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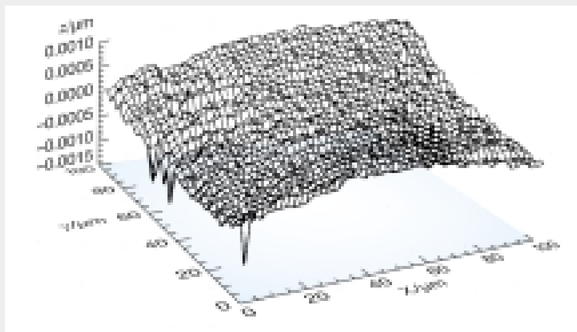
MicroPositioning, NanoPositioning, NanoAutomation®

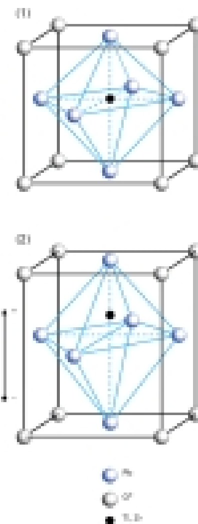
Tutorial: Piezoelectrics in Positioning

Tutorial

Piezoelectrics in Positioning

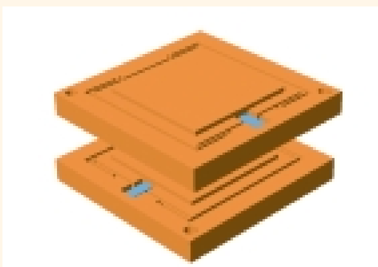


Flatness of a NanoPositioning stage with active trajectory control is better than of 1 nanometer over a 100 x 100 µm scanning range.



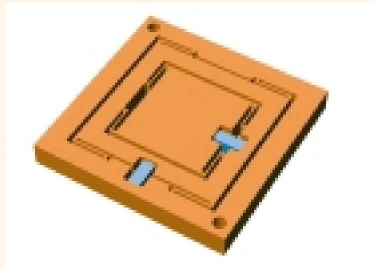
PZT unit cell: 1) Perovskite-type lead zirconate titanate (PZT) unit cell in the symmetric cubic state above the Curie temperature. 2) Tetragonally distorted unit cell below the Curie temperature

Different Ways of Designing Multi-Axis NanoPositioning Flexure Stages



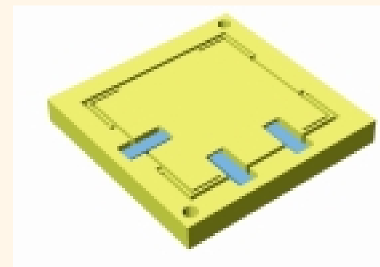
A) Stacking 2 single-axis stages.

Pro: Simple.
Con: Slower response (lower stage carries inertial mass of upper stage); orthogonality error is mounting-angle dependant; runout in Y cannot be monitored/ compensated by the sensor in the X stage or vice versa.



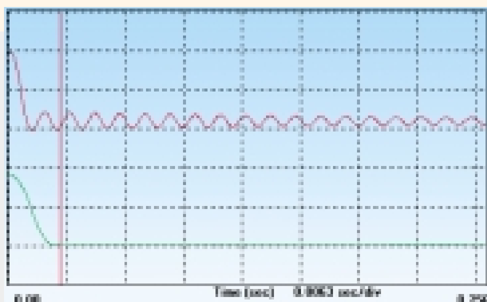
B) Single module (monolithic) but nested (serial) X and Y.

Better response than A) but X and Y still work without "knowledge" of each other.

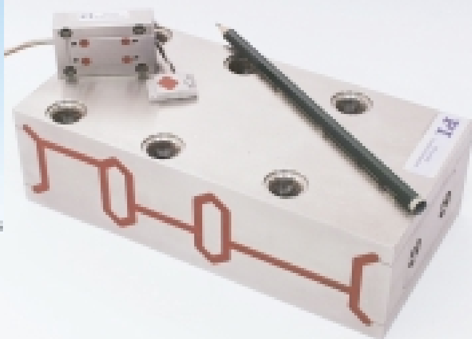


C) Single-module parallel-kinematics X and Y (with crosstalk compensation).

Best solution.
Same low inertia for X and Y motion, providing higher responsiveness and axis-independent performance.
Best orthogonality. X sensor can monitor and correct for Y runout and vice versa.
Additional rotation axis (θ_Z) feasible with 3 actuators / sensors and digital controller.

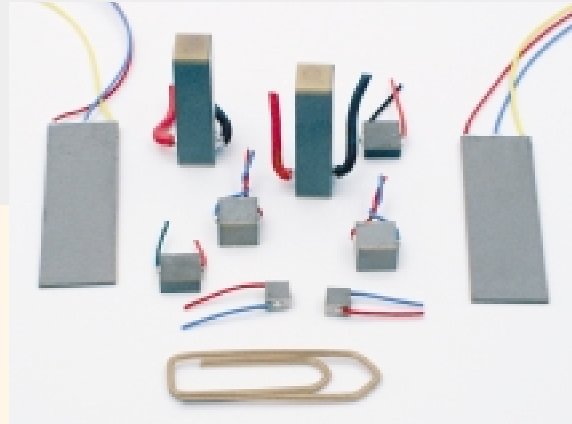


Patented InputShaping™ feedforward algorithm eliminates resonance-driven vibration of parts on and around the NanoPositioning system.



Piezoelectric NanoPositioning Systems: small (e.g. data storage), medium (e.g. fiber optics), large (e.g. precision machining).

Ceramic spray dryer at PI Ceramic ensures piezo ceramics quality.



Variety of multilayer piezo stack and bender actuators.

PI offers the **largest selection** of research and industrial-reliability *Piezo Actuators*, *PiezoNanoPositioning Systems*, *Steering Mirrors* and *Control Electronics* worldwide.

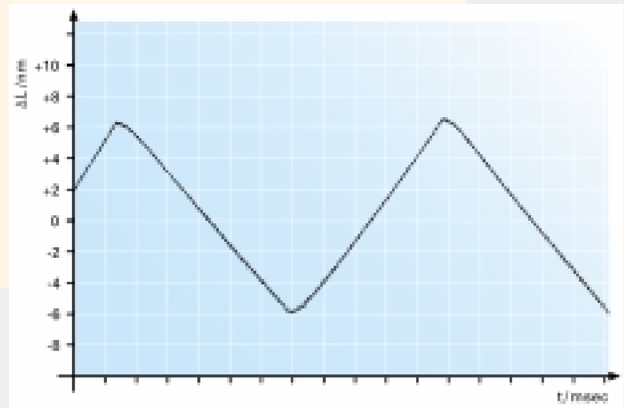
In addition to the hundreds of models presented in this catalog, we manufacture custom designs tailored to the customer's requirements.

PI is highly vertically integrated, controlling each manufacturing step from PZT raw materials to finished systems *thus ensuring the best quality*.

Equipment for multilayer piezo actuator production, at the PI Ceramic factory.

Variety of "cofired" and "classical" piezo stacks and rings.

Sputtering (vacuum plating) process of piezo ceramic discs at PI Ceramic.



Response of an open-loop piezo actuator to triangule-wave drive signal shows sub-nanometer resolution.

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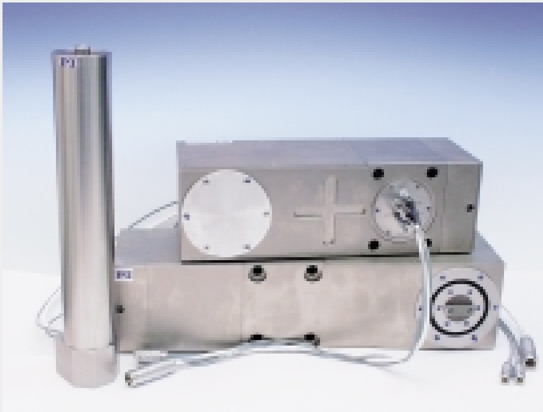
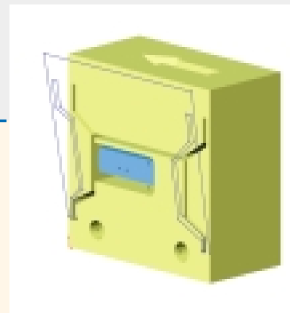


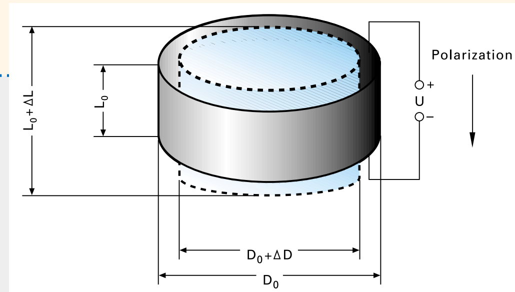
Heavy-duty closed-loop piezoelectric positioning systems for machining applications.



Principle of a simple motion-amplified NanoPositioning stage.

Variety of digital motion controllers for piezoelectric NanoPositioning systems.

Variety of piezoelectric flexure nanopositioners.



Elongation and contraction of a piezo disk when a voltage is applied.

Advantages of Piezoelectric Positioning

Unlimited Resolution

A piezoelectric actuator (PZT) can produce extremely fine position changes down to the sub-nanometer range. The smallest changes in operating voltage are converted into smooth movements. Motion is not influenced by stiction, friction or threshold voltages.

Large Force Generation

PZTs can generate forces of several 10,000 N. PI offers units that move loads up to several tons and position over a range of more than 100 µm with sub-nanometer resolution (see "PZT Actuators" section).

No Magnetic Fields

The piezoelectric effect is related to electric fields. PZT actuators do not produce magnetic fields nor are they affected by them. Piezo devices are especially well suited for applications where magnetic fields cannot be tolerated.

Rapid Response

Piezo actuators offer the fastest response time available (microsecond time constants). Acceleration rates of more than 10,000 g's can be obtained.

Advantages of Piezoelectric Positioning...(continued)

Low Power Consumption

In a PZT electrical energy is converted directly into motion, absorbing electrical energy during movement only. Static operation, even holding heavy loads, consumes virtually no energy.

Operation at Cryogenic Temperatures

The piezo effect is based on electric fields and functions down to almost zero Kelvin.

Vacuum and Clean-Room Compatible

Piezo actuators employ ceramic elements that do not need any lubricants and exhibit no wear or abrasion. This makes them clean-room compatible and ideally suited for ultra-high-vacuum applications.

No Wear and Tear

A piezo actuator has neither gears nor rotating shafts. Its displacement is based on solid-state phenomena and exhibits no wear and tear. PI has conducted endurance tests on PZTs in which virtually no change in performance was observed after several billion cycles.

Applications for Piezo Positioning Technology

Life Science, Medicine, Biology

- Scanning microscopy
- Patch-clamp
- Gene manipulation
- Micromanipulation
- Cell penetration
- Micro-dispensing devices

Semiconductors, Microelectronics

- Nano-metrology
- Wafer and mask positioning / alignment
- Critical-dimension measurement
- Microlithography
- Inspection systems
- Vibration cancellation

Data Storage

- MR head testing
- Pole tip recession
- Spin stands
- Disk testing
- Vibration cancellation

Optics, Photonics, Fiber Optics Metrology and Measuring Technology

- Fiber optic alignment & switching
- Image stabilization
- Adaptive optics
- Scanning microscopy
- Auto-focus systems
- Interferometry
- Adaptive and active optics
- Laser tuning
- Mirror positioning

Precision Mechanics and Mechanical Engineering

- Fast tool servos
- Out-of-roundness finishing (boring, drilling, turning)
- Vibration cancellation
- Smart structures / structural deformation
- Wear correction
- Needle-valve actuation
- Micro-pumps
- Knife edge control in extrusion tools
- Micro-engraving systems

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Tutorial: Piezoelectrics in Positioning
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Glossary

See also "MicroPositioning Terms," page 7-10.

Actuator:
A device that produces motion (displacement).

Blocked Force:
The maximum force an actuator can generate if blocked by an infinitely rigid restraint.

Ceramic:
A polycrystalline, inorganic material.

Closed-Loop Operation:
The actuator is used with a position sensor which provides feedback to the position servo-controller, compensating for nonlinearity, hysteresis and creep (see "open-loop").

Compliance:
Displacement produced per unit force. The reciprocal of stiffness.

Compressive Force:
Force tending to compress the piezo material. Opposite of tensile force.

Creep:
An unwanted change in the displacement over time.

Curie Temperature:
The temperature at which the crystalline structure changes from a piezoelectric (non-symmetrical) to a non-piezoelectric (symmetrical) form when headed up. At this temperature a PZT ceramic looses its piezoelectric properties.

Domain:
A region of permanent electric dipoles with the same orientation.

Drift:
See "creep"

Effective Mass:
Ideal mass having same resonant frequency as the actual, non-ideal mass.

HVPZT:
Acronym for high voltage PZT (actuator).

Hysteresis:
Hysteresis is based on crystalline polarization and molecular effects and occurs when reversing driving direction. Hysteresis is not to be confused with backlash.

LVPZT:
Acronym for low voltage PZT (actuator).

Load Capacity:
Maximum working load. Load capacities are generally specified at levels that allow long lifetime. Note that compressive and tensile capacities differ.

Load Limits:
Maximum force that a PZT device can survive without damage. Note that the compressive and tensile limits are different. Also called the "maximum compressive / tensile force." See also "load capacity."

Maximum Compressive/ Tensile Force:
Same as "load limit", see above.

Multilayer Actuator:
An actuator manufactured in a fashion similar to multilayer ceramic capacitors. PZT ceramic and electrode material are "co-fired" in one step. Layer thickness is typically on the order of 20 to 100 µm.

Normal:
At right angles to, as in "normal force" or "displacement normal to the field".

Open-Loop Operation:
The actuator is used without a position sensor. Displacement roughly corresponds to the drive voltage. Creep, nonlinearity and hysteresis remain compensated.

Piezoelectric Materials:
Materials that change their dimensions when a voltage is applied and produce a charge when pressure is applied.

Piezo Gain:
Strain coefficients d_{33} and d_{31} .

Polarization:
The electric orientation of molecules in a piezoelectric material.

PZT:
Acronym for *plumbum* (lead) zirconate titanate. Polycrystalline ceramic material with piezoelectric properties. Often also used as acronym for piezo translator.

Stiffness:
The spring constant (of a piezo actuator).

Tensile Force:
Force tending to stretch the piezo material.

Trajectory Control:
Measures taken to reduce off-axis motion. Used are both passive measures (e.g. flexure guiding) and active measures (compensation with additional active axes.)

Translator:
An actuator which produces linear motion.

Symbols and Units

A	Surface area [m²] (meter²)
α	Coefficient of Thermal Expansion (CTE) [K^{-1}] (1 / kelvin)
C	Capacitance (F) [A·s / V]
d_{ij}	Piezo modulus (tensor components) [m/V] (meter/volt)
d_s	Distance, thickness [m] (meter)
ϵ	Dielectric constant [A·s/V·m] (ampere · second / volt · meter)
E	Electric field strength [V/m] (volt/meter)
f	Operating frequency [Hz] (hertz = 1/second)
F	Force [N] (newton)
f_0	Unloaded resonant frequency [Hz] (hertz = 1/second)
g	Acceleration due to gravity: 9.81 m/s^2 (meter/second²)
i	Current [A] (ampere)
k_S	Stiffness of restraint (load) [N/m] (newton/meter)
k_T	Stiffness of piezo actuator [N/m] (newton/meter)
L_0	Length of non-energized actuator [m] (meter)
ΔL	Change in length (displacement) [m] (meter)
ΔL_0	Nominal displacement with zero applied force, [m] (meter)
$\Delta L_{t=0.1}$	Displacement at time t = 0.1 sec after voltage change, [m] (meter)
m	Mass [kg] (kilogram)
P	Power [W] (watt)
Q	Charge [C] (coulomb = ampere × second)
S	Strain [ΔL/L] (dimensionless)
t	Time [s] (second)
U	voltage [V] (volt)
$U_{p\text{-}p}$	Peak-to-peak voltage [V] (volt)

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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 ceramic 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. In the 1940's scientists discovered that barium titanate ceramics could be made piezoelectric by application of 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 30 years ago and have changed the world of precision positioning.

Features of PZT Actuators

- **Repeatable nanometer and sub-nanometer 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 tens of 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 crystalline cells.**

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

Basic Introduction ... (cont.)

Low-Voltage and High-Voltage PZTs

Two main types of piezo actuators are available: low-voltage (multilayer) devices requiring 100 volts or less 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. 1). The total displacement is the sum of the displacements 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 consist of bulk ceramic disks which are 0.4 to 1 mm thick and glued together to form a stack.

Low-voltage piezo actuators are manufactured in a lamination process, where thick-film electrodes are printed on green ceramic foils. The layers of ceramics and electrodes are then pressed together and cofired to form a monolithic block.

Typical layer thicknesses are in the range of 20 to 100 µm. After cutting the individual stacks to size, wire leads are applied.

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 suitable for higher-load applications (up to several tons) than low voltage ceramics.

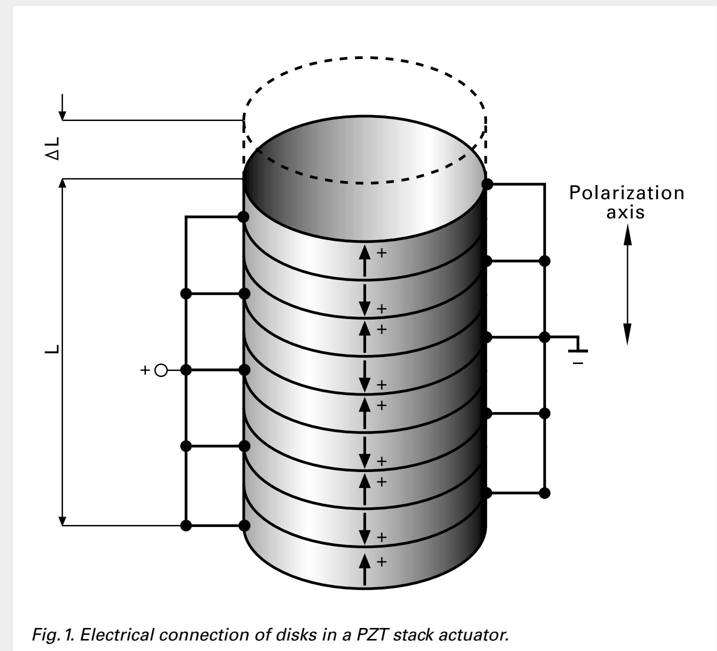

Fig. 1. Electrical connection of disks in a PZT stack actuator.

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 the piezo control amplifier (electronic noise results in unwanted displacement) and sensor & control electronics (noise and sensitivity to EMI affect the positional resolution and stability). Mechanical parameters are also important (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.

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Open- and Closed-Loop Operation

PZT actuators can be operated in open- and closed-loop modes. In open-loop mode, 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, just 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 subnanometer resolution or bandwidth up to 10 kHz. A servo-controller (digital or analog) determines the voltage to send to the PZT by comparing a reference signal (commanded position) to the actual position, as reported by the feedback position sensor (for more information see "Position Servo-Control," page 4-34).

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 nm cube (see the "PZT Flexure Nano-Positioners" 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 vibration will cause changes in position at the nanometer level.

Dynamic Behavior

A piezo actuator can reach its nominal displacement in approximately one third of the period of its resonant frequency. Rise times on the order of microseconds and accelerations of more than 10,000 g's are possible. This feature makes PZTs suitable for 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 of 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 effective 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 can endanger the structural integrity of the ceramic material.

Basic Introduction … (cont.)

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 4-23).

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 nominal displacement. 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 4-23).

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 (preload) the ceramic inside and increase the ceramic's pulling capabilities for dynamic push/pull applications (for more information see "Mounting Guidelines", page 4-47).

Power Requirements

Piezo actuators operate as capacitive loads. Since the current leakage rate of the ceramic material is very low (resistance typically 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 "Electrical Requirements," page 4-30).

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Different Piezo Actuator Designs to Suit Various Applications

Fig. 2. P-845 Closed-loop LVPZT translator

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 placed around it. This case may also contain built-in springs to compress the ceramic to allow both push and pull operation.

The P-845 closed-loop LVPZT translator (Fig. 2) is one example of a low voltage translator with internal spring preload and integrated high-resolution strain gauge position sensor. This translator is available with displacements up to 90 microns. It can handle loads up to 300 kilograms and withstand pulling forces to 700 N (see the "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.

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 "Basic Designs," page 4-41 *ff* for more information.

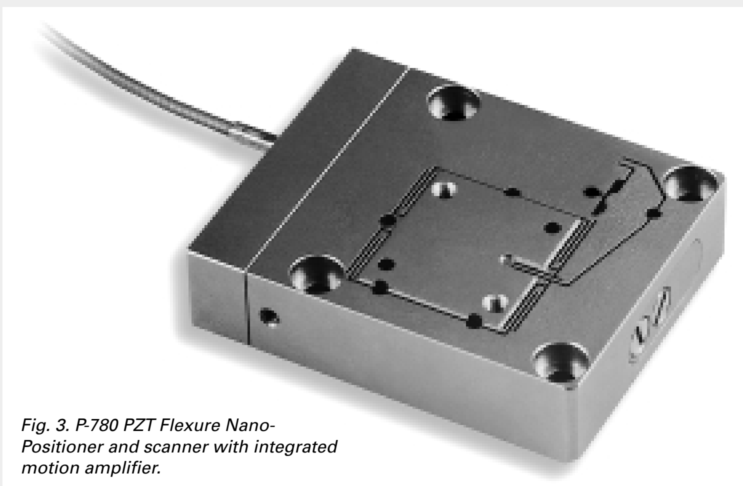

Fig. 3. P-780 PZT Flexure Nano-Positioner and scanner with integrated motion amplifier.

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 tens of 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.

Fig. 3 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 built into to the

Basic Introduction ... (cont.)

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 in the nanometer realm and even this low figure can be reduced with a larger flexure base. Sub-nanometer, sub-microradian flatness can be achieved with multi-axis systems using active error compensation (see the "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. Examples are 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.

Fig. 4. Combination of a DC-Mike linear drive and P-250 PZT translator

Piezo Actuators Combined with Motorized Long-Travel Positioning Systems

Piezo actuators can be combined with other actuators to form long-travel, high-resolution systems. A good example is the combination of a P-250 piezo actuator with a closed-loop motor-driven leadscrew (Fig. 4). 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.

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 that the right actuator design is chosen for your application. PI has more than 30 years of experience in designing piezoelectric actuators and systems and offers a wide variety of options which can adapt PZTs to various environmental conditions.

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Fundamentals of Piezoelectricity and Piezo Actuators

Notes

The following pages give a detailed look at piezo actuator theory and their operation. For basic knowledge read "Basic Introduction to NanoPositioning with Piezoelectric Technology", page 4-9. For definition of units, dimensions and terms, see "Glossary" on page 4-7.

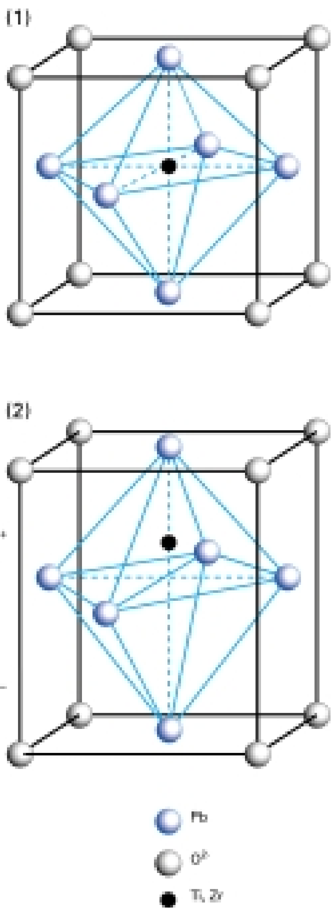

Fig. 5. PZT unit cell: 1) Perovskite-type lead zirconate titanate (PZT) unit cell in the symmetric cubic state above the Curie temperature.
2) Tetragonally distorted unit cell below the Curie temperature

Material Properties

Since the piezo effect exhibited by natural materials such as quartz, tourmaline, Rochelle salt, etc. is very small, polycrystalline ferroelectric ceramic materials such as barium titanate and lead (*plumbum*) zirconate titanate (PZT) with improved properties have been developed. These ferroelectric ceramics become piezoelectric when poled.

PZT ceramics are available in many variations and are still the most widely used materials for actuator applications today. At temperatures below the Curie temperature, PZT crystallites exhibit tetragonal or rhombohedric structure. Due to their permanent electrical and mechanical asymmetry, these types of unit cells exhibit spontaneous polarization and deformation. Groups of unit cells with the same polarization and deformation orientation are called domains. Because of the random distribution of the domain orientations in the ceramic material, a ferroelectric poling process is required to obtain any macroscopic anisotropy and the associated piezoelectric properties (see Fig. 5.).

If heated above the Curie temperature, however, the PZT crystallite unit cells take on cubic centrosymmetric (isotropic) structure. When cooled, the domains reform, but with randomized orientations, and the material does not regain its macroscopic piezoelectric properties.

The asymmetric arrangement of the positive and negative ions imparts permanent electric dipole behavior to the crystals. Before the poling treatment, the domains are randomly oriented in the raw PZT material. During poling, an intense electric field (> 2000 V/mm) is applied to the piezo ceramic. With the field applied, the material expands along the axis of the field and contracts perpendicular to that axis as the domains line up. When the field is removed, the electric dipoles stay roughly, but not completely, in alignment. The material now has a remanent polarization (which can be degraded by exceeding the mechanical, thermal and electrical limits of the material).

Subsequently, when a voltage is applied to the poled piezoelectric material, the ions in the unit cells are shifted and, additionally, the domains change their degree of alignment. (see Fig. 6.). The result is a corresponding change of the dimensions (expansion, contraction) of the PZT material.

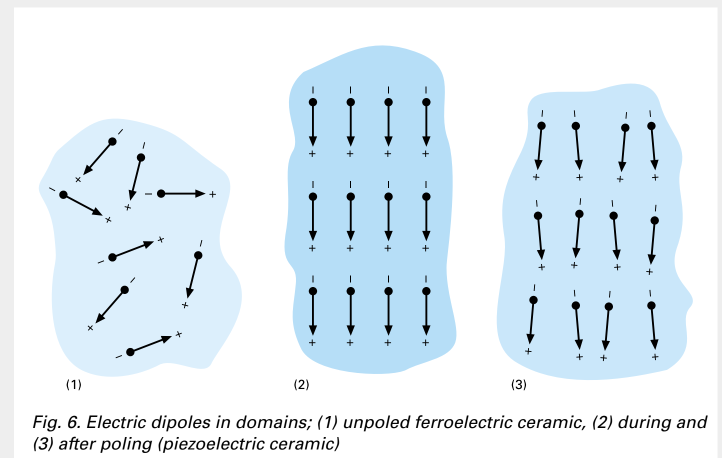

Fig. 6. Electric dipoles in domains; (1) unpoled ferroelectric ceramic, (2) during and (3) after poling (piezoelectric ceramic)

Fundamentals ... (cont.)

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 ceramic is heated slowly to burn out the binder.

The next phase is sintering at temperatures between 1250°C and 1350 °C. Then 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 the 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, wire lead termination and poling.

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

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Definition of Piezoelectric Coefficients and Directions

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., determined by individual measurements.

Because of the anisotropic nature of PZT ceramics, piezoelectric effects are dependent on direction (see Fig. 7). To identify directions, the axes 1, 2, and 3, will be introduced (corresponding to X, Y, Z of the classical right-hand orthogonal axis set). The axes 4, 5 and 6 identify rotations (shear), θ_x, θ_y, θ_z, also known as U, V, W.

The direction of polarization (axis 3) 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 the most important (largest deflection).

Piezoelectric materials are characterized by several coefficients

Examples are:

- **d_{ij}: Strain coefficients [m/V]** or **charge output coefficients [C/N]:** Strain developed [m/m] per unit of electric field strength applied [V/m] **or** (due to the sensor / actuator properties of PZT material) 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 [dimensionless].** 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_r.

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 material 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 for the mechanical or dielectrical parameters.

Definition:

S for strain = 0 (mechanically clamped)

T for stress = 0 (not clamped)

E for field = 0 (short circuit)

D for charge displacement (current) = 0 (open circuit)

The individual piezoelectric parameters are related by several equations that are not explained here.

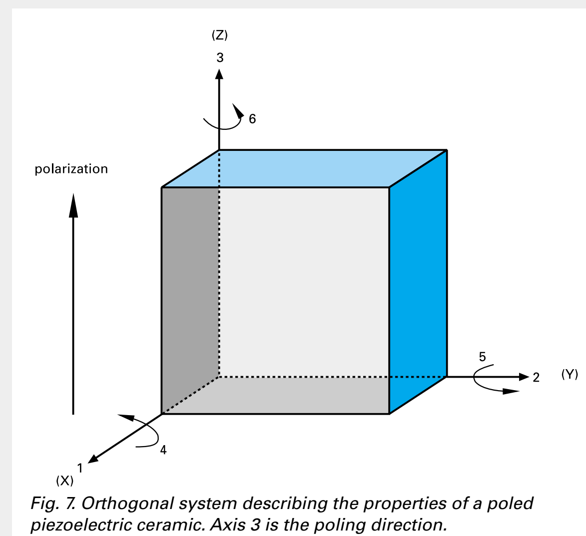

Fig. 7. Orthogonal system describing the properties of a poled piezoelectric ceramic. Axis 3 is the poling direction.

Fundamentals ... (cont.)

Resolution

Notes

The level of performance described can only be attained 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 dovetail slides, 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. Their practical usefulness is limited to a precision of two orders of magnitude less than with PI PZT NanoPositioners.

Since the displacement of a piezo actuator is based on ionic shift and orientation of the PZT unit cells, the resolution depends on the electrical field applied and is theoretically unlimited. Infinitesimally small changes in operating voltage are converted to smooth movements (see Fig. 8).

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.

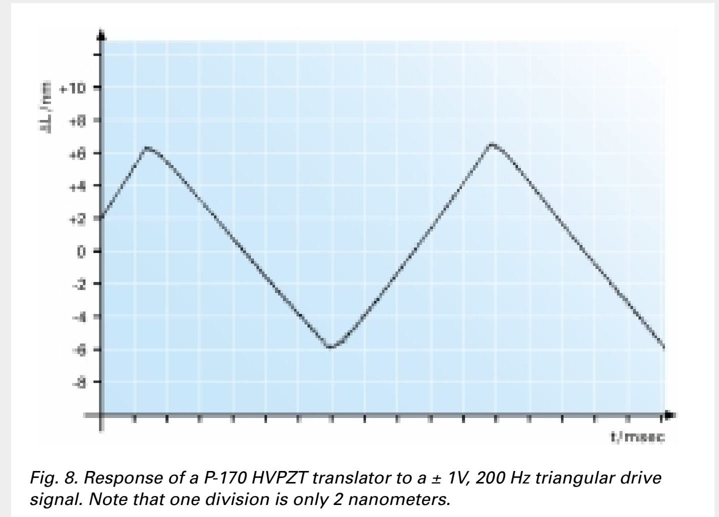

Fig. 8. Response of a P-170 HVPZT translator to a ± 1V, 200 Hz triangular drive signal. Note that one division is only 2 nanometers.

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 p. 4-34 *ff.*

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Displacement of Piezo Actuators (Stack & Contraction Type)

Note

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 under conditions not restricted to research labs. Since we manufacture our own ceramics (in contrast to most other PZT vendors) we could modify material parameters to trade lifetime for displacement. When you are choosing piezo actuators for your application, "maximum displacement" may not be the only important design parameter.

Displacement of PZT ceramics is primarily 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 following equation:

(Equation 1)

$$\Delta L = S \cdot L_o \approx \pm E \cdot d_{ij} \cdot L_o$$

Where:

S = strain (relative length change ΔL/L, dimensionless)
L_o = ceramic length [m]
E = electrical field strength [V/m]
d_{ij} = piezoelectric coefficient [m/V]

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. 9 for explanation. The strain coefficient d_{33} applies for PZT stack actuators, d_{31} applies for tube and strip actuators.

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 (short term only) to the poling direction (semi-bipolar mode), see Fig. 10 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 to the PZT.**

With the inverse field, negative expansion (contraction) occurs giving an additional 20% of the nominal displacement. If both the regular and inverse electric fields are used, a relative expansion (strain) up to 0.2 % is achievable with PZT stack actuators. Stacks can be built with aspect ratios up to 12:1 (length:diameter). Maximum travel for medium size piezo stack actuators (15 mm diameter), is therefore limited to approximately 200 µm. Longer travel ranges can be achieved by mechanical amplification techniques (see "Lever Motion Amplifiers" on page 4-44).

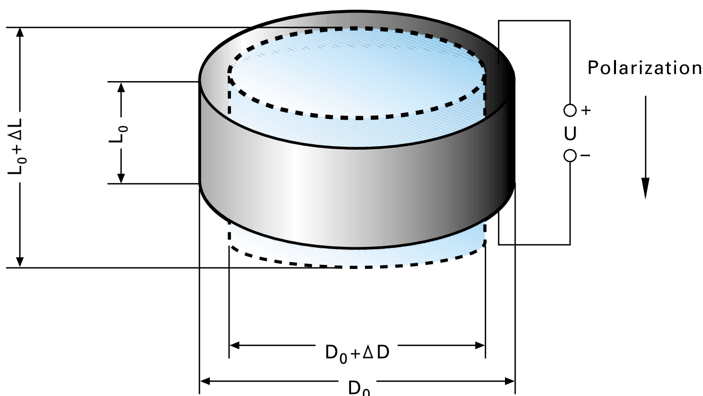

Fig. 9. Elongation and contraction of a PZT disk when a voltage is applied. Note that d_{31} (affecting lateral deformation, ΔD) is negative.

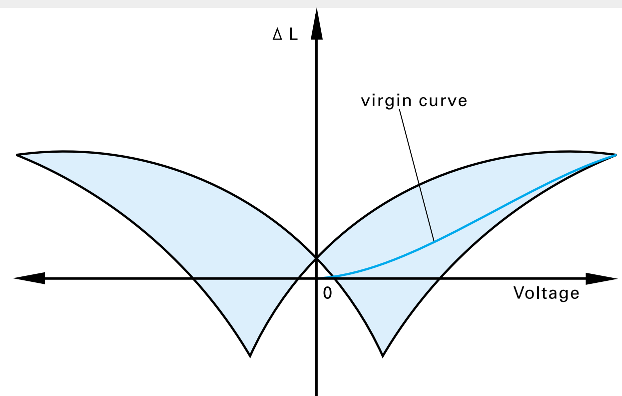

Fig. 10. Response of a PZT actuator to a bipolar drive voltage. When a certain threshold voltage (negative to the polarization direction) is exceeded, reversal of polarization can occur.

Fundamentals ... (cont.)

Notes

For periodic motion, creep and hysteresis do not affect repeatability.

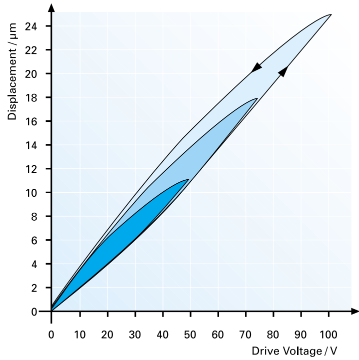

Fig. 11. Hysteresis curves of an open-loop piezo actuator for various peak voltages. The hysteresis is related to the distance moved.

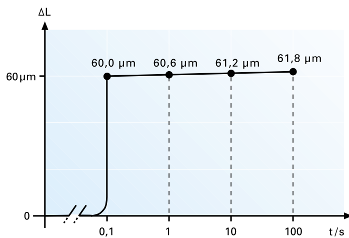

Fig. 12. Creep of open-loop PZT motion after a 60 µm change in length as a function of time. Creep is on the order of 1% of the last commanded motion per time decade.

Hysteresis (Open-Loop PZTs)

Hysteresis can be virtually eliminated in closed-loop PZT actuators (see page 4-34 *ff*). Similar to electromagnetic devices, open-loop piezo actuators exhibit hysteresis (they, too, are referred to as ferroelectric actuators). Hysteresis is based on crystalline polarization effects and molecular effects.

The absolute displacement generated by an open-loop PZT depends on the applied voltage 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, the deflection depends on whether the PZT was previously operated at a higher or a lower field strength (and some other factors). Hysteresis is typically on the order of 10% to 15% of the **commanded** motion (see Fig. 11).

For example, if the drive voltage of a 50 µm piezo actuator is changed by 10%, (equivalent to about 5 µm displacement) the position repeatability is still on the order of 1% full travel or better than 1 µm. Classical motor-driven leadscrew positioners will have difficulty beating this repeatability.

In PI closed-loop piezo actuator systems hysteresis is fully compensated. PI offers these systems for applications requiring absolute position information, as well as motion with high linearity, repeatability and accuracy in the nanometer and sub-nanometer range (see page 4-34 *ff*).

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.

Example: Piezoelectrically driven fiber aligners derive the control signal from the optical power transmitted from one fiber to the other. The goal is to maximize the optical signal level, not to determine the exact position. An open-loop PZT system is sufficient for this application, offering unlimited resolution, fast response, zero backlash and zero stick/slip effect.

Creep (Drift) (Open-Loop PZTs)

Creep only occurs in open-loop operation, and can be eliminated by servo-control (see page 4-34 *ff*). Like hysteresis, creep is related to the effect of the applied voltage on the remanent polarization of the piezo ceramics. Creep is the expression of the slow realignment of the crystal domains in a constant electric field over time. If the operating voltage of a PZT is changed, after the voltage change is complete, the remanent polarization (piezo gain) continues to change, manifesting itself in a slow creep. The rate of creep decreases logarithmically with time.

The following equation describes this effect:

(Equation 2)

$$\Delta L(t) \approx \Delta L_{t=0.1}\left[1+\gamma \cdot \lg\left(\frac{t}{0.1}\right)\right]$$

Creep of PZT motion as a function of time.

where:

$\Delta L(t)$ = *creep as a function of time [m]*

$\Delta L_{t=0.1}$ = *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 which is 1 to 2% per decade).*

Maximum creep (after a few hours) can add up to a few percent of the commanded motion

Aging

Aging refers to reduced piezo gain, among other things 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 is applied to the actuator material in the poling direction.

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High-Resolution Sensors

Notes:

The description explains the features of different high-resolution sensor types used for closed-loop control of PZT actuators. The bandwidth given is the 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 Gauge Sensors

A resistive film bonded to the PZT stack changes resistance when strain occurs. Up to four strain gauges (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 proportional to the displacement.

Resolution: better than 1 nm (for 15 µm actuator)

Repeatability: to 0.1% of nominal displacement

Bandwidth: to 5 kHz

Advantages:

- High bandwidth
- Vacuum compatible
- Extremely small (no extra mounting space, no reduction of active cross-section causing reduced stiffness)
- Cost-effective

Other characteristics:

- Low heat generation (0.01 to 0.05 W sensor excitation power)

Examples:
Most PI LVPZT and HVPZT actuators are available with strain gauge sensors for closed-loop control (see "PZT Actuators Selection Guide" p. 1-6).

Fig. 13. Strain gauge sensors. Paper clip for size comparison

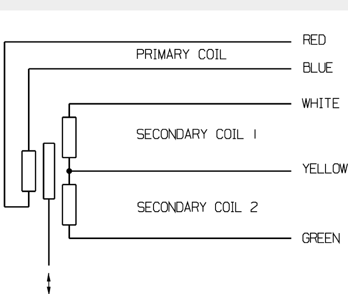

Fig. 14. Operating principle of an LVDT sensor

Linear Variable Differential Transformers (LVDTs)

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: to 5 nm

Bandwidth: to 1 kHz

Repeatability: to 5 nm

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 characteristics:

- Outgassing of insulation materials may limit applications in vacuum
- Extra space for mounting required

Examples:
P-780, p. 2-16; P-721.10, p. 2-10; P-762, p. 2-38 ; etc., (see "PZT Flexure NanoPositioners" section).

Fig. 15. LVDT sensor, coil and core. Paper clip for size comparison

Fundamentals … (cont.)

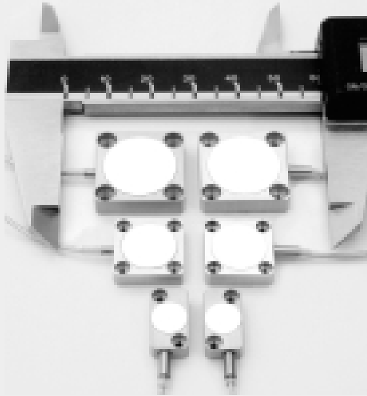

Fig. 16. Two-plate capacitive position sensors provide up to 10,000 times higher resolution than calipers

Capacitive Position Sensors

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: to 0.1 nm

Bandwidth: to 10 kHz

Advantages:

- Highest resolution of all commercially available sensors
- Excellent long-term stability
- Excellent frequency response

Other characteristics:

- Extra space for mounting required
- Parallelism of the plates must be controlled for optimal performance

Examples:

P-500 series of Flexure Stages, p. 2-32; P-753 LISA NanoAutomation® Actuators, 2-22.

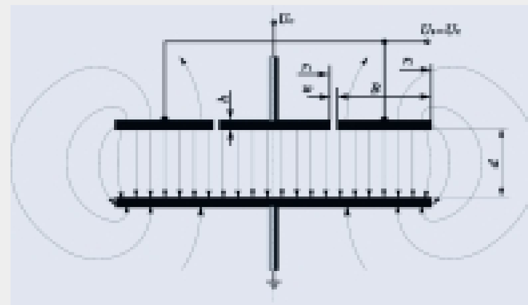

Fig. 17. Operating principle of two-plate capacitive position sensors

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Mechanical Considerations

Notes

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

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

Maximum Applicable Forces

(Compressive Load Limit, Tensile Load Limit)

The mechanical strength values of PZT ceramic material (given in the literature) are often confused with the practical long-term load capacity of a PZT actuator. PZT ceramic material can withstand pressures up to a few hundred MPa (a few 10,000 psi) before it breaks mechanically. This value must not be approached in practical applications, because depolarization occurs at pressures on the order of 20% to 30% of the mechanical limit. For stacked actuators (which are a combination of several materials) additional limitations apply. Parameters such asaspect ratio, buckling, interaction at the interfaces, etc. must be considered. If the specified "maximum compressive force" for a PZT is exceeded, mechanical 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 (maximum compressive force). 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 ceramic stiffness is an important parameter. In solid bodies stiffness depends on the Young's modulus of the material, i.e. the ratio of stress (force per unit area) to strain (change in length per unit length). Stiffness 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 is of limited application for PZT ceramics because the cases of static, dynamic, large-signal and small-signal operation with open and shorted electrodes must all 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, must be superimposed on the 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 counterforce opposing the mechanical stress. (This is why a PZT element with open electrodes appears stiffer than one with shorted electrodes). Mechanical stressing of PZT actuators with open electrodes, e.g. open wire leads, should be avoided, because the resulting induced voltage might damage the stack electrically.

Fundamentals ... (cont.)

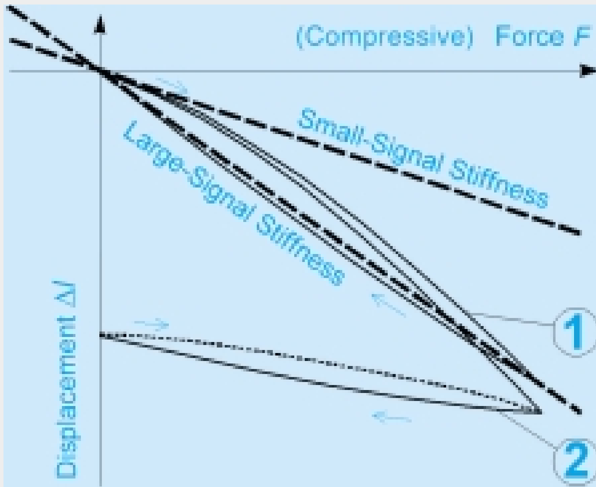

Fig. 18. Quasi-static characteristic mechanical stress/strain curves for piezo ceramic actuators and the derived stiffness values (note that displacement is negative because the applied force is compressive). Curve 1 is with the nominal operating voltage (voltage giving nominal maximum displacement) on the electrodes, Curve 2 is with the electrodes shorted (showing ceramics after depolarization)

The curves expressing the displacement of piezoelectric ceramics under mechanical stress are similar to those for electrically induced displacement. The action of high pressures on the domains within the material cause it to exhibit a non-linear response, with hysteresis, that has been called "ferro-elastic" behavior.

The curves are strongly influenced by the state of the electrodes. Fig. 18 shows the two cases of nominal operating voltage (for maximum displacement) applied (1), and shorted electrodes with the ceramics depoled (2). A third case, that with open contacts (not shown in the graph) gives a very different result with higher stiffness.

Since Hook's law is not obeyed, no single stiffness value can reasonably be given. If, for example, stiffness is determined using very low-amplitude displacements (small-signal stiffness), the value measured may be almost twice as high as that measured using large-amplitude displacements (large-signal stiffness).

The relevant value is, in the final instance, dependent on the details of the application.

Static Large-Signal Stiffness

The static large-signal stiffness is calculated from the slope of the secant between the end-points of the response curve, measured with the nominal operating voltage on the electrodes (e.g. Curve 1 in Fig. 18). The values are obtained with a quasi-static, triangle-wave force signal of 0.02 Hz, and any "memory" anomalies are cleared by measuring the third cycle. The end points of the force curve are chosen in conjunction with the cross section of the piezo actuator, such that the variation in mechanical stress is from 10 MPa to 40 MPa.

Dynamic Small-Signal Stiffness

Dynamic small-signal stiffness is another term sometimes used to characterize PZT ceramics. This value is calculated from the observed mechanical resonant frequency of the actuator in response to very low-amplitude mechanical stress with the electrodes shorted. The dynamic small-signal stiffness and the resonant frequency provide information about the dynamic characteristics that can be expected of the system—for example, how it will respond to a change in load.

For the use of piezo ceramics in positioning systems, the static large-signal stiffness is usually far more important than the small-signal value, as it describes the behavior of the actuator when working against an elastic load.

With piezoelectric positioning systems and actuators (compound structures of different active and passive materials) the stiffness scenario is even more complicated. This fact explains why the (dynamically measured) resonant frequency of a piezo actuator or positioning system does not necessarily match the results calculated with the simple harmonic oscillator equation:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k_T}{m_{eff}}}$$

For more details see "Resonant Frequency," p. 4-28.

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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 4-26.

(Equation 3)

$$F_{max} \approx k_T \cdot \Delta L_0$$

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:

(Equation 4)

$$F_{max\ eff} \approx k_T \cdot \Delta L_0 \left(1- \frac{k_T}{k_T+k_S}\right)$$

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 = *stiffness of external spring [N/m]*

Example: Force generation of a PZT actuator with nominal displacement of 30 µm and stiffness of 200 N/µm. The PZT can produce a maximum force of 30 µm × 200 N/µm = 6000 N. When force generation is maximum, displacement is zero and vice versa (see Fig. 19 for details).

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 × 100 N = 3000 N (30 microns are lost motion due to the distance between the sheet and the PZT tip). In practice the force generation depends on the stiffness of the metal and the support. If the support were 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 were stiff but the metal itself were 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 metal 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.

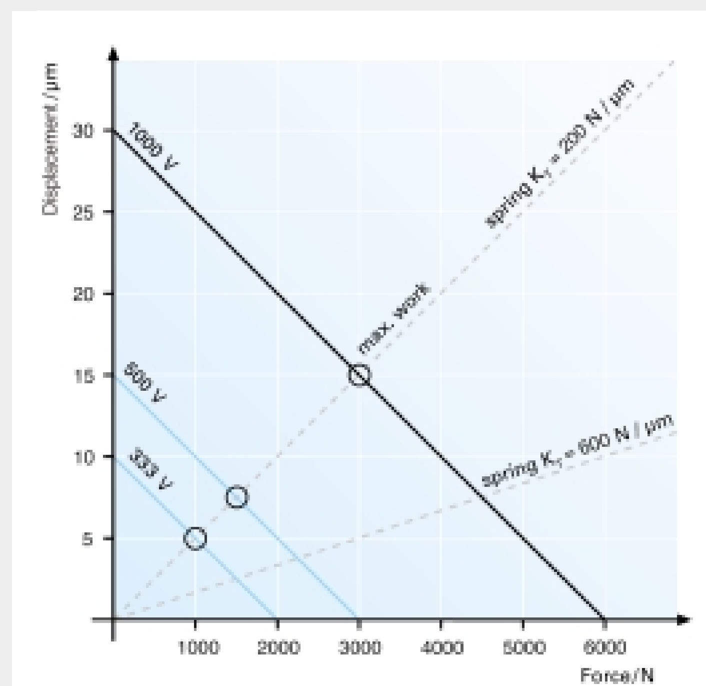

Fig. 19. Force generation vs. displacement of a PZT actuator (displacement 30 µm, stiffness 200 N/µm) at various operating voltages. The points where the dashed lines (external spring curves) intersect the PZT force/displacement curves determine the force and displacement for a given setup with an external spring. Maximum work can be done when the stiffness of the PZT actuator and external spring are identical.

Fundamentals ... (cont.)

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.

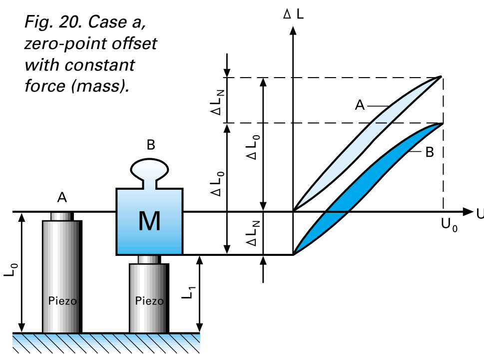

Fig. 20. Case a, zero-point offset with constant force (mass).

a Constant Force

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 (see product technical data), full displacement can be obtained at full operating voltage (see Fig. 20).

(Equation 5)

$$\Delta L_N \approx \frac{F}{k_T}$$

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]*

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 x 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 reduced by this constant force.

b Changing Force

(Force = Function of ΔL, e.g. a spring load):

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 the elasticity of the piezo element. The total available displacement can be related to the spring stiffness by the following equations:

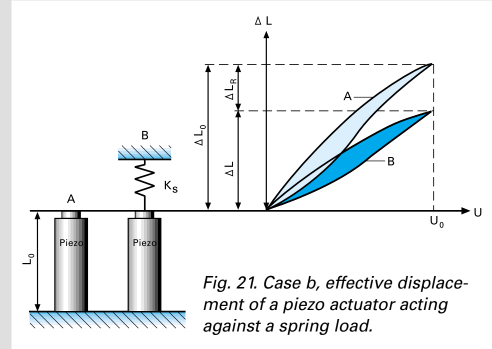

Fig. 21. Case b, effective displacement of a piezo actuator acting against a spring load.

(Equation 6)

$$\Delta L \approx \Delta L_0 \left(\frac{k_T}{k_T + k_S}\right)$$

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

(Equation 7)

$$\Delta L_R \approx \Delta L_0 \left(1- \frac{k_T}{k_T + k_S}\right)$$

Maximum loss of displacement 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 = *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*

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 a spring constant k_s (stiffness) of 100 N/µm?

A: Equation 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).

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.

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Mechanical Considerations for Dynamic Operation of PZTs

Notes

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.

Dynamic Forces

Every time the PZT drive voltage changes, the piezo element changes its dimensions. Due to the inertia of the PZT mass (plus any additional load), a rapid change will generate a force (pushing or pulling) acting on the piezo. The maximum force that can be generated is equal to the blocked force, described by:

(Equation 8)

$$F_{max} \approx \pm k_T \cdot \Delta L_0$$

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

where:

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

k_T = *PZT actuator stiffness [N/m]*

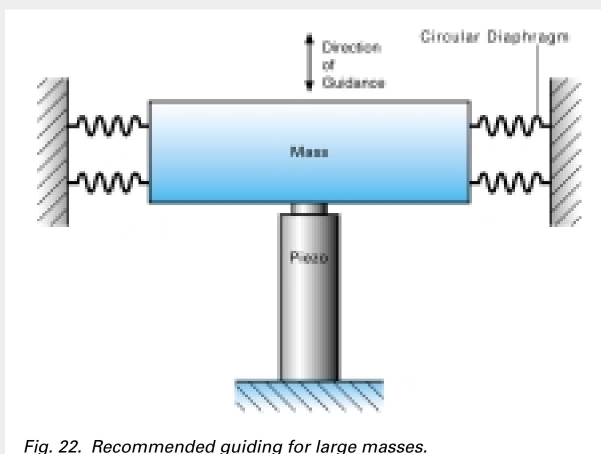

Fig. 22. Recommended guiding for large masses.

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 amplitude $\Delta L/2$, peak forces can be expressed as:

(Equation 9)

$$F_{dyn} = \pm 4\pi^2 \cdot m_{eff} \left(\frac{\Delta L}{2}\right) f^2$$

Dynamic forces on a PZT in sinusoidal operation at 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-to-peak and 1 kg load reach approximately ± 40 N.

Fundamentals ... (cont.)

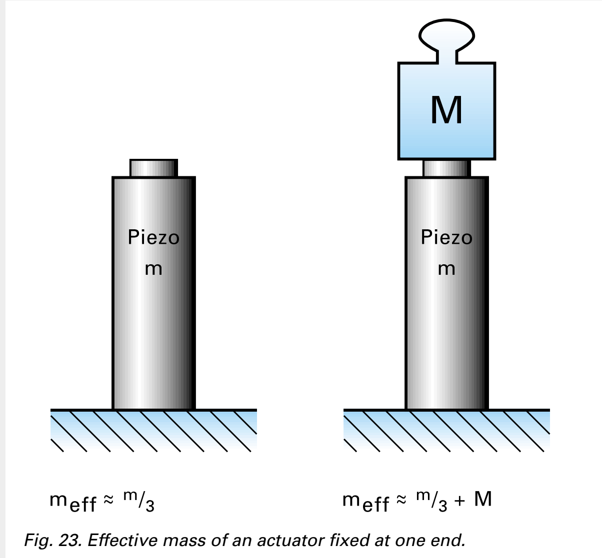

Fig. 23. Effective mass of an actuator fixed at one end.

Resonant Frequency

In general, the resonant frequency of any spring/mass system is a function of its stiffness and effective mass (see Fig. 23). The resonant frequency given in the technical data tables always refers to the unloaded actuators, with one end rigidly attached.

(Equation 10)

$$f_0 = \left(\frac{1}{2\pi}\right)\sqrt{\frac{k_T}{m_{eff}}}$$

Resonant frequency of an ideal spring/mass system.

where:

f_0 = *resonant frequency [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 from the above equation does not necessarily match the real-world behavior of the PZT system under large signal conditions.

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

(Equation 11)

$$f_0' = f_0\sqrt{\frac{m_{eff}}{m'_{eff}}}$$

Resonant frequency with new effective mass

m'_{eff} = *additional mass M +* m_{eff}.

The above equations show that increasing the effective mass of the loaded 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 the equation:

(Equation 12)

$$\varphi \approx 2 \cdot \arctan\left(\frac{f}{f_0}\right)$$

φ = *phase angle [deg]*

f_0 = *resonant frequency [Hz]*

f = *operating frequency [Hz]*

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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, albeit with significant overshoot (see Fig. 24).

(Equation 13)

$$T_{min} \approx \frac{1}{3f_0}$$

Minimum 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", page 4-31.

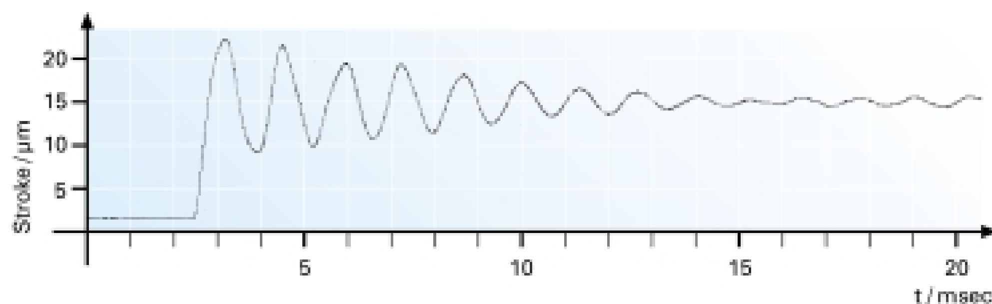

Fig. 24. Response of an undamped, lever-amplified PZT actuator (low resonant frequency) to a rapid drive-voltage change.

Fundamentals … (cont.)

Electrical Requirements for Piezo Operation

Notes

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, to up to 200% of the unloaded, small-signal, room-temperature value. For detailed information on power requirements, refer to the amplifier frequency response curves in the "PZT Control Electronics" section.

General

When operated well below the resonant frequency, a PZT behaves as a capacitor: displacement is proportional to charge (first order estimate).

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

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

(Equation 14)

$$C \approx n \cdot \epsilon_{33T} \cdot A/d_s$$

Where:

n = number of layers $\frac{l_0}{d_s}$

ϵ_{33T} = dielectric constant [As/Vm]

A = electrode surface area of a single layer [m^2]

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

l_0 = actuator length

The equation explains that for a given actuator length $l_0 = n \cdot d_s$ and a given disk thickness d_s, the capacitance is a quadratic function of the ratio d_s / d_1 where $d_1 < d_s$. 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:

(Equation 15)

$$i = \frac{dQ}{dt} = C \cdot \frac{dU}{dt}$$

Relationship of current and voltage for the piezo actuator

Where:

i = current [A]

Q = charge [coulomb (As)]

C = capacitance [F]

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 the 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 (time constant of several minutes).

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. (Suitable amplifiers can be found using the Control Electronics Selection Guide on page 6-6).

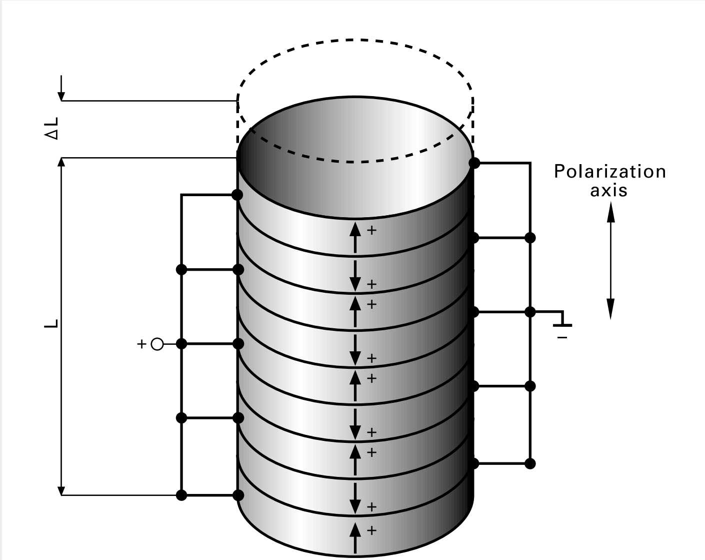

Fig. 25. Design of a PZT stack actuator.

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.

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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:

- If the piezo element is installed in a positioning mechanism (and sufficient electrical power is available from the amplifier), the maximum drive frequency can be limited by dynamic forces (see "Dynamic Operation", page 4-27).
- 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.
- 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.

(Equation 16)

$$i_a \approx f \cdot C \cdot U_{p\text{-}p}$$

Average current required for sinusoidal operation

(Equation 17)

$$i_{max} \approx f \cdot \pi \cdot C \cdot U_{p\text{-}p}$$

Peak current required for sinusoidal operation

(Equation 18)

$$f_{max} \approx \frac{i_{max}}{2 \cdot C U_{p\text{-}p}}$$

Maximum operating frequency with triangular waveform 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 [F]

$U_{p\text{-}p}$ = peak-to-peak drive voltage [V]

f = operating frequency [Hz]

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

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 waveform of 1000 Hz at 20 µm displacement?

A: With a nominal displacement of 40 µm @ 1000 volts, approximately 500 $V_{p\text{-}p}$ are required to expand the actuator by 20 µm. With Equation 17 the peak current is calculated to be ≈ 63 mA. (Suitable amplifiers can be found using the Control Electronics Selection Guide on page 6-6).

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 given by:

(Equation 19)

$$P_a \approx C \cdot U_{max} \cdot U_{p\text{-}p} \cdot f$$

Peak power for sinusoidal operation is:

(Equation 20)

$$P_{max} \approx \pi \cdot C \cdot U_{max} \cdot U_{p\text{-}p} \cdot f$$

Where:

P_a = average power [W]

P_{max} = peak power [W]

C = PZT actuator capacitance [F]

f = operating frequency [Hz]

$U_{p\text{-}p}$ = peak-peak drive voltage [V]

U_{max} = nominal voltage of the amplifier [V]

Fundamentals ... (cont.)

Notes

Rapid actuation of nanomechanisms can cause recoil-generated ringing of their load and any adjacent components. This ringing can take hundreds of milliseconds to damp out. The problem obviously grows more serious as motion throughputs increase and resolution requirements tighten.

A patented real-time feedforward technology called **InputShaping™** nullifies resonances before *they start, rather than waiting for them to damp out (and turn into heat). The result: the fastest possible motion, with virtually instant settling.*

Input Shaping™ was developed based on research at the Massachusetts Institute of Technology and commercialized by Convolve, Inc., (www.convolve.com). It is an (internal) option in several PI digital piezo controllers

Dynamic Operating Current Coefficient (DOCC)

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 ("PZT Control Electronics" section).

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 that must be supplied by the amplifier to drive the 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 peak-to-peak displacement, multiply the PZT's DOCC by 50 x 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 further information see "Dynamic Forces," page 4-27).

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

(Equation 21)

$$U(t) = U_o + U_{p\text{-}p} \cdot (1 - e^{-t/RC})$$

Voltage on the piezo after switching event.

Where:

U_0 = *start voltage [V]*

$U_{p\text{-}p}$ = *peak-to-peak drive voltage [V]*

R = *resistance in drive circuit [Ω]*

C = *PZT actuator capacitance [F]*

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 one third of the period of the resonant frequency (see "How Fast Can a Piezo Actuator Expand?", page 4-29). 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. that provided by a linear amplifier), the following equation applies:

(Equation 22)

$$t \approx C \cdot (U_{p\text{-}p} / i_{max})$$

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

Where:

t = *time to charge to $U_{p\text{-}p}$ [s]*

C = *PZT actuator capacitance [F]*

$U_{p\text{-}p}$ = *peak-to-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. Preshaped input signals (optimized for minimum resonance excitation) reduce the time to reach a stable position.

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Heat Generation in a PZT in Dynamic Operation

As mentioned before, PZTs are reactive loads and therefore require charge and discharge currents that increase with operating frequency. The thermal active power, P (apparent power × power factor, cos φ), generated in the actuator during harmonic excitation can be estimated with the following equation:

(Equation 23)

$$P \approx \frac{\pi}{4} \cdot \tan\delta \cdot f \cdot C \cdot U_{p\text{-}p}^2$$

Heat generation in a PZT.

Where:

P = power converted to heat [W]

tan δ = dielectric loss factor (≈ power factor, cos φ, for small angles δ and φ)

f = operating frequency [Hz]

C = PZT actuator capacitance [F]

$U_{p\text{-}p}$ = peak-peak drive voltage [V]

For the description of the loss power, we use the loss factor tan δ instead of the power factor cos φ, because it is the more common parameter for characterizing dielectric materials. For standard actuator PZT ceramics the loss factor is on the order of 1 to 2% (small-signal conditions only). In large-signal conditions however, 8 to 12% of the electrical power pumped into the actuator is converted to heat (varies with frequency, temperature, amplitude etc.). Therefore, the maximum operating temperature can limit the PZT dynamics. For large amplitudes and high frequencies, cooling measures may be necessary. A temperature sensor mounted on the ceramics is suggested for monitoring purposes.

In addition, a new generation of amplifiers employing energy recovery technology has been developed for high-power applications. Fig. 26 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 in a step-up transformation process. The combination of low-loss, high-energy PZT ceramics and amplifiers with energy recovery are the key to new high-level dynamic piezo actuator applications.

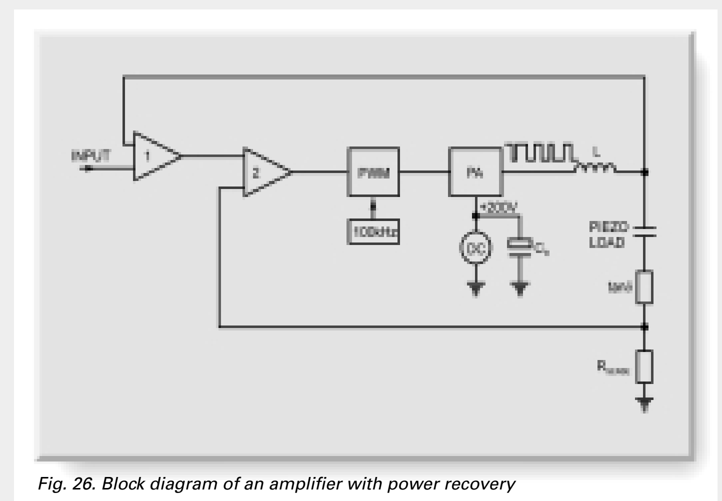

Fig. 26. Block diagram of an amplifier with power recovery

Fundamentals ... (cont.)

Position Servo-Control (Closed-Loop Operation)

Fig. 27. Variety of digital piezo controllers

Position servo-control eliminates nonlinear behavior of PZT ceramics and is the key to highly repeatable nanometric motion.

PI offers the largest selection of closed-loop piezo mechanisms and control electronics worldwide. The advantages of position servo-control are:

- Very good linearity, stability, repeatability and accuracy
- Automatic compensation for varying loads or forces
- Virtually infinite stiffness (within load limits)
- Elimination of hysteresis and creep effects

PI closed-loop PZT actuators and 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 0.003%.

For maximum accuracy, it is necessary to mount the sensor as close as possible to the part whose position is to be controlled. PI offers piezo actuators with integrated sensors as well as external sensors.

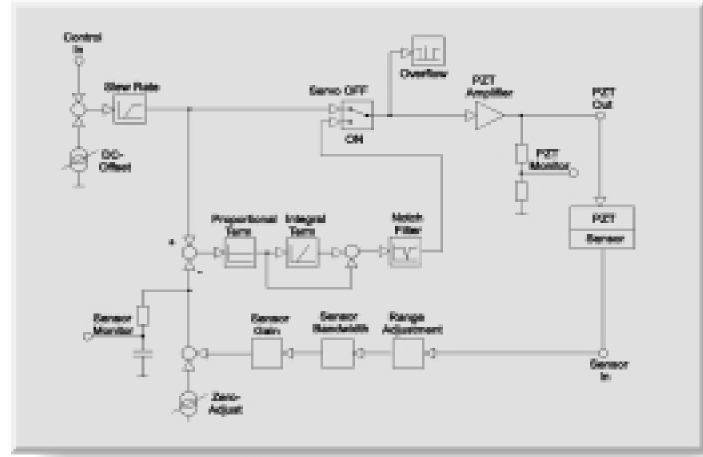

Fig. 28. Block diagram of a typical PI closed-loop PZT positioning system.

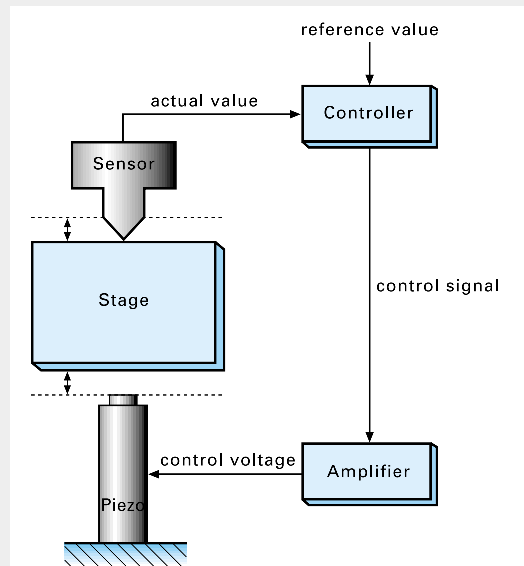

Fig. 29. Closed-loop position control of a stage driven by a piezo actuator. For optimum performance, the sensor is mounted directly on the object to be positioned.

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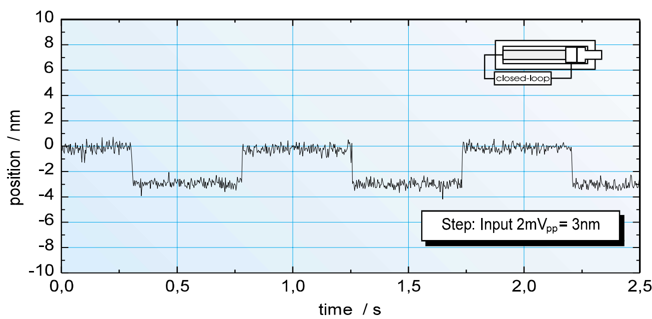

Fig. 30. Response of a closed-loop PI PZT actuator (P-841.10, 15 µm, strain gauge sensor) to a 3 nm peak-to-peak square-wave control input signal, measured with servo-control bandwidth set to 240 Hz and 2 msec settling time. Note the crisp response to the square wave control signal.

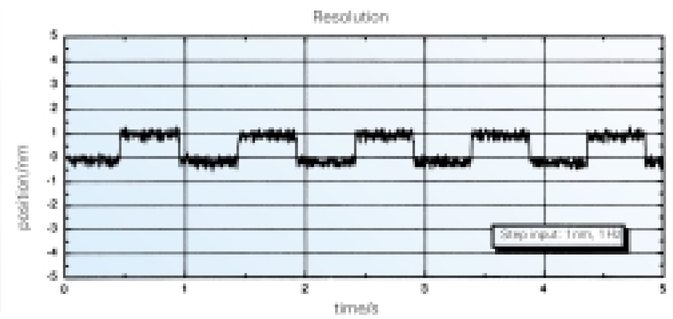

Fig. 31. Response of a closed-loop PI PZT actuator with capacitive position sensors, shows true sub-nm positional stability, incremental motion and bidirectional repeatability.

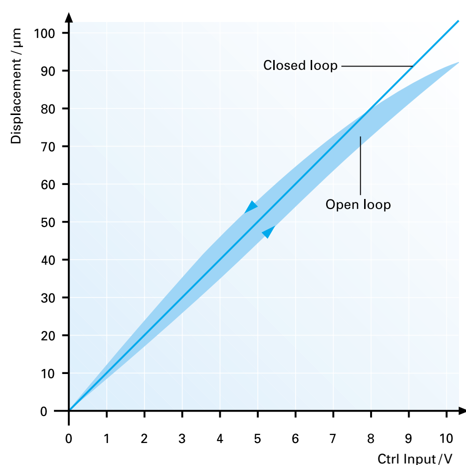

Fig. 32. Open-loop vs. closed-loop performance graph of a typical PI PZT actuator (supplied with each closed-loop system).

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. The calibration is performed at the factory and 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 the “PZT Control Electronics” section for details.

Fundamentals ... (cont.)

Methods to Improve Piezo Dynamics

The dynamic behavior of a piezo positioning system depends on the system's resonant frequency, any position sensor, and the controller properties. Simple controller designs limit the usable closed-loop tracking bandwidth of a piezoelectric system to 1/10 of the system's resonant frequency. PI has developed controllers featuring a variety of techniques for increased system dynamics (see table). Two of the methods are described below; additional information is available on request.

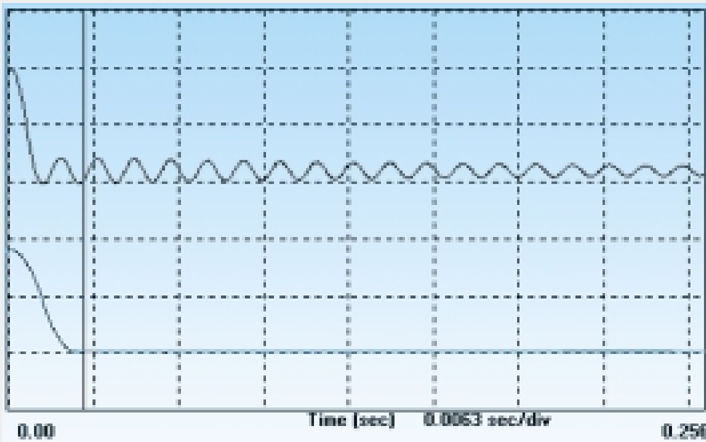

Fig. 33. InputShaping™ eliminates the recoil-driven resonant reaction of loads and neighboring components due to rapid NanoPositioner actuation.
Top: Laser Vibrometer reveals the resonant behavior of an undamped fixture when the nanomechanism is stepped.
Bottom: Same fixture, same step, with InputShaping ™. The structural ringing is eliminated.

InputShaping™ Stops Structural Ringing Caused by High-Throughput Motions

Rapid actuation of nanomechanisms can cause recoil-generated ringing of their loads and any adjacent components. This ringing can take hundreds of milliseconds to damp out. The problem obviously grows more serious as motion throughputs increase and resolution requirements tighten.

Conventional wisdom suggests that there is nothing that can be done about these resonant reactions, since they occur outside the servo loop and cannot be observed by the controls.

A patented real-time feedforward technology called InputShaping™ nullifies resonances *before* they start, rather than waiting for them to damp out (turn into heat). The result: the fastest possible motion, with virtually instant settling, as shown in actual vibrometer testing.

InputShaping™ was developed based on research at the Massachusetts Institute of Technology and commercialized by Convolve, Inc., (http://www.convolve.com). It is a (built-in) option in several PI digital piezo controllers, is easy to set up for a particular OEM application and robust against dynamic changes in the setup. It requires no change to the system software, application, physical setup or servo parameters. InputShaping™ eliminates unwanted motion-driven resonances and ringing in step-mode and continuous-motion (scanning) applications, and it greatly improves throughput and resolution in high-speed applications.

Various Methods to Improve Piezo Dynamics

Method	Goals
Feedforward	Reduce phase difference between output and input (tracking error)
Signal preshaping (software)	Increase operating frequency of the system, correct amplitude and phase response. Two learning phases required; only for periodic signals.
Adaptive preshaping (hardware)	Increase operating frequency of the system, correct amplitude and phase response No learning phase, but settling phase required; only for periodic signals.
Linearization (analog, in power amplifier)	Compensate for piezo hysteresis
Linearization (digital, in DSP)	Compensate for piezo hysteresis and creep effects
InputShaping™	Cancel recoil-generated ringing of load and any adjacent components. Reduce the settling time. Closed and open-loop.
Learning control	Increase operating frequency of the system, correct amplitude and phase response in scanning processes. Online learning phase and trigger for start of period required. Only periodic signals

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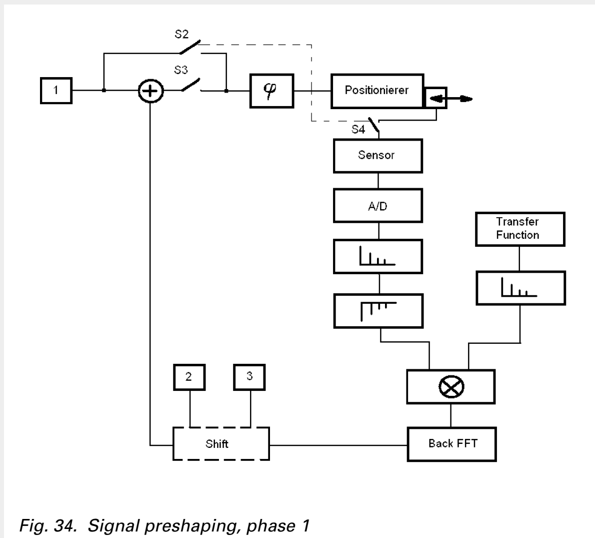

Fig. 34. Signal preshaping, phase 1

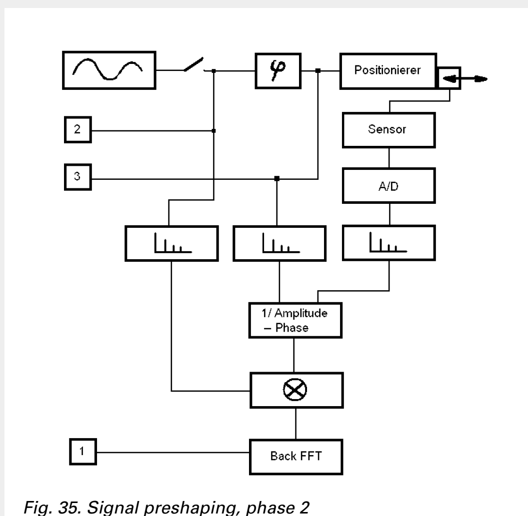

Fig. 35. Signal preshaping, phase 2

Signal Preshaping

For applications with continuous, repetitive (periodic) inputs, a new preshaping technique can reduce the rolloff, phase error and hysteresis of the servo-system. The result is to improve the effective bandwidth and allow more accurate tracking. Signal Preshaping is implemented in object code, based on an analytical approach in which the complex transfer function of the system is calculated, then mathematically transformed and applied in a feedforward manner to reduce the tracking error. Signal Preshaping improves the effective bandwidth by a factor of 10 and is more effective than classical phase-shifting approaches in reducing tracking error in multi-frequency applications.

Signal Preshaping is based on FFT (fast Fourier transformation) techniques. Frequency response and harmonics (caused by nonlinearity) are determined in two steps. The results are applied to the original control function and a new control function is calculated.

E. g. for a PZT positioning system with 400 Hz resonant frequency, the command transfer function (amplitude and phase) can be improved from 20 Hz to 200 Hz without affecting the system stability. At the same time, the tracking error is reduced by a factor of up to 50 compared to that using the uncorrected control input signal.

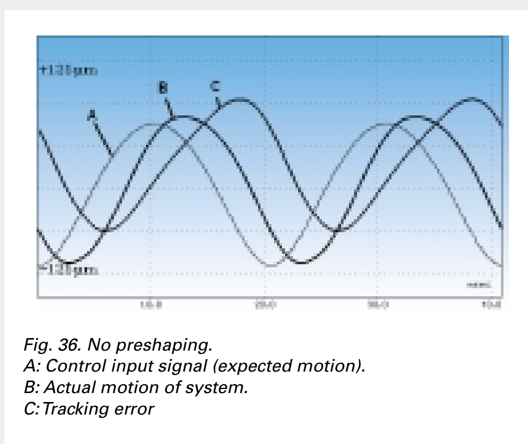

Fig. 36. No preshaping.
A: Control input signal (expected motion).
B: Actual motion of system.
C: Tracking error

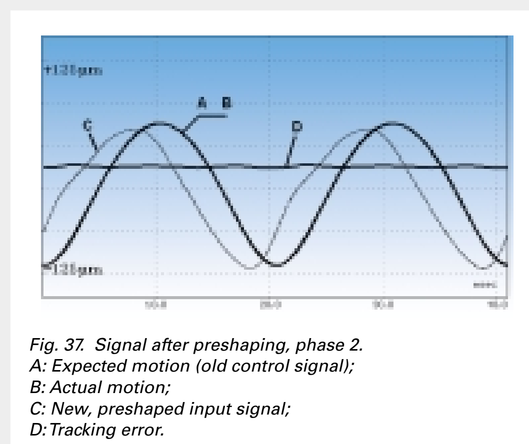

Fig. 37. Signal after preshaping, phase 2.
A: Expected motion (old control signal);
B: Actual motion;
C: New, preshaped input signal;
D: Tracking error.

Fundamentals ... (cont.)

Temperature Effects

Notes

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 calibration temperature (22 °C). See calibration test sheet for details.

Two effects must be considered:

Linear Thermal Expansion

Thermal stability of PZT ceramics is better than that of most other materials (steel, aluminum, etc.). Fig 39 shows the behavior of several types of PZT ceramics used by PI. The curves only describe the behavior of the PZT ceramics. Actuators and positioning systems consist of a combination of PZT ceramics and other materials and their overall behavior differs accordingly.

Temperature Dependency of the Piezo Effect

Piezo translators work in a wide temperature range. The piezo effect in PZT ceramics is known to function down to almost zero kelvin. For several reasons the magnitude of the piezoelectric effect (piezo gain) is dependent on the temperature.

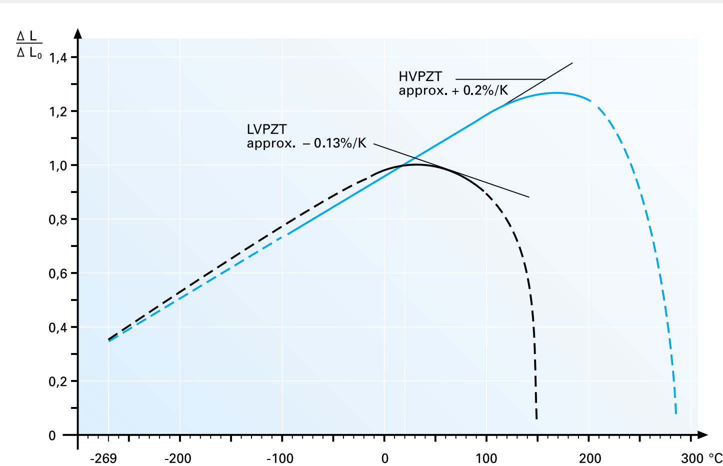

Fig. 38. Temperature dependency of the piezo effect.

At liquid helium temperature piezo gain drops to approximately 20% of its room-temperature value. See Fig. 38, for temperature dependency.

PZT ceramics must be poled to exhibit the piezo effect. A poled PZT may depole when heated above the maximum allowable operating temperature. The “rate” of depoling is related to the Curie temperature of the material. PI HVPZTs have a Curie temperature of 250 °C and can be operated up to 150 °C (with the high-temperature option). LVPZTs have a Curie temperature of 150 °C and can be operated up to 80 °C. See “Options,” p. 1-39 in the “PZT Actuators” section, for temperature range modifications.

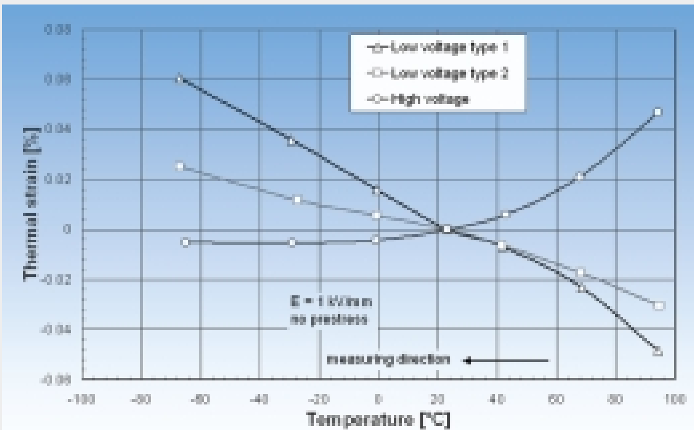

Fig. 39. Linear thermal expansion of several PZT materials.

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Environmental Considerations

PZT Operation in Normal Atmospheres

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 60%). For higher humidity environments, PI offers special systems with enclosed stacks, or integrated dry-air flushing mechanisms.

PZT Operation in Inert Gas Atmospheres

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 electric field strength, while producing reasonable displacement.

Vacuum Operation of PZTs

All PI piezo actuators can be operated at pressures below 0.1 hPa (~0.1 torr). When piezo actuators are used in a vacuum, two factors must be considered:

I. Dielectric stability

II. Outgassing

I. The dielectric breakdown strength of a gas is a function of pressure. Air displays a high insulation capacity at atmospheric pressure and below 0.1 hPa (~0.1 torr). However, in the corona area range from 100 to 0.1 hPa (~100 to 0.1 torr), its insulation properties are greatly degraded. PZTs should not be operated in this range because an electric breakdown may occur.

II. Outgassing (of the insulation materials) may limit the use of PZTs in applications where contamination or virtual leaks are an issue. Outgassing behavior varies from model to model depending on design. High-vacuum options for minimum outgassing are available for several standard LVPZTs and HVPZTs (see "Options," p. 1-39 *ff.*, in the "PZT Actuators" section for details). UHV (ultra-high-vacuum) compatible PZT flexure positioners are available on request.

Fundamentals . . . (cont.)

Lifetime of PZTs

The lifetime of a PZT is not limited by wear and tear. Tests have shown that PI PZTs can perform **billions (10^9)** 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 offers 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 a (nonlinear) influence. PI PZTs are designed and built for maximum lifetime under actual operating conditions. The operating voltage range values 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 table.

Example: The P-842.60 LVPZT (see p. 1-18 in the "PZT Actuators" section) is to operate a switch with a stroke of 100 µm. The switch is to be in operation 8 hours a day. Of its operating time, it is to be open for 70% and closed for 30 %.

Optimum solution: The actuator should be linked to the switch in such 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-842.60 can be operated down to -20 volts, the closed position should be achieved with 90 V, and the open position with -20 volts. When the switch is not in use at all, the voltage on the PZT should be 0 volts.

Statistics show that most failures with piezo actuators occur because mechanical installation guidelines are not observed and mechanical stress, shear forces or torque are allowed to 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 or conductive materials such as metal dust degrade the PZTs insulation, leading to dielectric breakdown. **PI has designed enclosed actuators for applications in hostile environments.**

PZT Operating Guidelines

Duty Cycle	LVPZT Translators	HVPZT Translators (1000 V type)	HVPZT Translators (1500 V type)
	Operate up to	Operate up to	Operate up to
100 %	50 V	250 V	500 V
35 %	70 V	600 V	750 V
15 %	100 V	750 V	1000 V
1 %	120 V	1000 V	1500 V

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Basic Designs of Piezoelectric Positioning Elements

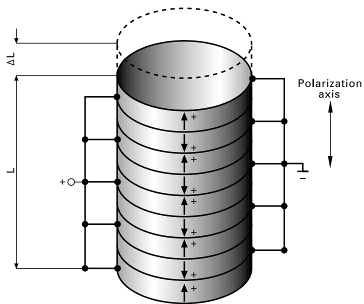

Fig. 40. Electrical design of a stack translator

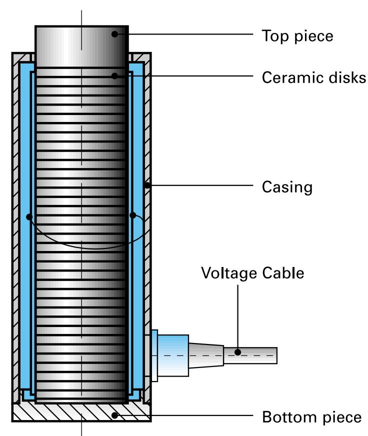

Fig. 41. Mechanical design of a stack translator

Stack Design

The active part of the positioning element consists of a stack of ceramic disks separated by thin metallic electrodes. The 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 pressures and exhibit 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", page 4-23.

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

(Equation 24)

$$\Delta L \approx d_{33} \cdot n \cdot U$$

where:

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

n = number of ceramic layers

U = operating voltage [V]

Example:
P-845, p. 1-20, etc. (see the "PZT Actuators" section)

Laminar Design (Contraction-Type Actuator)

The active material in the laminar actuators consists of thin ceramic strips. The displacement exploited in these devices is that **perpendicular** to the direction of polarization and electric field application. When the voltage is increased, the strip contracts. The piezo strain coefficient d_{31} (negative!) describes the relative change in length. Its absolute value 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:

(Equation 25)

$$\Delta L \approx d_{31} \cdot L \cdot \frac{U}{d}$$

where:

d_{31} = strain coefficient (displacement 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 and P-282, p. 2-24, p. 2-25 Flexure Positioners (see the "PZT Flexure Nano-Positioners" section).

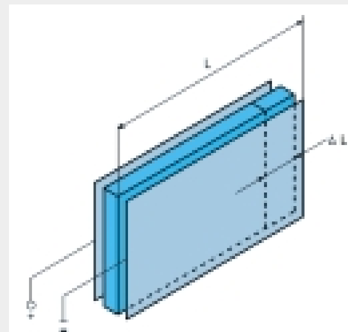

Fig. 42. Laminar design

Basic Designs ... (cont.)

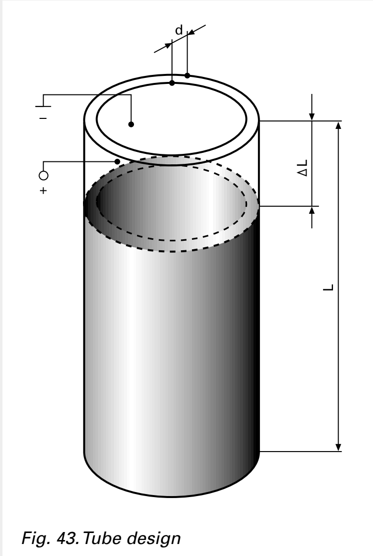

Fig. 43. Tube design

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 of a thin-walled tube, the tube contracts axially and radially. Axial contraction can be estimated by the following equation:

(Equation 26 a)

$$\Delta L \approx d_{31} \cdot L \cdot \frac{U}{d}$$

where:

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

L = *length of the PZT ceramic tube [m]*

U = *operating voltage [V]*

d = *wall thickness [m]*

The radial displacement is the result of the superposition of increase in wall thickness (equation 26 b) and the tangential contraction

$$\frac{\Delta r}{r} \approx d_{31} \frac{U}{d}$$

r = *tube radius*

(Equation 26 b)

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

where:

Δd = *change in wall thickness [m]*

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

U = *operating voltage [V]*

When the outside electrode of a tube is separated into four 90° segments, placing differential drive voltages ± U on opposing electrodes will lead to bending of one end (if the other end is clamped). Such 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:

(Equation 27)

$$\Delta x \approx \frac{2\sqrt{2} \cdot d_{31} \cdot L^2 \cdot U}{\pi \cdot ID \cdot d}$$

where:

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

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

U = *symmetric operating voltage [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.

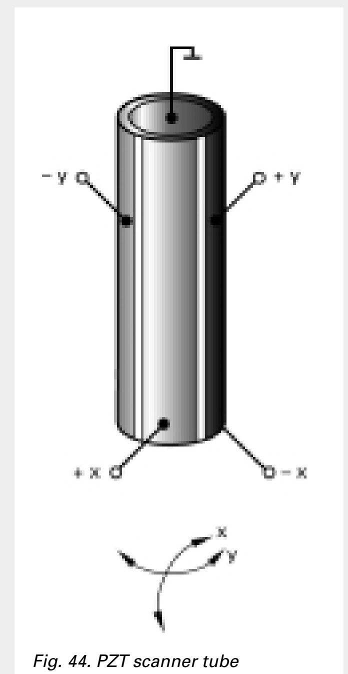

Fig. 44. PZT scanner tube

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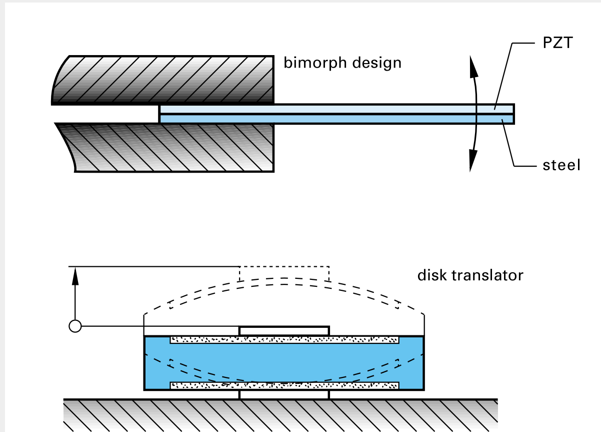

Fig. 45. Bimorph design (strip and disk translator).

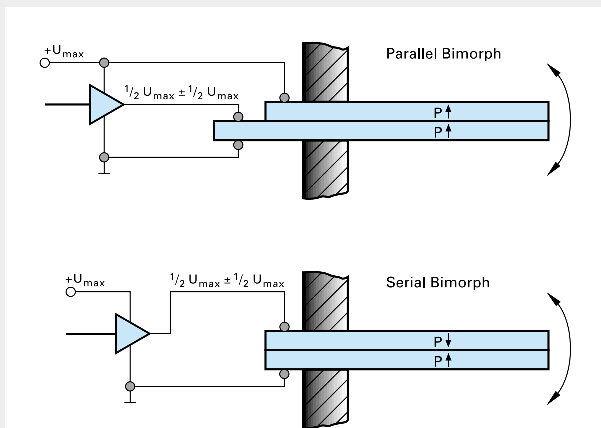

Fig. 46. Parallel bimorph and serial bimorph.

Bender Type Actuators (Bimorph and Multimorph Design)

A PZT bimorph operates similarly to the bimetallic strip in a thermostat (see Fig. 45). When the ceramic is energized it contracts or expands proportional to the applied voltage. Since the metal substrate does not change its length, a deflection proportional to the applied voltage occurs. Bimorph actuators providing motion up to 1000 µm and more are available. In addition to the classical strip form, bimorph disk actuators where the center arches when a voltage is applied, are offered.

PZT/PZT combinations, where individual PZT layers are operated in opposite modes (contraction/expansion), are also available.

Two basic versions exist: the two-electrode bimorph (serial bimorph) and the three-electrode bimorph (parallel bimorph), see Fig. 46. 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.

Monolithic multilayer-type PZT benders are also available. Similar to multilayer stack actuators, they run on a low operating voltage (60 to 100 V).

Bender type actuators provide large motion in a small package at the expense of stiffness, force and speed.

Example:
P-286 - 289 disk translators

PL122 multilayer bender actuators

Basic Designs . . . (cont.)

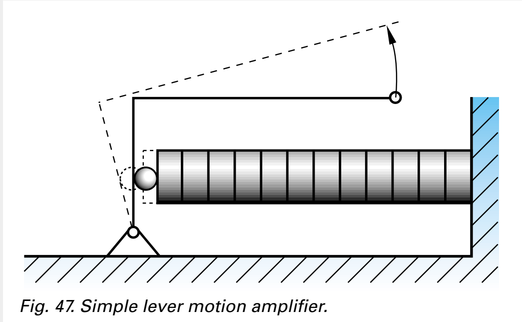
Fig. 47. Simple lever motion amplifier.

Piezo Actuators with Integrated Lever Motion Amplifier

Piezo actuators or positioning stages can be designed in such a way that a lever motion amplifier is integrated into the system, typically increasing the PZT displacement by a factor of 2 to 20. To maintain sub-nanometer resolution with the increased travel range, the lever system must be stiff, backlash- and friction-free, which means ball or roller bearings cannot be used. PI employs a proprietary finite element analysis (FEA) computer program to design PZT flexure NanoPositioners with or without integrated lever motion amplifiers (see Fig. 48. and Fig 49.).

Piezo positioners with integrated motion amplifiers have several advantages over standard piezo actuators:

- Compact size compared to stack actuators with equal displacement
- Reduced capacitance (= reduced drive current)

In combination with a flexure guiding system, extremely straight multi-axis motion is possible (see "Flexure Nano-Positioners," page 4-45).

When using (ideal) levers to amplify motion of any primary drive system, the following relations apply:

$$k_{sys} = \frac{k_0}{r^2}$$

$$\Delta L_{sys} = \Delta L_0 \cdot r$$

$$f_{res\text{-}sys} = \frac{f_{res\text{-}0}}{r}$$

where:

ΔL = displacement [m]

k_{sys} = stiffness of the lever-amplified system [N/m]

k_0 = stiffness of the primary drive system (PZT stack and joints) [N/m]

r = lever transmission ratio

$f_{res\text{-}sys}$ = resonant frequency of the amplified system [Hz]

$f_{res\text{-}0}$ = resonant frequency of the primary drive system (PZT stack and joints) [Hz]

Note:

The above equations are based on an ideal lever design with infinite stiffness and zero mass. They also imply that no stiffness is lost at the coupling interface between the PZT stack and the lever. In real applications the design of a good lever requires a sound understanding of micromechanics and nanomechanisms. A balance between mass, stiffness and cost must be found, while maintaining zero-friction and zero-backlash conditions.

Coupling the PZT stack to the lever system is actually quite complex. The coupling must be very stiff in the pushing direction but should be soft in all other degrees of freedom to avoid damage to the ceramics. Even if the stiffness of the interface is as high as that of the PZT stack alone, a 50% loss of overall stiffness still results.

Our experience shows that most often PZT stiffness is not the limiting factor when using piezo actuators in a mechanism. PI has more than 30 years experience in designing piezo actuators and flexure systems. Our engineers will be happy to help you find an optimal solution for your positioning problem.

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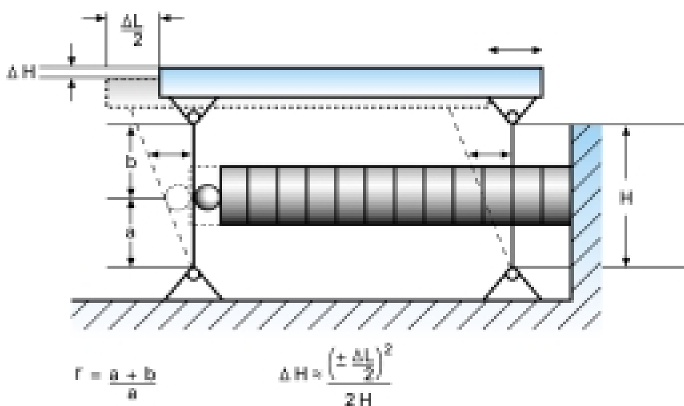

Fig. 48. Basic parallelogram flexure guiding system with motion amplification. The amplification r (transmission ratio) is given by (a+b)/a.

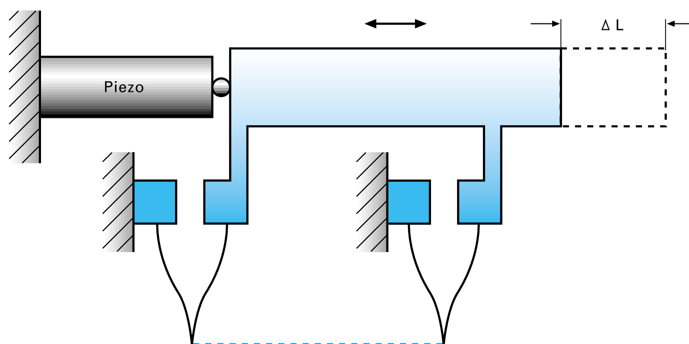

Fig. 49.Zero-arcuate-error flexure guiding system.

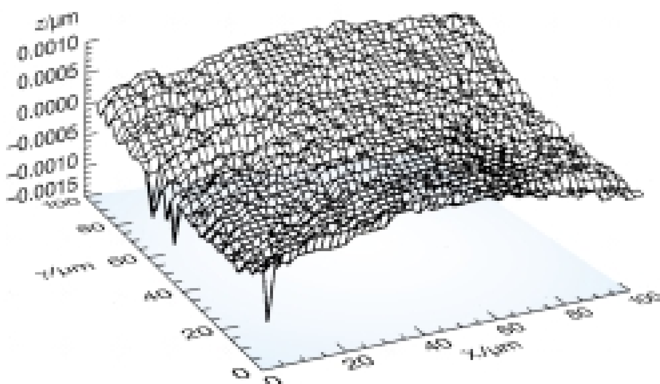

Fig. 50. Flatness (Z) of an actively error compensated flexure stage over a 100 x 100 µm scanning range.

PZT Flexure NanoPositioners

For applications where extremely straight motion in one or more axes is needed and only nanometer deviation from the ideal trajectory can be tolerated, simple stacks, tubes and other basic actuators are not ideal because they may exhibit too much off-axis error. Furthermore, they may not provide sufficient motion in a small enough package. PI PZT Flexure NanoPositioners with passive or active trajectory control provide an excellent solution in such situations.

A flexure is a frictionless, stictionless device based on the elastic deformation (flexing) of a solid material. Sliding and rolling are entirely eliminated. In addition to absence of internal friction, flexure devices exhibit high stiffness and high load capacity. Flexures are also less sensitive to shock and vibration than other guiding systems.

Basic parallelogram flexure actuators show a second-order cross-coupling (parasitic motion) between two axes due to arcuate motion (travel is in an arc). This can lead to out-of-plane errors on the order of 0.1% of the distance traveled (see Fig. 48). The error can be estimated by the following equation:

(Equation 28)

$$\Delta H \approx \left(\pm \frac{\Delta L}{2}\right)^2 \frac{1}{2H}$$

where:

ΔH = Lateral runout (out-of-plane error) [m]

ΔL = Distance traveled [m]

H = Length of the flexures [m]

For applications where this error is intolerable, PI has designed a **zero-arcuate-error multi-flexure guiding system**. This special design, employed in most PI flexure stages, eliminates the cross-coupling inherent in common parallelogram guiding systems and provides flatness and straightness in the nanometer and micro-radian ranges respectively (see Fig. 49).

For applications requiring sub-nanometer and sub-µrad flatness and straightness, PI offers a system with integrated multi-axis error compensation (active trajectory control). It measures and actively controls motion in all six degrees of freedom to sub-nanometer and sub-microradian tolerances. The exceptional flatness provided by this system is shown in Fig. 50.

Examples:

P-527, P-734, p. 2-28 *ff.* in the "PZT Flexure NanoPositioners" section.

Notes

Flexure positioners are far superior to traditional positioners (ball bearings, crossed roller bearings, dovetails etc.) in terms of resolution, straightness and flatness. Inherent friction and stiction in these traditional designs limit applications to those requiring repeatability on the order of 0.5 to 0.1 µm.

Basic Designs ... (cont.)

Electrostrictive Actuators

Electrostrictive actuators are solid state actuators similar to PZTs. The electrostrictive effect can be observed in all dielectric materials, even in liquids. Although sometimes advertised as a recent discovery, the material used has been around for 20 years. Electrostrictive actuators are made of a lead magnesiumniobate (PMN) ceramic material. PMN is a ceramic exhibiting displacement proportional to the square of the applied voltage under small-signal conditions, for certain compositions and temperature ranges. Under these conditions PMN unit cells are centro-symmetric at zero volts. An electrical field separates the positively and negatively charged ions, changing the dimensions of the cell and resulting in an expansion. Electrostrictive actuators must be operated above the Curie temperature, which is typically very low when compared to PZT materials.

In a limited temperature range, electrostrictive actuators exhibit less hysteresis (on the order of 3%) than PZT actuators. Despite the reduced hysteresis, they provide highly nonlinear motion because of the quadratic relationship between voltage and displacement. They are also unable to take advantage of the reduced electric field strength of bipolar mode operation, because reversing the electric field does not result in contraction (see Fig. 51). Furthermore, PMN actuators show an electrical capacitance four to five times as high as piezo actuators and hence require significantly higher drive currents for dynamic applications.

PZT materials have much greater temperature stability than electrostrictive materials, especially over large (10 °C) temperature variations. Both displacement and hysteresis of PMN materials are strongly dependent on the actuator temperature. When the temperature increases, displacement decreases (see Fig. 52.;) at low temperatures, where displacement is at a maximum, hysteresis also reaches a maximum (see Fig. 53.), greatly restricting application.

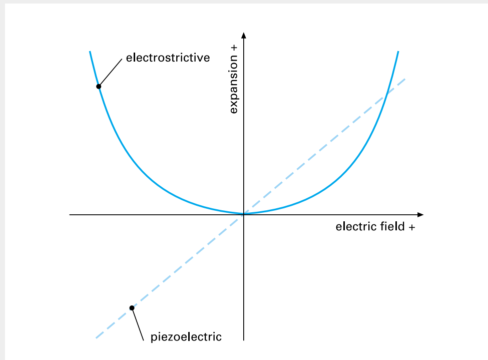

Fig. 51. Displacement vs. voltage behavior of PZT and PMN actuators (generalized)

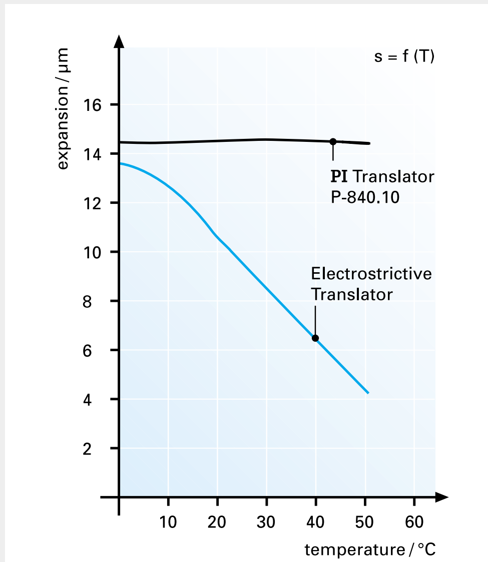

Fig. 52. Displacement vs. temperature behavior of PZT and PMN actuators.

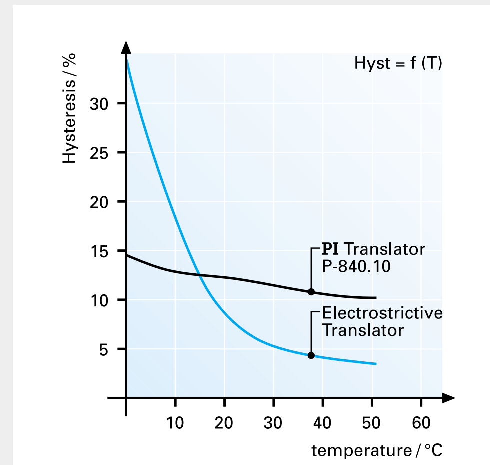

Fig. 53. Hysteresis vs. temperature behavior of PZT and PMN actuators.

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Mounting Guidelines for PZT Translators

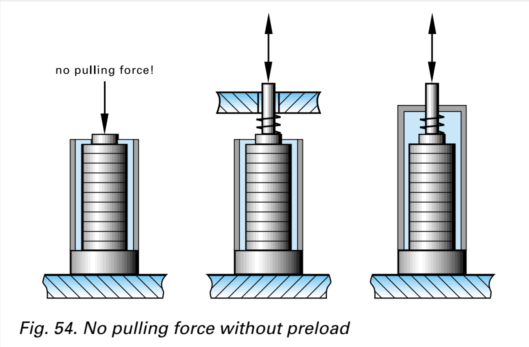

Fig. 54. No pulling force without preload

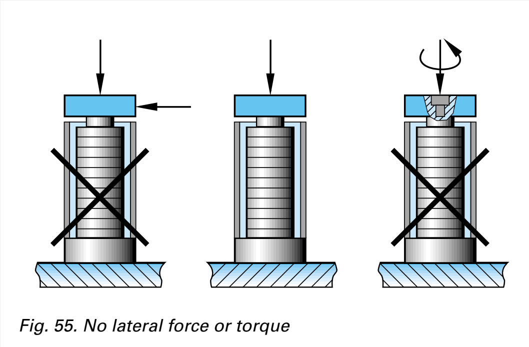

Fig. 55. No lateral force or torque

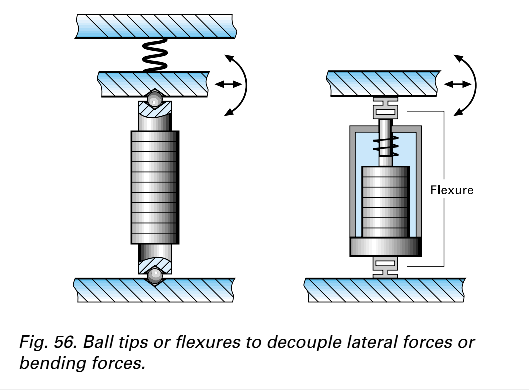

Fig. 56. Ball tips or flexures to decouple lateral forces or bending forces.

Adherence to the following guidelines will help you obtain maximum performance and lifetime from your PZT actuators:

I. PZT stack actuators must only be stressed axially. Tilting and shearing forces can be avoided by use of ball tips, flexible tips, etc.

II. PZTs without internal preload are sensitive to pulling forces. An external preload is recommended for applications requiring strong pulling forces (dynamic operation, heavy loads, etc.).

III. Maximum torque allowable at the top-piece can be found in the technical data tables for all PZT stacks and must not be exceeded. Proper use of wrench flats to apply a counter-torque to the top-piece when a mating piece is installed will protect the ceramics.

IV. When PZTs are installed between plates, a ball tip is recommended to avoid bending and shear forces.

Summary

Piezoelectric actuators offer today's motion engineer a practical way to achieve extremely high positioning accuracy in a wide variety of applications. Examples given in this discussion indicate but a few of the many applications of piezo actuators. In the near future, PZT-based motion will more and more replace classical motion systems. In addition, the unique features of PZTs will trigger development of products that could not exist without this technology and help push back the frontiers of miniaturization, precision and throughput.

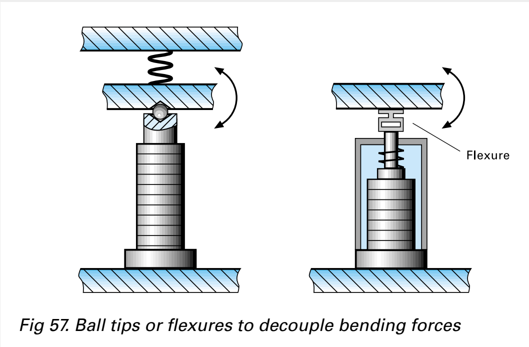

Fig 57. Ball tips or flexures to decouple bending forces

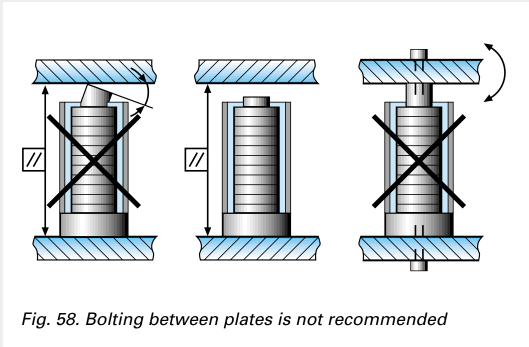

Fig. 58. Bolting between plates is not recommended

Units of Measure and Conversion Tables

Length

		[m]	[mm]	[µm]	[nm]	[Å]	[″] [in]
1 meter [m]	=	1	1000	10^6	10^9	10^{10}	39.37
1 millimeter [mm]	=	10^{-3}	1	1000	10^6	10^7	0.03937
1 micrometer [µm]	=	10^{-6}	10^{-3}	1	1000	10000	39.37 x 10^{-6}
1 nanometer [nm]	=	10^{-9}	10^{-6}	10^{-3}	1	10	39.37 x 10^{-9}
1 angstrom [Å]	=	10^{-10}	10^{-7}	10^{-4}	0.1	1	39.37 x 10^{-10}
1 inch [in], [″]	=	0.0254	25.4	25,400	25.4 x 10^6	25.4 x 10^7	1

Angle Measure

		[°]	[arc sec]	[mrad]	[µrad]
1 degree [°]	=	1	3600	17.45	17,450
1 arc second	=	2.778 x 10^{-4}	1	4.848 x 10^{-3}	4.848-
1 milliradian [mrad]	=	57.30 x 10^{-3}	206.3	1	1000
1 microradian [µrad]	=	57.30 x 10^{-6}	0.2063	10^{-3}	1

Mass*

		[kg]	[g]	[lb]
1 kilogram (of mass) [kg]	=	1	1000	2.205
1 gram (of mass) [g]	=	10^{-3}	1	2.205 x 10^{-3}
1 pound (of mass, also known as a *slug)* [lb]	=	0.4536	453.6	1

Force* (Mass x Acceleration)

		[N]	[kg] (force)	[lb] (force)
1 newton [N]	=	1	0.102	0.2248
1 kilogram of force [kg]	=	9.807	1	2.205 x 10^{-6}
1 pound of force [lb]	=	4.448	0.4536	1

Torque (Lever Arm x Force)

		[N·m]	[mN·m]	[ft·lb]	[in·lb]
1 newton-meter [N·m]	=	1	1000	0.7376	8.8512
1 millinewton-meter [mN·m]	=	0.001	1	73.76 x 10^{-5}	8.8512 x 10^{-3}
1 foot-pound [ft·lb]	=	1.3563	1356.3	1	12
1 inch-pound [in·lb]	=	0.113	113	0.083	1

Energy (Force Acting over Distance)

		[N·m]	[W·s]	[ft·lb]	[in·lb]
1 newton-meter [N·m]	=	1	1	0.7376	8.85
1 watt-second [W·s]	=	1	1	0.7376	8.85
1 foot-pound [ft·lb]	=	1.3563	1.3563	1	12
1 inch-pound [in·lb]	=	0.113	0.113	0.083	1

Power (Energy per Unit Time)

		[N·m/s]	[W]	[ft·lb/s]	[in·lb/s]
1 newton-meter per second [N·m/s]	=	1	1	0.7376	8.85
1 watt [W]	=	1	1	0.7376	8.85
1 foot-pound / sec [ft·lb/s]	=	1.3563	1.3563	1	12
1 inch-pound / sec [in·lb/s]	=	0.113	0.113	0.083	1

Pressure (Stress, Force per Unit Area)

		[N/m²]	[Pa]	[hPa]	[torr]	[psi] [lb/in²]
1 newton per square meter [N/m²]	=	1	1	0.01	750.1 x 10^{-5}	14.50 x 10^{-5}
1 pascal [Pa]	=	1	1	0.01	750.1 x 10^{-5}	14.50 x 10^{-5}
1 Hectopascal [hPa]	=	100	100	1	0.7501	14.50 x 10^{-3}
1 torr [torr]	=	133	133	1.33	1	19.34 x 10^{-3}
1 pound per square inch [lb/in²] = [psi]	=	689.5	689.5	6.895	51.71	1

Illumination

	[lm/m²]	[lm/ft²]
1 lux [lm/m²]	1	0.0929
foot-candle [lm/ft²]	10.76	1

Temperature

	[K]	[°C]	[°F]
kelvin [K]	1	K - 273.16	K · (9/5) - 459.688
degree Centigrade [°C]	°C+273.16	1	(°C + 40) · (9/5) - 40
degree Fahrenheit [°F]	(°F + 459.688) · 5/9	(°F + 40) · (5/9) - 40	1

**The names and abbreviations of certain units of force conflict with those of certain units of mass. Which is meant can usually be determined by the context. For example, when it is stated that a Hexapod can tolerate a load of 200 kg vertically, kilograms of force are meant, but when it is a question of moving a 20 g load at 2 kHz, grams of mass are meant.*

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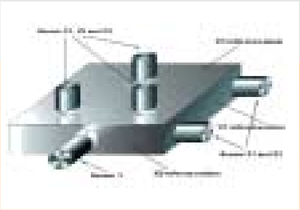
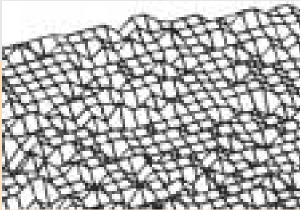
Technologies that set PI apart:

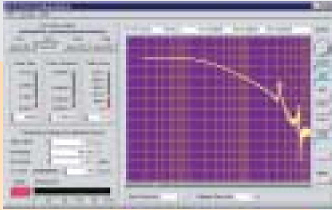
Parallel Kinematics Multi-Axis Micro- & Nano-positioning Systems
reduced inertia, faster response, more compact, higher stiffness, no accumulation of errors, no moving cables (no friction), parallel metrology (higher multi-axis precision).



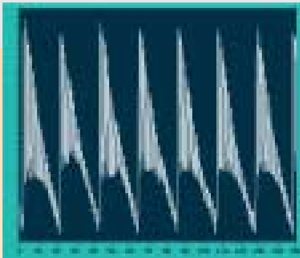
Parallel Metrology
monitors all controlled degrees of freedom simultaneously; allows active trajectory control.



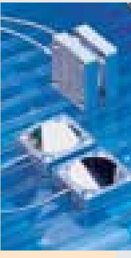
Active Trajectory Control
allows active elimination of runout and off-axis errors to sub-nanometer and sub-microradian precision.



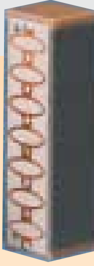
Dynamic Digital Linearization
reduces phase lag and non-linearity in high-speed positioning, scanning and tracking applications. Improves effective bandwidth up to 3 orders of magnitude.



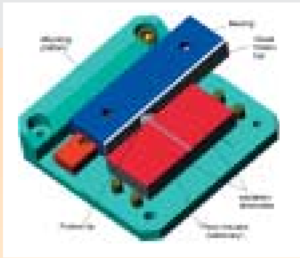
InputShaping®
Eliminates self-generated ringing of components inside and outside the servo-loop. Allows settling within one period of the resonant frequency.



Capacitive Sensors
Non-contact, absolute measuring devices providing sub-nanometer resolution, very high linearity and high bandwidth. Excellent for parallel-metrology configurations.



PICMA® Technology
A new monolithic piezo actuator design with all-ceramic insulation, insensitive to humidity and providing significantly higher reliability, lifetime and operating temperature ranges than conventional piezo actuators. Ideal for vacuum applications.



PI*line*™ Piezo Motors
are based on a novel solid-state ultrasonic piezo-ceramic drive. They are lightweight, low-profile and provide a number of advantages over conventional motors, such as negligible EMI, ultra-fast response, auto-locking, zero-backlash and excellent power-to-weight ratio.

PI—History of Innovation

The following examples emphasize PI's four decades of innovation in micro- and nanopositioning technology

70's

- First commercially available piezo translators
- First PZT translators with integrated preload for industrial reliability

80's

- First commercially available closed-loop piezo actuators
- First flexure-guided piezo-driven nanopositioning systems
- First hybrid multiaxis fiber alignment systems
- First preloaded actuators with monolithic low-voltage PZTs
- Nanopositioning systems with PC interface
- First closed-loop, image stabilization platforms

90's

- First flexure-guided, high-speed nano-focus device
- First two-plate capacitive sensors / controllers w/ integrated linearization for sub-nanometer precision
- First parallel kinematics multiaxis piezo nanopositioning stage with integrated parallel metrology
- First piezoelectrically driven high-speed tool servo
- PI becomes the first nanopositioning systems supplier with piezoceramics-manufacturing capabilities
- First sub-micron 6-DOF Hexapod
- First fully automated fiber alignment system with high-resolution PiezoWalk™ drive (10 nm)
- First piezo stage with 6D active trajectory control
- First fully automated 6-DOF photonics alignment system with virtual pivot point
- First piezo controller with InputShaping® vibration elimination algorithms

2000–

- Patented high-force compact piezomotors
- First 6-axis digital piezo controller
- First piezo controller with dynamic linearization (improves dynamic linearity by up to 3 orders of magnitude)
- First closed-loop piezo-driven steering mirror with 50 mrad range
- First PICMA® monolithic piezo actuators w/ ceramic insulation for increased lifetime and zero outgassing
- Fastest open-frame, closed-loop XY nanopositioning stage
- Lowest out-of-plane motion nanopositioning stages (< 1 nm)

With over four decades experience, PI has evolved into the world-leading supplier of nanopositioning technology.

*In the **70's,** when space exploration spurred new research in optics, PI introduced piezo actuators to help scientists control motion to sub-micron levels.*

*In the **80's,** when the introduction of microcomputers created the first semiconductor boom and the need for smaller and smaller feature sizes, PI nanopositioning systems were ready to take on the challenge.*

*The fall of the Berlin wall in the **90's** marked the end of the cold war and the beginning of a new age of borderless communications. It also meant the beginning of a new age for PI: the start of the piezoceramic division PI Ceramic.*

*The new **millennium** saw worldwide efforts advancing fiber-optic technologies, nanotechnology and biotechnology, fields where "smaller" and "more precise" is the key to success. PI is there to lead the way with faster and higher-performance motion control systems.*

Nanopositioning, Nanomechanics Leadership

PI has been developing and manufacturing products in the field of nanomechanics and nanotechnology for more than 30 years. During this time, we have achieved and continually consolidated our position as a global market leader. Prime examples of our core competencies and cutting-edge technology are to be found in the development of parallel kinematics—integrated 6-axis positioners based on the Hexapod—and in the field of nanopositioning with piezoceramic actuators.

PI employs more than 300 staff worldwide and maintains sales, support and service offices in Germany, the USA, England, France, Italy, Japan and China with nanometrology capabilities on three continents. PI is represented in many countries around the world.

At the Heart of our Systems: the Piezo Effect

One small step for Pierre Curie—one great leap for the world. The piezo effect—Pierre Curie's discovery of about a hundred years ago—now forms the basis of the smallest mechanical, electronic or control-technology products. When voltage is applied to piezoelectric crystals or ceramics, they expand. We exploit this effect to create positioning systems with nanometer accuracy.

PI Products—Innovation & Superior Quality

PI has been ISO 9001 certified since 1994. Our products are characterized by their quality and innovation. Developed to give the highest degree of precision, we employ the most-modern tools and software for product development like FEM calculations and simulations. To determine the performance level of our products, we had to design equipment capable of resolving to fractions of a nanometer, pushing measurement accuracies to the limit.

Precision Advances

Over the years we have seen many technological advances make the transition from the laboratory to daily life, advances requiring the utmost in positioning accuracy, advances inconceivable without PI. Finer and finer structures on semiconductor wafers for cost-effective mass-production of high-performance electronics, or higher and higher density in telecommunications streams with millisecond switching from network to network, all in the minimum amount of space: this is where PI is at home.

PI's Customers

PI customers come from all sectors of manufacturing, quality assurance, research and development. And they are spread across many branches of industry:

- Astronomy
- Semiconductors
- Semiconductor Test Systems
- Medical Engineering
- Bio- / Nanotechnology
- Telecommunications
- Precision Engineering
- Aerospace Engineering

PI's customers even include national standardization institutes.

As our customer, you also profit from our more than 30 years' experience in micro- and nanopositioning technology. You will join an ever-increasing number of renowned companies and institutes whose products are at the cutting edge of innovation, research and technology. PI moves the nanoworld.

PI USA. The east coast office in Auburn, MA, also hosts a service department with nano metrology equipment.

PI Headquarters, Karlsruhe, Germany. PI employs the world's most experienced design and manufacturing teams for nanopositioning and nanomechanics products.

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Section 1

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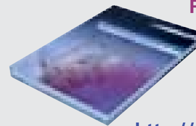
Section 3

Capacitive Position Sensors
Section 5

Motion Controllers for NanoPositioners
(Piezo Controllers, Drivers, Power Amplifers)
Section 6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Photonics Alignment & Packing Systems
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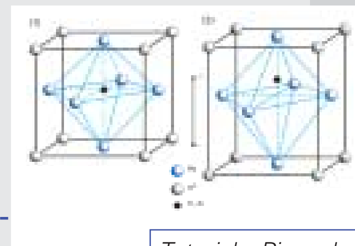
Tutorial—Piezoelectrics in Positioning
Section 4

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