Basic Introduction to NanoPositioning with Piezoelectric Technology

Notes

For more detailed information see "Fundamentals of Piezoelectricity and Piezo Actuators", page 4-15.

Basics

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

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

As stated above, piezoelectric materials can be used to convert electrical energy into mechanical energy and vice versa. For NanoPositioning, the precise motion which results when an electric field is applied to a piezoelectric material is of great value. Actuators using this effect first became available around 30 years ago and have changed the world of precision positioning.

Features of PZT Actuators

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

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

Low-Voltage and High-Voltage PZTs

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

The maximum electrical field PZT ceramics can withstand is on the order of 1 to 2 kV/mm. In order to keep the operating voltage within practical limits, PZT actuators consist of thin layers of electroactive ceramic material electrically connected in parallel (Fig. 1). The total displacement is the sum of the displacements of the individual layers. The thickness of the individual layer determines the maximum operating voltage for the actuator (for more information see "Displacement of Piezo Actuators (Stack & Contraction Type)", page 4-19).

High-voltage piezo actuators consist of bulk ceramic disks which are 0.4 to 1 mm thick and glued together to form a stack.

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

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

Both types of piezo actuators can be used for many applications: Low-voltage actuators facilitate drive electronics design, high-voltage types operate to higher temperatures (150 °C compared to 80 °C).

Due to manufacturing technology, high-voltage ceramics can be designed with larger cross-sections suitable for higher-load applications (up to several tons) than low voltage ceramics.

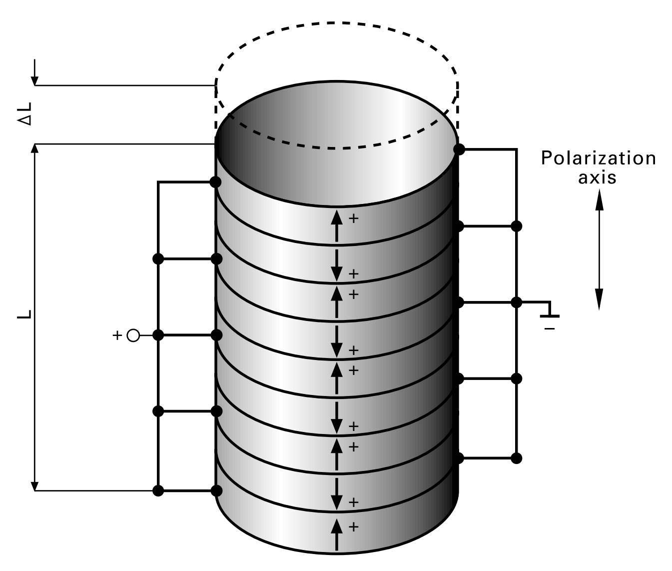

Fig. 1. Electrical connection of disks in a PZT stack actuator.

Resolution

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

Open- and Closed-Loop Operation

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

Closed-loop actuators are ideal for applications requiring high linearity, long-term position stability, repeatability and accuracy. PI closed-loop PZT actuators & systems are equipped with position measuring systems providing sub-nanometer resolution or bandwidth up to 10 kHz. A servo-controller (digital or analog) determines the voltage to send to the PZT by comparing a reference signal (commanded position) to the actual position, as reported by the feedback position sensor (for more information see “Position Servo-Control,” page 4-34).

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

Dynamic Behavior

A piezo actuator can reach its nominal displacement in approximately one third of the period of its resonant frequency. Rise times on the order of microseconds and accelerations of more than 10,000 g’s are possible. This feature makes PZTs suitable for rapid switching applications. Injector nozzle valves, hydraulic valves, electrical relays, adaptive optics and optical switches are a few examples of fast switching applications.

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

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

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Mechanical Considerations

Stiffness

In a first approximation, a piezo actuator can be regarded as a spring/mass system. The stiffness or spring constant of a piezo actuator depends on the Young’s Modulus of the ceramic (approximately 25 % that of steel), the cross section and length of the active material and a number of other non-linear parameters (for more information see “Stiffness,” page 4-23).

Load Capacity and Force Generation

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

Load capacity and force generation must be distinguished. The maximum force (blocked force) a piezo can generate is determined by the product of the stiffness and the nominal displacement. A piezo actuator (as most other actuators) pushing against a spring load will not reach its nominal displacement. The reduction in displacement is dependent on the ratio of the piezo stiffness to the spring stiffness. As the spring stiffness increases, the displacement decreases and the generated force increases (for more information see ”Stiffness”, page 4-23).

Protection from Mechanical Damage

Since PZT ceramics are brittle and cannot withstand high pulling or shear forces, the mechanical actuator design must isolate these undesirable forces from the ceramic. For example, spring preloads can be integrated in the mechanical actuator assembly to compress (preload) the ceramic inside and increase the ceramic’s pulling capabilities for dynamic push/pull applications (for more information see “Mounting Guidelines”, page 4-47).

Power Requirements

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

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

For example, a typical medium-load LVPZT actuator with a motion range of 15 microns and 10 kg load capacity requires only five watts to be driven at 1000 Hz while a high-load actuator capable of carrying a few tons may require hundreds of watts for the same frequency (for more information see “Electrical Requirements,” page 4-30).

Different Piezo Actuator Designs to Suit Various Applications


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

Stack Actuators (Translators)

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

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

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

Other Basic Actuators

Apart from stack translators, a number of other basic PZT actuators are available: bender actuators providing long travel (millimeter range), contraction actuators, tube actuators, shear actuators etc. See "Basic Designs," page 4-41 *ff* for more information.

Actuators with Motion Amplifiers & Trajectory Control

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


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

Fig. 3 shows one example of a piezoelectrically driven miniature flexure stage with integrated flexure guiding system and motion amplifier. The stage is made of stainless steel and all flexures are wire EDM (electrical discharge machining) cut. The flexures are computer designed by an FEA (Finite Element Analysis) program. The central part of the stage can move +/- 40 micrometers along one axis. The movement is accomplished by an integrated 3:1 lever, driven by a PZT stack pushing a spherical tip built into to the

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lever. The resonant frequency of the unloaded stage is 1 kHz (high when the lever amplification is considered).

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

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

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

Piezo Actuators Combined with Motorized Long-Travel Positioning Systems

Piezo actuators can be combined with other actuators to form long-travel, high-resolution systems. A good example is the combination of a P-250 piezo actuator with a closed-loop motor-driven leadscrew (Fig. 4). This combination provides 25 mm coarse range (versions with 50 mm are available) but preserves the high-resolution characteristics intrinsic to PZTs. Coarse motion is provided by a micrometer with a non-rotating tip driven by a DC motor/encoder/gearhead unit capable of < 0.1 µm resolution. A short PZT stack providing sub-nanometer resolution is mounted inside the micrometer tip. Both piezo and DC motor can be computer controlled.

Design Points to Remember

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

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