplifier source/sink current [A]
i_{max} = peak amplifier source/sink current [A]
f_{max} = maximum operating frequency [Hz]
C = PZT actuator capacitance [Farad (As/V)]
$U_{p\text{-}p}$ = peak-peak drive voltage [V]
f = operating frequency [Hz]

The average current and maximum current for each PI PZT amplifier can be found in the technical data.

Example:

Q: What peak current is required to operate a HVPZT actuator with a nominal displacement of 40 µm @ 1000 V and capacitance of 40 nF with a sinusoidal wave form of 1000 Hz at 20 µm displacement?

A: With a nominal displacement of 40 µm @ 1000 volts, approximately 500 $U_{p\text{-}p}$ are required to expand the actuator by 20 µm. With equation 4-17 the peak current is calculated to be ≈ 63 mA. (Matching amplifiers can be found in the "PZT Control Electronics" section of this catalog).

The following equations describe the relationship between (reactive) drive power, actuator capacitance, operating frequency and drive voltage.

The average power a piezo driver has to be able to provide for sinusoidal operation is

$$P_a \approx C * U_{max} * U_{p\text{-}p} * f \qquad (4\text{-}19)$$

Peak power for sinusoidal operation is:

$$P_{max} \approx \pi * C * U_{max} * U_{p\text{-}p} * f \qquad (4\text{-}20)$$

Where
P_a = average power [W]
P_{max} = peak power [W]
C = PZT actuator capacitance [Farad (As/V)]
f = operating frequency [Hz]
$U_{p\text{-}p}$ = peak-peak drive voltage [V]
U_{max} = maximum output voltage swing of the amplifier [V]

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Note:
The PZT capacitance values indicated in the technical data tables are small signal values (measured at 1 V, 1000 Hz, 20° C, no load). The capacitance of PZT ceramics changes with amplitude, temperature, and load, up to 200% of the unloaded, small signal capacitance at room temperature. For detailed information on power requirements, refer to the amplifier frequency response graphs in the "PZT Control Electronics" section of this catalog.

Instead of calculating the required drive power for a given application, it is easier to calculate the drive current because it grows linearly with both frequency and voltage (displacement). Output current capability for all PI High Voltage and Low Voltage amplifiers is given in the technical data tables (section "PZT Control Electronics").

Dynamic Operating Current Coefficient (DOCC)

The **Dynamic Operating Current Coefficient (DOCC)** value is provided for each PI piezo translator to facilitate selection of the appropriate drive/control electronics. The DOCC is the electrical current (supplied by the amplifier) required to drive a PZT per unit frequency (Hz) and unit displacement (sinewave operation). E.g. to find out if a selected amplifier can drive a given PZT at 50 Hz with 30 µm amplitude, multiply DOCC by 50 and 30 and check if the result is less than or equal the average output current of the selected amplifier.

Dynamic Operation (Switched)

For applications such as shock wave generation or valve control, switched operation (on/off) may be sufficient. PZTs can provide motion with rapid rise and fall times with accelerations up to thousands of g's. (For consideration of dynamic forces see "Dynamic Forces", page 4.25).

The simplest form of binary drive electronics for PZT applications would consist of a large capacitor that is "slowly" charged and rapidly discharged across the PZT.

Equation 4-21 relates applied voltage (which corresponds to displacement) to time.

$$U(t) = U_0 + U_{p\text{-}p} * (1 - e^{-t/RC}) \qquad (4\text{-}21)$$

Voltage on the piezo after switching event.

Where
U_0 = start voltage [V]
$U_{p\text{-}p}$ = peak-peak drive voltage [V]
R = resistance in drive circuit [Ω]
C = PZT actuator capacitance [Farad (As/V)]

The voltage rises or falls exponentially with the RC time constant. Under static conditions the expansion of the PZT is proportional to the voltage. In reality, dynamic PZT processes cannot be described by a simple equation. Whenever the PZT expands or contracts, dynamic forces act on the ceramic material. These forces generate a (positive or negative) voltage in the piezo element which adds to the drive voltage. A PZT can reach its nominal displacement in approximately 1/3 of the period of the resonant frequency (see "How Fast Can a Piezo Actuator Expand?", page 4.27). For example, a piezo element with 10 kHz resonant frequency can reach its nominal displacement within 30 µs if amplifier current and rise time are sufficient.

If the voltage rises fast enough to excite a resonant oscillation in the PZT, ringing and overshoot will occur.

For charging with constant current (e.g. provided by a linear amplifier), the following equation applies:

$$t \approx C * (U_{p-p}/i_{max}) \quad (4\text{-}22)$$

Time to charge a PZT with constant current. (Minimum amplifier rise time must also be considered).

Where

t = time to charge to U_{pp} [s]

C = PZT actuator capacitance [Farad (As/V)]

U_{pp} = peak-peak drive voltage [V]

i_{max} = peak amplifier source/sink current [A]

For fastest settling, switched operation is not the best solution. If the input signal rise time is limited to $1/f_0$ the overshoot can be reduced significantly Pre-shaped input signals (optimized for minimum resonance excitation) reduce the time to reach a stable position.

Heat Generation in a PZT at Dynamic Operation

As mentioned before, PZTs are reactive loads and therefore require charge and discharge currents that increase with operating frequency. The thermal heat, P, generated in the actuator can be estimated with the following equation:

$$P \approx \tan\delta * f * C * U_{p-p}^2 \quad (4\text{-}23)$$

Heat generation in a PZT.

Where

P = power converted to heat [W]

tan δ = tangent of the loss angle (ratio of parallel resistance to parallel reactance)

f = operating frequency [Hz]

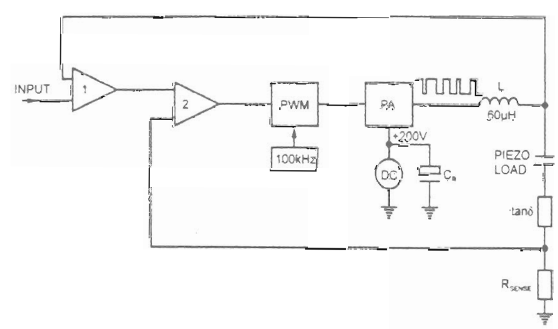
C = PZT actuator capacitance [Farad (As/V)]

U_{pp} = peak-peak drive voltage [V]

For standard actuator PZT ceramics the loss factor is on the order of 0.01 to 0.02 (large signal conditions, smaller for small signal conditions). This means that up to 2% of the electrical power pumped into the actuator is converted to heat. Therefore, the maximum operating temperature can limit the PZT dynamics. For large amplitude and high frequency, operation cooling measures may be necessary. A temperature sensor mounted on the ceramics is suggested for monitoring purposes.

PI is currently investigating the design of new PZT materials showing extremely low loss angles while still displaying a large d_{33} effect. These types of ceramics will allow high-frequency, long-term operation without cooling measures.

In addition, a new generation of amplifiers employing energy recovery technology has been developed for high power applications. Fig. 4.31/1 shows the block diagram of such an amplifier. Instead of dissipating the reactive power at the heat sinks, only the active power used by the piezo actuator has to be delivered. The energy not used in the actuator is returned to the amplifier and reused as supply voltage by a step-up transforming process. The combination of low loss, high energy PZT ceramics and amplifiers with energy recovery are the key to new high-dynamic piezo actuator applications in the near future.

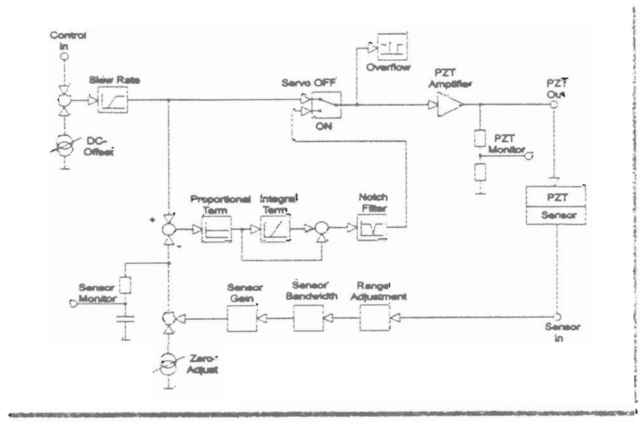


4.31/1 Block diagram of an amplifier with power recovery.

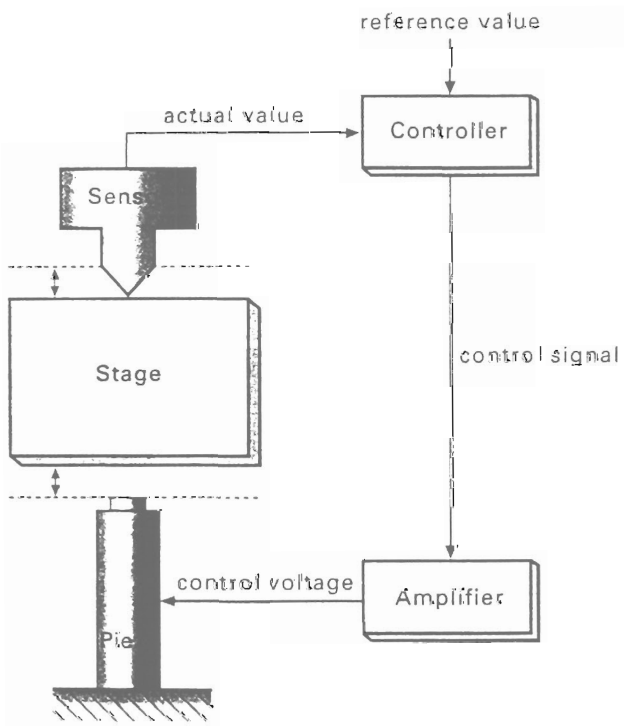
Position Servo Control (Closed Loop Operation)

PI offers the largest selection of closed loop piezo actuators and systems worldwide. The advantages of position servo control are:

- **very good linearity, stability, repeatability and accuracy**
- **automatic compensation for varying loads or forces**
- **virtual infinite stiffness (within load limits)**
- **elimination of hysteresis and creep effects**



4.32/2 Block diagram of a typical PI Closed Loop PZT Positioning System.

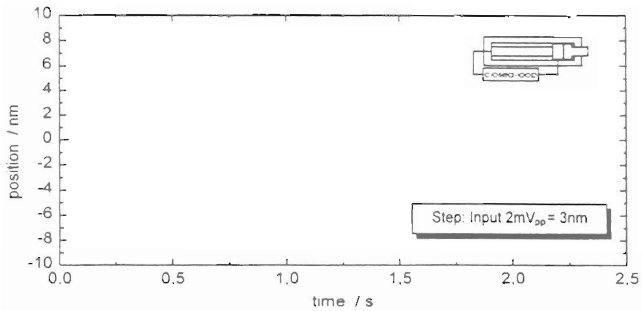


4.32/1 Closed loop position control of a stage driven by a piezo actuator. For optimum performance, the sensor is mounted directly at the object to be positioned.

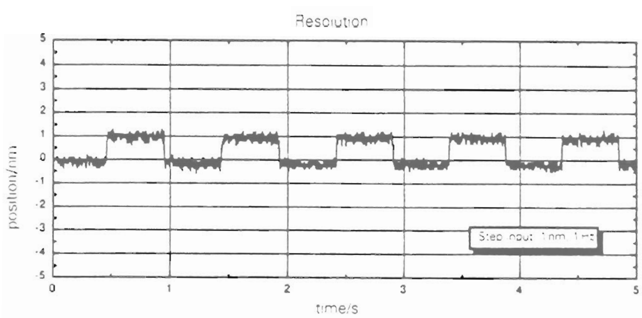
PI Closed Loop PZT Actuators & Systems are equipped with position measuring systems providing sub-nanometer resolution and bandwidths up to 10 kHz. A servo controller (digital or analog) determines the output voltage to the PZT by comparing a reference signal (commanded position) to the actual sensor position signal.

PI closed loop piezo actuators provide sub-nanometer resolution, repeatability and linearity to 0.03% (see Fig. 4.33/3).

For maximum accuracy, it is necessary to mount the sensor as close as possible to the part whose position is to be controlled. Sometimes this is not possible for various reasons. PI offer piezo actuators with integrated sensors as well as external sensors.



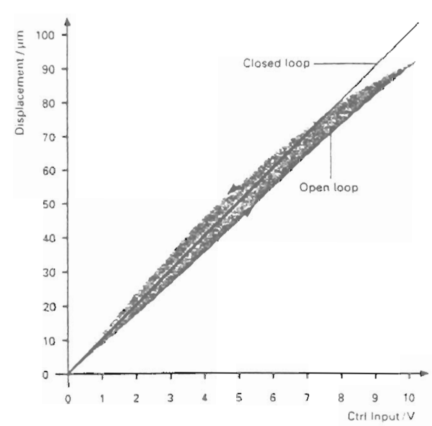
4.33/1 Response of a Closed Loop PI PZT Actuator (P-841.10, 15 µm, strain gage sensor) to a 3 nm peak-to-peak square wave control input signal, measured with servo control bandwidth set to 240 Hz and 2 msec settling time. Note the crisp response to the square wave control signal.



4.33/2 Response of a Closed Loop PI PZT Actuator (P-410.015, 15 µm, capacitive position sensor) shows true sub-nm positional stability, incremental motion and bidirectional repeatability.

PZT Calibration Data

Each PI PZT position servo controller is calibrated with the specific Closed Loop PZT (system) to achieve optimum displacement range, frequency response and settling time. This calibration is done at the factory and is free of charge. A report with plotted and tabulated positioning accuracy data will be supplied with the system. **To optimize calibration, information about the specific application is needed.** See "PZT Control Electronics" section for details.



4.33/3 Open loop vs. closed loop performance of a typical PI PZT actuator.

High Resolution Sensors

The following description explains the features of different high resolution sensor types used for closed loop control of PZT actuators. The given bandwidth is open loop bandwidth of the sensor. Closed loop bandwidth of a PZT/sensor/servo controller system is limited by the mechanical and electrical properties of the system.

Strain Gage Sensors

Based on the principle of electrical resistance.

A resistive film bonded to the PZT stack changes resistance when strain is applied. Up to four strain gages (the actual configuration varies with the PZT construction) form a Wheatstone bridge driven by a DC voltage (5 to 10 V). When the bridge resistance changes, electronics converts the resulting voltage change into a signal analogous to displacement.

Resolution:	better than 1 nm (for 15 µm actuator)
Repeatability:	up to 0.1% of nominal displacement
Bandwidth:	up to 5 kHz

Advantages:

- **high bandwidth**
- **high-vacuum compatible**
- **extremely small (no extra mounting space/ no reduction of active cross section causing reduced stiffness)**
- **cost effective**

Other Features

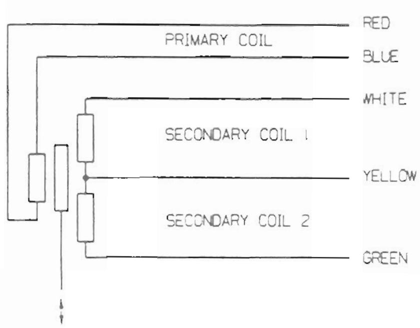
- **low heat generation (0.01 to 0.05 W sensor excitation power)**
- **long term position accuracy (> 1 h) may be affected by the bond between sensor and PZT ceramics**
- **measuring principle (ceramic stack strain rather than top piece position) can lead to reduced accuracy with heavy loads (when buckling of the stack occurs)**

Examples:

Most PI LVPZT and HVPZT actuators are available with strain gage sensors for closed loop control (see "PZT Actuators" section).

Linear Variable Differential Transformers (LVDTs)

Based on the principle of magnetic induction.



4.35/1
Principle diagram of an LVDT sensor

A magnetic core, attached to the moving part, determines the amount of magnetic energy induced from the primary windings into the two differential secondary windings. The carrier frequency is typically 10 kHz.

Resolution: up to 10 nm

Repeatability: up to 0.1% of nominal displacement

Bandwidth: up to 1 kHz

Advantages:

- **good temperature stability**
- **very good long term stability**
- **controls the position of the moving part rather than the position of the PZT stack**
- **cost effective**

Other features

- **outgassing of insulation materials may limit applications in UHV**
- **extra space for mounting required**

Examples:

P-780, P-721.10, P-762 (see "PZT Flexure NanoPositioners" section).

Capacitive Position Sensors

Based on the capacitance between two plates.

The sensor consists of two RF excited plates that are part of a capacitive bridge. One plate is fixed, the other plate is connected to the object to be positioned. The distance between the plates is inversely proportional to the capacitance which is a measure for the displacement. Resolution on the order of picometers is achievable with short range capacitive position sensors. (See "Capacitive Displacement Sensors" section for details).

Resolution: better than 0.1 nm

Repeatability: up to 0.1 nm

Bandwidth: up to 10 kHz

Advantages:

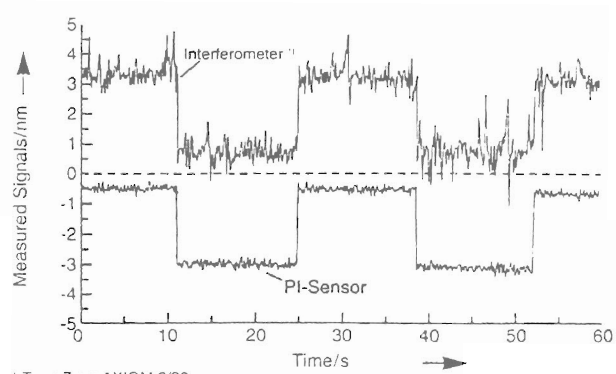
- **highest resolution of all commercially available sensors**
- **excellent long term stability**
- **excellent frequency response**

Other features:

- **extra space for mounting required**
- **parallelism of the plates must be controlled for optimal performance of the plates**

Examples:

P-500 series of Flexure Stages ("PZT Flexure NanoPositioners" section), P-410 series of Piezo Translators ("PZT Actuators" section).



*) Type Zygo AXIOM 2/20

4.35/2 Resolution of PI D-015 Capacitive Position Sensor compared to interferometer.

Temperature Effects

Two effects must be considered:

a) Linear Thermal Expansion

Thermal stability of PZT ceramics is better than most other materials (steel, aluminum etc.). It is characterized by the coefficient of thermal expansion (CTE, α) which specifies relative change in length $\Delta L/L$ per unit change in temperature. The following values apply to HVPZT and LVPZT ceramics used in PI piezo actuators:

HVPZT ceramics : $\alpha \approx 11 * 10^{-6}/K$

LVPZT ceramics: $\alpha \approx -3.5 * 10^{-6}/K$

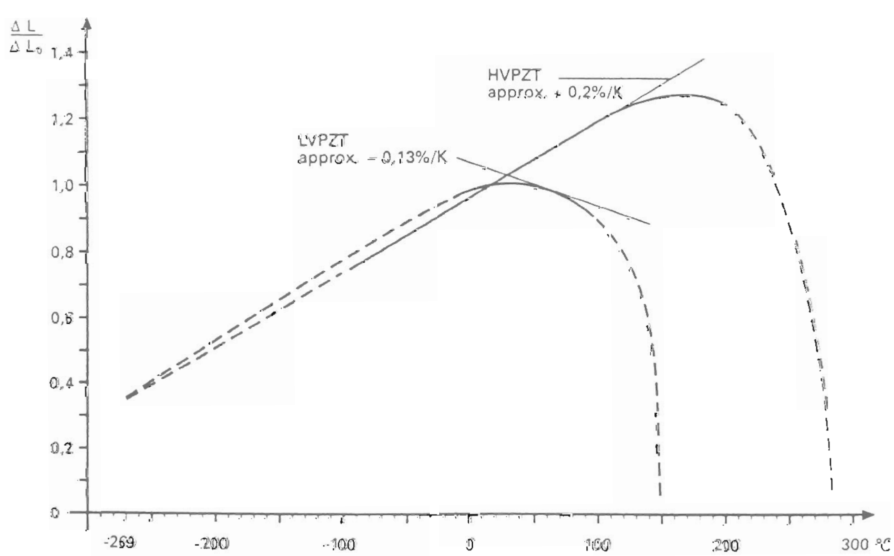
The CTEs change with temperature, the values given above are valid for room temperature.

b) Temperature Dependency of the Piezo Effect

Piezo translators work in a wide temperature range. Since the piezo effect is based on electric fields it functions down to zero degrees Kelvin. For several reasons the magnitude of the piezoelectric effect (piezo gain) is dependent on the temperature; however around room temperature it is very stable. At cryogenic temperatures it reaches approximately 20 to 30% of its room temperature value. See Fig. 4.36/1, for temperature dependency.

PZT ceramics must be poled to exhibit the piezo effect. During polarization the ceramic is heated (to allow alignment of the dipoles) and an electric field is applied. Conversely, a poled PZT will depole when heated above the maximum allowed operating temperature. PI HVPZTs have a Curie temperature of 300° C and can be operated up to 150° C (with P-702.10 high temperature option). LVPZTs show a Curie temperature of 150° C and can be operated up to 80° C. See "Options" at the end of "PZT Actuators" section for temperature range modifications.

Note:
Closed loop piezo positioning systems are less sensitive to temperature changes than open loop systems. Optimum accuracy is achieved if the operating temperature is identical to the temperature during calibration (22° C). See calibration test sheet for details.



4.36/1 Temperature dependency of the piezo effect

Environmental Considerations

Application of PZTs in Normal Atmosphere

The insulation materials used in **standard** piezo actuators are sensitive to humidity. These PZTs are not recommended in environments with high relative humidity (more than 75%). For higher humidity environments PI offers special systems with hermetically sealed stacks, or integrated dry air flushing mechanisms.

Application of PZTs in Inert Gas Atmosphere

Piezo actuators can be damaged if operated at maximum drive voltage in a helium or argon atmosphere. Low Voltage actuators are recommended for these conditions. To reduce the risk of dielectric breakdown, the PZTs should be operated at minimum possible voltage (HVPZTs: < 300 V, LVPZTs: < 80 V). Semi-bipolar operation helps to further reduce the electrical field strength while yielding reasonable displacement.

Vacuum Application of PZTs

When piezo actuators are used in a vacuum, two factors must be considered:

1) dielectric stability
2) outgassing

The dielectric strength of a gas is a function of pressure. Air displays a high insulation capability at atmospheric pressure and below 10^{-2} Torr. However, in the range from 10 to 0.01 Torr (corona area) insulation properties are degraded. PZTs should not be operated in this range because an electric breakdown may occur.

All PI piezo actuators can be operated at pressures below 0.01 Torr. Outgassing (of the insulation materials) may limit their use in applications where contamination or virtual leaks are an issue. Outgassing behavior varies from model to model depending on construction. High vacuum options for minimum outgassing are available for several standard LVPZTs and HVPZTs (see "PZT Actuators" section for details). UHV compatible PZT Flexure Positioners are available on request.

Lifetime of PZTs

The lifetime of a PZT is not limited by wear and tear. Tests have shown that PI PZTs can perform BILLIONS of cycles without loss of performance if operated under suitable conditions.

Generally, as with capacitors, the lifetime of a PZT is a function of the applied voltage. The average voltage should be kept as low as possible. This is why PI has specially designed actuators and electronics for semi-bipolar operation, an important advantage over conventional actuator/driver combinations.

There is no generic formula to determine the lifetime of a PZT because of the many parameters such as temperature, humidity, voltage, acceleration, load, operating frequency, insulation materials, etc. which have an (nonlinear) influence. PI PZTs are built for maximum lifetime under actual operating conditions. We do not manufacture our PZT ceramics with the goal of maximum displacement at the expense of long-term reliability. The operating voltage range figures in the technical data tables are based on years of experience with scientific and industrial OEM applications. For maximum lifetime, operating voltage should not exceed the figures given in the following tables.

LVPZT TRANSLATORS

(Maximum Operating Voltage: 120 V)

Operation up to	Max. Duty Cycle [%]
50 V	100 %
70 V	35 %
100 V	10 %
120 V	1 %

HVPZT TRANSLATORS

(Maximum Operating Voltage: 1000 V)

Operation up to	Max. Duty Cycle
250 V	100 %
500 V	40 %
750 V	15 %
1000 V	1 %

HVPZT TRANSLATORS

(Maximum Operating Voltage: 1500 V)

Operation up to	Max. Duty Cycle
500 V	100 %
750 V	35 %
1000 V	15 %
1500 V	1 %

Statistics show that most failures with piezo actuators occur because mechanical installation guidelines are not observed and mechanical stress, shear forces and torque exceed the permissible limits. **PI offers a variety of preloaded actuators, ball tips, flexible tips and custom designs to eliminate these critical forces**. Failures can also occur when humidity and conductive materials such as metal dust degrade the PZT's insulation strength, leading to dielectric breakdown. **PI has designed hermetically sealed actuators for applications in critical environments.**

Example:

The P-843.60 LVPZT (see "PZT Actuators" section) shall operate a switch with a stroke of 100 µm. The switch shall be open for 70% and closed for 30 % of it's operating time.

Optimum solution: The switch should be designed in a way that the open position is achieved with the lowest possible operating voltage. To reach a displacement of 100 µm, a voltage amplitude of approximately 110 volts is required (nominal displacement @ 100 V is only 90 µm). Since the P-843.60 can be operated with -20 volts, the closed position should be assigned to 90 V, and the open position to -20 volts. When the switch is not operating at all, the voltage on the PZT should be 0 volts.

Basic Designs of Piezoelectric Positioning Elements

Stack Design

The active part of the positioning element consists of a stack of ceramic disks separated by thin metallic electrodes. Maximum operating voltage is proportional to the thickness of the disks. PI stack actuators are manufactured with layers from 0.02 to 1 mm thickness.

Stack elements can withstand high pressure and show the highest stiffness of all piezo actuator designs. Since the ceramics cannot withstand large pulling forces, spring preloaded actuators are available. Stack models can be used for static and dynamic operation. For further information see "Maximum Applicable Forces (Compressive Load Limit, Tensile Load Limit)", page 4.22.

Displacement of a PZT stack actuator can be estimated by the following equation:

$$\Delta L = d_{33} \cdot n \cdot U \qquad (4\text{-}24)$$

where

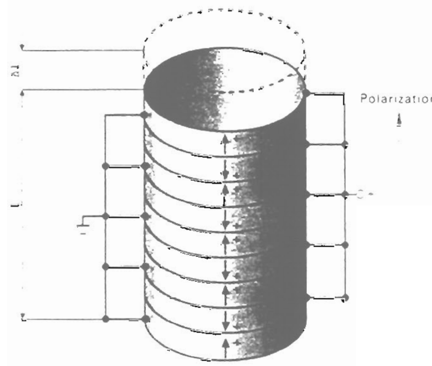
d_{33} = strain coefficient (field and deflection in polarization direction) [m/V]

n = number of ceramic layers

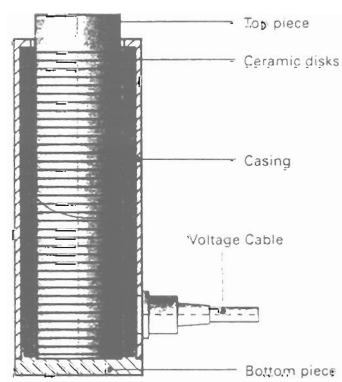
U = operating voltage [V]

Example:

P-845, etc. (see "PZT Actuators" section)



4.39/1
Electrical Design of a Stack Translator



4.39/2
Mechanical Design of a Stack Translator

Laminar Design (Contraction Type Actuator)

The active material in the laminar actuators consists of thin ceramic strips. The displacement of these actuators is **perpendicular** to the direction of polarization and electric field. When the voltage is increased the strip contracts. The piezo strain coefficient d_{31} (negative!) describes the relative change in length. It is on the order of 50% of d_{33}.

The maximum travel is a function of the length of the strips, while the number of strips arranged in parallel determines the stiffness and the stability of the element.

Displacement of a PZT contraction actuator can be estimated by the following equation:

$\Delta L \approx d_{31} * L * U/d$ (4-25)

where

d_{31} = strain coefficient (deflection normal to polarization direction) [m/V]

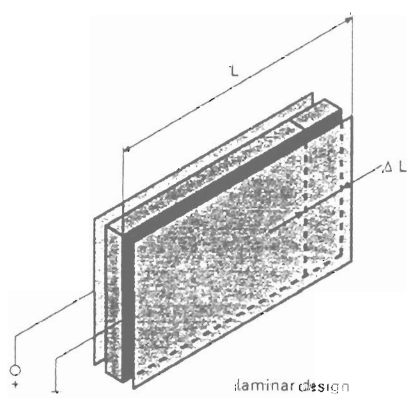
L = length of the PZT ceramics [m]

U = operating voltage [V]

d = thickness of one ceramic layer [m]

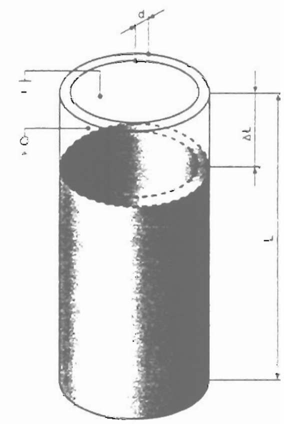
Example:

Laminar piezos are used in the P-280. P-282 Flexure Positioners (see "PZT Flexure NanoPositioners" section.



4.40/1 Laminar Design

Tube Design



4.40/2 Tube Design

Monolithic ceramic tubes are yet another form of piezo actuator. Tubes are silvered inside and out and operate on the transversal piezo effect. When an electric voltage is applied between the outer and inner diameter, the tube contracts axially and radially. Axial contraction can be estimated by the following equation:

$\Delta L \approx d_{31} * L * U/d$ (4-26)

where

d_{31} = strain coefficient (deflection normal to polarization direction) [m/V]

L = length of the PZT ceramic tube [m]

U = operating voltage [V]

d = wall thickness [m]

$\Delta d \approx d_{33} * U$

where

Δd = change in wall thickness [m]

d_{33} = strain coefficient (field and deflection in polarization direction) [m/V]

U = operating voltage [V]

The radial contraction is a superposition of several effects and cannot be expressed by a simple equation.

When the outside electrode of a tube is separated into four 90° segments, differential drive voltage of opposing electrodes will lead to bending of one end (if the other end is clamped). Scanner tubes that flex in X and Y are widely used in scanning probe microscopes.

The scan range of a scanner tube is defined by

$$\Delta x \approx (2\sqrt{2} * d_{31} * L^2) / (\pi * ID * d) \quad (4\text{-}27)$$

Where

Δx = scan range in X and Y (for symmetrical electrodes) [m]

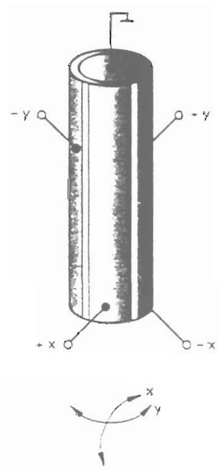
d_{31} = strain coefficient (deflection normal to polarization direction) [m/V]

L = length [m]

ID = inner diameter [m]

d = wall thickness [m]

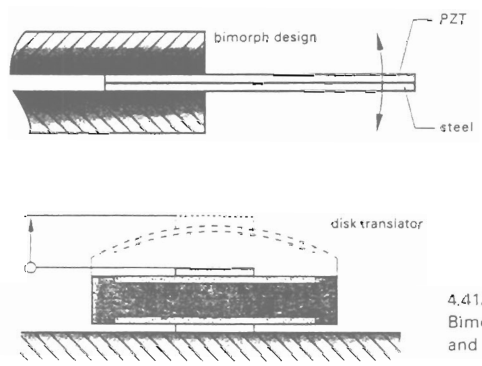
Tube actuators are not designed to withstand large forces. Application examples are scanning microscopy, ink jet printers etc.



4.41/1
PZT Scanner Tube

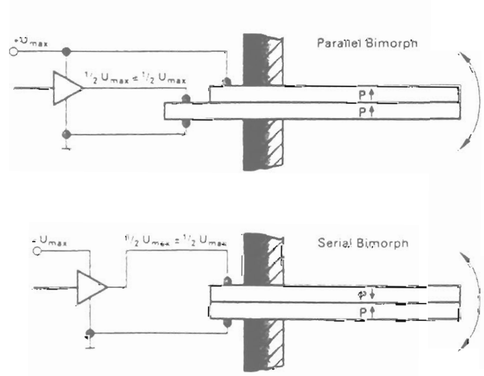
Bender Type Actuators (Bimorph and Multimorph Design)

A PZT bimorph operates similarly to a bimetallic strip in a thermostat (see Fig. 4.41/2). When the ceramic is energized the metal substrate is deflected with a motion proportional to the applied voltage. Bimorph actuators providing motion up to 1000 µm are available and greater travel range is possible. Apart from the classical strip form, bimorph disk actuators are available, where the center arches when a voltage is supplied.



4.41/2
Bimorph design (strip and disk translator).

Instead of a PZT/metal combination PZT/PZT combinations are possible where individual PZT layers are operated in opposite mode (contraction/expansion). Two basic versions are available: the two electrode bimorph (serial bimorph) and the three electrode bimorph (parallel bimorph), see Fig. 4.41/3. In the serial type, one of the two ceramic plates is always operated opposite to the direction of polarization. To avoid depolarization the maximum electric field is limited to a few hundred volts per millimeter. Serial bimorph benders are widely used as force sensors.



4.41/3
Parallel Bimorph and Serial Bimorph.