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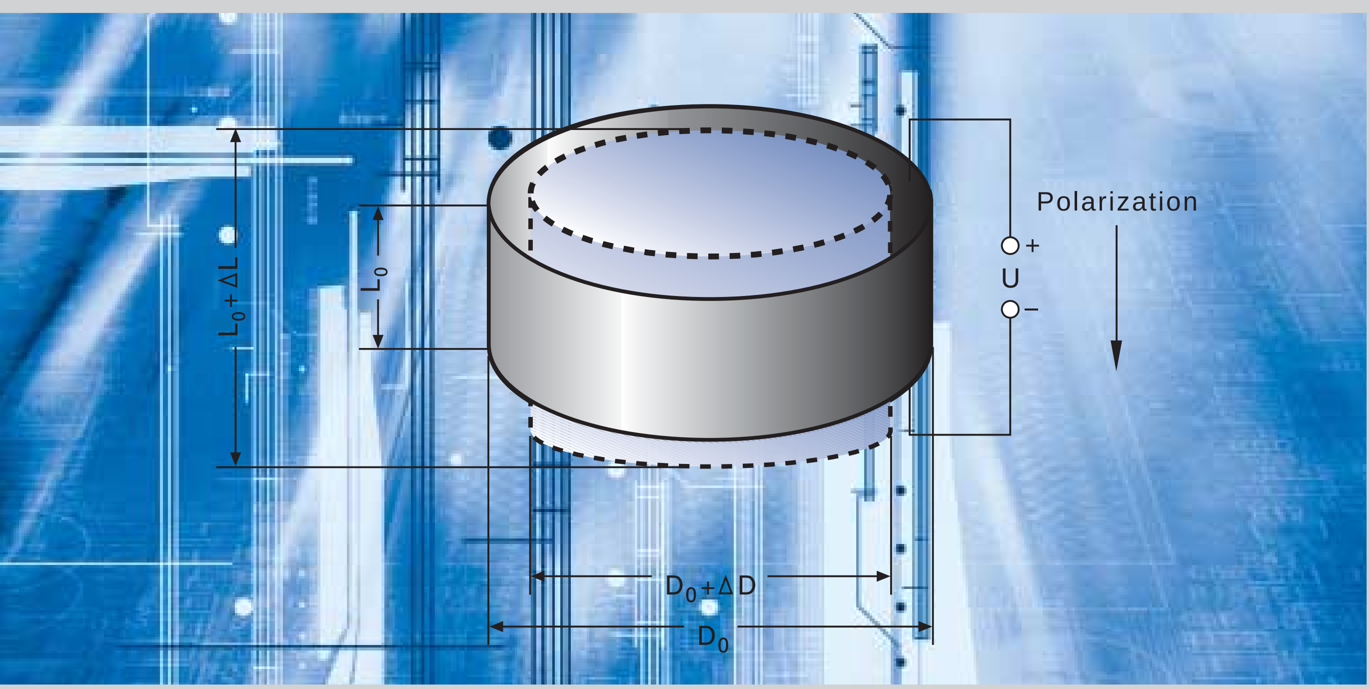
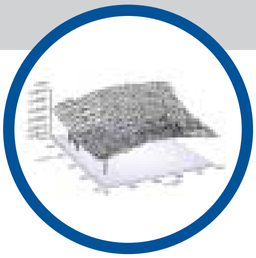
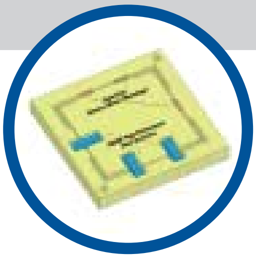
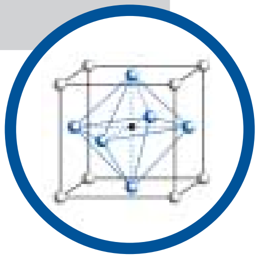
Designing with Piezoelectric Transducers: Nanopositioning Fundamentals

09/2005









Contents

Tutorial: Piezoelectric Transducers / Actuators in Positioning

Properties / Applications

Features of Piezoelectric Positioning Systems

Unlimited Resolution

Piezoelectric actuators convert electrical energy directly to mechanical energy. They make motion in the sub-nanometer range possible. There are no moving parts in contact with each other to limit resolution.

Fast Expansion

Piezo actuators react in a matter of microseconds. Acceleration rates of more than 10,000 g can be obtained.

High Force Generation

High-load piezo actuators capable of moving loads of several tons are available today. They can cover travel ranges of several 100 µm with resolutions in the sub-nanometer range (see examples like the P-056, in the "Piezo Actuators" section).

No Magnetic Fields

The piezoelectric effect is related to electric fields. Piezo 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.

Low Power Consumption

Static operation, even holding heavy loads for long periods, consumes virtually no power. A piezo actuator behaves very much like an electrical capacitor. When at rest, no heat is generated.

No Wear and Tear

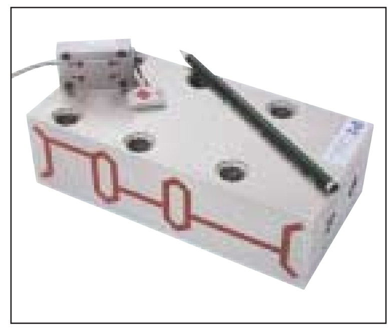
A piezo actuator has no moving parts like gears or bearings. Its displacement is based on solid state dynamics and shows no wear and tear. PI has conducted endurance tests on piezo actuators in which no measurable change in performance was observed after several billion cycles.

Vacuum and Clean Room Compatible

Piezoelectric actuators neither cause wear nor require lubricants. The new PICMA® actuators with ceramic insulation have no polymer coating and are thus ideal for UHV (ultra-high vacuum) applications.

Operation at Cryogenic Temperatures

The piezoelectric effect continues to operate even at temperatures close to 0 kelvin. PI offers specially prepared actuators for use at cryogenic temperatures.



Piezoelectric nano positioners, large (e.g. for precision machining), medium (e.g. for interferometry), small (e.g. for data storage medium testing)

Applications for Piezoelectric Positioning Technology

Data Storage

- MR head testing
- Spin stands
- Disk testing
- Active vibration cancellation
- Pole-tip recession test

Semiconductors, Microelectronics

- Nano & Microlithography
- Nanometrologie
- Wafer and mask positioning
- Critical-dimension-test
- Inspection systems
- Active vibration cancellation

Precision Mechanics

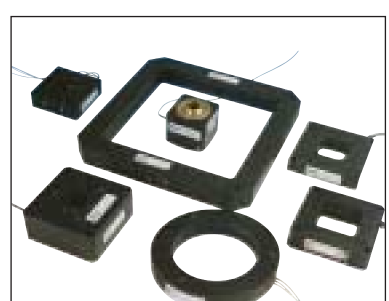
- Fast tool servos
- Non-circular grinding, drilling, turning
- Active vibration cancellation
- Structural deformation
- Tool adjustment
- Wear compensation
- Needle-valve actuation
- Micropumps
- Linear drives
- Knife edge control in extrusion tools
- Micro engraving systems
- Shock wave generation

Life Science, Medical Technology

- Scanning microscopy
- Patch clamp
- Nanoliter pumps
- Gene manipulation
- Micromanipulation
- Cell penetration
- Microdispensers

Optics, Photonics, Nanometrologie

- Scanning mirrors
- Image stabilization, pixel multiplication
- Scanning microscopy
- Auto focus systems
- Interferometry
- Fiber optic alignment
- Fiber optics switching
- Adaptive and active optics
- Laser tuning
- Stimulation of vibrations



Selection of piezo nanopositioning stages

Glossary

See also the Micropositioning Glossary, p. 7-12.

Actuator:
A device that can produce force or 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 displacement of the actuator is corrected by a servo-controller compensating for nonlinearity, hysteresis and creep. See also "Open-Loop Operation".

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

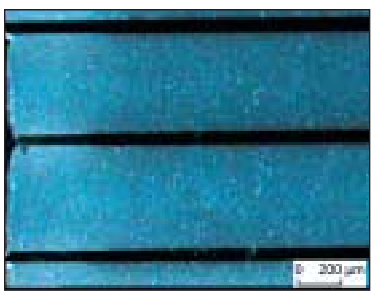
Creep:
An unwanted change in the displacement over time.

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

Drift:
See "creep"

Domain:
A region of electric dipoles with similar orientation.

HVPZT:
Acronym for High-Voltage PZT (actuator).

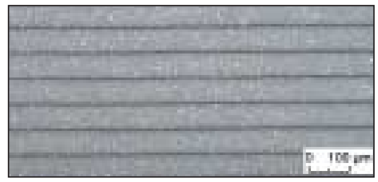


Piezoceramic layers in a "classical" stack actuator (HVPZT).

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

Equipment for fully automated screen printing of electrodes on piezoelectric and dielectric ceramics.

LVPZT:
Acronym for low-voltage PZT (actuator).

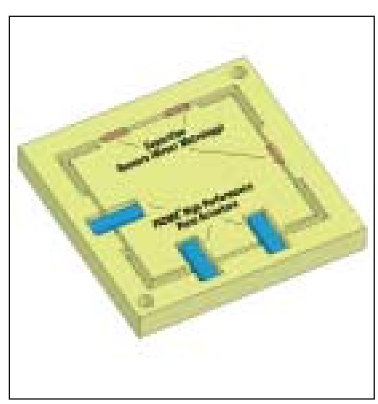


Piezoceramic layers in a monolithic actuator (LVPZT).

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

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

Parallel Kinematics:
Unlike in serial kinematics designs, all actuators act upon the same moving platform. Advantages: Minimized inertia, no moving cables, lower center of gravity, no cumulative guiding errors and more-compact construction.



Nanopositioning system featuring parallel kinematics and parallel metrology.

Glossary

Parallel Metrology:

Unlike in serial metrology designs, each sensor measures the position of the same moving platform in the respective degree of freedom. This keeps the off-axis runout of all actuators inside the servo-control loop and allows it to be corrected automatically (active guidance).

Piezoelectric Materials:

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

Poling / Polarization:

The procedure by which the bulk material is made to take on piezoelectric properties, i.e. the electrical alignment of the unit cells in a piezoelectric material.

PZT:

Acronym for plumbum (lead) zirconate titanate. Polycrystalline ceramic material with piezoelectric properties. Often also used to refer to a piezo actuator or translator.

Serial Kinematics:

Unlike in parallel kinematics designs, each actuator acts upon a separate platform of its own. There is a clear relationship between actuators and axes.

Advantages: Simpler to assemble; simpler control algorithm.

Disadvantages: Poorer dynamic characteristics, integrated "Parallel Metrology" is not possible, cumulative guiding errors, lower accuracy.

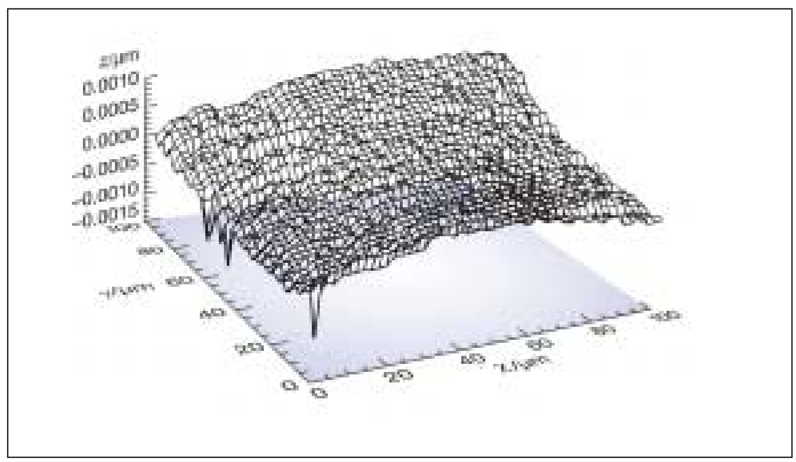
Design principle of a stacked XY piezo stage (serial kinematics).

Serial Metrology:

One sensor is assigned to each degree of freedom to be servo-controlled. Undesired off-axis motion (guiding error) from other axes in the direction of a given sensor, go unrecognized and uncorrected (see also "Parallel Metrology").

Stiffness:

Spring constant (for piezoelectric materials, not linear).



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

Trajectory-Control:

Provisions to prevent deviation from the specified trajectory. Can be passive (e.g. flexure guidance) or active (e.g. using additional active axes).

Translator:

A linear actuator.

Symbols and Units

A	Surface area [m^2] (meter^2)
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/second^2)
i	Current [A] (ampere)
k_S	Stiffness of restraint (load) [N/m] (newton/meter)
k_T	Stiffness of piezo actuators [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 x second)
S	Strain [$\Delta L/L$] (dimensionless)
t	Time [s] (second)
T_c	Curie temperature [°C]
U	Voltage [V] (volt)
$U_{p\text{-}p}$	Peak-to-peak voltage [V] (volt)

Introduction

Nanopositioning with Piezoelectric Technology

Basics

The piezoelectric effect is often encountered in daily life, for example in lighters, loudspeakers and buzzers. In a gas lighter, pressure on a piezoceramic generates an electric potential high enough to create a spark. Most electronic alarm clocks do not use electromagnetic buzzers anymore, because piezoelectric ceramics are more compact and more efficient. In addition to such simple applications, piezo technology has recently established itself in the automotive branch. Piezo-driven injection valves in diesel engines require much lower transition times than conventional electromagnetic valves, providing quieter operation and lower emissions.

The term "piezo" is derived from the Greek word for pressure. In 1880 Jacques and Pierre Curie discovered that an electric potential could be generated by applying pressure to quarz crystals; they named this phenomenon the "piezo effect". Later they ascertained that when exposed to an electric potential, piezoelectric materials change shape. This they named the "inverse piezo effect". The first commercial applications of the inverse piezo effect were for sonar systems that were used in World War I. A breakthrough was made in the 1940's when scientists discovered that barium titanate could be bestowed with piezoelectric properties by exposing it to an electric field.

Features of Piezoelectric Actuators

- Piezo actuators can perform sub-nanometer moves at high frequencies because they derive their motion from solid-state crystaline effects. They have no rotating or sliding parts to cause friction
- Piezo actuators can move high loads, up to several tons
- Piezo actuators present capacitive loads and dissipate virtually no power in static operation
- Piezo actuators require no maintenance and are not subject to wear because they have no moving parts in the classical sense of the term

Piezoelectric materials are used to convert electrical energy to mechanical energy and vice-versa. The precise motion that results when an electric potential is applied to a piezoelectric material is of primordial importance for nanopositioning. Actuators using the piezo effect have been commercially available for 35 years and in that time have transformed the world of precision positioning and motion control.

Quick Facts

Actuator Designs

Note

This section gives a brief summary of the properties of piezoelectric drives and their applications. For detailed information, see "Fundamentals of Piezoelectricity" beginning on p. 4-13.

Stack actuators are the most common and can generate the highest forces. Units with travel ranges up to 500 µm are available. To protect the piezoceramic against destructive external conditions, they are often provided with a metal casing and an integrated preload spring to absorb tensile forces.

Piezo tube actuators exploit the radial contraction direction, and are often used in scanning microscopes and micropumps.

Bender and bimorph actuators achieve travel ranges in the millimeter range (despite their compact size) but with relatively low force generation (a few newtons).

Shear elements use the inverse-piezo-effect shear component and achieve long travel and high force.

For more information, see pp. 4-39 *ff.*

Guided piezo actuators (1 to 6 axes) are complex nanopositioners with integrated piezo drives and solid-state, friction-free linkages (flexures). They are used when requirements like the following need be met:

- Extremely straight and flat motion, or multi-axis motion with accuracy requirements in the sub-nanometer or sub-microradian range
- Isolation of the actuator from external forces and torques, protection from humidity and foreign particles

Such systems often also include lever amplification of up to 20 times the displacement of the piezo element, resulting in a travel range of several hundred µm.

Piezomotors are used where even longer travel ranges are required. Piezomotors can be divided into two main categories:

- Ultrasonic Motors (Fig. 2a)
- Piezo-Walk® Motors (Fig. 2b)

The motion of ultrasonic piezomotors is based on the friction between parts oscillating with microscopic amplitudes. Linear ultrasonic motors are very compact and can attain high speeds combined with resolutions of 0.1 µm or better. Rotary motors feature high torques even at low rpm.

Piezo-Walk® linear drives (see p. 10-3 *ff.*) offer high positioning and holding forces (up to hundreds of newtons) with moderate speeds and resolutions in the subnanometer range.

All implementations are self-locking when powered down.

Fig. 1a. Selection of classical piezo stack actuators, with adhesive used to join the layers.

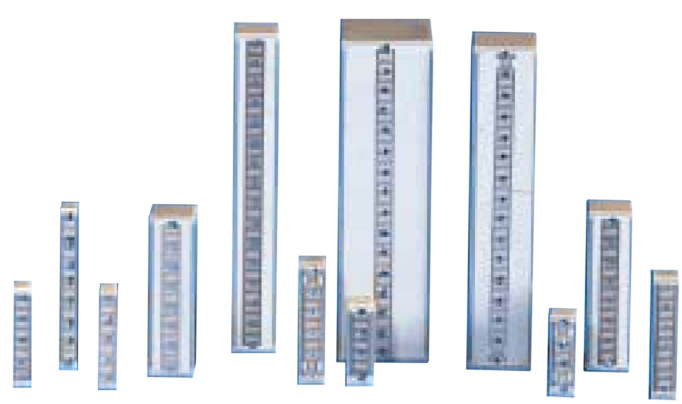


Fig. 1b. Selection of monolithic PICMA ® technology actuators.

Operating Characteristics of Piezoelectric Actuators

Operating Voltage

Two types of piezo actuators have become established. Monolithic-sintered, low-voltage actuators (LVPZT) operate with potential differences up to about 100 V and are made from ceramic layers from 20 to 100 µm in thickness. Classical high-voltage actuators (HVPZT), on the other hand, are made from ceramic layers of 0.5 to 1 mm thickness and operate with potential differences of up to 1000 V. High-voltage actuators can be made with larger cross-sections, making them suitable for larger loads than the more-compact, monolithic actuators.

Stiffness, Load Capacity, Force Generation

To a first approximation, a piezo actuator is a spring-and-mass system. The stiffness of the actuator depends on the Young's modulus of the ceramic (approx. 25 % that of steel), the cross-section and length of the active material and a number of other non-linear parameters (see p. 4-21). Typical actuators have stiffnesses between 1 and 2,000 N/µm and compressive limits between 10 and 100,000 N. If the unit will be exposed to pulling (tensile) forces, a casing with integrated preload or an external preload spring is required. Adequate measures must be taken to protect the piezoceramic from shear and bending forces and from torque.

Travel Range

Travel ranges of Piezo Actuators are typically between a few tens and a few hundreds of µm (linear actuators). Bender actuators and lever amplified systems can achieve a few mm. Ultrasonic piezomotors and Piezo-Walk® drives can be used for longer travel ranges.

Resolution

Piezoceramics are not subject to the "stick slip" effect and therefore offer theoretically unlimited resolution. In practice, the resolution actually attainable is limited by electronic and mechanical factors:

a) Sensor and servo-control electronics (amplifier): amplifier noise and sensitivity to electromagnetic interference (EMI) affect the position stability.

b) Mechanical parameters: design and mounting precision issues concerning the sensor, actuator and preload can induce micro-friction which limits resolution and accuracy.

PI offers piezo actuators and positioning systems that provide sub-nanometer resolution and stability. For more information, see pp. 4-15 *ff.*

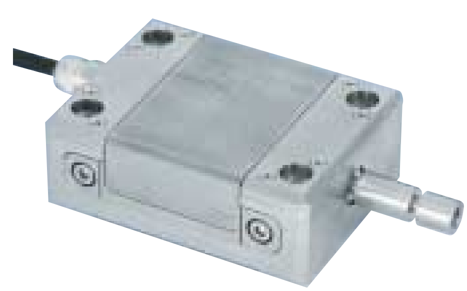


Fig. 2b. Custom linear drive with integrated NEXLINE® Piezo-Walk® piezomotor.

Fig. 2a. Ultrasonic linear piezo-motors.

Fig. 3. Example of a compact piezo nanopositioning and scanning system with integrated flexure guidance, sensor and motion amplifier.

Quick Facts (cont.)

Open- and Closed-Loop Operation

In contrast to many other types of drive systems, piezo actuators can be operated without servo-control. The displacement is approximately equal to the drive voltage. Hysteresis, nonlinearity and creep effects limit the absolute accuracy. For positioning tasks which require high linearity, long-term stability, repeatability and absolute accuracy, closed-loop (servo-controlled) piezo actuators and systems are used (see p. 4-31). With suitable controllers, closed-loop operation enables reproducibilities in the sub-nanometer range.

High-Resolution Sensors for Closed-Loop Operation

LVDT (linear variable differential transformer), strain gauge and capacitive sensors are the most common sensor types used for closed-loop operation. Capacitive sensors offer the greatest accuracy. For more information, see p. 4-19 *ff.*

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 are possible. This feature makes piezo actuators suitable for rapid switching applications such as controlling injector nozzle valves, hydraulic valves, electrical relays, optical switches and adaptive optics. For more information, see pp. 4-24 *ff.*

Power Requirements

Piezo actuators behave as almost pure capacitive loads. Static operation, even holding heavy loads, consumes virtually no power. In dynamic applications the energy requirement increases linearly with frequency and actuator capacitance. At 1000 Hz with 10 µm amplitude, a compact piezo translator with a load capacity of approx. 100 N requires less than 10 W, while a high-load actuator (> 10 kN capacity) would use several hundred watts under the same conditions. For more information, see pp. 4-27 *ff.*

Protection from Mechanical Damage

PZT ceramics are brittle and cannot withstand high pulling or shear forces. The mechanical actuator design must thus isolate these undesirable forces from the ceramic. This can be accomplished by measures such as spring preloads, use of ball tips, flexible couplings, etc. (for more mounting guidelines, see p. 4-48). In addition, the ceramics must be protected from moisture and the intrusion of foreign particles. Close contact between the piezo mechanics manufacturer and the user facilitates finding an optimal match between the piezo system and the application environment.

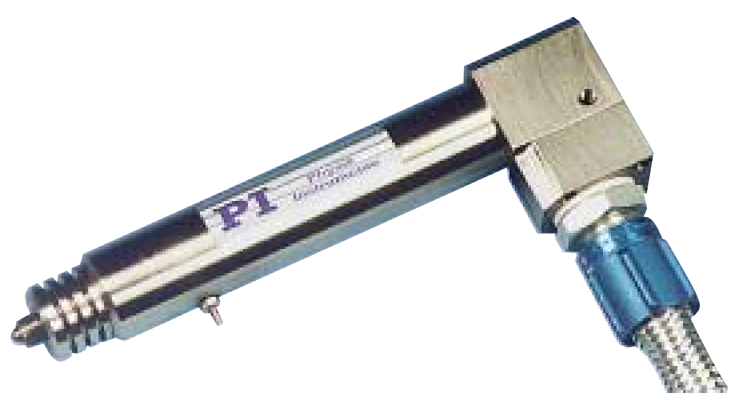


Fig. 4. Piezo actuator with water-proof case and connection for flushing/cooling air.

Fundamentals of Piezoelectricity

Material Properties

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Nanopositioning & Scanning Systems
Active Optics / Steering Mirrors
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Notes

The following pages give a detailed look at piezo actuator theory and their operation. For basic knowledge read "Quick Facts", p. 4-10. For definition of units, dimensions and terms, see "Symbols and Units", p. 4-7 and "Glossary", p. 4-5.

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.

PZT ceramics (piezoceramics) are available in many variations and are still the most widely used materials for actuator applications today.
Before polarization, PZT crystallites have symmetric cubic unit cells. At temperatures below the Curie temperature, the lattice structure becomes deformed and asymmetric. The unit cells exhibit spontaneous polarization (see Fig. 5), i.e. the individual PZT crystallites are piezoelectric.

Groups of unit cells with the same orientation are called Weiss domains. Because of the random distribution of the domain orientations in the ceramic material no macroscopic piezoelectric behavior is observable. Due to the ferroelectric nature of the material, it is possible to force permanent alignment of the different domains using a strong electric field. This process is called poling (see Fig. 6). Some PZT ceramics must be poled at an elevated temperature. The material now has a remnant polarization (which can be degraded by exceeding the mechanical, thermal and electrical limits of the material). The ceramic now exhibits piezoelectric properties and will change dimensions when an electric potential is applied.

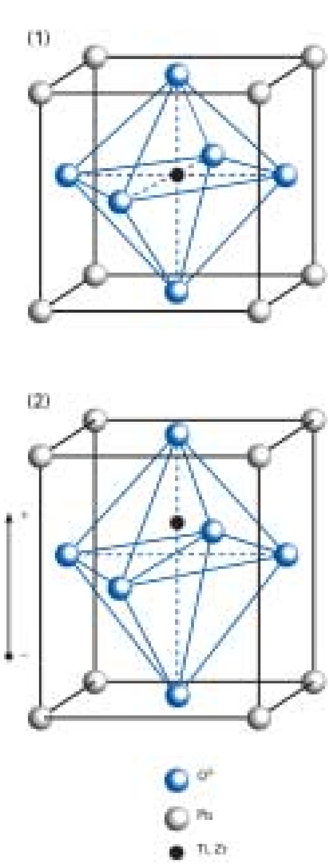

Fig. 5. PZT unit cell:
1) Perovskite-type lead zirconate titanate (PZT) unit cell in the symmetric cubic state above the Curie temperature.
2) Tetragonally distorted unit cell below the Curie temperature.

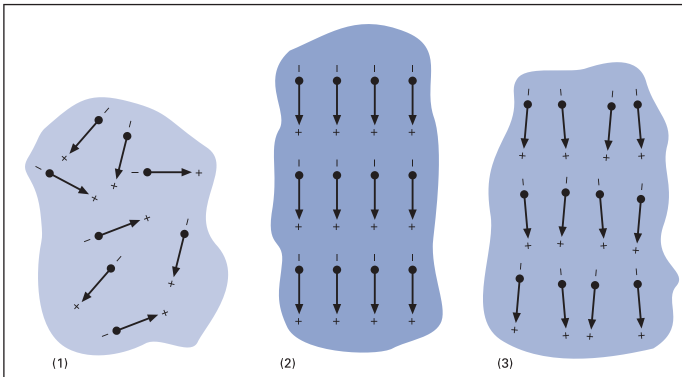

Fig. 6. Electric dipoles in domains; (1) unpoled ferroelectric ceramic, (2) during and (3) after poling (piezoelectric ceramic).

Fundamentals of Piezoelectricity

PZT Ceramics Manufacturing Process

PI develops and manufactures its own piezo ceramic materials at the PI Ceramic factory. The manufacturing process for high-voltage piezoceramic starts with mixing and ball milling of the raw materials. Next, to accelerate reaction of the components, the mixture is heated to 75 % of the sintering temperature, and then milled again. Granulation with the binder is next, to improve processing properties. After shaping and pressing, the green ceramic is heated to about 750 °C 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. Only here does the ceramic take on macroscopic piezoelectric properties.

Multilayer piezo actuators require a different manufacturing process. After milling, a slurry is prepared for use in a foil casting process which allows layer thickness down to 20 µm. Next, electrodes are screen printed and the sheets 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 deviation will affect the quality and properties of the PZT material. One hundred percent final testing of the piezo material and components at PI Ceramic guarantees the highest possible product quality.

Sputtering facility at PI Ceramic.

Definition of Piezoelectric Coefficients and Directions

Because of the anisotropic nature of PZT ceramics, piezoelectric effects are dependent on direction. 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 linear actuator (translator) 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 ε_r the relative dielectric coefficients (permittivity).

Double subscripts, as in d_{ij}, are used to describe the relationships between mechanical and electrical parameters. The first index indicates the direction of the stimulus, the second the direction of the reaction of the system.

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 deflection of interest is that along axis 1 (orthogonal to the polarization axis).

In addition the superscripts S, T, E, D can be used to describe an electrical or mechanical boundary condition.

Definition:

S for strain = constant (mechanically clamped)

T for stress = constant (not clamped)

E for field = 0 (short circuit)

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

The individual piezoelectric coefficients are related to each other by systems of equations that will not be explained here.

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Notes

The piezoelectric coefficients described here are often presented as constants. It should be clearly understood that their values are not invariable. The coefficients describe material properties under small-signal conditions only. They vary with temperature, pressure, electric field, form factor, mechanical and electrical boundary conditions, etc. Compound components, such as piezo stack actuators, let alone preloaded actuators or lever-amplified systems, cannot be described sufficiently by these material parameters alone. This is why each component or system manufactured by PI is accompanied by specific data such as stiffness, load capacity, displacement, resonant frequency, etc., determined by individual measurements. The parameters describing these systems are to be found in the technical data table for the product.

Important: There are no international standards for defining these specifications. This means that claims of different manufacturers can not necessarily be compared directly with one another.

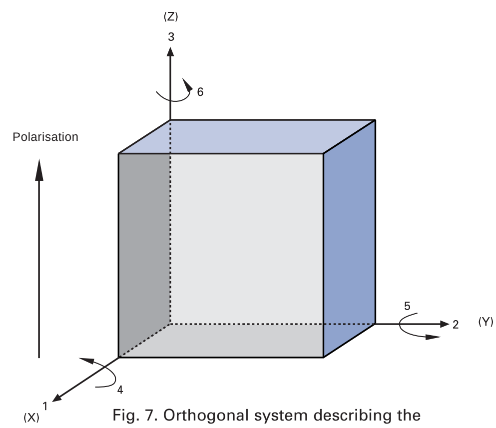

Fig. 7. Orthogonal system describing the properties of a poled piezoelectric ceramic. Axis 3 is the poling direction.

Resolution

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. Resolution is theoretically unlimited. Because there are no threshold voltages, the stability of the voltage source is critical; noise even in the µV range causes position changes. When driven with a low-noise amplifier, piezo actuators can be used in tunneling and atomic force microscopes providing smooth, continuous motion with sub-atomic resolution (see Fig. 8).

Amplifier Noise

One factor determining the position stability (resolution) of a piezo actuator is noise in the drive voltage. Specifying the noise value of the piezo driver electronics in millivolts, however, is of little practical 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 far more significant influence on the system stability.

Therefore, meaningful information about the stability and resolution of a piezo positioning system can only be acquired if the resolution of the complete system—piezo actuator and drive electronics—is measured in terms of nanometers rather than millivolts. For further information see p. 2-8 and p. 4-31 *ff.*

Notes

The smooth motion in the sub-nanometer range shown in Fig. 8 can only be attained by frictionless and stictionless solid state actuators and guidance such as piezo actuators and flexures. "Traditional" technologies used in motion positioners (stepper or DC servo-motor drives in combination with dovetail slides, ball bearings, and roller bearings) all have excessive amounts of friction and stiction. This fundamental property limits resolution, causes wobble, hysteresis, backlash, and an uncertainty in position repeatability. Their practical usefulness is thus limited to a precision of several orders of magnitude below that obtainable with PI piezo nanopositioners.

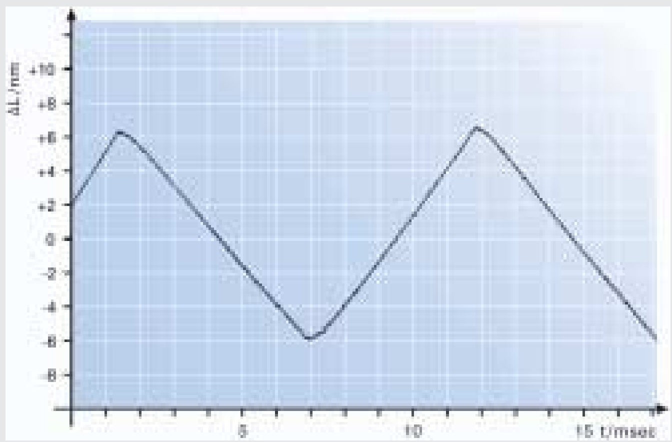

Fig. 8. Smooth response of a P-170 HVPZT translator to a 1 V, 200 Hz triangular drive signal. Note that one division is only 2 nanometers.

Fundamentals of Piezomechanics

Displacement of Piezo Actuators (Stack & Contraction Type)

Commonly used stack actuators achieve a relative displacement of up to 0.2 %. Displacement of piezoceramic actuators is primarily a function of the applied electric field strength E, the length L of the actuator, the forces applied to it and the properties of the piezoelectric material used. The material properties can be described by the piezoelectric strain coefficients d_{ij}. These coefficients describe the relationship between the applied electric field and the mechanical strain produced.

The change in length, ΔL, of an unloaded single-layer piezo actuator can be estimated by the following equation:

(Equation 1)

$$\Delta L = S \cdot L_0 \approx \pm E \cdot d_{ij} \cdot L_0$$

Where:

S = *strain (relative length change ΔL/L, dimensionless)*
L_0 = *ceramic length [m]*
E = *electric field strength [V/m]*
d_{ij} = *piezoelectric coefficient of the material [m/V]*

d_{33} describes the strain parallel to the polarization vector of the ceramics (thickness) and is used when calculating the displacement of stack actuators; d_{31} is the strain orthogonal to the polarization vector (width) and is used for calculating tube and strip actuators (see Fig. 9). d_{33} and d_{31} are sometimes referred to as "piezo gain".

Notes

For the materials used in standard PI piezo actuators, d_{33} is on the order of 250 to 550 pm/V, d_{31} is on the order of -180 to -210 pm/V. The highest values are attainable with shear actuators in d_{15} mode. These figures only apply to the raw material at room temperature under small-signal conditions.

The maximum allowable field strength in piezo actuators is between 1 and 2 kV/mm in the polarization direction. In the reverse direction (semi-bipolar operation), at most 300 V/mm is allowable (see Fig. 10). The maximum voltage depends on the ceramic and insulation materials.

Exceeding the maximum voltage may cause dielectric breakdown and irreversible damage to the piezo actuator.

With the reverse field, negative expansion (contraction) occurs, giving an additional 20 % of the nominal displacement. If both the regular and reverse fields are used, a relative expansion (strain) up to 0.2 % is achievable with piezo stack actuators. This technique can reduce the average applied voltage without loss of displacement and thereby increase piezo lifetime.

Stacks can be built with aspect ratios up to 12:1 (length:diameter). This means that the maximum travel range of an actuator with 15 mm piezo diameter is limited to about 200 µm. Longer travel ranges can be achieved by mechanical amplification techniques (see "Lever Motion Amplifiers" p. 4-42).

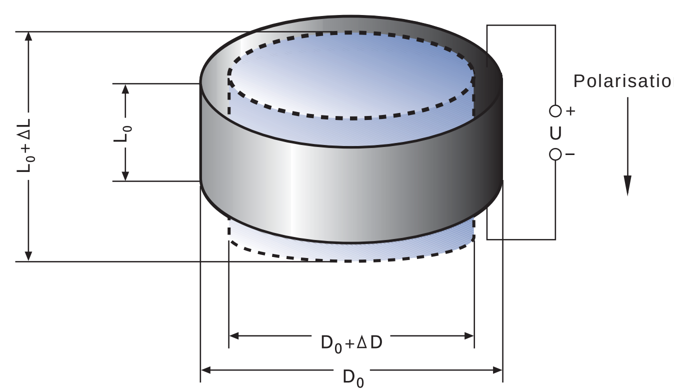

Fig. 9. Expansion and contraction of a piezoelectric disk in response to an applied voltage. Note that d_{31}, which describes the lateral motion, ΔD, is negative.

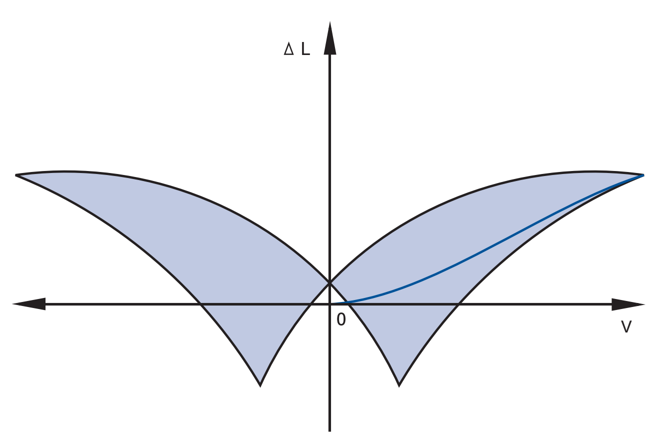

Fig. 10. Typical response of a "soft PZT" actuator to a bipolar drive voltage. When a certain threshold voltage negative to the polarization direction is exceeded, reversal of polarization can occur.

Note:

PI piezo actuators and stages are designed for high reliability in industrial applications. The travel, voltage and load ranges in the technical data tables can actually be used in practice. They have been collected over many years of experience in piezo actuator production and in numerous industrial applications.

In contrast to many other piezo suppliers, PI has its own piezo ceramic development and production facilities together with the necessary equipment and knowhow. The goal is always reliability and practical usefulness. Maximizing isolated parameters, such as expansion or stiffness, at the cost of piezo lifetime might be interesting to an experimenter, but has no place in practical application.

When selecting a suitable piezo actuator or stage, consider carefully the fact that "maximum travel" may not be the only critical design parameter.

Hysteresis (Open-Loop Piezo Operation)

Hysteresis is observable in open-loop operation; it can be reduced by charge control and virtually eliminated by closed-loop operation (see pp. 4-31 *ff.*).

Open-loop piezo actuators exhibit hysteresis in their dielectric and electromagnetic large-signal behavior. Hysteresis is based on crystalline polarization effects and molecular effects within the piezoelectric material.
The amount of hysteresis increases with increasing voltage (field strength) applied to the actuator. The "gap" in the voltage/displacement curve (see Fig. 11) typically begins around 2 % (small-signal) and widens to a maximum of 10 % to 15 % under large-signal conditions. The highest values are attainable with shear actuators in d_{15} mode.

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 % of full travel or better than 1 µm.

The smaller the move, the smaller the uncertainty. Hysteresis must not be confused with the backlash of conventional mechanics. Backlash is virtually independent of travel, so its relative importance increases for smaller moves.

For tasks where it is not the absolute position that counts, hysteresis is of secondary importance and open-loop actuators can be used, even if high resolution is required.

In 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 pp. 4-31 *ff.*).

Example: Piezoelectrically driven fiber aligners and tracking systems derive the control signal from an optical power meter in the system. There, the goal is to maximize the optical signal level as quickly as possible, not to attain a predetermined position value. An open-loop piezo system is sufficient for such applications. Advantages like unlimited resolution, fast response, zero backlash and zero stick/slip effect are most welcome, even without position control.

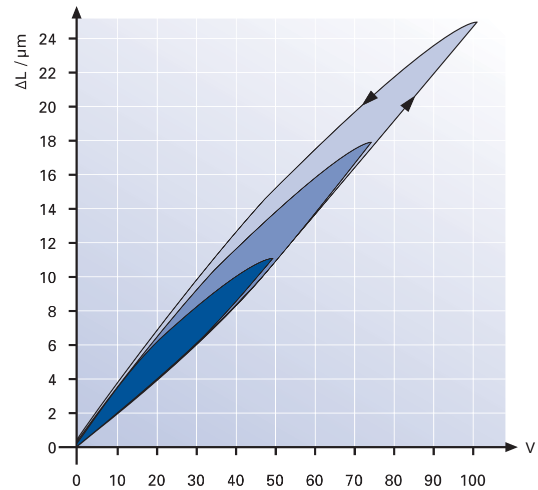

Fig. 11. Hysteresis curves of an open-loop piezo actuator for various peak voltages. The hysteresis is related to the distance moved, not to the nominal travel range.

Fundamentals of Piezomechanics

Creep / Drift (Open-Loop Piezo Operation)

The same material properties responsible for hysteresis also cause creep or drift. Creep is a change in displacement with time without any accompanying change in the control voltage. If the operating voltage of a piezo actuator is changed, the remnant polarization (piezo gain) continues to change, manifesting itself in a slow change of position. The rate of creep decreases logarithmically with time (see Fig. 12). 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:

t	=	*time [s]*
$\Delta L(t)$	=	*change in position as a function of time*
$\Delta L_{t=0.1}$	=	*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 time decade).*

In practice, maximum creep (after a few hours) can add up to a few percent of the commanded motion.

Aging

Aging refers to reduction in remnant polarization; it can be an issue for sensor or charge-generation applications (direct piezo effect). 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.

Note

For periodic motion, creep and hysteresis have only a minimal effect on repeatability.

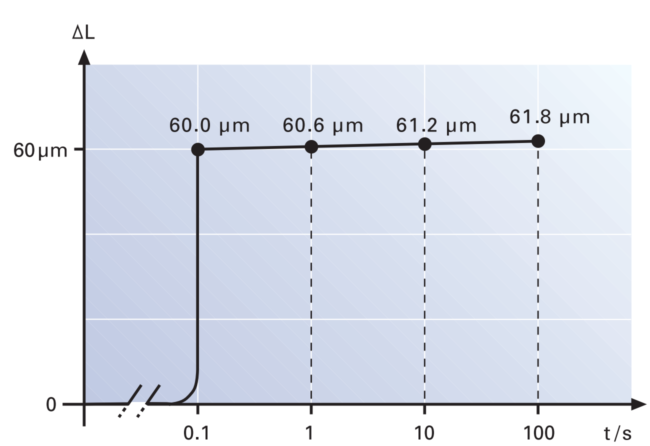

Fig. 12. Creep of open-loop PZT motion after a 60 µm change in length as a function of time. Creep is on the order of 1 % of the last commanded motion per time decade.

Actuators and Sensors

Metrology for Nanopositioning Systems

There are two basic techniques for determining the position of piezoelectric motion systems: Direct metrology and indirect metrology.

Indirect (Inferred) Metrology

Indirect metrology involves inferring the position of the platform by measuring position or deformation at the actuator or other component in the drive train. Motion inaccuracies which arise between the drive and the platform can not be accounted for.

Direct Metrology

With direct metrology, however, motion is measured at the point of interest; this can be done, for example, with an interferometer or capacitive sensor.
Direct metrology is more accurate and thus better suited to applications which need absolute position measurements. Direct metrology also eliminates phase shifts between the measuring point and the point of interest. This difference is apparent in higher-load, multi-axis dynamic applications.

Parallel and Serial Metrology

In multi-axis positioning systems parallel and serial metrology must also be distinguished.

With parallel metrology, all sensors measure the position of the same moving platform against the same stationary reference. This means that all motion is inside the servo-loop, no matter which actuator caused it (see Active Trajectory Control). Parallel metrology and parallel kinematics can be easily integrated.

With serial metrology the reference plane of one or more sensors is moved by one or more actuators. Because the off-axis motion of any moving reference plane is never measured, it can not be compensated.
See also p. 2-5 *ff.*

High-Resolution Sensors

Strain Gauge Sensors

SGS sensors are an implementation of inferred metrology and are typically chosen for cost-sensitive applications. An SGS sensor consists of a resistive film bonded to the piezo stack or a guidance element; the film resistance changes when strain occurs. Up to four strain gauges (the actual configuration varies with the actuator construction) form a Wheatstone bridge driven by a DC voltage (5 to 10 V). When the bridge resistance changes, the sensor electronics converts the resulting voltage change into a signal proportional to the displacement.

A special type of SGS is known as a piezoresistive sensor. It has good sensitivity, but mediocre linearity and temperature stability. See also p. 2-5 *ff.*

Resolution: better than 1 nm (for short travel ranges, up to about 15 µm)

Bandwidth: to 5 kHz

Advantages

- High Bandwidth
- Vacuum Compatible
- Highly Compact

Other characteristics:

- Low heat generation (0.01 to 0.05 W sensor excitation power)
- Long-term position stability depends on adhesive quality
- Indirect metrology

Examples

Most PI LVPZT and HVPZT actuators are available with strain gauge sensors for closed-loop control (see the "Piezo Actuators" section p. 1-8 *ff.*).

Note

The sensor bandwidth for the sensors described here should not be confused with the bandwidth of the piezo mechanics servo-control loop, which is further limited by the electronic and mechanical properties of the system.

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

Actuators and Sensors

Fig. 14. LVDT sensor, coil and core. Paper clip for size comparison.

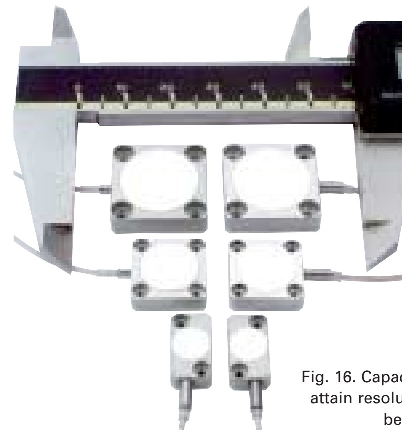

Fig. 16. Capacitive sensors can attain resolution 10,000 times better than calipers.

Linear Variable Differential Transformers (LVDTs)

LVDTs are well suited for direct metrology. 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 (Fig. 15). 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
- Non-contacting
- Controls the position of the moving part rather than the position of the piezo stack
- Cost-effective

Other characteristics:

- Outgassing of insulation materials may limit applications in very high vacuum
- Generates magnetic field

Examples

P-780, p. 2-32; P-721.LLQ, p. 2-20.

Capacitive Position Sensors

Capacitive sensors are the metrology system of choice for the most demanding applications.

Two-plate capacitive sensors consist of two RF-excited plates that are part of a capacitive bridge (Fig. 17). One plate is fixed, the other plate is connected to the object to be positioned (e.g. the platform of a stage). The distance between the plates is inversely proportional to the capacitance, from which the displacement is calculated. Short-range, two-plate sensors can achieve resolution on the order of picometers. See the "Capacitive Displacement Sensors" section pp. 5-2 *ff.* for details.

Resolution: Better than 0.1 nm possible

Repeatability: Better than 0.1 nm possible

Bandwidth: Up to 10 kHz

Advantages:

- Highest resolution of all commercially available sensors
- Ideally suited for parallel metrology
- Non-contacting
- Excellent long-term stability
- Excellent frequency response
- No magnetic field
- Excellent linearity

Other characteristics:

- Ideally suited for integration in flexure guidance systems, which maintain the necessary parallelism of the plates. Residual tip/tilt errors are greatly reduced by the ILS linearization system (see p. 5-6) developed by PI.

Examples

P-733 parallel kinematic nanopositioning system with parallel metrology, see p. 2-64.
P-753 LISA NanoAutomation® actuators, see p. 2-26; additional examples in the "Nanopositioning & Scanning Systems" section.

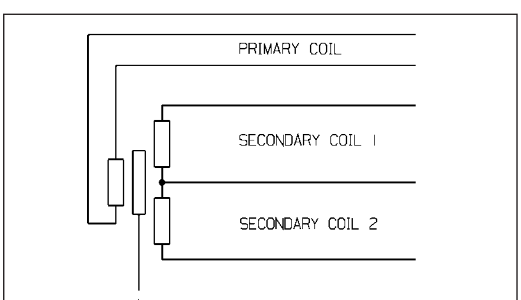

Fig. 15. Working principle of an LVDT sensor

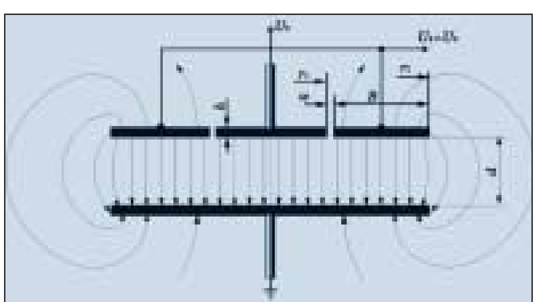

Fig. 17. Working principle of two-plate capacitive position sensors

Fundamentals of Piezoelectric Actuators

Forces and Stiffness

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 piezo actuator. PZT ceramic material can withstand pressures up to 250 MPa (250 x 10^6 N/m^2) without breaking. This value must never be approached in practical applications, however, because depolarization occurs at pressures on the order of 20 % to 30 % of the mechanical limit. For stacked actuators and stages (which are a combination of several materials) additional limitations apply. Parameters such aspect ratio, buckling, interaction at the interfaces, etc. must be considered.

The load capacity data listed for PI actuators are conservative values which allow long lifetime.

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

The PZT ceramic is especially sensitive to shear forces; they must be intercepted by external measures (flexure guides, etc.).

Stiffness

Actuator stiffness is an important parameter for calculating force generation, resonant frequency, full-system behavior, etc. The stiffness of a solid body depends on Young's modulus of the material. Stiffness is normally expressed in terms of the spring constant k_T, which describes the deformation of the body in response to an external force.

This narrow definition is of limited application for piezoceramics because the cases of static, dynamic, large-signal and small-signal operation with open and shorted electrodes must be distinguished. The poling process of piezoceramics leaves a remnant strain in the material which depends on the magnitude of polarization. The polarization is affected by both the applied voltage and external forces. When an external force is applied to poled piezoceramics, the dimensional change depends on the stiffness of the ceramic material and the change of the remnant strain (caused by the polarization change). The equation $\Delta L_N = F/k_T$ 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). If the electric charge cannot be drained from the PZT ceramics, it generates a counterforce opposing the mechanical stress. This is why a piezo element with open electrodes appears stiffer than one with shorted electrodes. Common voltage amplifiers with their low output impedances look like a short circuit to a piezo actuator.

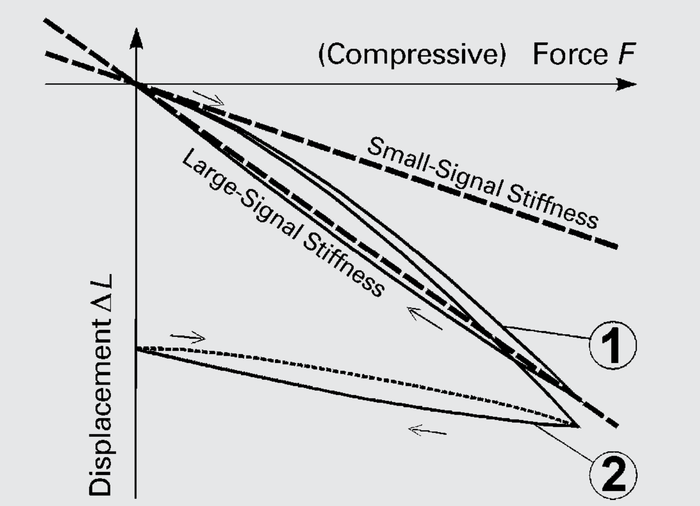

Fig. 18. Quasi-static characteristic mechanical stress/strain curves for piezo ceramic actuators and the derived stiffness values. Curve 1 is with the nominal operating voltage on the electrodes, Curve 2 is with the electrodes shorted (showing ceramics after depolarization)

Mechanical stressing of piezo actuators with open electrodes, e.g. open wire leads, should be avoided, because the resulting induced voltage might damage the stack electrically.

Note

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

Fundamentals of Piezoelectric Actuators

Force Generation

In most applications, piezo actuators are used to produce displacement. If used in a restraint, they can be used to generate forces, e.g. for stamping. 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 p. 4-23). At maximum force generation, displacement drops to zero.

(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).

Where:

ΔL_0 = *max. nominal displacement without external force or restraint [m]*
k_T = *piezo actuator stiffness [N/m]*

In actual applications the spring constant of the load can be larger or smaller than the piezo spring constant. The force generated by the piezo actuator 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 = *max. nominal displacement without external force or restraint [m]*
k_T = *piezo actuator stiffness [N/m]*
k_S = *stiffness of external spring [N/m]*

Example

What is the force generation of a piezo actuator with nominal displacement of 30 µm and stiffness of 200 N/µm? The piezo actuator can produce a maximum force of 30 µm x 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 nano imprint application. At rest (zero position) the distance between the piezo actuator tip and the material is 30 microns (given by mechanical system tolerances). A force of 500 N is required to emboss the material.

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

A: Under ideal conditions this actuator can generate a force of 30 x 100 N = 3000 N (30 microns are lost motion due to the distance between the sheet and the piezo actuator 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 piezo actuator could only generate a force of 300 N onto the metal when operated at maximum drive voltage. If the support were stiff but the material to be embossed itself were very soft 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 piezo actuator mount was too soft, the force generated by the piezo 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.

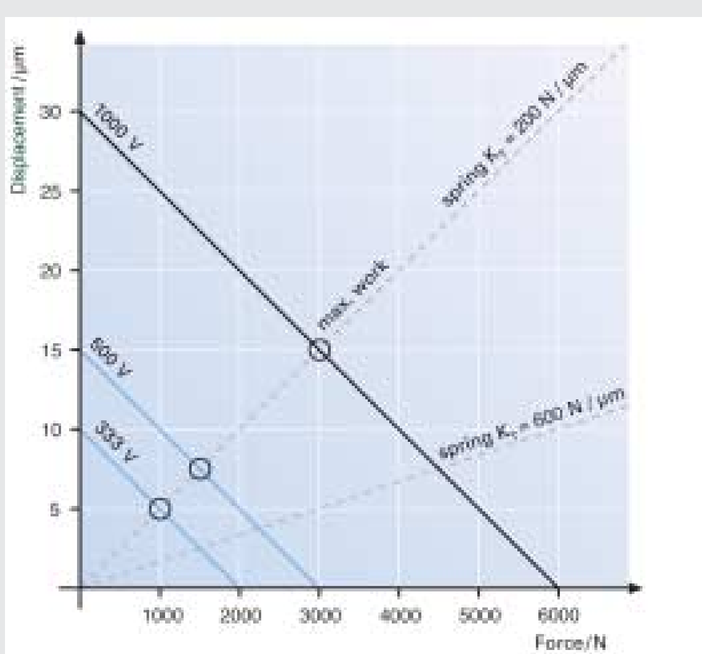

Fig. 19. Force generation vs. displacement of a piezo actuator (displacement 30 µm, stiffness 200 N/µm). Stiffness at various operating voltages. The points where the dashed lines (external spring curves) intersect the piezo actuator force/displacement curves determine the force and displacement for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

Displacement and External Forces

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

a) The load remains constant during the motion process.

b) The load changes during the motion process.

Note

To keep down the loss of travel, the stiffness of the preload spring should be under 1/10 that of the piezo actuator stiffness. If the preload stiffness were equal to the piezo actuator stiffness, the travel would be reduced by 50 %. For primarily dynamic applications, the resonant frequency of the preload must be above that of the piezo actuator.

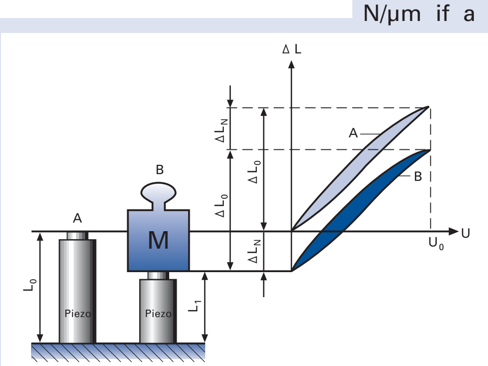

Fig. 20. Case a: Zero-point offset with constant force.

a Constant Force

Zero-point is offset

A mass is installed on the piezo actuator which applies a force F = M · g (M is the mass, g the acceleration due to gravity).

The zero-point will be shifted by $\Delta L_N \approx F/k_T$, where k_T is the stiffness of the actuator.

If this force is below 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 (mass x acceleration due to gravity) [N]*

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

Example

How large is the zero-point offset of a 30 µm piezo 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?

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

Displacement is reduced

For piezo actuator operation against an elastic load different rules apply. Part of the displacement generated by the piezo effect is lost due to the elasticity of the piezo element (Fig. 21). The total available displacement can be related to the spring stiffness by the following equations:

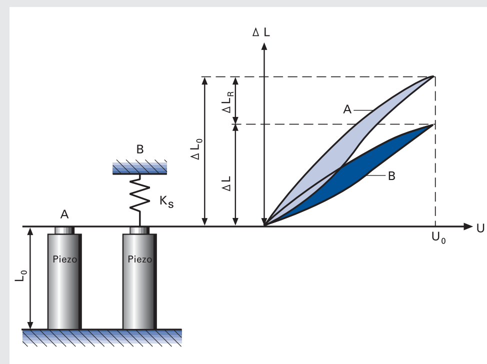

Fig. 21. Case b: Effective displacement of a piezo actuator acting against a spring load.

(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 restraint is infinitely rigid ($k_s = \infty$), the piezo actuator can produce no displacement but acts only 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 = *piezo actuator stiffness [N/m]*

Example

Q: What is the maximum displacement of a 15 µm piezo 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).

Dynamic Operation Fundamentals

Dynamic Forces

Every time the piezo drive voltage changes, the piezo element changes its dimensions. Due to the inertia of the piezo actuator mass (plus any additional load), a rapid move will generate a force acting on (pushing or pulling) 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. Tensile forces must be compensated, for example, by a spring preload.

Where:

F_{max} = max. force [N]

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

k_T = piezo actuator stiffness [N/m]

The preload force should be around 20% of the compressive load limit. The preload should be soft compared to the piezo actuator, at most 10% the actuator stiffness.

In sinusoidal operation 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 piezo actuator in sinusoidal operation at frequency f.

Where:

F_{dyn} = dynamic force [N]
m_{eff} = effective mass [kg], see p. 4-25
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 m peak-to-peak and 1 kg load reach approximately ±40 N.

Note

A guiding system (e.g. diaphragm type) is essential when loads which are heavy or large (relative to the piezo actuator diameter) are moved dynamically. Without a guiding system, there is a potential for tilt oscillations that may damage the piezoceramics.

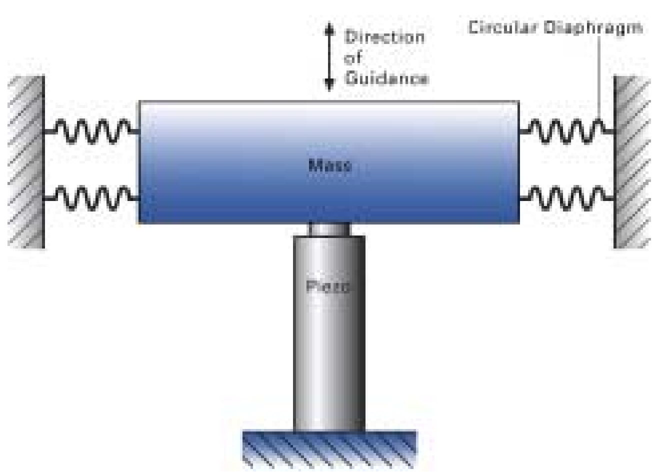

Fig. 22. Recommended guiding for large masses.

Resonant Frequency

In general, the resonant frequency of any spring/mass system is a function of its stiffness and effective mass (see Fig. 23). Unless otherwise stated, the resonant frequency given in the technical data tables for actuators always refer to the unloaded actuator with one end rigidly attached. For piezo positioning systems, the data refers to the unloaded system firmly attached to a significantly larger mass.

(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 of unloaded actuator [Hz]*

k_T = *piezo 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:
In positioning applications, piezo actuators are operated well below their resonant frequencies. Due to the non-ideal spring behavior of piezoceramics, the theoretical result from the above equation does not necessarily match the real-world behavior of the piezo actuator 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 added mass.

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

The above equations show that to double the resonant frequency of a spring-mass system, it is necessary to either increase the stiffness by a factor of 4 or decrease the effective mass to 25 % of its original value. As long as the resonant frequency of a preload spring is well above that of the actuator, forces it introduces do not significantly affect the actuator's resonant frequency.

The phase response of a piezo actuator system can be approximated by a second order system and is described by the following equation:

(Equation 12)

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

Where:

φ = *phase angle [deg]*

F_{max} = *resonant frequency [Hz]*

f = *operating frequency [Hz]*

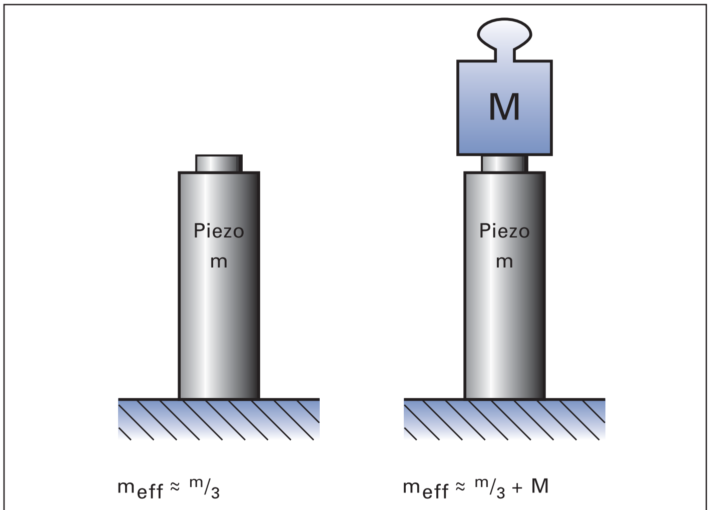

Fig. 23. Effective mass of an actuator fixed at one end.

Dynamic Operation Fundamentals

How Fast Can a Piezo Actuator Expand?

Fast response is one of the characteristic features of piezo actuators. A rapid drive voltage change results in a rapid position change. This property is especially welcome in dynamic applications such as scanning microscopy, image stabilization, switching of valves/shutters, shock-wave generation, vibration cancellation systems, etc.

A piezo actuator can reach its nominal displacement in approximately 1/3 of the period of the resonant frequency, provided the controller can deliver the necessary current. If not compensated by appropriate measures (e.g. notch filter, InputShaping®, see p. 4-33) in the servo-loop, such rapid expansion will be accompanied by significant overshoot.

(Equation 13)

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

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

Where:

T_{min} = time [s]

f_0 = resonant frequency [Hz]]

Example: A piezo translator with a 10 kHz resonant frequency can reach its nominal displacement within 30 µs.

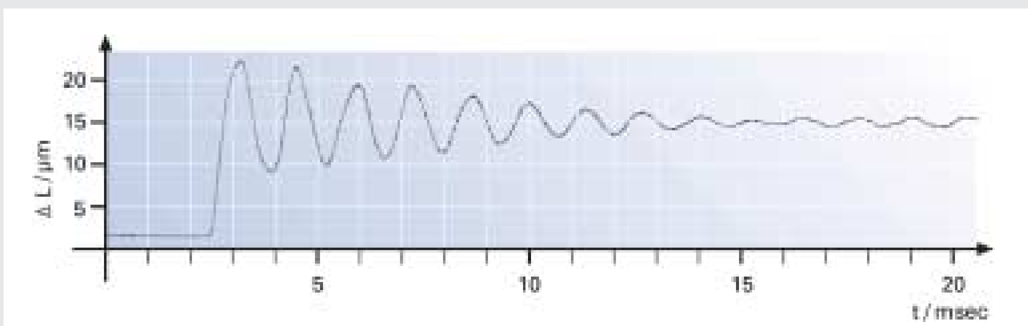

Fig. 24. Response of an undamped, lever-amplified piezo actuator (low resonant frequency) to a rapid drive-voltage change. This behavior can be prevented by intelligent control techniques or position servo-control.

Piezo Actuator Electrical Fundamentals

Electrical Requirements for Piezo Operation

General

When operated well below the resonant frequency, a piezo actuator behaves as a capacitor: The actuator displacement is proportional to stored charge (first order estimate). The capacitance of the actuator depends on the area and thickness of the ceramic, as well as on its material properties. For piezo stack actuators, which are assembled with thin, laminar wafers of electroactive ceramic material electrically connected in parallel, the capacitance also depends on the number of layers.

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

(Equation 14)

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

Where:

C = *capacitance [F (As/V)]*

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

ε_{33T} = *dielectric constant [As/Vm]*

A = *electrode surface area of a single layer [m²]*

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

l_0 = *actuator length*

The equation shows that for a given actuator length, the capacitance increases with the square of the number of layers. Therefore, the capacitance of a piezo actuator constructed of 100 µm thick layers is 100 times the capacitance of an actuator with 1 mm layers, if the two actuators have the same dimensions. Although the actuator with thinner layers draws 100 times as much current, the power requirements of the two actuators in this example are about the same. The PI high-voltage and low-voltage amplifiers in this catalog are designed to meet the requirements of the respective actuator types.

Static Operation

When electrically charged, the amount of energy stored in the piezo actuator is $E = (1/2)\ CU^2$ Every change in the charge (and therefore in displacement) of the PZT ceramics 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 need be supplied. The high internal resistance reduces leakage currents to the micro-amp range or less. Even when suddenly disconnected from the electrical source, the charged actuator will not make a sudden move, but return to its uncharged dimensions very slowly.

For slow position changes, only very low current is required.

Example: An amplifier with an output current of 20 µA can fully expand a 20 nF actuator in one second. Suitable amplifiers can be found using the "Control Electronics Selection Guide" on p. 6-8.

Note

The actuator capacitance values indicated in the technical data tables are small-signal values (measured at 1 V, 1000 Hz, 20 °C, unloaded) The capacitance of piezoceramics 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 "Piezo Drivers & Nanopositioning Controllers" section.

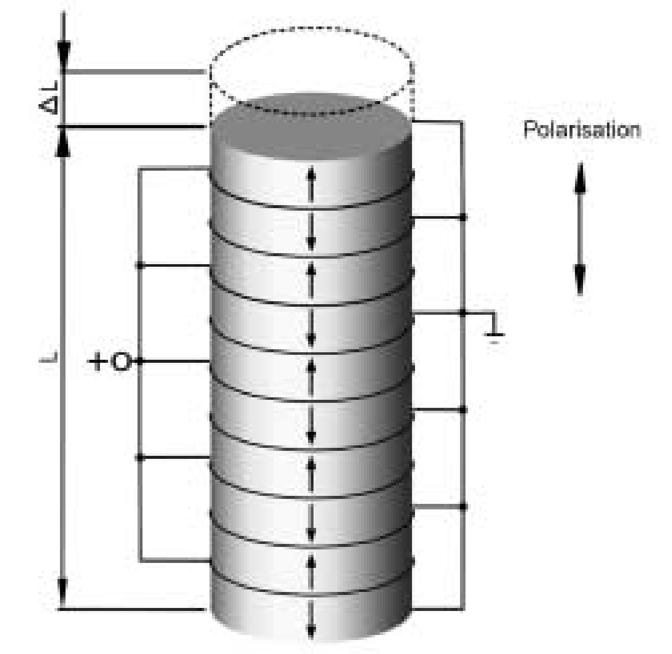

Fig. 25. Design of a piezo stack actuator.

Piezo Actuator Electrical Fundamentals

Dynamic Operation (Linear)

Piezo actuators can provide accelerations of thousands of g's and are ideally suited for dynamic applications.

Several parameters influence the dynamics of a piezo positioning system:

- The slew rate [V/s] and the maximum current capacity of the amplifier limit the operating frequency of the piezo system.
- If sufficient electrical power is available from the amplifier, the maximum drive frequency may be limited by dynamic forces (see "Dynamic Operation", p. 4-24).
- In closed-loop operation, the maximum operating frequency is also limited by the phase and amplitude response of the system. Rule of thumb: The higher the system resonant frequency, the better the phase and amplitude response, and the higher the maximum usable frequency. The sensor bandwidth and performance of the servo-controller (digital and analog filters, control algorithm, servo-bandwidth) determine the maximum operating frequency of a piezoelectric system.
- In continuous operation, heat generation can also limit the operating frequency.

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

(Equation 16)

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

Long-term 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** = piezo actuator capacitance [Farad (As/V)]*

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

f = operating frequency [Hz]

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

Example

Q: What peak current is required to obtain a sinewave displacement of 20 µm at 1000 Hz from a 40 nF HVPZT actuator with a nominal displacement of 40 µm at 1000 V?

A: The 20 µm displacement requires a drive voltage of about 500 V peak-to-peak. With Equation 17 the required peak current is calculated at ≈ 63 mA. For appropriate amplifiers, see the "Piezo Drivers & Nanopositioning Controllers" section, p. 6-8.

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** = piezo actuator capacitance [F]*

f = operating frequency [Hz]

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

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

It is also essential that the power supply be able to supply sufficient current.

** The power supply must be able to provide enough current.*

*** For large-signal conditions a margin of 70% of the small-signal value should be added.*

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 increases linearly with both frequency and voltage (displacement). For this purpose, the Dynamic Operating Current Coefficient (DOCC) has been introduced. The DOCC is the current that must be supplied by the amplifier to drive the piezo actuator per unit frequency (Hz) and unit displacement. DOCC values are valid for sinewave operation in open-loop mode. In closed-loop operation the current requirement can be up to 50% higher.

The peak and long-term average current capacities of the different piezo amplifiers can be found in the technical data tables for the electronics, the DOCC values in the tables for the piezo actuators.

Example: To determine whether a selected amplifier can drive a given piezo actuator at 50 Hz with 30 µm peak-to-peak displacement, multiply the actuator's DOCC by 50 x 30 and compare the result with the average output current of the selected amplifier. If the current required is less than or equal to the amplifier output, then the amplifier has sufficient capacity for the application.

Dynamic Operation (Switched)

For applications such as shock wave generation or valve control, switched operation (on/off) may be sufficient. Piezo actuators can provide motion with rapid rise and fall times with accelerations in the thousands of g's. For information on estimating the forces involved, see "Dynamic Forces," p. 4-24.

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

The following equation 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]*

$U_{p\text{-}p}$ = *source output voltage (peak-to-peak) [V]*

R = *source output resistance [ohm]*

C = *piezo actuator capacitance [F]*

t = *time [s]*

The voltage rises or falls exponentially with the RC time constant. Under quasi-static conditions, the expansion of the PZT ceramics is proportional to the voltage. In reality, dynamic piezo processes cannot be described by a simple equation. If the drive voltage rises too quickly, resonance occurs, causing ringing and overshoot. Furthermore, whenever the piezo actuator expands or contracts, dynamic forces act on the ceramic material. These forces generate a (positive or negative) voltage in the piezo element which is superimposed on the drive voltage. A piezo actuator can reach its nominal displacement in approximately 30 % of the period of the resonant frequency, provided the controller can deliver the necessary current. (see p. 4-26).

The following equation applies for constant-current charging (as with a linear amplifier):

(Equation 22)

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

Time to charge a piezoceramic with constant current. With lower-capacity electronics, amplifier slew rate can be a limiting factor.

Where:

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

C = *piezo actuator capacitance [F]*

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

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

For fastest settling, switched operation is not the best solution because of the resulting overshoot. Modern techniques like InputShaping® (see p. 4-33) solve the problem of resonances in and around the actuator with complex signal processing algorithms.

Note

Piezo drives are becoming more and more popular because they can deliver extremely high accelerations. This property is very important in applications such as beam steering and optics stabilization. Often, however, the actuators can accelerate faster than the mechanics they drive can

Piezo Actuator Electrical Fundamentals

follow. Rapid actuation of nanomechanisms can cause recoil-generated ringing of the actuator and any adjacent components. The time required for this ringing to damp out can be many times longer than the move itself. In time-critical industrial nanopositioning applications, this problem obviously grows more serious as motion throughputs increase and resolution requirements tighten.

Classical servo-control techniques cannot solve this problem, especially when resonances occur outside the servo-loop such as when ringing is excited in a sample on a fast piezo scanning stage as it reverses direction. A solution is often sought in reducing the scanning rate, thereby sacrificing part of the advantage of a piezo drive.

A patented real-time feedforward technology called InputShaping® nullifies resonances both inside and outside the servo-loop and thus eliminates the settling phase. For more information see p. 4-33 or visit www.Convolve.com.

Heat Generation in a Piezo Actuator in Dynamic Operation

PZT ceramics are (reactive) capacitive loads and therefore require charge and discharge currents that increase with operating frequency. The thermal active power, P (apparent power x 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 piezo actuator.

Where:

P = *power converted to heat [W]*

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

f = *operating frequency [Hz]*

C = *actuator capacitance [F]*

$U_{p\text{-}p}$ = *voltage (peak-to-peak)*

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 piezoceramics under small-signal conditions the loss factor is on the order of 0.01 to 0.02. This means that up to 2 % of the electrical "power" flowing through the actuator is converted into heat. 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, maximum operating temperature can limit the piezo actuator dynamics. For large amplitudes and high frequencies, cooling measures may be necessary. A temperature sensor mounted on the ceramics is suggested for monitoring purposes.

For higher frequency operation of high-load actuators with high capacitance (such as PICA™-Power actuators, see p. 1-20), a special amplifiers employing energy recovery technology has been developed. 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 shown in the block diagram in Fig. 26. The combination of low-loss, high-energy piezoceramics and amplifiers with energy recovery are the key to new high-level dynamic piezo actuator applications.

For dynamic applications with low to medium loads, the newly developed PICMA® actuators are also quite well suited. With their high Curie temperature of 320 °C, they can be operated with internal temperatures of up to 150 °C.

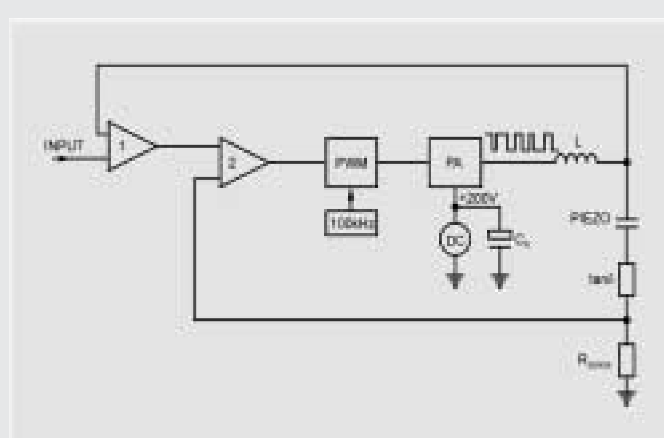

Fig. 26. Block diagram of an amplifier with energy recovery for higher frequency applications.

Control of Piezo Actuators and Stages

Position Servo-Control


Fig. 27. Variety of digital piezo controllers.

Position servo-control eliminates nonlinear behavior of piezoceramics such as hysteresis and creep 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:

- High 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 piezo actuators and systems are equipped with position measuring systems providing sub-nanometer resolution, linearity to 0.01 %, and bandwidths up to 10 kHz. A servo-controller (digital or analog) determines the output voltage to the PZT ceramics by comparing a reference signal (commanded position) to the actual sensor position signal (see Fig. 28).

For maximum accuracy, it is best if the sensor measures the motion of the part whose position is of interest (direct metrology). PI offers a large variety of piezo actuators with integrated direct-metrology sensors. Capacitive sensors provide the best accuracy (see section 5, "Capacitive Position Sensors"). Simpler, less accurate systems measure things like strain in drive elements.

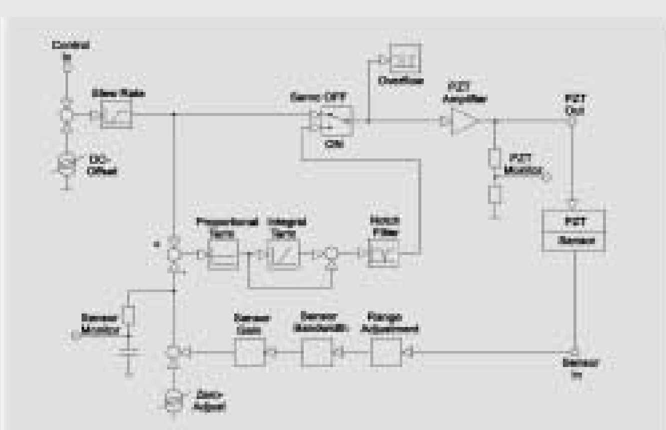
Fig. 28. Block diagram of a typical PI closed-loop piezo positioning system.

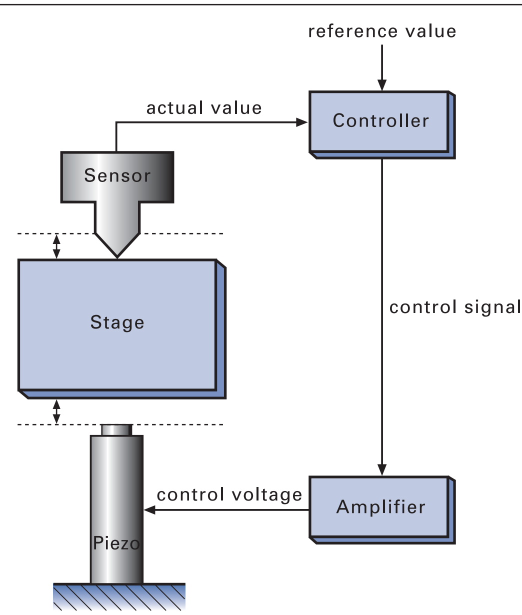

Fig. 29. Closed-loop position servo-control. For optimum performance, the sensor is mounted directly on the object to be positioned (direct metrology).

Control of Piezo Actuators and Stages

Open- and Closed-Loop Resolution

Position servo-controlled piezo drives offer linearity and repeatability many times better than that of open-loop systems. The resolution (minimum incremental motion) of piezo actuators is actually better for open-loop than for closed-loop systems. This is because piezo resolution is not limited by friction but rather by electronic noise. In open-loop, there is no sensor or servo-electronics to put additional noise on the control signal. In a servo-controlled piezo system, the sensor and control electronics are thus of considerable importance. With appropriate, high-quality systems, subnanometer resolution is also possible in closed-loop mode, as can be seen in Fig. 30 and 31. Capacitive sensors attain the highest resolution, linearity and stability.

Piezo Calibration Data

Each PI piezo position servo-controller is calibrated with the specific closed-loop piezo positioning 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 is supplied with the system (see p. 2-8, p. 3-7). To optimize calibration, information about the specific application is needed. For details see p. 6-53 in the "Piezo Drivers & Nanopositioning Controllers" section.

Digital controllers can automatically read important calibration values from an ID-chip integrated in the piezo mechanics. This feature facilitates using a controller with various stages/actuators and vice versa.

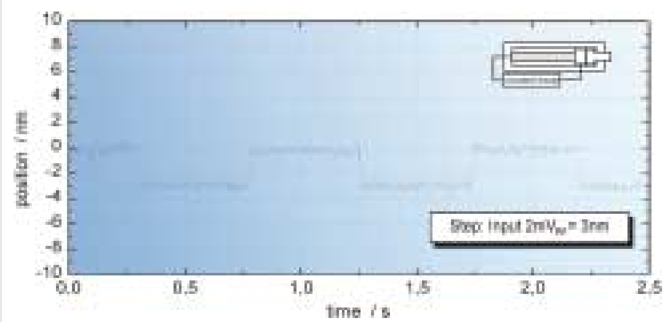

Fig. 30. Response of a closed-loop PI piezo actuator (P-841.10, 15 µm, strain gauge sensor) to a 3 nm peak-to-peak square-wave control input signal, measured with servo-control bandwidth set to 240 Hz and 2 msec settling time. Note the crisp, backlash-free behavior in the nanometer range.

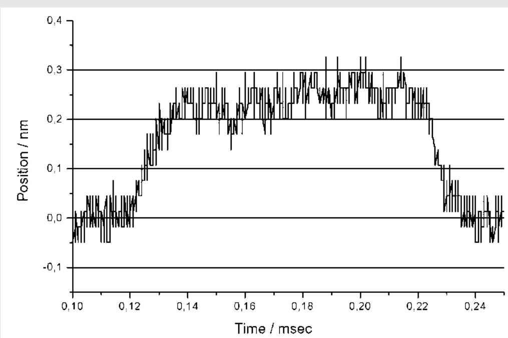

Fig. 31. PI piezo actuators with capacitive position sensors can achieve extremely high resolutions, as seen in the above result of a 250 picometer step by a S-303 phase corrector (Controller: E-509.C1A servo-controller and E-503 amplifier). The measurements were made with an ultra-sensitive capacitive sensor having a resolution of ±0.02 nm.

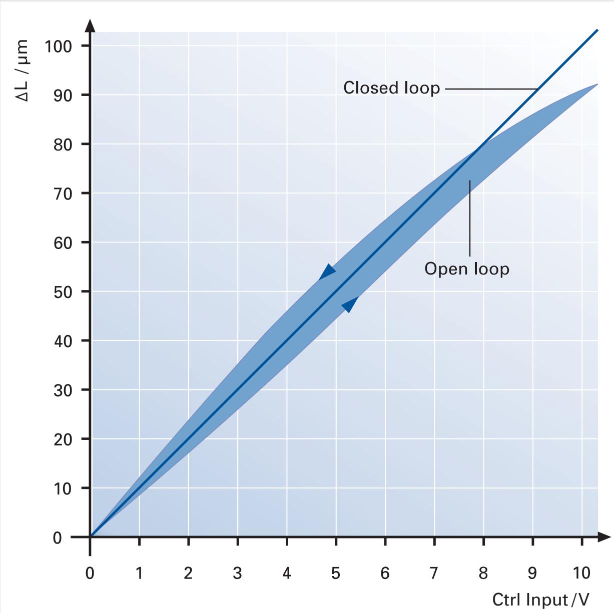

Fig. 32. Open-loop vs. closed-loop performance graph of a typical PI piezo actuator.

Methods to Improve Piezo Dynamics

The dynamic behavior of a piezo positioning system depends on factors including the system's resonant frequency, the position sensor and the controller used. Simple controller designs limit the usable closed-loop tracking bandwidth of a piezoelectric system to 1/10 of the system's resonant frequency. PI offers controllers that significantly increase piezo actuator system dynamics (see table). Two of the methods are described below; additional information is available on request.

InputShaping® Stops Structural Ringing Caused by High-Throughput Motion

A patented, real-time, feedforward technology called InputShaping® nullifies resonances both inside and outside the servo-loop and virtually eliminates the settling phase. The procedure requires determination of all critical resonant frequencies in the system. A non-contact instrument like a Polytec Laser Doppler Vibrometer is especially well-suited for such measurements. The values, most importantly the resonant frequency of the sample on the platform, are then fed into the InputShaping® Signal processor. There the sophisticated signal processing algorithms assure that none of the undesired resonances in the system or its auxillary components is excited. Because the processor is outside the servo-loop, it works in open-loop operation as well. The result: the fastest possible motion, with settling within a time equal one period of the lowest resonant frequency. InputShaping® was developed based on research at the Massachusetts Institute of Technology and commercialized by Convolve, Inc. (www.convolve.com). It is an option in several PI digital piezo controllers.

Piezo Actuators
Nanopositioning & Scanning Systems
Active Optics / Steering Mirrors
Tutorial: Piezoelectrics in Positioning
Capacitive Position Sensors
Piezo Drivers & Nanopositioning Controllers
Hexapods / Micropositioning
Photonics Alignment Solutions
Motion Controllers
Ceramic Linear Motors & Stages
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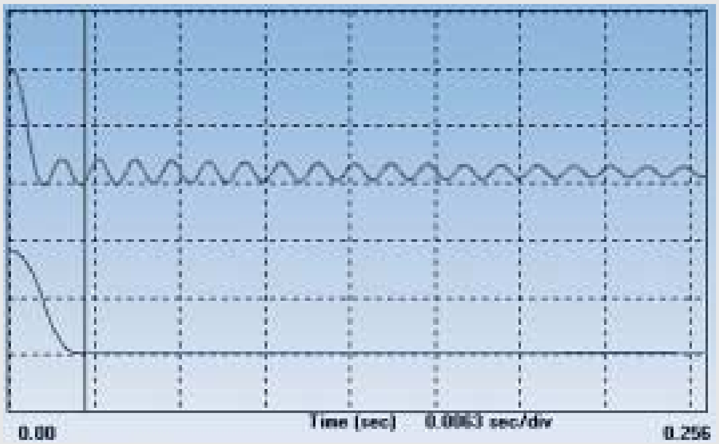


Fig. 33. InputShaping® eliminates the recoil-driven resonant reaction of loads and neighboring components due to rapid nanopositioner actuation.
Top: Polytec Laser Vibrometer reveals the resonant behavior of an undamped fixture when the nanomechanism is stepped.
Bottom: Same setup, same step, but with InputShaping®. Structural ringing is eliminated. With no excitation of vibration in the moved components, the target position is attained in a time smaller than one period of the resonant frequency.

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 (digital, in DSP)	Compensate for piezo hysteresis and creep effects
InputShaping®	Cancel recoil-generated ringing, whether inside or outside the servo-loop. Reduce the settling time. Closed- and open-loop.
Dynamic Digital Linearization (DDL)	Increase operating frequency of the system, correct amplitude and phase response. Integrated in digital controller. No external metrology necessary, for periodic signals only.

Methods to Improve Piezo Dynamics

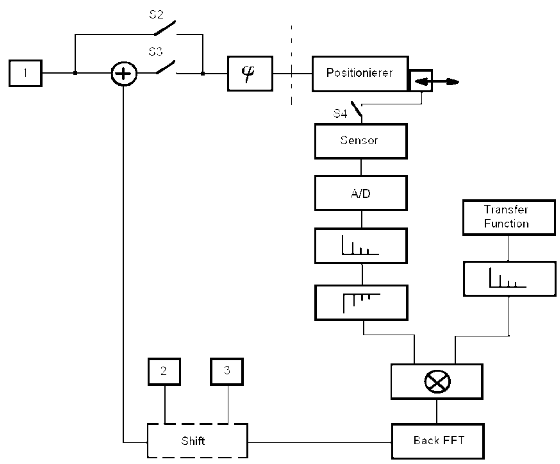


Fig. 34 a. Signal preshaping, phase 1.

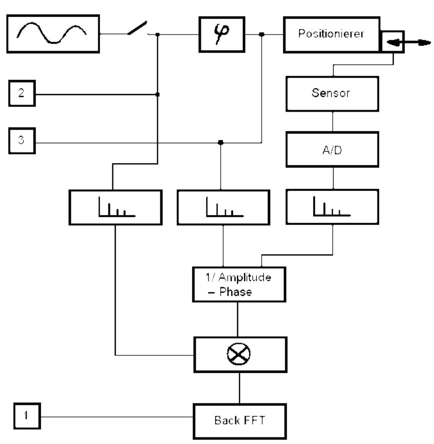


Fig. 34 b. Signal preshaping, phase 2.

Signal Preshaping / Dynamic Digital Linearization (DDL)

Signal Preshaping, a patented technique, can reduce rolloff, phase error and hysteresis in applications with repetitive (periodic) inputs. The result is to improve the effective bandwidth, especially for tracking applications such as out-of-round turning of precision mechanical or optical parts. 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 is more effective than simple phase-shifting approaches and can improve the effective bandwidth by a factor of 10 and in multi-frequency applications.

Frequency response and harmonics (caused by nonlinearity of the piezo-effect) are determined in two steps using Fast Fourier Transformation (FFT), and the results are used to calculate the new control profile for the trajectory. The new control signal compensates for the system non-linearities.

For example, it is possible to increase the command rate from 20 Hz to 200 Hz for a piezo system with a resonant frequency of 400 Hz without compromising stability. At the same time, the tracking error is reduced by a factor of about 50.

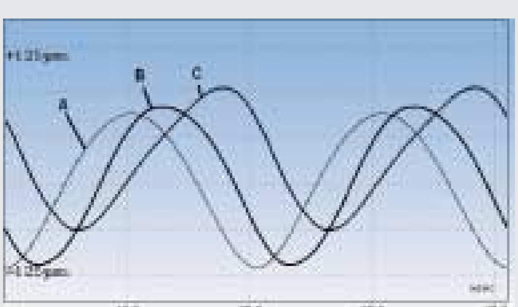


Fig. 35. No preshaping.
A: Control input signal (expected motion).
B: Actual motion of system.
C: Tracking error.

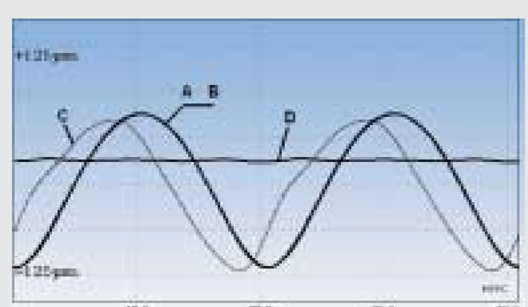


Fig. 36. Signal after preshaping phase 2.
A: Expected Motion (old control signal).
B: Actual motion of system.
C: New control input (producted by preshaping).
D: Tracking error.

Dynamic Digital Linearization (DDL)

DDL is similar in performance to Input Preshaping, but is simpler to use. In addition, it can optimize multi-axis motion such as a raster scan or tracing an ellipse. This method requires no external metrology or signal processing, but is fully integrated in E-710 and E-711 digital controllers. DDL uses the position information from capacitive sensors integrated in the piezo mechanics (requires direct metrology) to calculate the optimum control signal. As with preshaping, the result is an improvement in linearity and tracking accuracy of up to 3 orders of magnitude.

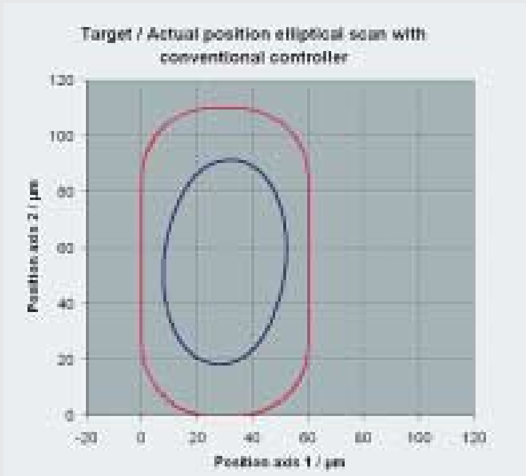


Fig. 37 a. Elliptical scan in a laser micro-drilling application with XY piezo scanning stage, conventional PID controller. The outer ellipse describes the target position, the inner ellipse shows the actual motion at the stage.

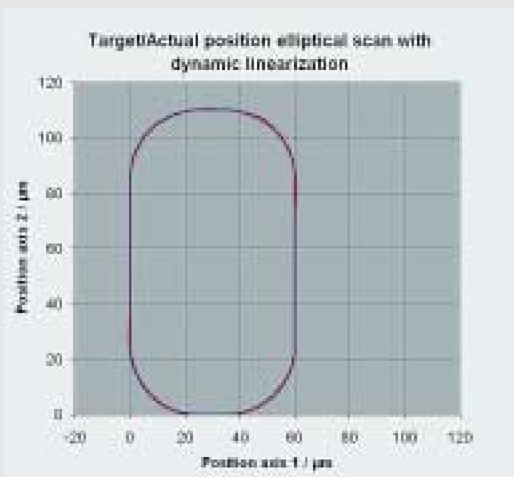


Fig. 37 b. Same scan as before, with a DDL controller. Target and actual data can hardly be discerned. The tracking error has been reduced to a few nanometers.

Environmental Conditions and Influences

Temperature Effects

Two effects must be considered:

- Linear Thermal Expansion
- Temperature Dependency of the Piezo Effect

Linear Thermal Expansion

Thermal stability of piezoceramics is better than that of most other materials. Fig. 38a shows the behavior of several types of piezoceramics used by PI. The curves only describe the behavior of the piezoceramics. Actuators and positioning systems consist of a combination of piezoceramics 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, but the magnitude of the piezo coefficients is temperature dependent.

At liquid helium temperature piezo gain drops to approximately 10–20 % of its room-temperature value.

Piezoceramics must be poled to exhibit the piezo effect. A poled PZT ceramic may depole when heated above the maximum allowable operating temperature. The “rate” of depoling is related to the Curie temperature of the material. PI HVPZT actuators have a Curie temperature of 350 °C and can be operated at up to 150 °C. LVPZT actuators have a Curie temperature of 150 °C and can be operated at up to 80 °C. The new monolithic PICMA® ceramics with their high Curie temperature of 320 °C allow operating at temperatures of up to 150 °C.

Note

Closed-loop piezo positioning systems are less sensitive to temperature changes than open-loop systems. Optimum accuracy is achieved if the operating temperature is identical to the calibration temperature. If not otherwise specified, PI piezomechanics are calibrated at 22 °C.

Piezo Operation in High Humidity

The polymer insulation materials used in piezoceramic actuators are sensitive to humidity. Water molecules diffuse through the polymer layer and can cause short circuiting of the piezoelectric layers. The insulation materials used in piezo actuators are sensitive to humidity. For higher humidity environments, PI offers special systems with waterproofed enclosed stacks, or integrated dry-air flushing mechanisms.
A better solution are PICMA® actuators (see Fig. 39a), which have ceramic-only insulation without any polymer covering and are thus less sensitive to water diffusion (see Fig. 39c).

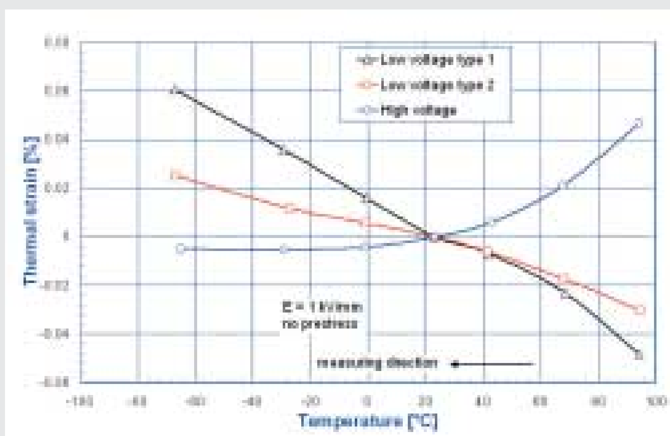


Fig. 38 a. Linear thermal expansion of different PZT ceramics.

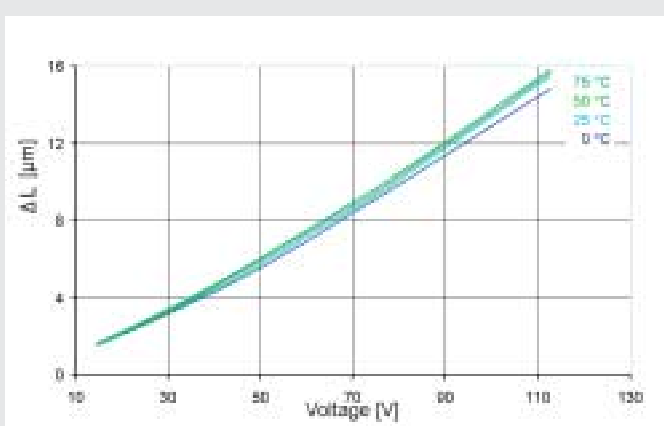


Fig. 38 b. The expansion of PICMA® piezoceramics is only slightly temperature dependent. This, and their low heat generation, makes them ideal for dynamic applications.

Piezo Operation in Inert Gas Atmospheres

Ceramic-insulated PICMA® actuators are also recommended for use in inert gases, such as helium. To reduce the danger of flashover with high-voltage piezos, the maximum operating voltage must be reduced. Semi-bipolar operation is recommended, because the average operating voltage can be kept very low.

Vacuum Operation of Piezo Actuators

All PI piezo actuators can be operated at pressures below 100 Pa (~1 torr). When piezo actuators are used in a vacuum, two factors must be considered:

I. Dielectric stability

II. Outgassing

I. The dielectric breakdown voltage of a sample in a specific gas is a function of the pressure *p* times the electrode distance *s*. Air displays a high insulation capacity at atmospheric pressure and at very low pressures. The minimum breakdown voltage of ~300 V can be found at a *ps*-product of 1000 mm Pa (~10 mm torr). That is why PICMA® actuators with a maximum operating voltage of 120 V can be used in any vacuum condition. However, the operation of HVPZT actuators with dielectric layer thicknesses of 0.2 – 1.0 mm and nominal voltages to 1000 V is not recommended in the pressure range of 100 – 50000 Pa (~1 – 500 torr).

II. Outgassing behavior varies from model to model depending on design. Ultra-high-vacuum options for minimum outgassing are available for many standard low-voltage and high-voltage piezo actuators. Best suited are PICMA® ceramics (see Fig. 39a), because they have no polymers and can withstand bakeout to 150 °C (see also "Options" in the "Piezo Actuators" sections, p. 1-44 *ff*).

All materials used in UHV-compatible piezo nanopositioners, including cables and connectors, are optimized for minimal outgassing rates (see Fig. 39b). Materials lists are available on request.

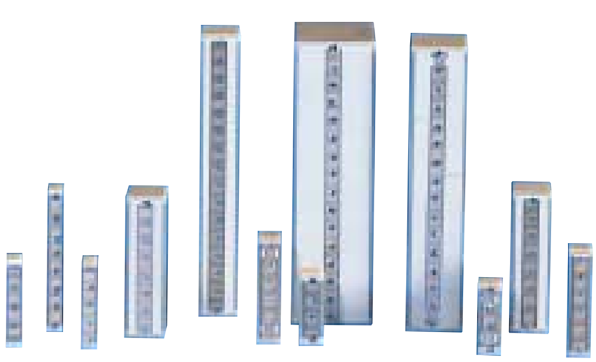


Fig. 39 a. PICMA® actuators are made with ceramic-only insulation and can dispense with any polymer coating. Result No measurable outgasing, insensitive to atmospheric humidity and a wider operating temperature range.

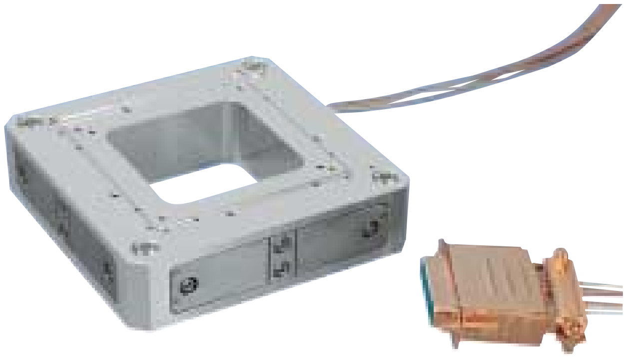


Fig. 39 b. P-733.UUD UHV-compatible XY stage for scanning microscopy applications. PICMA® ceramics are used here too. All materials used are optimized for minimal outgassing. Materials lists are available on request.

Piezo Actuators
Nanopositioning & Scanning Systems
Active Optics / Steering Mirrors
Tutorial: Piezo-electrics in Positioning
Capacitive Position Sensors
Piezo Drivers & Nano-positioning Controllers
Hexapods / Micropositioning
Photonics Alignment Solutions
Motion Controllers
Ceramic Linear Motors & Stages
Index

Environmental Conditions and Influences

Lifetime of Piezo Actuators

The lifetime of a piezo actuator is not limited by wear and tear. Tests have shown that PI piezo actuators can perform billions (10^9) of cycles without any measurable wear.

As with capacitors, however, the field strength does have an influence on lifetime. The average voltage should be kept as low as possible. Most PI piezo actuators and electronics are designed for semi-bipolar operation.

There is no generic formula to determine the lifetime of a piezo actuator because of the many parameters, such as temperature, humidity, voltage, acceleration, load, preload, operating frequency, insulation materials, etc., which have (nonlinear) influences. PI piezo actuators are not only optimized for maximum travel, but also designed for maximum lifetime under actual operating conditions.

The operating voltage range values in the technical data tables are based on decades of experience with nanomechanisms and piezo applications in industry. Longer travel can only be obtained with higher voltages at the cost of reduced reliability.

Example:

An P-842.60 LVPZT actuator (see p. 1-36 in the "Piezo Actuators" section) is to operate a switch with a stroke of 100 µm. 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 at 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 piezo actuator should be 0 volts.

Statistics show that most failures with piezo actuators occur because of excessive mechanical stress. Particularly destructive are tensile and shear forces, torque and mechanical shock. To protect the ceramic from such forces PI offers a variety of actuators with preloads, ball tips, flexible tips as well as custom designs.

Failures can also occur when humidity or conductive materials such as metal dust degrade the PZT ceramic insulation, leading to irreparable dielectric breakdown. In environments presenting these hazards, PICMA® actuators with their ceramic-only insulation are strongly recommended. PI also offers hermetically sealed actuators and stages.

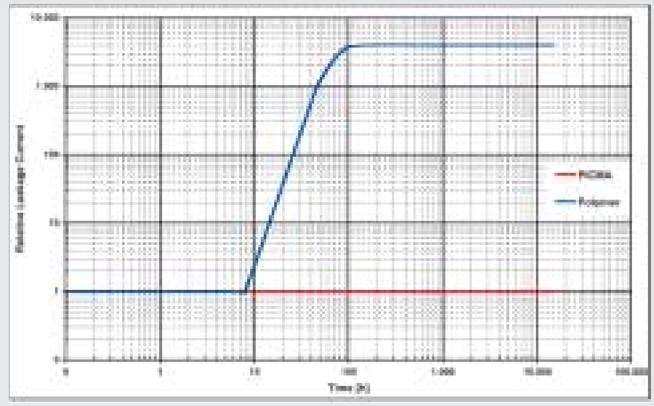


Fig. 39 c. PICMA® piezo actuators (lower curve) compared with conventional multilayer piezo actuators with polymer insulation. PICMA® actuators are insensitve to high humidity in this test. In conventional actuators, the leakage current begins to rise after only a few hours—an indication of degradation of the insulation and reduced lifetime.
Test conditions: U = 100 VDC, T = 25 °C, RH = 70%.

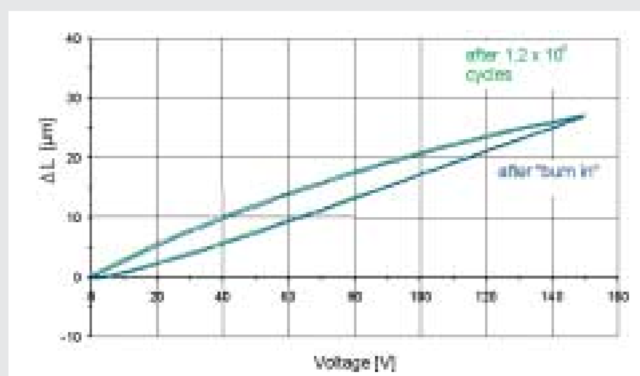


Fig. 39 d. P-885.50 PICMA® actuators with 15 MPa preload in dynamic motion test at 116 Hz. No observable wear after 1.2 billion (10^9) cycles.

Basic Designs of Piezoelectric Positioning Drives/Systems

Stack Design (Translators)

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. Most high-voltage actuators consist of ceramic layers measuring 0.4 to 1 mm in thickness. In low-voltage stack actuators, the layers are from 25 to 100 µm in thickness and are cofired with the electrodes to form a monolithic unit.

Stack elements can withstand high pressures and exhibit the highest stiffness of all piezo actuator designs. Standard designs which can withstand pressures of up to 100 kN are available, and preloaded actuators can also be operated in push-pull mode. For further information see “Maximum Applicable Forces”, p. 4-21.

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

(Equation 24)

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

where:

ΔL = displacement [m]

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

n = number of ceramic layers

U = operating voltage [V]

Example:

P-845, p. 1-36, etc. (see the “Piezo Actuators” section)

Laminar Design (Contraction-Type Actuators)

The active material in the laminar actuators consists of thin, laminated 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 force generation of the element.

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

(Equation 25)

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

where:

ΔL = displacement [m]

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

L = length of the piezoceramics in the electric field direction [m]

U = operating voltage [V]

d = thickness of one ceramic layer [m]

Examples:

Laminar piezos are used in the P-280 and P-282 nanopositioning systems, (see pp. 2-30 and 2-31).

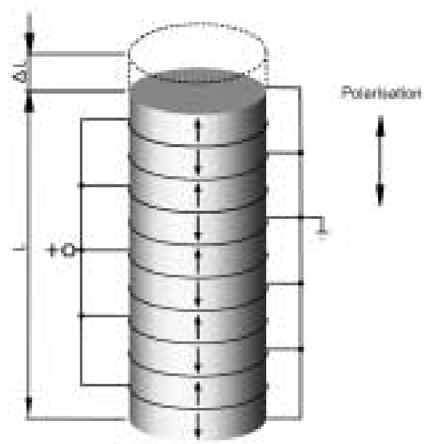


Fig. 40. Electrical design of a stack translator.

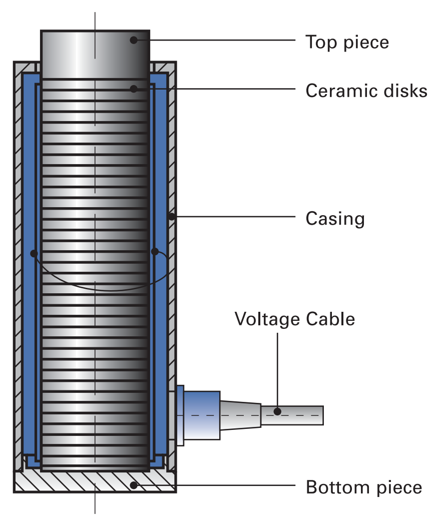


Fig. 41. Mechanical design of a stack translator.

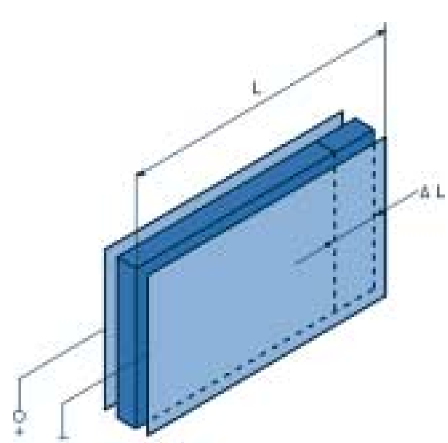


Fig. 42. Laminar actuator design.

Basic Designs of Piezoelectric Positioning Drives/Systems

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 piezo 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:

(Equation 26 b)

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

r = tube radius

(Equation 26 c)

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

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. Such scanner tubes that flex in X and Y are widely used in scanning-probe microscopes, such as scanning tunneling microscopes.

The scanning range can be estimated as follows:

(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 = differential operating voltage [V]

L = length [m]

ID = inside diameter [m]

d = wall thickness [m]

Tube actuators cannot generate or withstand large forces. Application examples: Microdosing, nanoliter pumping, scanning microscopy, ink jet printers.

Examples:

PT120, PT130, PT140 (p. 1-26).

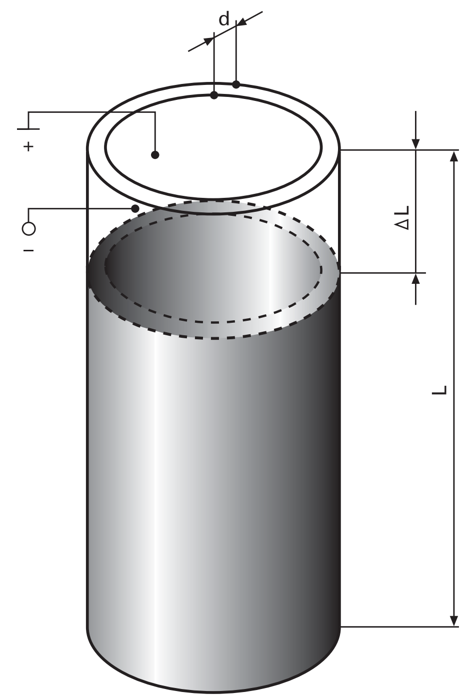


Fig. 43. Tube actuator design.

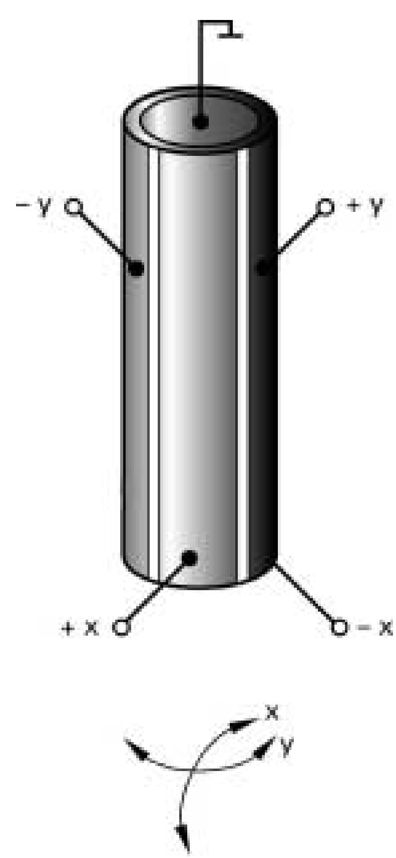


Fig. 44. Piezo scanner tube working principle.

Bender Type Actuators (Bimorph and Multimorph Design)

A simple bender actuator (bimorph design) consists of a passive metal substrate glued to a piezoceramic strip (see Fig. 45a). A piezo bimorph reacts to voltage changes the way the bimetallic strip in a thermostat reacts to temperature changes. 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. The bimorph design amplifies the dimension change of the piezo, providing motion up to several millimeters in an extremely small package. In addition to the classical strip form, bimorph disk actuators where the center arches when a voltage is applied, are also available.

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), as shown in Fig. 45b. 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 and acceleration sensors.

In addition to the two-layer benders, monolithic multilayer piezo benders are also available. As with multilayer stack actuators, they run on a lower operating voltage (60 to 100 V). Bender type actuators provide large motion in a small package at the cost of low stiffness, force and resonant frequency.

Examples:

P-286 - 289 disk translators (see p. 1-28), PL122 multilayer bender actuators (p. 1-14).

Shear Actuators

Shear actuators can generate high forces and large displacements. A further advantage is their suitability for bipolar operation, whereby the mid-position corresponds to a drive voltage of 0 V. In shear mode, unlike in the other modes, the electric field is applied perpendicular to the polarization direction. (see Fig. 46). The corresponding strain coefficient, d_{15}, has large-signal values as high as 1100 pm/V, providing double the displacement of linear actuators of comparable size based on d_{33}.

Shear actuators are suitable for applications like piezo linear motors, and are available as both single-axis and two-axis positioning elements.

Examples:

PX155 (p. 1-24), P-363 (p. 2-72), N-214 NEXLINE® Piezo-Walk® motor (p. 10-12).

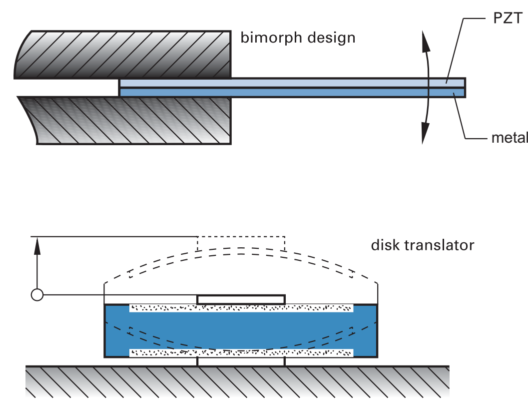


Fig. 45 a. Bimorph design (strip and disk translator).

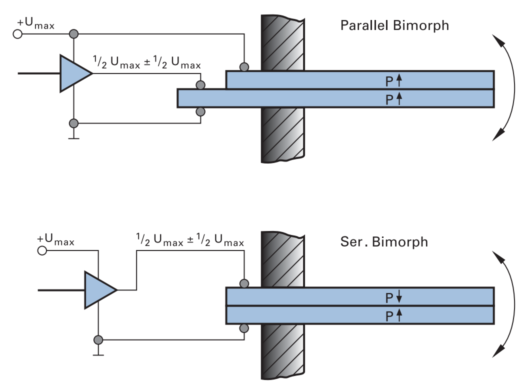


Fig. 45 b. Bender Actuators: Serial and parallel bimorphs.

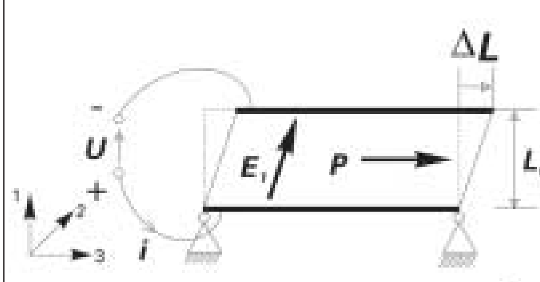


Fig. 46. Material deformation in a shear actuator.

Basic Designs of Piezoelectric Positioning Drives/Systems

Piezo Actuators with Integrated Lever Motion Amplifiers

Piezo actuators or positioning stages can be designed in such a way that a lever motion amplifier is integrated into the system. To maintain sub-nanometer resolution with the increased travel range, the lever system must be extremely stiff, backlash- and friction-free, which means ball or roller bearings cannot be used. Flexures are ideally suited as linkage elements. Using flexures, it is also possible to design multi-axis positioning systems with excellent guidance characteristics (see p. 4-43).

PI employs finite element analysis (FEA) computer simulation to optimize flexure nanopositioners for the best possible straightness and flatness (see Fig. 49 and Fig. 51).

Piezo positioners with integrated motion amplifiers have both advantages and disadvantages compared to standard piezo actuators:

Advantages:

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

Disadvantages:

- Reduced stiffness
- Lower resonant frequency

The following relations apply to (ideal) levers used to amplify motion of any primary drive system:

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

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

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

where:

r = lever transmission ratio

ΔL_0 = travel of the primary drive [m]

ΔL_{Sys} = travel of the lever-amplified system [m]

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

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

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

$f_{res\text{-}0}$ = resonant frequency of the primary drive system (piezo 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 piezo stack and the lever. In real applications, the design of a good lever requires long experience in micromechanics and nanomechanisms. A balance between mass, stiffness and cost must be found, while maintaining zero-friction and zero-backlash conditions.

Coupling the piezo stack to the lever system is crucial. 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 each of the two interfaces is as high as that of the piezo stack alone, a 67 % loss of overall stiffness still results. In many piezo-driven systems, the piezo stiffness is thus not the limiting factor in determining the stiffness of the mechanism as a whole.

PI piezomechanics are optimized in this regard as a result of more than 30 years experience with micromechanics, nanopositioning and flexures.

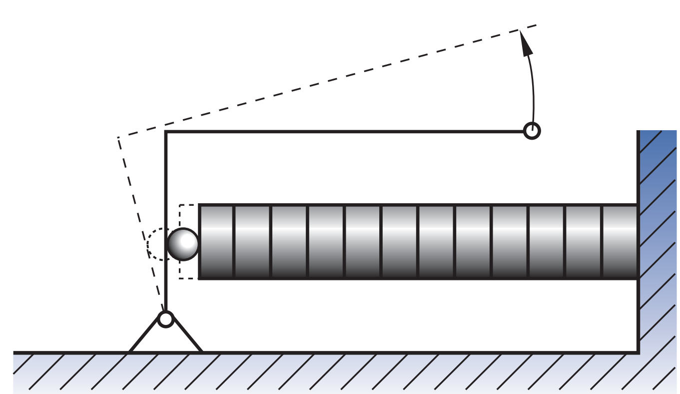


Fig. 47. Simple lever motion amplifier.

Piezo Flexure Nanopositioners

For applications where extremely straight motion in one or more axes is needed and only nanometer or microrad deviation from the ideal trajectory can be tolerated, flexures provide an excellent solution.

A flexure is a frictionless, stictionless device based on the elastic deformation (flexing) of a solid material (e.g. steel). Sliding and rolling are entirely eliminated. In addition, flexure devices can be designed with high stiffness, high load capacity and do not wear. They are also less sensitive to shock and vibration than other guiding systems. They are also maintenance-free, can be fabricated from non-magnetic materials, require no lubricants or consumables and hence, unlike air cushion bearings, are suitable for vacuum operation.

Parallelogram flexures exhibit excellent guidance characteristics. Depending on complexity and tolerances, they have straightness/flatness values in the nanometer range or better. Basic parallelogram flexures cause arcuate motion (travel in an arc) which introduces an out-of-plane error of about 0.1% of the travel range (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 = out-of-plane error [m]

ΔL = distance traveled [m]

H = length of flexures [m]

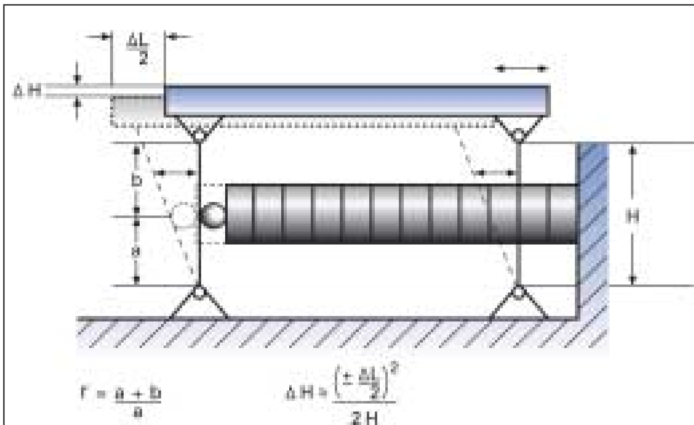


Fig. 48. Basic parallelogram flexure guiding system with motion amplification. The amplification r (transmission ratio) is given by (a+b)/a.

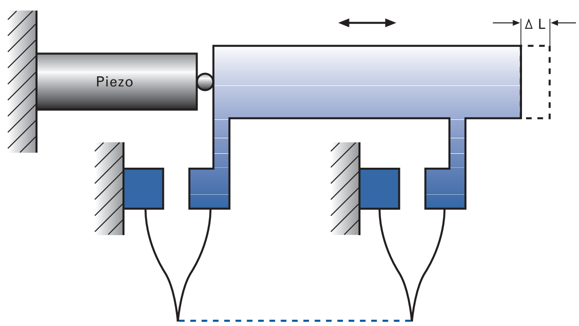


Fig. 49. Zero-arcuate-error multi-flexure guiding system.

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, makes possible straightness/flatness in the nanometer or microradian range (see Fig. 49).

Note:

Flexure positioners are far superior to traditional positioners (ball bearings, crossed roller bearings, etc.) in terms of resolution, straightness and flatness. Inherent friction and stiction in these traditional designs limit applications to those with repeatability requirements on the order of 0.5 to 0.1 µm. Piezo flexure nanopositioning systems have resolutions and repeatabilities which are superior by several orders of magnitude.

Parallel and Serial Kinematics / Metrology

Direct and Indirect Metrology

Non-contact sensors are used to obtain the most accurate position values possible for position servo-control systems. Two-plate capacitive sensors installed directly on the moving platform and measuring on the axis of motion offer the best performance. Resolution and repeatability can attain 0.1 nanometer in such systems. Indirect metrology—measuring strain at some point in the drive train—cannot be used in systems with the highest accuracy requirements.

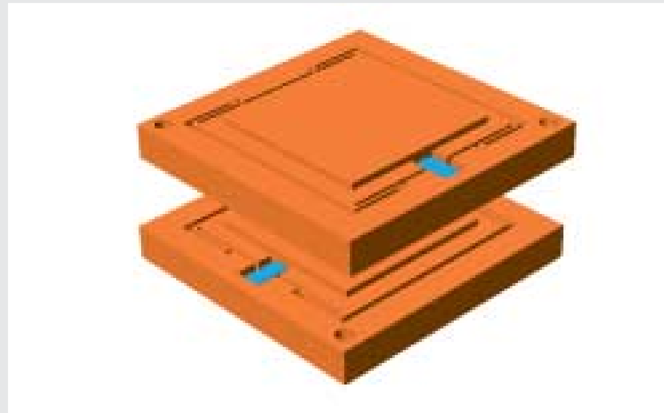


Fig. 50 a. Working principle of a stacked XY piezo stage (serial kinematics). Advantages: Modular, simple design. Disadvantages compared with parallel kinematics: More inertia, higher center of gravity, moving cables (can cause friction and hysteresis). Integrated parallel metrology and active trajectory control (automatic off-axis error correction) are not possible.

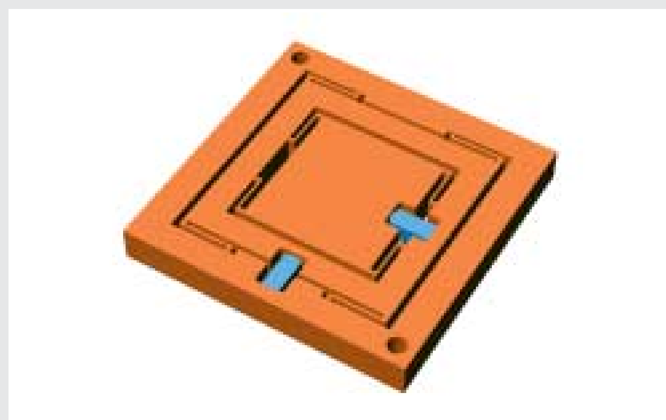


Fig. 50 b. Working principle of a nested XY piezo stage (serial kinematics). Lower center of gravity and somewhat better dynamics compared with stacked system, but retains all the other disadvantages of a stacked system, including asymmetric dynamic behavior of X and Y axes.

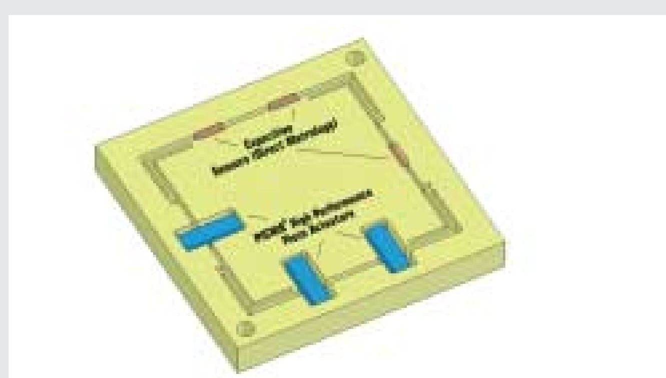


Fig. 50 c. Working principle of a monolithic $XY\Theta_Z$ parallel kinematics piezo stage. All actuators act directly on the central platform. Integrated parallel metrology keeps all motion in all controlled degrees of freedom inside the servo-loop. The position of the central, moving platform is measured directly with capacitive sensors, permitting all deviations from the prescribed trajectory to be corrected in real-time. This feature, called active trajectory control, is not possible with serial metrology.

Parallel and Serial Kinematics

There are two basic ways to design multi-axis positioning systems: Serial kinematics and parallel kinematics. Serial kinematics are easier to design and build and can be operated with simpler controllers. They do, however, have a number of disadvantages compared to higher-performance and more elegant parallel kinematics systems. In a multi-axis serial kinematics system, each actuator is assigned to exactly one degree of freedom. If there are integrated position sensors, they are also each assigned to one drive and measure only the motion caused by that drive and in its direction of motion. All undesired motion (guiding error) in the other five degrees of freedom are not seen and hence cannot be corrected in the servo-loop, which leads to cumulative error.

In a parallel kinematics multi-axis system, all actuators act directly on the same moving platform. Only in this way can the same resonant frequency and dynamic behavior be obtained for the X and Y axes. It is also easy to implement parallel metrology in parallel kinematics systems. A parallel metrology sensor sees all motion in its measurement direction, not just that of one actuator, so runout from all actuators can be compensated in real-time (active trajectory control). The results are significantly less deviation from the ideal trajectory, better repeatability and flatness, as shown in Fig. 51.

Examples:

P-734, P-561, p. 2-68 *ff.* in the "Piezo Nanopositioners & Scanning Systems" section.

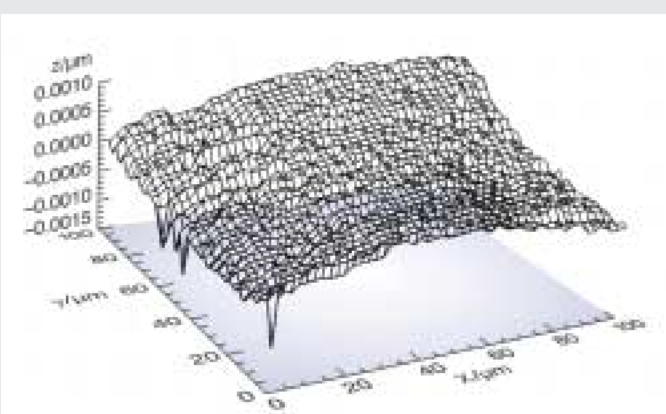


Fig. 51. Flatness (Z-axis) of a 6-axis nanopositioning system with active trajectory control over a 100 x 100 µm scanning range. The moving portion of this parallel metrology positioner is equipped with ultra-precise parallel metrology capacitive sensors in all six degrees of freedom. The sensors are continually measuring the actual position against the stationary external reference.

A digital controller compares the six coordinates of the actual position with the respective target positions. In addition to controlling the scanning motion in the X and Y directions, the controller also ensures that any deviations that occur in the other four degrees of freedom are corrected in real-time.

PMN Compared to PZT

Electrostrictive Actuators (PMN)

Electrostrictive actuators operate on a principle similar to that of PZT actuators. The electrostrictive effect can be observed in all dielectric materials, even in liquids.

Electrostrictive actuators are made of an unpolarized lead magnesium niobate (PMN) ceramic material. PMN is a ceramic exhibiting displacement proportional to the square of the applied voltage under small-signal conditions. 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.

The quadratic relationship between drive voltage and displacement means that PMN actuator are intrinsically nonlinear, in contrast to PZT actuators. PMN actuators have an electrical capacitance several times as high as piezo actuators and hence require higher drive currents for dynamic applications. However, in a limited temperature range, electrostrictive actuators exhibit less hysteresis (on the order of 3 %) than piezo actuators. An additional advantage is their greater ability to withstand pulling forces.

PZT materials have greater temperature stability than electrostrictive materials, especially with temperature variations of over 10 °C.
As temperature increases, available travel is reduced; at low temperatures where travel is greatest hysteresis increases (see Fig. 53 b). PMN actuators are thus best for applications with little or no temperature variations of the ceramic, be they caused by dynamic operation or by environmental factors.

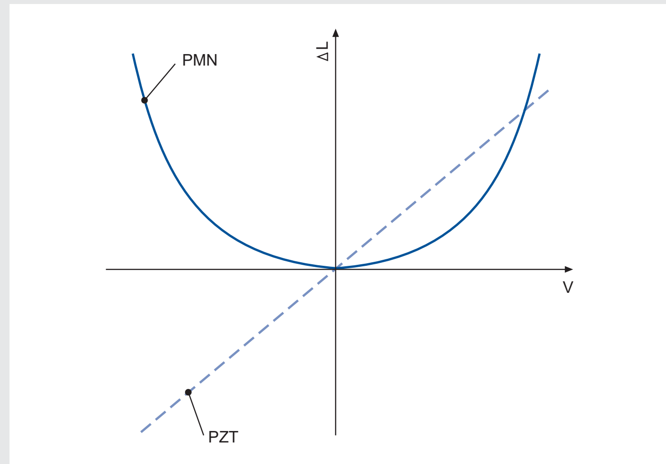


Fig. 52. Comparison of PMN and PZT material: displacement as a function of field strength (generalized).

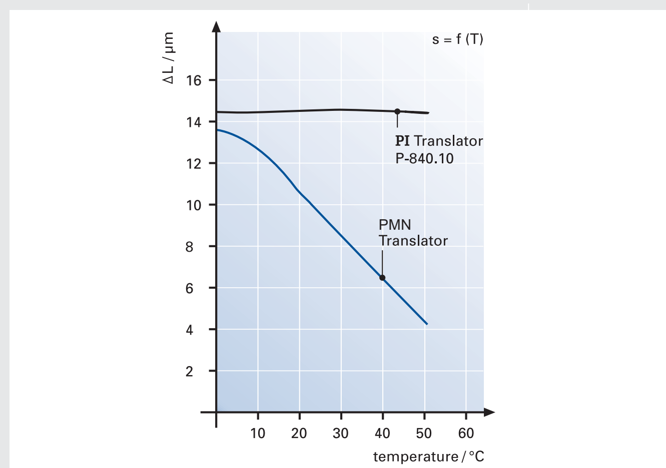


Fig. 53 a. Comparison of PMN and PZT material: displacement as a function of temperature.

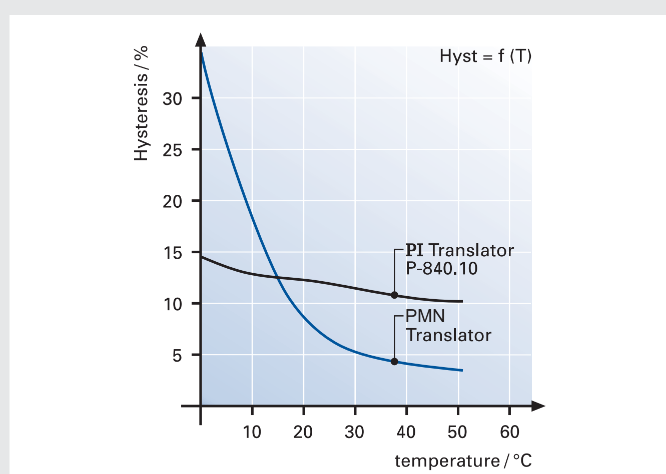


Fig. 53 b. Comparison of PMN and PZT material: hysteresis as a function of temperature.

Summary

Piezoelectric actuators offer a solution to many positioning tasks that depend on highest accuracy, speed and resolution.

Examples given in this tutorial indicate a selection of the many applications common today. The relentless push for more accuracy and speed—whether in the further miniaturization of microelectronics, production of optics and higher-performance data storage devices, precise positioning of optical fiber components for telecommunications, or in the fabrication of micromechanisms—drives both the application and the further development of piezo technology.
To use the advantages of piezo positioners to their full extent, it is important to carefully analyze the system in which a piezo actuator is used as a whole. Close contact between user and manufacturer is the best recipe for success.

Piezoelectric actuators will in the future partially replace, partially complement, conventional drive technologies. They will widen the realm of the possible, and will usher in developments in areas like nanotechnology which would be unthinkable with conventional drive technologies.

Mounting and Handling Guidelines

Adherence to the following guidelines will help you obtain maximum performance and lifetime from your piezo actuators: Do not use metal tools for actuator handling. Do not scratch the coating on the side surfaces. The following precautions are recommended during handling of piezoelectric actuators:

I. Piezoelectric stack actuators without axial preload are sensitive to pulling forces. A preload of up to 50% of the blocking force is generally recommended.

II. Piezoelectric stack actuators may be stressed in the axial direction only. The applied force must be centered very well. Tilting and shearing forces, which can also be induced by parallelism errors of the endplates, have to be avoided because they will damage the actuator. This can be ensured by the use of ball tips, flexible tips, adequate guiding mechanisms etc. An exception to this requirement is made for the PICA™-Shear actuators, because they operate in the shear direction.

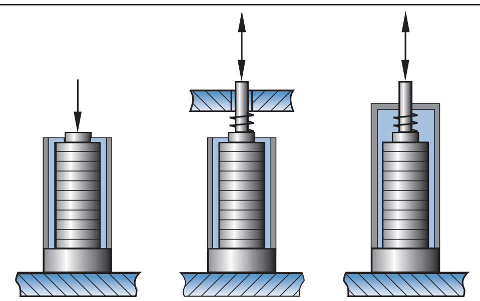
III. Piezoelectric stack actuators can be mounted by gluing them between even metal or ceramic surfaces by a cold or hot curing epoxy, respectively. Ground surfaces are preferred. Please, do not exceed the specified working temperature range of the actuator during curing.

IV. The environment of all actuators should be as dry as possible. PICMA® actuators are guarded against humidity by their ceramic coating. Other actuators must be protected by other measures (hermetic sealing, dry air flow, etc).

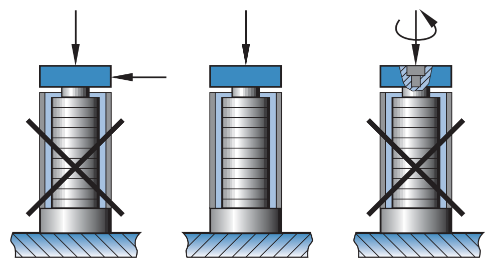
The combination of long-term high electric DC fields and high relative humidity values should be avoided with all piezoelectric actuators.

V. It is important to shortcircuit the piezoelectric stack actuators during any handling operation. Temperature changes and load changes will induce charges on the stack electrodes which might result in high electric fields if the leads are not shorted: Should the stack become charged, rapid discharging—especially without a preload—might damage the stack. Use a resistor for discharging.

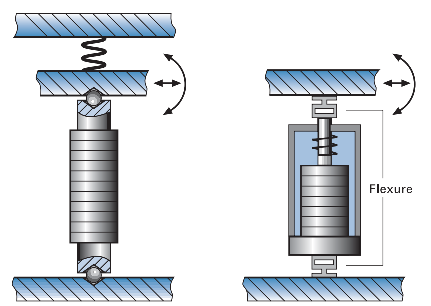
VI. Prevent any contamination of the piezo ceramic surfaces with conductive or corrosive substances. Isopropanol is recommended for cleaning. Avoid acetone and excessive ultrasonic cleaning at higher temperatures.



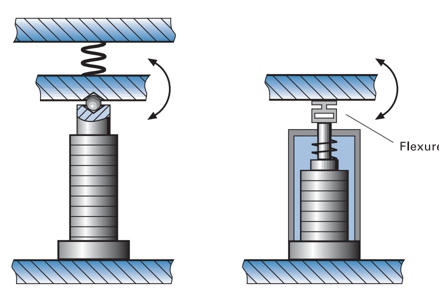
No pulling force without preload.



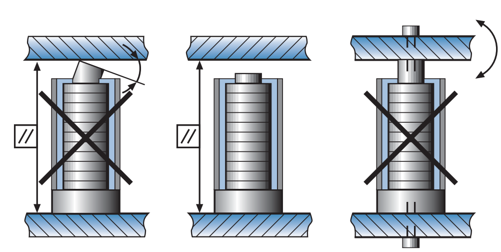
No lateral force or torque.



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



Ball tips or flexures to decouple bending forces.



Bolting between plates is not recommended.

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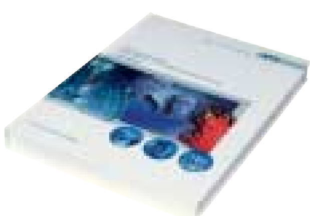

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Headquarters

Germany

Physik Instrumente (PI) GmbH & Co. KG
Auf der Römerstraße 1
76228 Karlsruhe
Tel. +49 721 4846-0
Fax +49 721 4846-100
info@pi.ws · http://www.pi.ws

PI Ceramic GmbH
Lindenstraße
07589 Lederhose
Tel. +49 36604 882-0
Fax +49 36604 882-25
info@piceramic.com
http://www.piceramic.com

Subsidiaries

USA (East) & Canada (East)

PI (Physik Instrumente) L.P.
16 Albert Street
Auburn, MA 01501
Tel. +1 508 8323456
Fax +1 508 8320506
info@pi-usa.us
http://www.pi-usa.us

PI (West), Canada (West), Mexico

PI (Physik Instrumente) L.P.
5420 Trabuco Road, Suite 100
Irvine, CA 92620-5743
Tel. +1 (949) 679-9191
Fax +1 (949) 679-9292
info@pi-usa.us
http://www.pi-usa.us

JAPAN

PI-Japan Co., Ltd.
2-38-5 Akebono-cho
Tachikawa-shi
J-Tokyo 190-0012
Tel. +81 42 5267300
Fax +81 42 5267301
info@pi-japan.jp
http://www.pi-japan.jp

PI-Japan Co., Ltd.
Hanahara Dai-ni-Building #703
4-11-27 Nishinakajima,
Yodogawa-ku, Osaka-shi
J-Osaka 532-0011
Tel. +81 6 63045605
Fax +81 6 63045606
info@pi-japan.jp
http://www.pi-japan.jp

CHINA

Physik Instrumente (PI Shanghai) Co., Ltd.
Building No. 7-306,
Longdong Avenue 3000
201203 Shanghai
Tel. +86 21 68790008
Fax +86 21 68790098
info@pi-china.cn
http://www.pi-china.cn

UK & Ireland

Lambda Photometrics Ltd.
Lambda House
Batford Mill
GB-Harpenden, Hertfordshire
AL5 5BZ
Tel. +44 1582 764334
Fax +44 1582 712084
info@lambdaphoto.co.uk
http://www.lambdaphoto.co.uk

France

Polytec PI S.A.
32 rue Delizy
F-93694 Pantin Cedex
Tel. +33 1 48103930
Fax +33 1 48100803
pi.phot@polytec-pi.fr
http://www.polytec-pi.fr

Italy

Physik Instrumente (PI) S.r.l.
Via G. Marconi, 28
I-20091 Bresso (MI)
Tel. +39 02 66501101
Fax +39 02 66501456
info@pionline.it
http://www.pionline.it