Piezoelectric Drives

Flexure technology provides the capability to design stages and component holders that are completely free from any hysteresis, creep, drift, friction, and stiction. The positioning and alignment capability of a device using well-designed flexures is limited only by the drive mechanism. A high-resolution thumbscrew or micrometer will provide precision travel from many millimeters down to about 1 μm. A state-of-the-art differential micrometer will provide a 50-nm resolution over a range of 300 μm, and a modern piezoelectric (PZT) drive will provide movement and resolution from about 200 μm down to the region of 1 nm using position feedback piezoelectric control.

PIEZOELECTRIC EFFECT

Piezoelectricity, or pressure electricity, a property of some crystalline materials, was discovered by Pierre and Jacques Curie in the 1880s. When these materials are compressed, they produce a voltage proportional to the applied pressure. This effect became known as the piezoelectric effect. Conversely, when an electric field is applied across the material, there is a change of shape. In fact, the change is proportional to the applied electric field, and it is this latter change in shape that is useful when producing the small dimensional changes required for precision positioning. The piezoelectric effect is extremely small in naturally occurring minerals, but present-day materials technology has produced a range of ceramics which can deliver linear extensions of up to 1 percent. Several natural materials exhibit piezoelectric properties, but most devices now use polycrystalline ceramics, such as lead zirconate titanate, and are generally known as PZT ceramics.

Typically, linear extensions of up to 200 μm are obtained when suitable voltages are applied to the appropriate ceramic geometries. Several families of ceramics and types of devices were developed when designers attempted to accentuate the more desirable properties and minimize the less appropriate ones for specific applications. Although similar materials are used, it is proper to refer to the devices that operate in the ferroelectric region below the Curie temperature as piezoelectric and to those that operate in the paraelectric region above the Curie temperature as electrostrictive.

Piezoelectric ceramics must be poled for them to exhibit piezoelectric properties. Above the Curie temperature, the electric dipoles are randomly arranged. If a strong electric field is applied when ceramic is cooled below the Curie temperature, the dipoles remain partially aligned and respond collectively to subsequent smaller field changes producing significant dimensional changes. Traditional piezoelectric materials are categorized as soft or hard. Both must be poled. Hard piezoelectrics have Curie temperatures above 300°C with limited dimensional changes; soft piezoelectrics have lower Curie temperatures and greater dimensional changes but depole more easily. However, soft piezoelectrics can be repoled quickly and easily. Traditionally, high voltages (up to 2000 Vdc) have been applied to stacks of thin slices of piezoelectric materials to produce the required extensions. Figure 8.16 illustrates the typical length increase when voltage is applied to such stacks. Note that the increase in length is approximately linear with the applied field and that there is some saturation at higher voltages. Also there is pronounced hysteresis, which is greater with the soft piezoelectric material.

Although high voltages are used, power consumption is low, and almost no energy is consumed in maintaining a fixed position with a fixed load. Piezoceramics can respond rapidly to changing input voltages (microsecond time constants), and the positional resolution is limited only by the noise of the power supply. The need for voltages in the 1 to 2 kV range has restricted their utilization because of the cost, electronic noise, reliability, and safety issues involved.

Piezoelectric drives

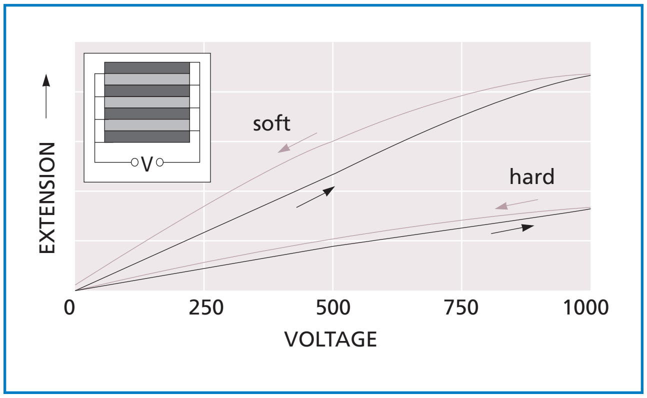


Figure 8.16 **Comparison of soft and hard piezoelectric ceramics** The curves show typical hysteresis behavior as the voltage applied to piezoelectric stacks is increased and decreased. The inset diagram shows how the voltage is applied to a stack made from seven slices of piezoelectric ceramic.

PIEZOELECTRIC DRIVES

Usually quite high voltages are required to produce a useful amount of expansion. In order to avoid excessive drive voltages, piezoelectric materials have been developed that can be used at low voltages. The piezoelectric drives themselves are generally constructed from thin ceramic elements, interleafed with electrodes, as shown in figure 8.17. In this way, the distance from positive to negative electrodes is very small, which means that a useful expansion can be obtained with only a modest drive voltage (75 V is typical in the case of CVI Melles Griot actuators).

Drives made from such piezoelectric ceramics are ideal for producing small, friction-free motions appropriate to the adjustment of optical components.

Actuators made from piezoelectric materials, called piezoactuators, have the following advantages over other actuators:

- Although the expansion is very small it can be controlled in an extremely fine fashion by varying the strength of the applied electric field, or voltage. In fact, the resolution is limited only by the inherent noise and stability of the electronic driver providing the voltage.
- The motion produced is smooth and continuous because the expansion is a process at the atomic level, and therefore there is no friction or stiction.
- The force generated by an expanding piezo can be very large, up to several hundreds of Newtons.
- Piezoactuators respond very quickly to the applied voltage and can therefore produce oscillating motion at high input frequencies.
- The power dissipation of a piezoactuator is very small, especially when static (typically milliwatts when moving and microwatts when static).

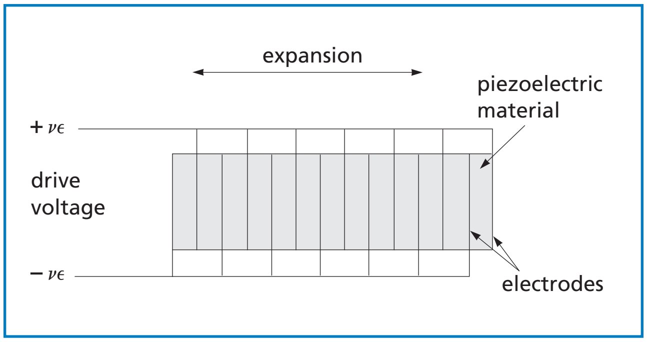


Figure 8.17 **Schematic representation of a low-voltage piezoelectric stack**

Open-loop piezoelectric drives, however, also have their disadvantages:

- They are nonlinear and suffer from hysteresis and drift.
- High-strain materials have a low Curie temperature (i.e., the temperature at which polarization is lost).
- They do not perform efficiently when pulling.
- They require a continuous voltage source to maintain their position.

HYSTERESIS EFFECT

If the voltage applied to a piezoelectric device is increased from zero, the expansion vs voltage curve follows path 1 as shown in figure 8.18. If the voltage is decreased, path 2 is followed. Path 3 is followed when the voltage is increased again. If the voltage is cycled between two fixed levels, the extension follows the closed loop defined by paths 2 and 3.

Hysteresis is defined as the maximum difference between the upward and downward paths expressed as a percentage of the full range.

If hysteresis is likely to be a problem in a particular application, the final position can always be approached from one direction. This unidirectional approach, together with computer routines, can be used to linearize the motion and correct for any fine hysteresis, creep, and temperature changes. Such software linearization can be very effective for routine operation of a well-characterized system.

A more powerful and generally applicable technique is to use piezoelectric actuators with closed-loop feedback control of their extension. Hysteresis and creep are then of no importance. CVI Melles Griot has developed a

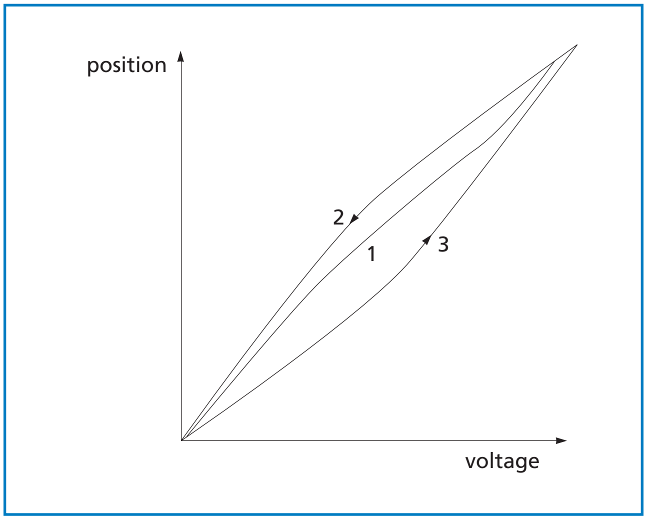


Figure 8.18 **Simplified schematic representation of hysteresis loop**

range of piezoelectric actuators fitted with closed-loop position feedback sensors. These are designed to produce linear movement with the highest possible resolution and stability, as shown in figure 8.19. When used with the appropriate controllers, the linearity of response is better than ± 0.5 percent, and the noise equivalent motion is ±5 nm.

Clearly, piezoceramics (piezoelectrics or electrostrictives) are not perfect voltage-to-displacement transducers, but they are friction and stiction free, with motions ranging from hundreds of microns down to less than 1 nm. With modern low-voltage and preloaded designs, operation is simple and reliable. In many optical and fiber-optical applications, the positioning and alignment requirements, although requiring submicron control, can readily be met by standard low-voltage preloaded piezoelectrics when operated with low-drift and low-noise controllers.

LOW-VOLTAGE PIEZOELECTRIC AND ELECTROSTRICTIVE DEVICES

Piezoceramic stacks rated for operation at much lower voltages (0 to 150 Vdc) are available. CVI Melles Griot offers very reliable, long-life actuators for operation at even lower voltages, in the range of from 0 to 75 Vdc, with good response even below 10 Vdc. These actuators have been optimized for operation in optical and fiber-optical applications. This extremely low-voltage piezoelectric technology has been chosen by CVI Melles Griot because it is more appropriate than any other currently available.

A possible alternate technology is to use piezoelectric materials in the electrostrictive mode. A major electrostrictive material is lead magnesium niobate, a centrosymmetric material, which can be operated in a multilayer stack structure using from 0 to 150 Vdc. The hysteresis of low-voltage soft piezoelectrics is typically between 10 and 15 percent, but it remains essentially constant from −60°C to +60°C, whereas the electrostrictive hysteresis is less but changes with temperature, from 3 percent at 30°C to 10 percent at 5°C. These figures, which are for full-cycle motions, are the ratio of the maximum difference of the displacement position on the voltage increasing path to that on the voltage decreasing path, compared to the displacement at maximum voltage (see figures 8.20 and 8.21). Notice that the hysteresis cycle for the piezoelectric is much smaller when small local movement corrections are required. Instant smooth positive and negative adjustments are available with high resolution and no backlash (note: hysteresis does not equate with backlash).

Hysteresis curves for piezoelectric materials are truncated near the origin (zero applied voltage). A low-voltage piezoelectric stack can be easily preloaded so that the motion shows fewer effects of saturation, the hysteresis is reduced, and the truncation disappears, leaving a well-defined zero datum.

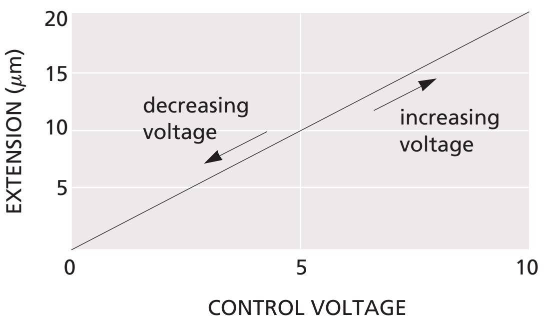


Figure 8.19 **Piezoelectric with position feedback control**

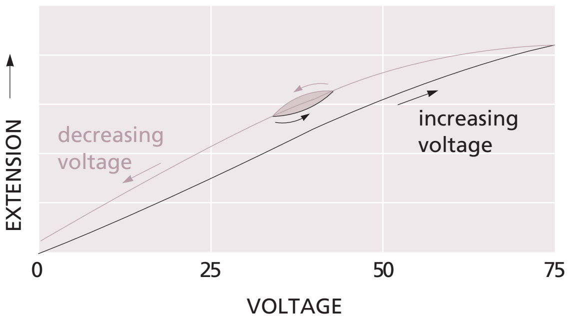


Figure 8.20 **Typical piezoelectric hysteresis curves** The size of the hysteresis loop depends on the size of the voltage excursions and can be small for small voltage reversals. Compare the small hysteresis loop for the approximately 7.5-Vdc cycle with the larger loop for the full 75-Vdc cycle.

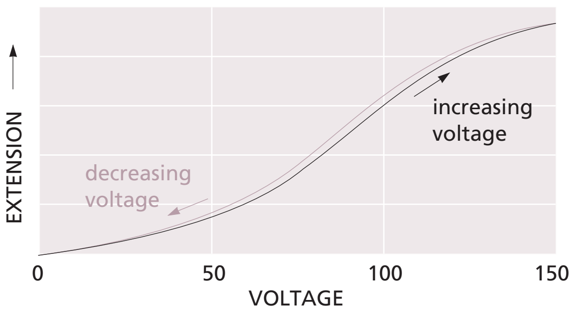


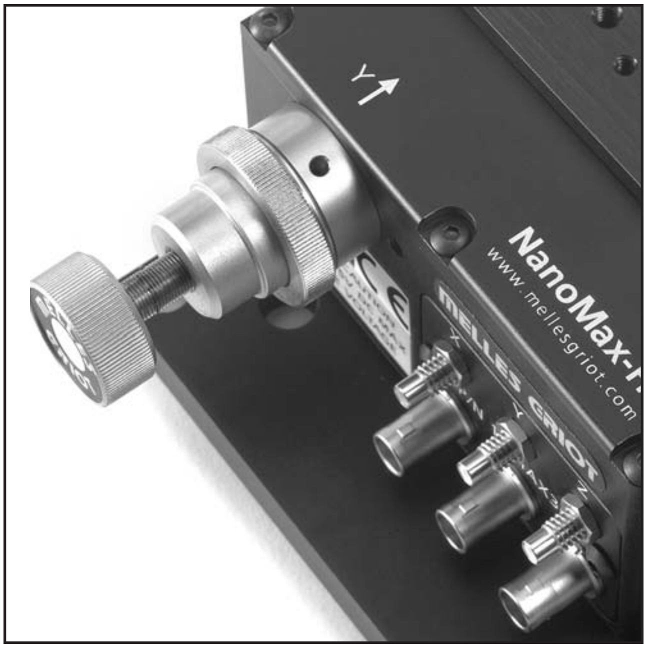
Figure 8.21 **Typical electrostrictive hysteresis curve** The hysteresis is low, but the response is nonlinear and there is very little sensitivity at low voltages.

The general shape of the hysteresis curve for an electrostrictive stack is very different from that for a piezoelectric stack because the expansion of piezoelectric devices (to first order) is linear in the applied field, whereas the electrostrictive devices expand according to the square of the field (to first order). This has several consequences. For example, in the case of electrostrictive devices, a logarithmic rather than linear voltage amplifier is required; consequently, any precision linearization system will be more difficult to implement and will require greater dynamic response. Also, at low voltages, because the expansion is almost zero for electrostrictive materials, it is difficult to make systems operate in the range of from 0 to 15 Vdc.

For fiber-alignment applications, as for most optical-alignment and orientation applications, neither the higher hysteresis of piezoelectrics nor the higher nonlinearity of electrostrictives is important. What is most important is the stability of the alignment once it is obtained. This, of course, is a combination of the quality of construction of the alignment mechanism and the stability of the ceramic stack. The two biggest problem areas associated with piezoceramics involve changes with temperature and positional creep or drift.

The length of low-voltage piezoelectrics varies slowly with changes in temperature. The exact value of the effective linear expansion coefficient will depend on both the piezoelectric material and the housing. Typically, devices can be used from −20°C to +80°C, the upper temperature being restricted to avoid depolarization of the soft ceramic. Electrostrictive ceramics are carefully designed to have a maximum electric-field-dependent movement over a limited temperature range. Typically, the response changes up to 50 percent for a 25°C temperature change.

After the operating voltage of a piezoelectric or electrostrictive device is changed, there will be a further drift in the same direction, following the immediate movement. This creep or drift may total several percentage points, but its magnitude decreases exponentially with time and usually is negligible after a few seconds. The creep in low-voltage piezoelectrics and electrostrictives is almost identical, and both exhibit much better creep performance than the traditional high-voltage devices.



Flexure stage with built-in piezoactuators

Piezoactuator electronic controller