Nonlinearity

The voltage-dependent displacement curves of piezo actuators have a strongly nonlinear course that is subject to hysteresis due to the extrinsic domain contributions. It is therefore not possible to interpolate linearly from the nominal displacement to intermediate positions with a particular driving voltage. The electromechanical and dielectric large-signal curves of piezo ceramics illustrate the characteristics (Fig. 20). The origin of each graph is defined by the respective thermally depolarized condition.

The shape of both bipolar large-signal curves is determined by the ferroelectric polarity reversal process when the coercive field strength $E_c$ is achieved in the opposing field. The dielectric curve shows the very large polarization changes at these switch-over points. At the same time, the contraction of the ceramic after reversing the polarity turns into an expansion again, since the polarization and the field strength have the same orientation once more. This property gives the electromechanical curve its characteristic butterfly shape. Without the electric field, the remnant polarizations $P_{\text{rem}}$ and the remnant strain $S_{\text{rem}}$ remain.

Piezo actuators are usually driven unipolarly. A semibipolar operation increases the strain amplitude while causing a stronger nonlinearity and hysteresis which result from the increasing extrinsic domain portions of the displacement signal (Fig. 21).

In the PI and PIC data sheets, the free displacements of the actuators are given at nominal voltage.

Piezoelectric Deformation Coefficient (Piezo Modulus)

The gradient $\Delta S/\Delta E$ between the two switch-over points of the nonlinear hysteresis curves is defined as the piezoelectric large-signal deformation coefficients $d_{(GS)}$ (Fig. 21). As the progressive course of the curves shows, these coefficients normally increase along with the field amplitude (Fig. 22).
Estimation of the Expected Displacement

If the values from fig. 22 are entered into the equations 3 to 10 (p. 39-41), the attainable displacement at a particular piezo voltage can be estimated. The field strength can be calculated from the layer heights of the specific component and the piezo voltage $V_{PP}$. The layer thickness of the PI Ceramic standard products can be found starting on p. 42.

The free displacement of the components that can actually be attained depends on further factors such as the mechanical preload, the temperature, the control frequency, the dimensions, and the amount of passive material.
Position Control

Hysteresis and creep of piezo actuators can be eliminated the most effectively through position control in a closed servo loop. To build position-controlled systems, the PI Ceramic piezo actuators of the PICA Stack and PICA Power product line can be optionally offered with applied strain gauges.

In applications with a purely dynamic control, the hysteresis can be effectively reduced to values of 1 to 2% even with open-loop control by using a charge-control amplifier (p. 63).

PI offers a wide range of position-controlled piezo systems with capacitive sensors or strain gauges. When the actuator and sensor are combined with suitable guiding mechanics, a low-noise amplifier and corresponding control algorithms, these systems achieve positioning accuracies in the subnanometer range.

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Fig. 26: Elimination of hysteresis and creep in a piezo actuator through position control
Below the Curie temperature, the temperature dependence of the remnant strain and the coercive field strength is decisive for the temperature behavior. Both the attainable displacement with electric operation and the dimensions of the piezoceramic element change depending on the temperature. The cooler the piezo actuator, the greater the remnant strain $S_{rem}$ and the coercive field strength $E_{rem}$ (fig. 27). The curves become increasingly flatter with decreasing temperatures. This causes the strain induced by a unipolar control to become smaller and smaller even though the total amplitude of the bipolar strain curve hardly changes over wide temperature ranges. The lower the temperature, the greater the remnant strain. All in all, the piezo ceramic has a negative thermal expansion coefficient, i.e. the piezo ceramic becomes longer when it cools down. In comparison: A technical ceramic contracts with a relatively low thermal expansion coefficient upon cooling. This surprising effect is stronger, the more completely the piezo ceramic is polarized.

**Displacement as a Function of the Temperature**

How much a key parameter of the piezo actuator changes with the temperature depends on the distance from the Curie temperature. PICMA® actuators have a relatively high Curie temperature of 350°C. At high operating temperatures, their displacement only changes by the factor of 0.05%/K.
At cryogenic temperatures, the displacement decreases. When controlled unipolarly in the liquid-helium temperature range, piezo actuators only achieve 10 to 15% of the displacement at room temperature. Considerably higher displacements at lower temperatures can be achieved with a bipolar drive. Since the coercive field strength increases with cooling (fig. 27), it is possible to operate the actuator with higher voltages, even against its polarization direction.

**Dimension as a Function of the Temperature**

The temperature expansion coefficient of an all-ceramic PICMA® stack actuator is approximately -2.5 ppm/K. In contrast, the additional metal contact plates as well as the adhesive layers in a PICA stack actuator lead to a nonlinear characteristic with a positive total coefficient (fig. 29).

If a nanopositioning system is operated in a closed servo loop, this will eliminate temperature drift in addition to the nonlinearity, hysteresis, and creep. The control reserve to be kept for this purpose, however, reduces the usable displacement.

For this reason, the temperature drift is often passively compensated for by a suitable selection of the involved materials, the actuator types, and the system design. For example, all-ceramic PICMA® bender actuators show only a minimal temperature drift in the displacement direction due to their symmetrical structure.

**Temperature Operating Range**

The standard temperature operating range of glued actuators is -20 to 85°C. Selecting piezo ceramics with high Curie temperatures and suitable adhesives can increase this range. Most PICMA® multilayer products are specified for the extended range of -40 to 150°C. With special solders, the temperature range can be increased so that special models of PICMA® actuators can be used between -271°C and 200°C, i.e., over a range of almost 500 K.

![Fig. 29: Temperature expansion behavior of PICMA® and PICA actuators with electric large-signal control](image-url)