

## Low-Inertia PZT NanoPositioning Stages with Direct Motion Metrology for Scanning Microscopy, Semiconductor Manufacturing/Inspection

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**Piezoelectric actuators (PZTs) have long been used in precision positioning systems. Recent advances in sensor technology, flexure design and digital control electronics have significantly increased their application range especially for semiconductor fabrication / inspection technology, microlithography and scanning microscopy.**

The piezoelectric effect describes the property of some materials to convert electrical energy into mechanical energy and vice versa. This effect was discovered more than 100 years ago but actuators using this effect only became commercially available some 30 years ago.

Piezoelectric actuators offer the user several benefits and advantages over other motion techniques:

**Unlimited Resolution:** A PZT can produce sub-nanometer movements. Resolution is neither limited by stick-slip effects nor by threshold voltages.

**Fast Expansion:** PZT actuators are the fastest responding positioning elements available (microsecond time constants).

**No Wear and Tear:** PZTs require no maintenance because they are solid state.

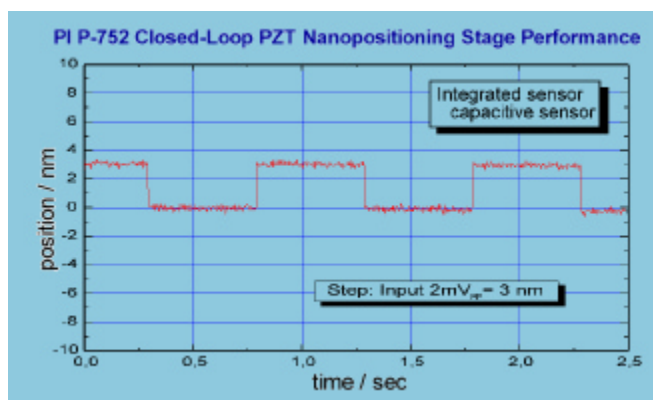


Fig. 1 Position response of a PI PZT Flexure Stage (integrated capacitive direct motion metrology) to a 1 Hz square wave input signal. The commanded motion is 3 nm peak-peak. Position stability is 0.144 nm RMS. Measured with capacitive gauge (resolution: 1.5  $\mu\text{m}/16$  bit)

Simple PZT linear actuators consist of a cylindrical ceramic stack protected by a metal case. They offer typical motion ranges up to 200  $\mu\text{m}$  with sub-nanometer resolution and sub-msec response. Although providing resolution and responsiveness second to none, the progress of PZT positioning technology was somewhat hampered by effects such as hysteresis and nonlinearity.

Recent advances in digital control electronics, flexure design, and sensor technology have overcome these obstacles. By replacing strain gauge type sensors such as piezo resistive sensors with these capacitive sensors, a quantum leap in precision was accomplished. These non-contacting, direct measuring sensors provide sub-nanometer stability, repeatability and resolution (see Fig. 1).

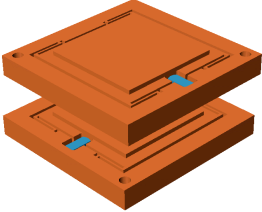
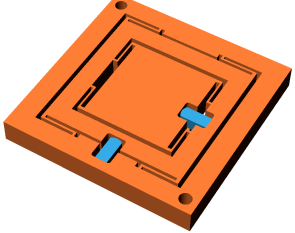
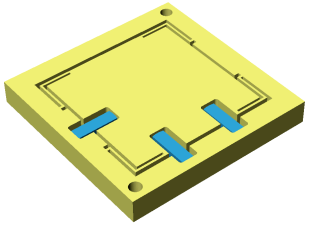
### Low-Inertia PZT Flexure Nano-Positioning Stages

In most applications a PZT stack actuator alone is not enough to perform complex tasks. For example when extremely straight motion or multi-axis motion is required, PZT Flexure Stages provide exceptional precision.

A flexure is a frictionless, stictionless device that relies upon the elastic deformation (flexing) of a solid material. Sliding and rolling are entirely eliminated from the design. Flexure positioners are far superior to traditional positioners (ball bearings, crossed roller bearings, etc.) in terms of resolution, straightness and flatness. Fig 2 shows different PZT flexure scanning stage designs.

Straightness/flatness of high precision XY PZT flexure scanning stages is on the order of a few nm with tilt of only a few arcseconds. This extraordinary precision is ideal for positioning mechanisms in applications such as X-ray steppers, wafer and mask alignment, mask repair systems, CD measurement, scanning microscopy, surface profilers etc.

Fig. 2, Different Flexure Designs

		
<p><b>Stack of single-axis stages</b></p> <p>Slower response (lower stage carries inertial mass of upper stage); Non-symmetric resonant frequencies (lower stage is slower than upper stage, requires different servo settings). Orthogonality error is mounting-angle dependant. Runout in Y cannot be monitored/compensated by the sensor in the X stage or vice versa.</p>	<p><b>Single module (monolithic) nested (serial) X and Y.</b></p> <p>Better response than A) but still non-symmetric and X and Y work without "knowledge" of each other.</p>	<p><b>C) Single-module parallel-kinematics X and Y with parallel direct metrology for crosstalk compensation.</b></p> <p>Best Solution: Same <b>ultra-low inertia</b> for X and Y motion, providing higher responsiveness and axis-independent performance (this results in higher scanning frequencies and better image fidelity in microscopy applications). Excellent, mounting independent orthogonality. Reduced runout: X sensor (PI uses non-contact two plate capacitance sensors) can correct for Y runout and vice versa. Additional rotation axis (Theta z) feasible with 3 actuators / sensors and digital controller.</p>

The ongoing trend in nanotechnology to smaller structures will soon require positioning systems with guiding precision in the sub-nm and sub-arcsec range. Conventional multi-axis flexure designs cannot satisfy these requirements due to cross talk induced by the multi-axis arrangement and other mechanical limitations.

### Adaptive Mechanics Overcomes Limitations

Research results on adaptive mechanics by scientists at PI for a project at the PTB (German Institute of Standards & Technology) proved that by measuring and controlling all six degrees of freedom (X, Y, Z, Theta<sub>x,y,z</sub>) with sufficient accuracy, these limitations can be overcome.

To accomplish a 6 DOF closed-loop nanopositioning system, PI developed a novel multi-axis flexure stage, a digital position controller and a two plate capacitive displacement sensor. The stage is equipped with eight independent PZT actuators and six high resolution capacitive displacement sensors. It provides 100x100 μm<sup>2</sup> XY motion with sub-nanometer resolution while automatically compensating for unwanted out-of-plane Z motion as well as unwanted rotational errors (Theta<sub>x,y,z</sub>). The nominal range of the error compensating actuators is 6 μm (Z), ±500 μrad, (Theta<sub>z</sub>), and ±100 μrad (Theta<sub>x,y</sub>).

### Direct Motion Metrology

The precision of closed-loop PZT stages has traditionally been limited by the feedback devices used. In the past, strain gauge type sensors (e.g. piezo resistive sensors) have often been used to close the loop in PZT positioning systems. While these devices are small and low cost, their use is limited to lower performance applications, where stability, linearity and accuracy are of secondary importance. Strain gauge sensors are contacting devices measuring strain in the drive system (actuator or flexure) instead of motion (where it matters). In scanning applications they cannot distinguish between actual position changes of the moving part and strain changes caused by acceleration / deceleration forces. In addition, bonding forces between the strain gauge and the actuator / flexure induce micro-friction and shear, limiting resolution, repeatability and even the precision of the flexure guiding mechanism.

Currently, non contact, two-plate capacitive sensors provide the highest performance in nanopositioning applications. Two-plate sensors consist of a probe and a slightly larger target plate. This type of sensor was chosen because of its sub-nanometer resolution, insensitivity to lateral motion and because it can be used in multi-axis, parallel metrology arrangements. In the 6-DOF stage, six target plates form a coordinate reference. Digital control electronics evaluate the combined information of all six sensors and transform it into six individual signals proportional to X, Y, Z linear displacement and Theta<sub>x,y,z</sub> rotation.

XY-position repeatability was tested to be better

than 0.5 nm (RMS) over the full 100x100  $\mu\text{m}^2$  range. Z-direction stability is better than 0.033 nm (RMS).

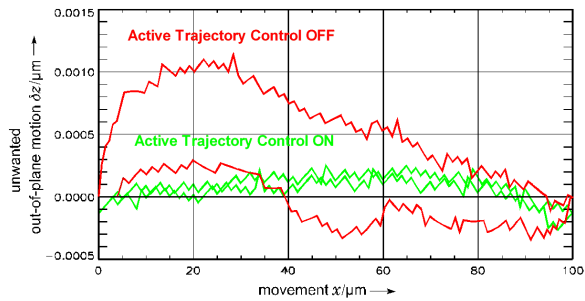


Fig. 3 Comparison of out-of-plane error between an (excellent) standard flexure stage and actively compensated system.

The residual out-of-plane and rotary errors are less than 0.4 nm and 0.1 arcsec, respectively (see Fig. 3). Step response is  $\leq 8$  ms, independent of the scan range (the digital controller features scan range dependent loop-gain setting).

Fig. 4 shows Z out-of-plane motion of the system over a 100 x 100  $\mu\text{m}^2$  XY scan.

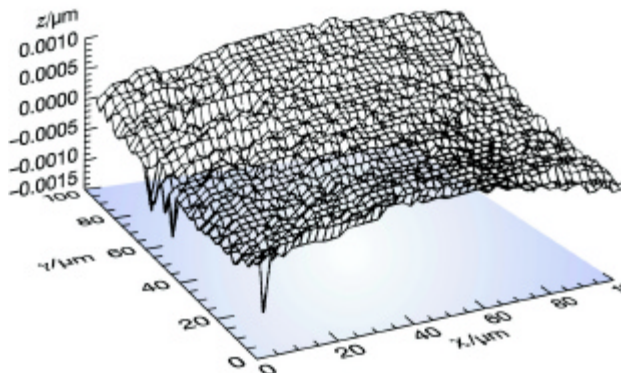


Fig. 4 Z out-of-plane motion of the actively error compensated PZT Flexure Stage over a 100 x 100  $\mu\text{m}^2$  XY scan.

Based on the experience with this system a new series of standard flexure stages was developed. A variety of versions from 100x100  $\mu\text{m}^2$  two-axis to 6 degree-of-freedom 800x800x200  $\mu\text{m} \times \pm 500 \mu\text{rad}$  (Theta  $x, y, z$ ) are available now (Fig. 5).

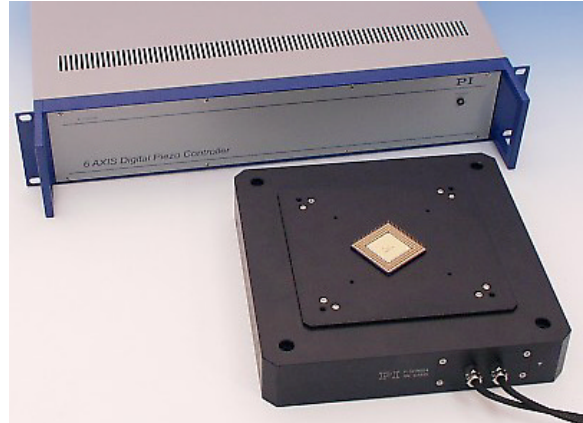


Fig. 5a P-587.6CD, 6-Axis NanoPositioning Stage with digital controller, 800x800x200  $\mu\text{m} \times \pm 500 \mu\text{rad}$



Fig. 5b Custom Super Invar, 6-Axis NanoPositioning Stage with digital controller

## Summary

The combination of digital piezo control, parallel-kinematics flexure designs and multi-axis parallel-metrology with the latest generation two-plate capacitive position sensors promises to help solve nanopositioning problems in a variety of fields from scanning microscopy and semiconductor test systems to nanotechnology. Recent applications such as single molecule fluorescence microscopy, cell trapping and other life sciences related research will also greatly benefit from the current advances in piezo nanopositioning technology.