Nanopositioning / Piezoelectrics

Piezo Systems, Fast Piezo Steering Mirrors

PI Piezo • Nano • Positioning

Nanopositioning Solutions from PI

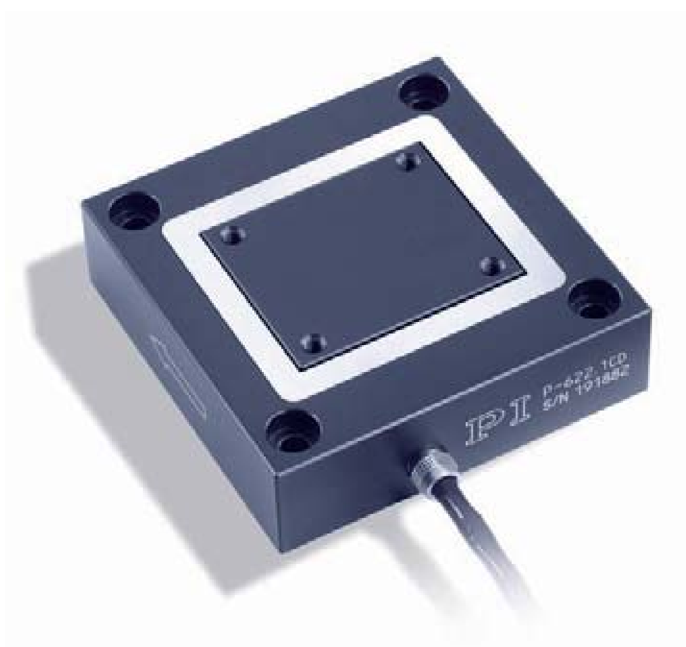
- 1- to 6-axis standard, OEM and custom designs
- Parallel kinematics and parallel metrology for better multi-axis accuracy
- Closed-loop operation with SGS and capacitive position sensors for higher linearity and repeatability
- Integrated capacitive position sensors for sub-nanometer-resolution and stability
- Finite Element Analysis (FEA) computer-designed flexures for nanometer and microradian trajectory control
- Invar, titanium, steel and aluminum versions for optimized thermal match
- High-performance controllers and amplifiers (digital, analog, modular, OEM) with 60 to 1500 V output ranges; Ultra-high-output power amplifiers featuring energy recovery and 2000 W peak power
- Single- and multi-channel digital controllers with dynamic digital linearization (DDL) to eliminate tracking error
- Patented feedforward technology and digital signal processing for faster settling and higher bandwidth
- Modular NanoAutomation® piezo controllers with high-speed parallel interfaces
- Optional opto-isolated inputs for maximum EMI immunity
- Optimized mechanical design, control algorithms and software for highest throughput

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

Typical Applications

- CD, DVD mastering, testing
- Image stabilization, resolution enhancement
- Photonics alignment & packaging
- Fiber optic switches
- Scanning interferometry
- Vibration cancellation
- Laser beam steering
- Adaptive optics
- Scanning microscopy
- Auto-focus systems
- Nanometrology
- Wafer and mask positioning / alignment
- Microlithography
- Fast tool servos
- Smart structures / structural deformation
- Nanopositioning
- Semiconductor test equipment
- Precision machining (non-circular turning, boring, grinding, polishing)
- Biotechnology

Piezo Flexure Stages / High-Speed Scanning Systems



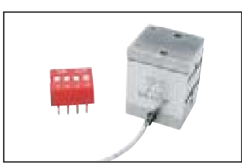
Selection Guide: Single-Axis Piezo Stages

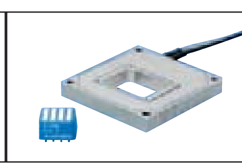
Nanometer Precision, Travel Ranges 15 µm to 1,800 µm

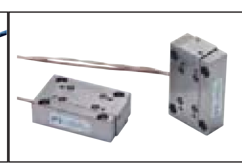
All models are precision flexure guided, and equipped with the patented PICMA® long-life piezo actuators. Capacitive position feedback sensors are available for the highest performance applications, alternatively, strain gauge sensors are available as well as open loop models.

Models	Description	Travel [µm]	Sensor	Dynamics*	Precision**	Page
P-772	Ultra-compact flexure guided system	10	Capacitive	●●●●●	●●●●●	2-24
P-712	Compact scanner, fast, low profile, aperture, ideal for imaging	15	SGS	●●●●●	●●○○○	2-14
P-753	Nanopositioning stage and actuator in one, very compact, fast and accurate	12, 25, 38	Capacitive	●●●●●	●●●●●	2-16
P-752	Nanopositioning stage, very fast and accurate, outstanding guiding accuracy	15, 30	Capacitive	●●●●●	●●●●○	2-18
P-750	High load stage, outstanding guiding accuracy	75	Capacitive	●●●●○	●●●●●	2-24
P-611	Compact, low-cost. X, Z, XY and XYZ combinations	100	SGS	●●●○○	●●●○○	2-20
P-631	Compact precision OEM stage for high-volume applications	100, more on request	Capacitive	●●●○○	●●●●○	2-24
P-62x.1	PIHera® piezo nanopositioners, compact, very accurate, long travel ranges, excellent value. X, XY and XYZ combinations	50 to 1800	Capacitive	●●●●○ to ●○○○○	●●●●○ to ●●●○○	2-22
P-721, P-725	PIFOC® objective nanofocusing system, very fast and accurate, with QuickLock mounting system, direct metrology	100, 250, 500	Capacitive / SGS	●●●○○	●●●●○/●●○○○	2-26 2-28
P-2601	Closed-loop, with flexure guidance	110, 300, 400	SGS	●●●●○	●●○○○	1-68
S-303	Phase shifter, extremely precise, 25 kHz resonant frequency, optional sensors	3	Capacitive	●●●●●	●●●●●	2-96
M-511.HD, M-714	Hybrid drive: piezo & servo motor, extremely accurate, 2 nm linear encoder, long travel to 100 mm	Up to 100 mm	Linear Encoder	●●●●○	●●●●○	4-46

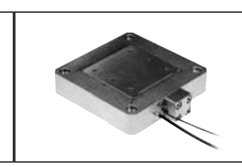
*Dynamics: Combination of system settling time / bandwidth / load capacity relative to the typical application of the product
**Precision: Combination of guiding precision, sensor precision, resolution, relative to comparable products in class

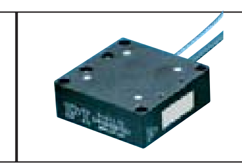

P-772 Smallest stage with direct metrology. 12 µm

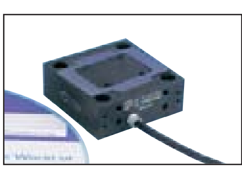

P-712 Low profile, low cost, 30 µm

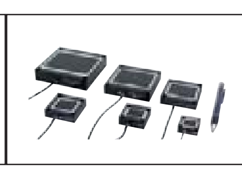

P-753 LISA Stage / actuator, to 38 µm


P-752 Fast & extremely precise to 30 µm

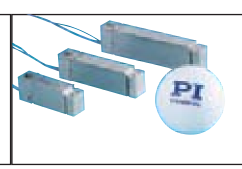

P-750 High-load stage, 75 µm

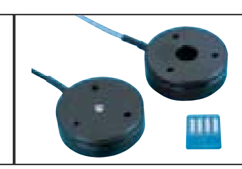

P-611 100 µm, compact, low cost


P-631 OEM high-volume stage


P-62x.1 Family: 50 to 1800 µm, compact


P-721, P-725: PIFOC® lens positioners, 100 to 500 µm,


P-601 Flexure-guided actuator, 100 to 400 µm


S-303 Phase shifter, very fast


M-511.HD, M-714 Hybrid stage, travel to 100 mm

Multi-Axis Piezo Stages: see p. 2-6

Piezo Motor Driven Long Travel Stages: see p. 4-19 *ff*

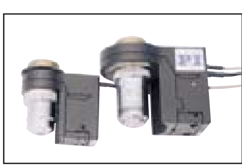
Notes on Specifications see p. 2-78 *ff*

Selection Guide: Z & Z/Tip/Tilt Piezo Stages

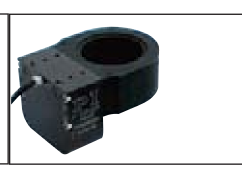
Highly Responsive, Flexure Guided Piezo Nanopositioning Systems

All models are precision flexure guided, and equipped with the patented PICMA® long-life piezo actuators. Capacitive position feedback sensors are available for the highest performance applications. Alternatively, strain gauge sensors are available as well as open loop models. Multi-axis systems are based on parallel-kinematics with one moving platform.

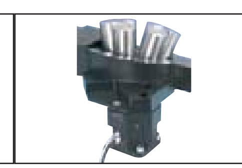
Models	Description	Travel [µm / mrad]	Sensor	Dyna-mics*	Preci-sion**	Page
P-720	PIFOC® objective nanofocusing system, very compact, for small objectives, open loop	100	–	●●○○○	●●○○○	2-25
P-721	PIFOC® objective nanofocusing system, very fast and accurate, with QuickLock mounting system, direct metrology	100	Capacitive / SGS	●●●○○	●●●●○ / ●●○○○	2-26
P-725	PIFOC® objective nanofocusing system, compact, light-weight, long travel ranges, QuickLock mounting system, direct metrology	100, 250, 400	Capacitive	●●○○○	●●●○○	2-28
P-725.xDD	PIFOC® objective nanofocusing system, high-dynamics, direct-metrology	20	Capacitive /SGS	●●●●●	●●●●●	2-30
P-726	PIFOC® high-power nanofocusing system for large objectives	100	Capacitive	●●●●●	●●●●●	2-32
P-721KTPZ	PIFOC® nosepiece nanopositioning system, high stiffness, direct metrology	80	Capacitive	●●●○○	●●●●○	2-25
P-721KPTZ	High-load PIFOC® nosepiece nanopositioner, direct metrology	150	Capacitive	●●●●○	●●●●○	2-25
P-737	PIFOC® Z-axis microscopy piezo stage for high-resolution sample positioning and scanning	to 250	SGS	●●○○○	●●●○○	2-34
P-611.Z	Compact, low-cost Z nanopositioning piezo stage	100	SGS	●●○○○	●●○○○	2-36
P-612.Z	Compact nanopositioning Z-stage, clear aperture	100	SGS	●●○○○	●●○○○	2-38
P-601	Closed-loop, with flexure guidance	110, 300, 400	SGS	●●●●○	●●○○○	1-68
P-620.Z – P-622.Z	PIHera® Z-axis nanopositioners, compact, very accurate, long travel range	50, 100, 250	Capacitive	●●●○○	●●●○○	2-40
P-732	High-dynamics vertical nanopositioning/scanning stage	15	Capacitive	●●●●○	●●●○○	2-48
P-733.Z	Z scanning piezo stage 50 x 50 mm aperture, vacuum versions available	100	Capacitive	●●●○○	●●●○○	2-42
P-541.Z	Low-profile Z-stage, 80 x 80 mm aperture	100 / 1 mrad	Capacitive / SGS	●●○○○	●●●○○	2-44
P-518, P-528, P-558	Z-axis and tip/tilt piezo stage platforms 66 x 66 mm clear aperture	to 200 / 4 mrad	Capacitive	●●●○○	●●●●○	2-46
N-510	Tripod Z-tip/tilt nanopositioning platform with NEXLINE® piezo motors	1.3 mm / 10 mrad	Linear encoder	●●●○○		2-49
P-915KVPZ	Vacuum-compatible piezo Z stage	45	Capacitive	●●●●○	●●●●○	2-48
P-915KLPZ	Low-profile piezo objective scanner, open-loop	75	–	●●●●○	●●●○○	2-48
N-515KNPH	Nonmagnetic 6-axis piezo Hexapod precision positioning system with NEXLINE® piezo motor actuators	to 10 mm / 6°	Linear encoder	●●○○○	●●●○○	2-49
N-510KHFS	Tripod Z-Tip/Tilt nanopositioning platform with additional fine positioning	400 plus	Capacitive 40 µm	●●○○○	●●●●○	2-49


P-721, P-720 Compact nanofocusing systems

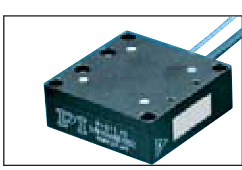

P-725 PIFOC® long travel nanofocusing system

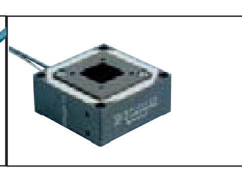

P-725.xDD PIFOC® high-dynamics piezo scanner

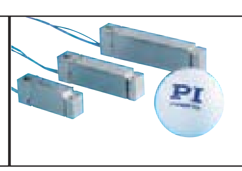

P-726 Fast nanofocusing system for heavy objectives

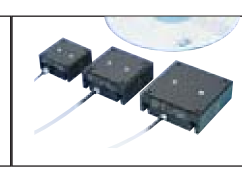

P-721K PIFOC® nosepiece positioners

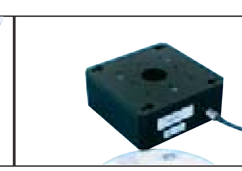

P-737 microscopy Z-stage for sample positioning

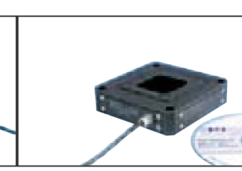

P-611.Z Compact, low-cost, nanopositioning stage

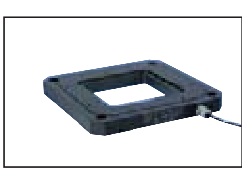

P-612.Z compact nanopositioner w/ aperture

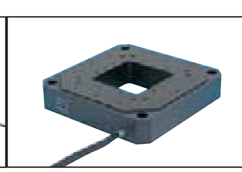

P-601 Flexure guided OEM Z-actuator / stage, 100 to 400 µm

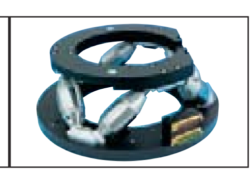

P-620.Z, P-622.Z Compact, long-travel stages, to 400 µm


P-732 High-Dynamics scanning stage w/aperture


P-733.Z 100 µm Z-stage with aperture


P-541.Z Low- profile Z-/tip/tilt stage


P-518, P-528, P-558 Z/tip/tilt stages


N-515KNPH Non-magnetic NEXLINE Hexapod

Notes on Specifications see p. 2-78 *ff*

*Dynamics: Combination of system settling time / bandwidth / load capacity relative to the typical application of the product

**Precision: Combination of guiding precision, sensor precision, resolution, relative to comparable products in class

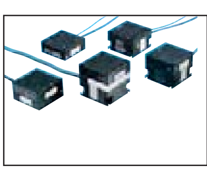
Selection Guide: Multi-Axis Piezo Stages

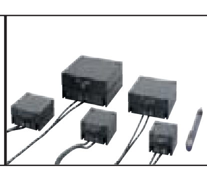
Nanometer Precision, Travel from 15 µm to 1,800 µm, Serial & Parallel Designs

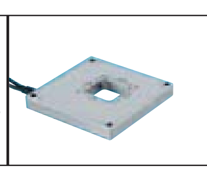
All models are precision flexure guided, and equipped with the patented PICMA® long-life piezo actuators. Capacitive position feedback sensors are available for highest performance applications, alternatively, strain gauge sensors are available as well as open loop models. For the highest precision and dynamics requirements, parallel-kinematics / parallel metrology stages are recommended.

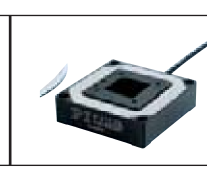
Models	Description	Travel [µm]	Sensor	Dynamics*	Precision**	Page
P-611	Compact, low-cost X, Z, XY and XYZ nanopositioning stages	100 / Axis	SGS	●●○○○	●●○○○	2-50 *ff*
P-620.2– P-629.2	PIHera® XY piezo nanopositioners. Very compact & accurate (direct metrology), long travel range.	50, 100, 250, 500, 1000, 1800	Capacitive	●●●○○	●●●○○	2-54
P-713, P-714	Compact XY-scanner, low cost, fast.	15 x 15	–/SGS	●●●●●	●●○○○	2-56
P-612	Compact, low-cost, XY stage. 100 x 100 µm travel, clear aperture.	100 x 100	SGS	●●○○○	●●○○○	2-58
P-541.2	Low profile XY scanning piezo stage 80 x 80 mm aperture, parallel kinematics.	to 200 x 200	SGS/ Capacitive	●●○○○	●●●○○	2-60
P-733.2DD, P-733.3DD	High-speed scanning piezo stage, XY and XYZ versions, ideal for scanning microscopy, parallel kinematics	30 x 30 (x10)	Capacitive	●●●●●	●●●●●	2-62
P-733.2, P-733.3	XY(Z) piezo scanning piezo stage 50 x 50 mm aperture, vacuum versions available, parallel kinematics	100 x 100 (x10)	Capacitive	●●●○○	●●●●○	2-62
P-734	XY nano-scanning piezo stage, extremely flat and straight motion (1–2 nm); 56 x 56 mm clear aperture, parallel kinematics.	100 x 100	Capacitive	●●●○○	●●●●●	2-64
P-363	PicoCube® XY and XYZ high-precision system for AFM, SPM, nanomanipulation; 50 picometer resolution, parallel metrology	5 x 5 and 5 x 5 x 5	Capacitive	●●●●●	●●●●●	2-66
P-313	PicoCube® XYZ high-precision scanner for bio- / nanomanipulation	1 x 1 x 1	–	●●●○○	●●●○○	2-74
P-615	NanoCube® XYZ piezo alignment system, clear aperture, ideal for fiber alignment, parallel kinematics.	to 350 / Axis	Capacitive	●●●○○	●●●○○	2-68
P-517, P-527	Multi-axis piezo stage 66 x 66 mm clear aperture, parallel kinematics, custom 6-axis model available	to 200 in XY, 20 in Z, to 2 mrad	Capacitive	●●●○○	●●●●○	2-70
P-561 – P-563	PIMars™ XYZ piezo stage; 66 x 66 mm clear aperture, parallel kinematics, custom 6-axis model available	to 300 x 300 x 300	Capacitive	●●●○○	●●●●○	2-72
P-587	6-axis-nanopositioning stage, XYZ, $\theta_x \theta_y \theta_z$.	to 800 µm / 8 mrad	Capacitive	●●●○○	●●●●●	2-76
P-915KPPS	XY-Theta-Z piezo stage, high stiffness	250 x 250; ±8 mrad	SGS	●●●●○	●●●○○	2-74
P-628KHFS	Long-travel XY piezo stage, nanometer flatness	800 x 800	Capacitive	●●○○○	●●●●○	2-74
P-915KXYS	Fast XY OEM scanner, cost-effective	4 x 4	–	●●●●○	●●●○○	2-75
P-915KHDS	XY OEM slide, large aperture, direct drive	15 x 15	–	●●●●○	●●●○○	2-75
P-915KLVS	Vacuum compatible XYZ stage, w/ large aperture	100 x 100 x 100	Capacitive	●●●○○	●●●●○	2-75

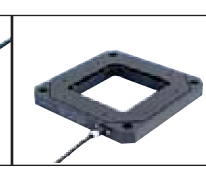
*Dynamics: Combination of system settling time / bandwidth / load capacity relative to the typical application of the product.
**Precision: Combination of guiding precision, sensor precision, resolution, relative to comparable products in class.

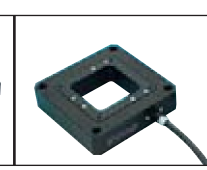

P-611 NanoCube® family. Compact, low-cost, 100 µm

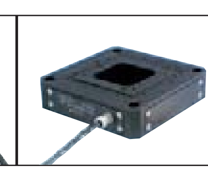

P-620.2 – P-629.2 XY stages. Compact, accurate, long travel


P-713, P-714 Compact XY-scanner, low cost, fast

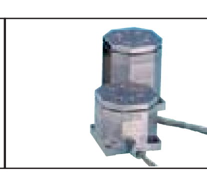

P-612 Compact, economical XY stage, 100 µm


P-541.2 Low profile, 100 and to 200 µm in XY

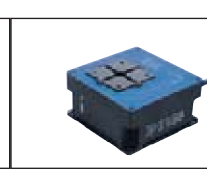

P-733.2DD, /.3DD High speed, ultra-high resolution stages

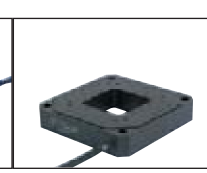

P-733 Scanning stage. Vacuum version available

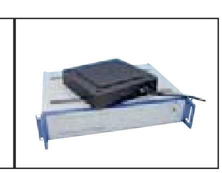

P-734 Ultra low bow scanning stage


P-363, P-313 PicoCube® for AFM, SPM


P-561, P-562, P-563 Multi-axis piezo stage compact


P-615 NanoCube® XYZ alignment system


P-517, P-527 Multi-axis piezo stage


P-587 6-axis nanopositioning stage

Single Axis Piezo Stages and Z/Tip/Tilt stages: See page 2-14 *ff* and 2-25 *ff*
Piezo Motor Driven Stages: See page 4-25 *ff*. Notes on Specifications see p. see p. 2-78 *ff*

Piezo Systems

Precision Flexure-Guided Nanopositioners and Scanners


Drive, sensors, mechanics and control electronics with software – components of PI's positioning systems

From Piezo Actuators to Piezo Nanopositioning and Scanning Systems

Piezo ceramic actuators are at the heart of most PI nanopositioning systems. These actuators provide sub-nanometer resolution and sub-millisecond response time by frictionless motion based on molecular effects. To form a high performance nanopositioning system, the intrinsic advantages of the piezo drive have to be complemented by a frictionless, stiff guidance system and highly linear, responsive nanometrology sensors for position feedback. Sophisticated digital servo systems, low noise drivers and control algorithms are necessary to support the mechanical part of the nanopositioning system.

Flexures – the Main Mechanical Component

Flexure motion is based on the elastic deformation (flexing) of a solid material. Friction and stiction are entirely eliminated, and flexures exhibit high stiffness, load capacity and resistance to shock and vibration. Flexures are maintenance free and not subject to wear. They are vacuum compatible, operate over a wide temperature range and require neither lubricants nor compressed air for operation. PI flexures are optimized for highest possible stiffness and straightness / flatness in the nanometer realm combined in many cases with integrated motion amplifiers. This allows for extended travel up to the millimeter range.

Excellent Guiding Accuracy

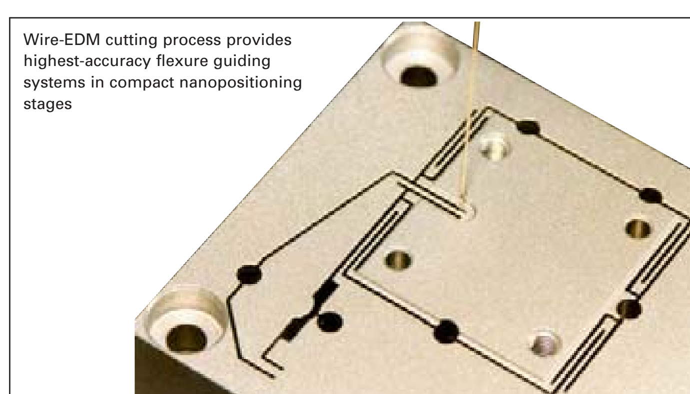
The multilink flexure guiding systems employed in most PI piezo nanopositioners eliminate cosine errors and provide bidirectional flatness and straightness in the nanometer or microradian range. This high precision means that even the most demanding positioning tasks can be run bidirectionally for higher throughput.

Lifetime / PICMA® Piezo Actuators

PI nanopositioning systems employ the award-winning PICMA® piezo actuators, the only actuators with co-fired ceramic encapsulation. The PICMA® piezo technology was specifically developed by PI's piezo ceramic division to provide higher performance and lifetime in nanopositioning applications.

Multilayer piezo actuators are similar to ceramic capacitors and are not affected by wear and tear. Read p. 2-12 *ff* for details.


P-733 low-profile XY and XYZ scanning stages


Wire-EDM cutting process provides highest-accuracy flexure guiding systems in compact nanopositioning stages

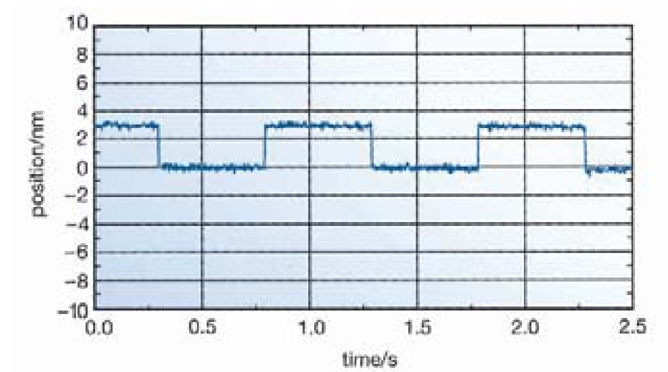
CE & RoHS Compliance

All standard PI nanopositioning systems are fully CE and RoHS compliant.

Measuring Nanometers: Stage Metrology Selection

Achieving nanometer and subnanometer precision requires a stage internal metrology system, capable of measuring motion on the nanometer scale. The five primary characteristics to consider when selecting a stage metrology system are linearity, sensitivity (resolution), stability, bandwidth, and cost. Other factors include the ability to measure the moving platform directly and contact vs. noncontact measurement. Three types of sensors are typically used in piezo nanopositioning applications—capacitive, strain, and LVDT. Table 1 summarizes the characteristics of each sensor type. For long travel ranges of 1mm and above, classical piezo multilayer or stack drives are replaced by PiezoWalk® motors. These unique drives are complemented by special optical linear sensors to achieve nanometer precision and linearities of 0.001%.

PI capacitive sensors measure the gap between two plates or one plate and a planar, conducting surface based on electrical capacitance. These sensors can be designed to become an integral part of a nanopositioning system, with virtually no effect on size and mass (inertia). Capacitive sensors offer the highest resolution, stability, and bandwidth. They enable direct measurement of the moving platform and are noncontact. Capacitive sensors also offer the highest linearity (accuracy). PI's capacitive sensors / control electronics use a high-frequency AC excitation signal for enhanced bandwidth and drift-free measurement stability (subnanometer stability over several hours, see p. 3-17 *ff*). PI's exclusive ILS linearization system further improves system linearity. If used with PI's digital controllers, digital polynomial linearization of mechanics and electronics makes possible an overall system linearity of better than 0.01%. Capacitive sensors are the metrology system of choice for the most demanding applications.



Response of a PI Nanopositioning stage to a square wave control signal clearly shows the true sub-nm positional stability, incremental motion and bidirectional repeatability. Measured with external capacitive gauge, 20 pm resolution.

A strain gauge sensor is a resistive metal or semiconductor film bonded to a piezo stack or—for enhanced precision—to the guiding system of a flexure stage. It offers high resolution and bandwidth and is typically chosen for cost-sensitive applications. As a contact type sensor, it measures indirectly, in that the position of the moving platform is inferred from a measurement at the lever, flexure or stack. PI employs full-bridge implementations with multiple strain gauges per axis for enhanced thermal stability. PI's PICMA® drive technology also enables higher performance of actuator-applied strain gauge sensors.

LVDT sensors measure magnetic energy in a coil. A magnetic core attached to the moving platform moves within a coil attached to the frame producing a change in the inductance equivalent to the position change. LVDT sensors provide noncontact, direct measurements of position. They are cost-effective and offer high stability and repeatability.

Table 1

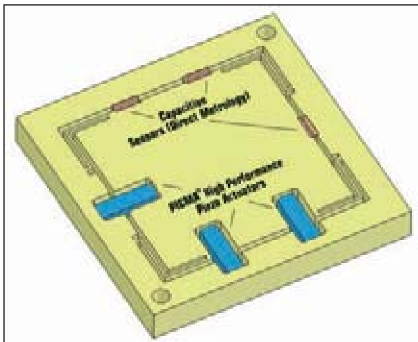
Sensor Type	Sensitivity* (Resolution)	Linearity*	Sability* / Repeatability	Bandwidth*	Metrology Type	Excitation Signal
Capacitive	Best	Best	Best	Best	Direct / Noncontact	AC
Strain	Better	Good	Good	Better	Inferred** (Indirect) / Contact	DC
LVDT	Good	Good	Better	Good	Direct / Noncontact	AC
Linear Encoder	Best***	Best***	Best***	Better	Direct / Noncontact	DC

*The ratings describe the influence of the sensor on the performance of the whole nanopositioning system. Resolution, linearity, repeatability, etc. specifications in the PI product data sheets indicate the performance of the complete system and include the controller, mechanics and sensor. They are verified using external nanometrology equipment (Zygo Interferometers). It is important not to confuse these figures with the theoretical performance of the sensor alone.
**Strain type sensors (metal foil, semiconductor, or piezoresistive) infer position information from strain.
***for travel ranges >1mm

Parallel and Serial Designs

There are two ways to achieve multi-axis motion: parallel and serial kinematics. Serial kinematics (nested or stacked systems) are simpler and less costly to implement, but they have some limitations compared to parallel kinematics systems.

In a multi-axis serial kinematics system, each actuator (and usually each sensor) is assigned to exactly one degree of freedom. In a parallel kinematics multi-axis system, all actuators act directly on the same moving platform (relative to ground), enabling reduced size and inertia, and the elimination of microfriction caused by moving cables. This way, the same resonant frequency and dynamic behavior can be obtained for both the X and Y axes. The advantages are higher dynamics and scanning rates, better trajectory guidance as well as better reproducibility and stability.

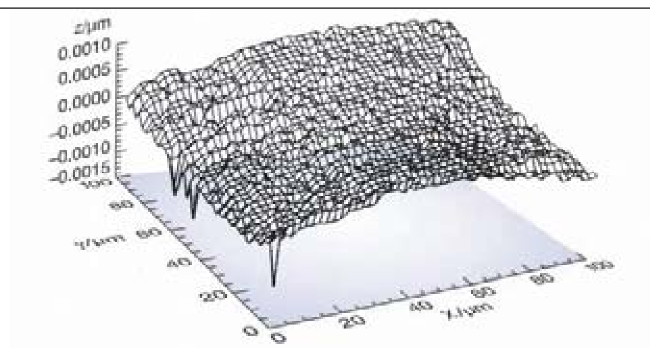


Principle of a PI XY-Theta-Z, minimum-inertial-mass, monolithic, parallel kinematics nanopositioning system. Accuracy, responsiveness and straightness/flatness are much better than in stacked multi-axis (serial kinematics) systems.

Direct Parallel Metrology: Multi-Axis Measurements Relative to a Fixed Reference

Parallel kinematics facilitates implementation of Direct Parallel Metrology—measurement of all controlled degrees of freedom relative to ground. This is a more difficult design to build but it leads to clear performance advantages.

A parallel metrology sensor sees all motion in its measurement direction, not just that of one actuator. This means that all motion is inside the servo-loop, no matter which actuator may have caused it, resulting in superior multi-axis precision, repeatability and flatness, as shown in the figure below. Direct parallel metrology also allows stiffer servo settings for faster response. Off-axis disturbances—external or internal, such as induced vibration caused by a fast step of one axis—can be damped by the servo.



Flatness of an active-trajectory-controlled nanopositioning stage over 100 x 100 µm scanning range is about 1 nm

Analog and Digital Controllers

PI offers the largest selection of digital and analog piezo drivers / linear amplifiers and piezo motion controllers worldwide.

The electronics play a key role for maximum performance of piezoelectric nanopositioning stages, tip/tilt mirrors and actuators. Ultra-low-noise, high-stability servo-controllers and linear amplifiers are essential, because piezoelectric actuators respond to even microvolt changes of the control voltage with motion.

For industrial applications, where maximum throughput is crucial, PI offers digital control algorithms for dynamic linearization and reduced settling times. For dynamic high-power applications, PI's unique energy-recovery power amplifiers provide up to 2000 W of peak power!

State-of-the-art PI digital control systems offer several advantages over analog control systems: coordinate transformation, real-time linearity compensation and elimination of some types of drift. Digital controllers also allow virtually instant changes of servo parameters for different load conditions, etc. However, not all digital controllers are created equal. Poor implementations can add noise and lack certain capabilities of a well-designed analog implementation, such as fast settling time, compatibility with advanced feed-forward techniques, stability and robust operation.

PI digital controllers can download device-specific parameters from ID-chip-equipped nanopositioning stages, facilitating interchangeability of nanomechanisms and controllers.

All PI nanopositioning controllers (analog and digital) are equipped with one or more user-tunable notch filters. A controller with notch filter can be tuned to provide higher bandwidth because side-effects of system resonances can be suppressed before they affect system stability. For the most demanding step-and-settle applications, PI's exclusive Mach™ InputShaping® implementation is available as an option.

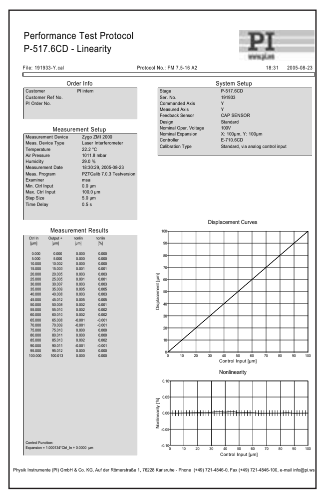
See page 2-100 *ff* Section for a complete overview on PI's piezo drivers and controllers.

Test & Metrology Protocol for Piezo Systems Getting What You Bargained For

Piezo nanopositioning systems are significant investments and PI believes in optimizing the performance of every customer's system. PI individually tests every stage and optimizes the static and dynamic performance for the customer's application. The metrology test protocol is part of the system's delivery package. It shows the customer what the performance of the system was at the time of delivery and which system components belong together. For PI every metrology procedure and its recording is a quality assurance instrument, and only nanopositioning systems which meet their specifications will leave the premises.

Furthermore, PI makes significant continuing investments in improved-quality, higher-performance nanometrology equipment so that we can deliver better value to our customers.

Because a nanomechanism can only be as accurate as the equipment it was tuned and tested with, PI closed-loop stages are measured exclusively with prestigious Zygo interferometers. PI's nanometrology metrology laboratories are seismically, electromagnetically and thermally isolated, with temperatures controlled to better than 0.25 °C / 24 hrs. We are confident that our metrology capabilities and procedures are the benchmark for the industry.



Performance Test Protocol
P-517.6CD - Linearity

File: 191933-Y.cal | Protocol No.: FM 7.5-16 A2 | 18:31 2005-08-23

Order Info

Customer	PI intern
Customer Ref No.	
PI Order No.	

System Setup

Stage	P-517.6CD
Ser. No.	191933
Commanded Axis	Y
Measured Axis	Y
Feedback Sensor	CAP SENSOR
Design	Standard
Nominal Oper. Voltage	100V
Nominal Expansion	X: 100µm, Y: 100µm
Controller	E-710.6CD
Calibration Type	Standard, via analog control input

Measurement Setup

Measurement Device	Zygo ZMI 2000
Meas. Device Type	Laser Interferometer
Temperature	22.2 °C
Air Pressure	1011.8 mbar
Humidity	29.0 %
Measurement Date	18:30:29, 2005-08-23
Meas. Program	PZTCalib 7.0.3 Testversion
Examiner	msa
Min. Ctrl Input	0.0 µm
Max. Ctrl Input	100.0 µm
Step Size	5.0 µm
Time Delay	0.5 s

Measurement Results

Ctrl In [µm]	Output + [µm]	nonlin [µm]	nonlin [%]
0.000	0.000	0.000	0.000
5.000	5.000	0.000	0.000
10.000	10.002	0.000	0.000
15.000	15.003	0.001	0.001
20.000	20.005	0.003	0.003
25.000	25.005	0.001	0.001
30.000	30.007	0.003	0.003
35.000	35.009	0.005	0.005
40.000	40.008	0.003	0.003
45.000	45.012	0.005	0.005
50.000	50.008	0.002	0.001
55.000	55.010	0.002	0.002
60.000	60.010	0.002	0.002
65.000	65.008	-0.001	-0.001
70.000	70.009	-0.001	-0.001
75.000	75.010	0.000	0.000
80.000	80.011	0.000	0.000
85.000	85.013	0.002	0.002
90.000	90.011	-0.001	-0.001
95.000	95.012	0.000	0.000
100.000	100.013	0.000	0.000

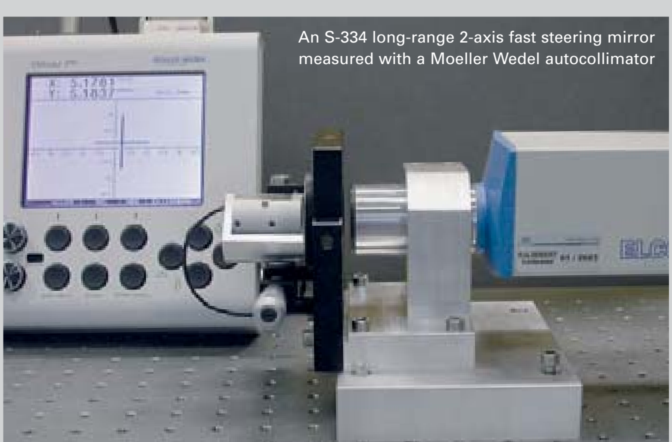
Control Function:
Expansion = 1.000134*Ctrl_In + 0.0000 µm

Displacement Curves
Displacement [µm]
Control Input [µm]

Nonlinearity
Nonlinearity [%]
Control Input [µm]

Physik Instrumente (PI) GmbH & Co. KG, Auf der Römerstraße 1, 76228 Karlsruhe - Phone (+49) 721-4846-0, Fax (+49) 721-4846-100, e-mail info@pi.ws

All PI nanopositioning systems come with extensive system performance documentation



An S-334 long-range 2-axis fast steering mirror measured with a Moeller Wedel autocollimator

An S-340 2-axis fast steering mirror platform measured with a Zygo interferometer

PICMA® Piezo Actuators—Extreme Lifetime, for Industrial Reliability Requirements

Full-Ceramic Encapsulation & Patented Design

PICMA® award-winning multilayer piezo actuators feature full-ceramic insulation

PI has 4 decades of experience with piezo ceramic actuators in motion control applications in industry and research. Currently PI employs more than 100 people fully dedicated to piezo ceramic research, development and production. Extensive know-how and the most modern equipment make for the unique flexibility and worldwide leadership in piezo matters.

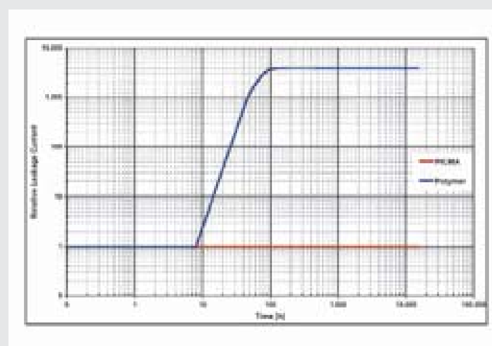
PI piezo actuators not only show an optimal combination of travel and stiffness, but are also designed for maximum lifetime under actual operating conditions in industrial environments.

Maximum lifetime means highest possible reliability. PI's award-winning, patented PICMA® actuators are based upon the newest technology which reduces the failure rate by a factor 10 compared to conventionally designed multilayer actuators.

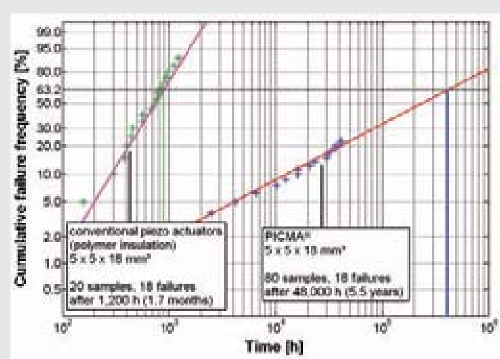
Long Term Tests Prove DC Reliability

PI's monolithic ceramic-encapsulated design provides better humidity protection than conventional polymer-film insulation. Diffusion of water molecules into the insulation layer is greatly reduced by the use of co-fired, outer ceramic encapsulation. Humidity is the main influence on the long-term reliability in low-dynamics or quasi-static operation modes, where the piezo actuator is supplied with a DC voltage to maintain a position for a long time.

Comparative tests with both PICMA® and conventional multilayer piezo actuators have proven the positive effects of the ceramic encapsulation. While polymer-coated piezos typically only survive 30 days of continuous operation - PICMA® actuators are still working after more than 4 years!



PICMA® piezo actuators (lower curve) compared with polymer-insulated multilayer piezo actuators. PICMA® actuators are insensitive 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.



Results of an accelerated DC-lifetime-test of PICMA® actuators compared to conventional actuators (100 V DC, room temperature, 90% R.H.). The expected MTTF (Mean Time To Failure) for PICMA® is 80 years (700 000 hrs of continuous operation). All of the polymer-insulated samples have failed after 1,600 hrs (MTTF 805 hrs = 1 month)

Continuous Dynamic Operation

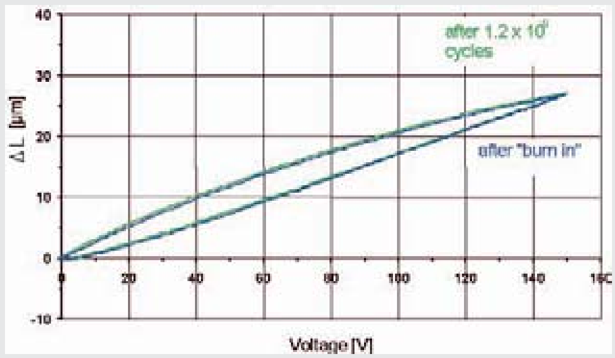
Here, the well-known lifetime-limiting factors of conventional designs are humidity, crack formation inside the ceramic leading to rising leakage currents and delamination of electrodes under extreme dynamic conditions.

PI reduces the cracking probability by a special patented design where segmented slots take care of excessive tensional stresses. Furthermore, the special electrode design ensures excellent, stable, electric contact even after billions of cycles.

PICMA® multilayer piezo actuators show no significant decrease in displacement even after many billions of cycles.

Long-Term Test under Cryogenic Conditions

To suit an application requiring 10 years minimum lifetime under cryogenic conditions, accelerated lifetime tests with PICMA® piezo actuators have been successfully performed. Inserted in a cryogenic bath of liquid nitrogen (75 K), the piezo is placed in a vacuum chamber (2 • 10^{-3} mbar) and subjected to dynamic operation at 90 % of the maximum voltage range (>105 V) with an operating frequency up to 1000 Hz. After one month of continuous operation there were no degradations in piezo performance to be measured, neither mechanic concerning the displacement, nor electrical concerning electrical capacitance or resonant frequency (Dr. Bosotti et al., University of Milano, Italy, 2005).



AC tests were performed for 4.0 x 109 cycles at 8 samples PICMA® 5x5x18 using a 116 Hz-sine wave excitation (1.0 x 107 cycles per day) at a unipolar operating voltage of 100 V, 15 MPa preload. Control measurements were taken every 109 cycles. There was no significant decrease in displacement.

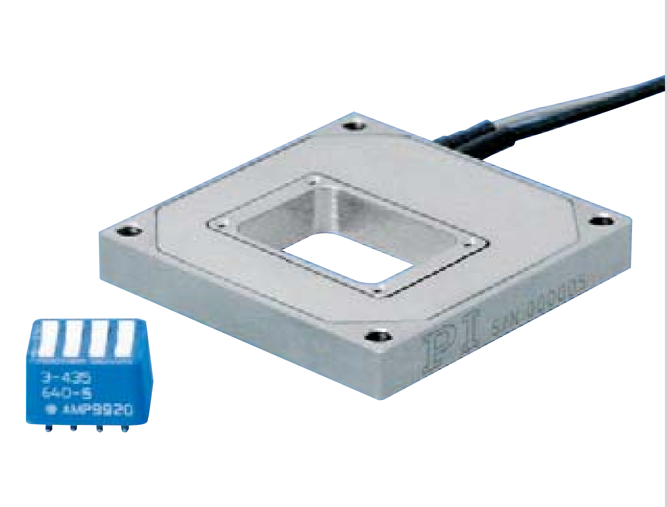
Large Operating Temperature Range , Optimum UHV Compatibility—Minimum Outgassing

Another advantage of fully ceramic-encapsulation PICMA® actuators is the extended operating temperature range, up to 150 °C, a huge improvement over the 80 °C limit common for other, polymer-insulated, monolithic actuators. The heat generation in dynamic operation is proportional to the operating frequency. Thus, a higher operating temperature allows for higher operating frequencies and duty cycles. Additionally, the lack of polymer insulation and the high Curie temperature make for optimal ultra-high-vacuum compatibility (no outgassing / high bake-out temperatures, up to 150 °C).

Piezo • Nano • Positioning

P-712 Low-Profile Piezo Scanner

Compact OEM System



P-712 piezo scanner with up to 40 µm travel range

- **High Dynamic, to 5 ms Settling Time**
- **Travel Range up to 40 µm**
- **Resolution to 0.2 nm**
- **Compact Design with Low Profile, 40 x 40 x 6 mm**
- **Clear Aperture 25 x 15 mm**
- **PICMA® High-Power Actuators**

P -712 piezo scanners are ideal for applications where limited space requires small-sized equipment. The high resonant frequency allows for fast linear scanning with 30 µm travel in one axis and provides settling times of about 5 ms. The P-712 linear scanner is offered in two versions, one with SGS position sensors for closed-loop operation, and one without sensors for open-loop.

Application Examples

- Optical path tuning
- Biotechnology
- Medical technology
- Image processing / stablilization
- CCD / CMOS camera technology

A similar XY version is available with product number P-713 / P-714 (see p. 2-56).

Excellent Guiding Accuracy

Flexures optimized with Finite Element Analysis (FEA) are used to guide the stage. FEA techniques are used to give the design the highest possible stiffness in, and perpendicular to, the direction of motion, and to minimize linear and angular runout. Flexures allow extremely high-precision motion, no matter how minute, as they are completely free of play and friction.

Electric discharge machining (EDM) with fine cutting wires is used to obtain the required precision for the flexures which make up the guidance system and determine the stiffness.

Optional Position Control

High-resolution, broadband, strain gauge sensors (SGS) are applied to appropriate locations on the drive train and measure the displacement of the moving part of the stage relative to the base indirectly. The SGS sensors assure optimum position stability in the nanometer range and fast response.

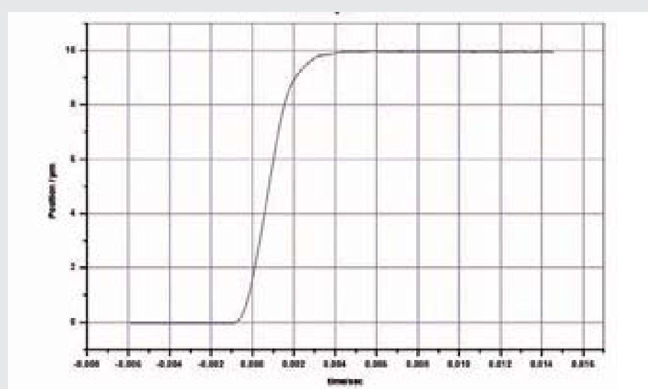
Ceramic Insulated Piezo Actuators Provide Long Lifetime

Highest possible reliability is assured by the use of award-winning PICMA® multilayer piezo actuators. PICMA® actuators are the only actuators on the market with ceramic-only insulation, which makes them resistant to ambient humidity and leakage-current failures. They are thus far superior to conventional actuators in reliability and lifetime.

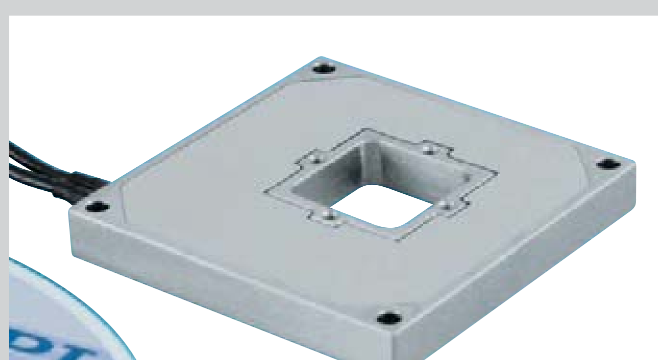
Ordering Information

P-712.10L
Low-Profile OEM Nanoscanner, 40 µm, Open-Loop

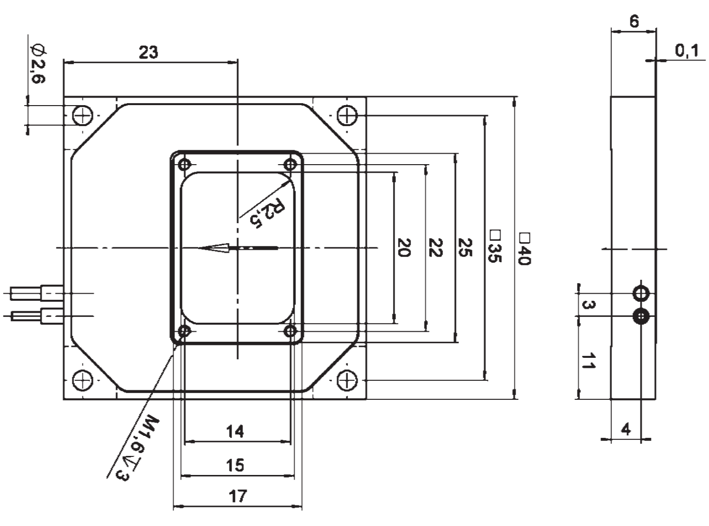
P-712.1SL
Low-Profile OEM Nanoscanner, 30 µm, SGS-Sensor



Settling time for the P -712 at 30 µm is in the 5 ms range



The P -713 XY-scanner is based on the same principle as the P -712 offering a travel range of 15 x 15 µm and a very high resonant frequency of over 2 kHz



P-712 dimensions in mm

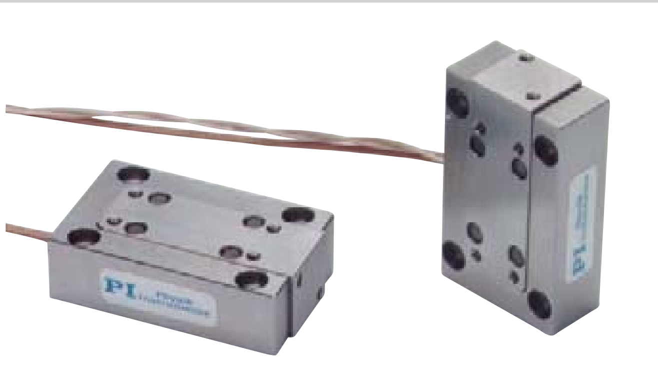
Technical Data

Model	P-712.1SL	P-712.10L	Units	Tolerance
Active axes	X	X		
Motion and positioning				
Integrated sensor	SGS	–		
Open-loop travel, -20 to +120 V	40	40	µm	min. (+20 %/0 %)
Closed-loop travel	30	–	µm	calibrated
Closed-loop resolution	2	–	nm	typ.
Open-loop resolution	0.2	0.2	nm	typ.
Linearity, closed-loop	0.3	–	%	typ.
Repeatability	±5	–	nm	typ.
Pitch	±5	±5	µrad	typ.
Yaw	±20	±20	µrad	typ.
Mechanical properties				
Stiffness in motion direction	0.6	0.6	N/µm	±20 %
Unloaded resonant frequency	1550	1550	Hz	±20 %
Resonant frequency under load	1090 (20 g)	1090 (20 g)	Hz	±20 %
Push/pull force capacity in motion direction	6	6	N	Max.
Load capacity	5	5	N	Max.
Lateral Force	6	6	N	Max.
Drive properties				
Ceramic type	PICMA® P-882	PICMA® P-882		
Electrical capacitance	0.3	0.3	µF	±20 %
Dynamic operating current coefficient	1.3	1.3	µA/(Hz • µm)	±20 %
Miscellaneous				
Operating temperature range	-20 to 80	-20 to 80		
Material	Stainless steel	Stainless steel		
Dimensions	40 x 40 x 6	40 x 40 x 6	mm	
Mass	0.095	0.095	kg	±5 %
Cable length	1.5	1.5	m	±10 mm
Voltage connection	LEMO	LEMO		
Sensor connector	LEMO	–		

Recommended controller / amplifier
Single-channel (1 per axis): E-610 servo controller / amplifier (p. 2-110), E-625 servo controller, bench-top (p. 2-114)

P-753 LISA Linear Actuator & Stage

High-Dynamics, Very Stable Piezo Nanopositioner


P-753.11C LISA nano-precision actuators / positioning stages

- **Versatile Design: Flexure Stage or Actuator**
- **Resolution 0.05 nm, Rapid Response**
- **Capacitive Sensors for Highest Linearity**
- **Frictionless Precision Flexure Guidance for Frictionless, Ultra-Straight Motion**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **Vacuum-Compatible and Nonmagnetic Versions Available**

The P-753 LISA (Linear Stage Actuators) high-speed nanopositioners can be used both as linear actuators or as translation stages. They are equipped with capacitive feedback sensors, frictionless, flexure guiding systems and high-performance piezo drives providing a positioning and scanning range of up to 38 µm with very fast settling time and extremely low tip/tilt error.

Application Examples

- Disc-drive-testing
- Metrology
- Nanopositioning
- Scanning microscopy
- Photonics / integrated optics
- Interferometry
- Biotechnology
- Micromanipulation

Direct-Drive Design for Fastest Response

The direct-drive design, together with careful attention to mass minimization, results in significant reduction in inertial recoil forces applied to the supporting structures, enhancing overall system response, throughput and stability with settling times in the millisecond range.

PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz.

Automatic Configuration

The „.CD“ versions are equipped with an ID-chip that stores all individual stage data and servo-control parameters. This data is read out automatically by the AutoCalibration Function of PI's digital piezo controllers. Thus, digital controllers and nanopositioning stages with ID-chip can be operated in any combination.

High Reliability and Long Lifetime

The compact P-753 LISA systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and thus offer better performance and reliability than conventional piezo actuators. Actuators, guidance and sensors are maintenance-free and not subject to wear, and thus offer an extraordinary reliability.

Ordering Information

P-753.11C
LISA High-Dynamics Nanopositioning System, 12 µm, Direct Metrology, Capacitive Sensor, LEMO Connector

P-753.21C
LISA High-Dynamics Nanopositioning System, 25 µm, Direct Metrology, Capacitive Sensor, LEMO Connector

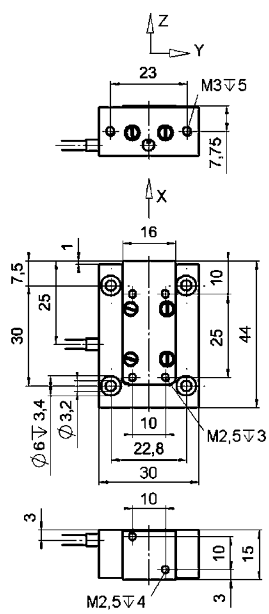
P-753.31C
LISA High-Dynamics Nanopositioning System, 38 µm, Direct Metrology, Capacitive Sensor, LEMO Connector

P-753.1CD*
LISA High-Dynamics Nanopositioning System, 12 µm, Direct Metrology, Capacitive Sensor, Sub-D Connector

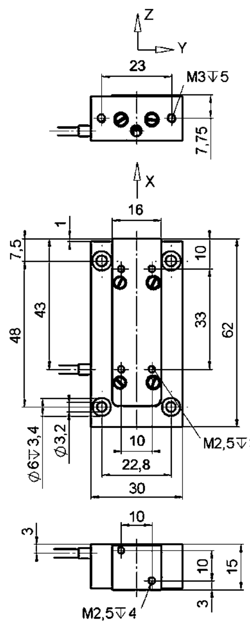
P-753.2CD*
LISA High-Dynamics Nanopositioning System, 25 µm, Direct Metrology, Capacitive Sensor, Sub-D Connector

P-753.3CD*
LISA High-Dynamics Nanopositioning System, 38 µm, Direct Metrology, Capacitive Sensor, Sub-D Connector

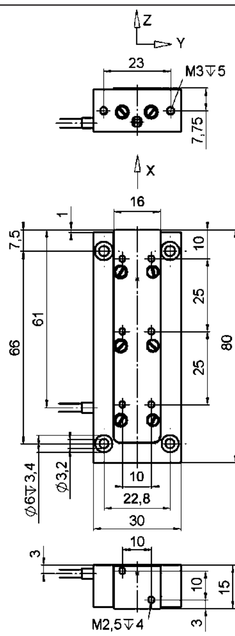
*Vacuum versions to 10^{-9} hPa are available as P-753.xUD, non-magnetic vacuum versions can be ordered as P-753.xND.



P-753.1 dimensions in mm, max. torque at M2.5 threads: 30 Ncm



Picture sub text 03
P-753.2 dimensions in mm, max. torque at M2.5 threads: 30 Ncm



P-753.3 dimensions in mm, max. torque at M2.5 threads: 30 Ncm

Technical Data

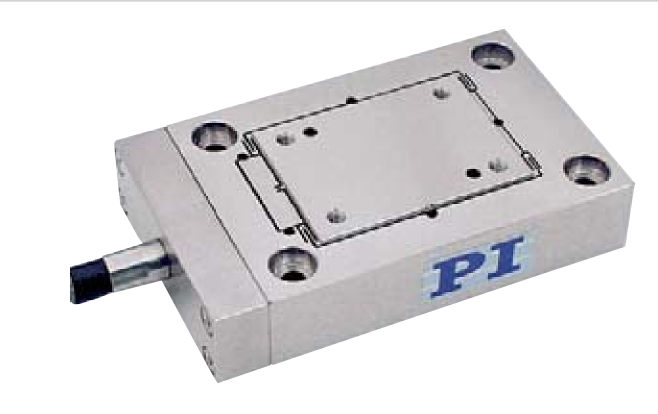
Model	P-753.11C	P-753.21C	P-753.31C	P-753.1CD	P-753.2CD	P-753.3CD	Units	Tolerance
Active axes	X	X	X	X	X	X		
Motion and positioning								
Integrated sensor	Capacitive	Capacitive	Capacitive	Capacitive	Capacitive	Capacitive		
Closed-loop travel	12	25	38	12	25	38	µm	calibrated
Closed-loop / open-loop resolution	0.05	0.1	0.2	0.05	0.1	0.2	nm	typ., full travel
Linearity, closed-loop	0.03	0.03	0.03	0.03	0.03	0.03	%	typ.
Repeatability	±1	±2	±3	±1	±2	±3	nm	typ.
Pitch / yaw	±5	±7	±10	±5	±7	±10	µrad	typ.
Mechanical properties								
Stiffness in motion direction	45	24	16	45	24	16	N/µm	±20 %
Unloaded resonant frequency	5.6	3.7	2.9	5.6	3.7	2.9	Hz	±20 %
Resonant frequency @ 200 g	2.5	1.7	1.4	2.5	1.7	1.4	Hz	±20 %
Push/pull force capacity in motion direction	100 / 20	100 / 20	100 / 20	100 / 20	100 / 20	100 / 20	N	Max.
Load capacity (vertical/horizontal mounting)	10 / 2	10 / 2	10 / 2	10 / 2	10 / 2	10 / 2	kg	Max.
Drive properties								
Ceramic type	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885		
Electrical capacitance	1.5	3.1	4.6	1.5	3.1	4.6	µF	±20 %
Dynamic operating current coefficient	12	15	15	12	15	15	µA/(Hz • µm)	±20 %
Miscellaneous								
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80	°C	
Material	Stainless steel	Stainless steel	Stainless steel	Stainless steel	Stainless steel	Stainless steel		
Dimensions	44 x 30 x 15	44 x 30 x 62	44 x 30 x 80	44 x 30 x 15	44 x 30 x 62	44 x 30 x 80	mm	
Mass	0.15	0.205	0.25	0.16	0.215	0.26	kg	±5 %
Cable length	1.5	1.5	1.5	1.5	1.5	1.5	m	±10 mm
Sensor / voltage connection	LEMO	LEMO	LEMO	Sub-D Special	Sub-D Special	Sub-D Special		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E-503 (p. 2-146) amplifier.
Recommended controller / amplifier
LEMO connector: E-500 (p. 2-142) piezo controller system with E-505 high-power amplifier (p. 2-147) and E-509 servo module (p. 2-152)
Sub-D special connector: E-610 servo controller / amplifier card (p. 2-110), E-625 servo controller, bench-top (p. 2-114), E-665 high-power display controller, bench-top (p. 2-116), E-753 digital controller (p. 2-108)

Piezo • Nano • Positioning

P-752 High Precision Nanopositioning Stage

High-Dynamics, Very Stable Piezo Scanner with Extreme Guiding Accuracy



P-752.11C piezo nanopositioning system

- **0.1 nm Resolution, Fast Response**
- **Travel to 35 µm**
- **Capacitive Sensors for Highest Linearity**
- **Flexure Guidance for Frictionless, Ultra-Straight Motion**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**

P-752 series high-speed nanopositioning stages are extremely precise devices, providing a positioning and scanning range up to 30 µm with very rapid settling and extremely low tip/tilt errors. These stages were specially designed for high-speed dithering and disk drive testing applications.

Application Examples

- Disc-drive-testing
- Metrology
- Nanopositioning
- Scanning microscopy
- Photonics / integrated optics
- Interferometry
- Biotechnology
- Micromanipulation

Direct-Drive Design for Fastest Response

The direct-drive design, together with careful attention to mass minimization, results in significant reduction in inertial recoil forces applied to the supporting structures, enhancing overall system response, throughput and stability. In combination with the E-500 controller system the P-752.11C stage with 300 g load settles to better than 1 % with less 10 msec.

P-752 stages are equipped with capacitive sensors providing sub-nanometer resolution and stability. PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. Further advantages of direct metrology with capacitive sensors are the high phase fidelity and the high bandwidth of up to 10 kHz.

Automatic Configuration

The ".CD" versions are equipped with an ID-chip that stores all individual stage data and servo-control parameters. This data is read out automatically by the AutoCalibration function of PI's digital piezo controllers. Thus, digital controllers and nanopositioning stages with ID-chip can be operated in any combination.

Higher Precision in Periodic Motion

The highest dynamic accuracy in scanning applications is made possible by the DDL algorithm, which is available in most of PI's modern digital controllers. DDL eliminates tracking errors, improving dynamic linearity and usable bandwidth by up to three orders of magnitude!

High Reliability and Long Lifetime

The compact P-752 systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and thus offer better performance and reliability than conventional piezo actuators. Actuators, guidance and sensors are maintenance-free and not subject to wear, and thus offer an extraordinary reliability.

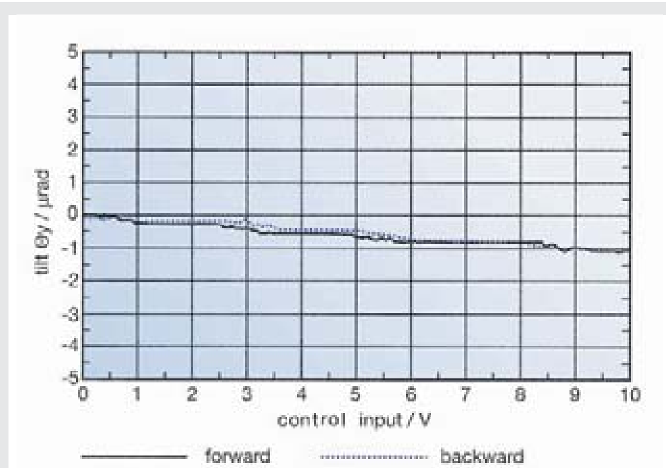
Ordering Information

P-752.11C
High-Dynamics Piezo Nanopositioning System, 15 µm, Direct Metrology, Capacitive Sensor, LEMO Connector

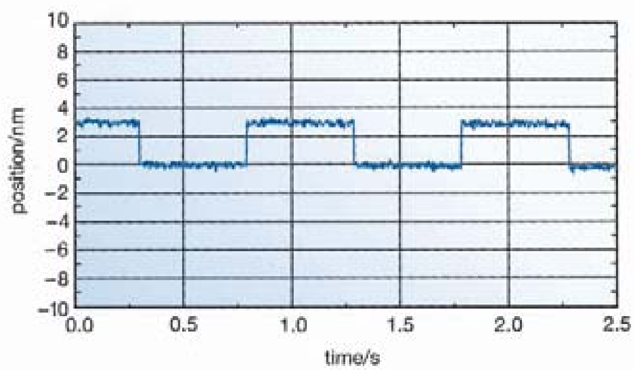
P-752.21C
High-Dynamics Piezo Nanopositioning System, 30 µm, Direct Metrology, Capacitive Sensor, LEMO Connector

P-752.1CD
High-Dynamics Piezo Nanopositioning System, 15 µm, Direct Metrology, Capacitive Sensor, Sub-D Connector

P-752.2CD
High-Dynamics Piezo Nanopositioning System, 30 µm, Direct Metrology, Capacitive Sensor, Sub-D Connector



Typical 0.5 µrad bidirectional trajectory repeatability (P-752.11C stage) means processes may be performed bidirectionally for twice the productivity



Response of a P-752.11C to a square wave control signal with 3 nm amplitude shows true sub-nm positional stability, incremental motion and bidirectional repeatability (measured with E-501 & E-503.00 & E-509.C1 controller, bandwidth set to 240 Hz)

Technical Data

Model	P-752.11C	P-752.1CD	P-752.21C	P-752.2CD	Units	Tolerance
Active axes	X	X	X	X		
Motion and positioning						
Integrated sensor	Capacitive	Capacitive	Capacitive	Capacitive		
Open-loop travel, -20 to +120 V	20	20	35	35	µm	min. (+20 %/-0 %)
Closed-loop travel	15	15	30	30	µm	calibrated
Closed-loop / open-loop resolution	0.1	0.1	0.2	0.2	nm	typ.
Linearity, closed-loop	0.03	0.03	0.03	0.03	%	typ.
Repeatability	±1	±1	±2	±2	nm	typ., full travel
Pitch / yaw	±1	±1	±1	±1	µrad	typ.
Mechanical properties						
Stiffness in motion direction	30	30	20	20	N/µm	±20 %
Unloaded resonant frequency	3200	3200	2100	2100	Hz	±20 %
Resonant frequency @ 300 g	980	980	600	600	Hz	±20 %
Push/pull force capacity in motion direction	100 / 10	100 / 10	100 / 10	100 / 10	N	Max.
Load capacity	30	30	30	30	N	Max.
Drive properties						
Ceramic type	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885		
Electrical capacitance	2.1	2.1	3.7	3.7	µF	±20 %
Dynamic operating current coefficient	17	17	15	15	µA/(Hz • µm)	±20 %
Miscellaneous						
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	°C	
Material	Stainless steel	Stainless steel	Stainless steel	Stainless steel		
Dimensions	66 x 40 x 13.5	66 x 40 x 13.5	84 x 40 x 13.5	84 x 40 x 13.5	mm	
Mass	0.25	0.25	0.35	0.35	kg	±5 %
Cable length	1.5	1.5	1.5	1.5	m	±10 mm
Sensor / voltage connection	LEMO	Sub-D Special	LEMO	Sub-D Special		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E-503 (p. 2-146) amplifier.

Recommended controller / amplifier
LEMO connector: E-500 piezo controller system (p. 2-142) with E-505 high-power amplifier (p. 2-147) and E-509 servo module (p. 2-152)
Sub-D special connector: E-610 servo controller / amplifier (p. 2-110), E-625 servo controller, bench-top (p. 2-114), E-665 high-power display controller, bench-top (p. 2-116), E-753 digital controller (p. 2-108)

P-611.1 Piezo Nanopositioner

Cost-Effective, Compact Linear Positioning System

P-611.1 linear nanopositioning system, 100 µm travel, resolution of 0.2 nm

- **Compact Design: Footprint 44 x 44 mm**
- **Travel Range to 120 µm**
- **Resolution to 0.2 nm**
- **Cost-Effective Mechanics/Electronics System Configurations**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **Z Stage, XY, XZ and XYZ Versions Available**

P-611.1 piezo stages are flexure-guided nanopositioning systems featuring a compact footprint of only 44 x 44 mm. The linear stages described here are part of the P-611 family of positioners available in 1 to 3 axis configurations. Despite their small dimensions, the systems provide up to 120 µm travel with sub-nanometer resolution. They are ideally suited for positioning tasks such as optical-path length correction in interferometry, sample positioning in microscopy or scanning applications. Equipped with ceramic-encapsulated piezo drives and a stiff zero-stiction, zero-friction flexure guiding system, all P-611 piezo stages combine millisecond responsiveness with nanometric precision and extreme reliability.

Application Examples

- Micromachining
- Microscopy
- Micromanipulation
- Semiconductor testing

Closed-Loop and Open-Loop Versions

High-resolution, fast-responding, strain gauge sensors (SGS) are applied to appropriate locations on the drive train and provide a high-bandwidth, nanometer-precision position feedback signal to the controller. The sensors are connected in a full-bridge configuration to eliminate thermal drift, and assure optimal position stability in the nanometer range.

The open-loop models are ideal for applications where fast response and very high resolution are essential, but absolute positioning is not important. They can also be used when the position is controlled by an external feedback system such as an interferometer, a PSD (position sensitive diode), CCD chip / image processing system, or the eyes and hands of an operator.

Versatility & Combination with Motorized Stages

The P-611 family of piezo stages comprises a variety of single- and multi-axis versions (X, XY, Z, XZ and XYZ) that can be easily combined with a number of very compact manual or motorized micropositioning systems to form coarse/fine positioners with longer travel ranges (see p. 2-36, 2-50 *ff*).

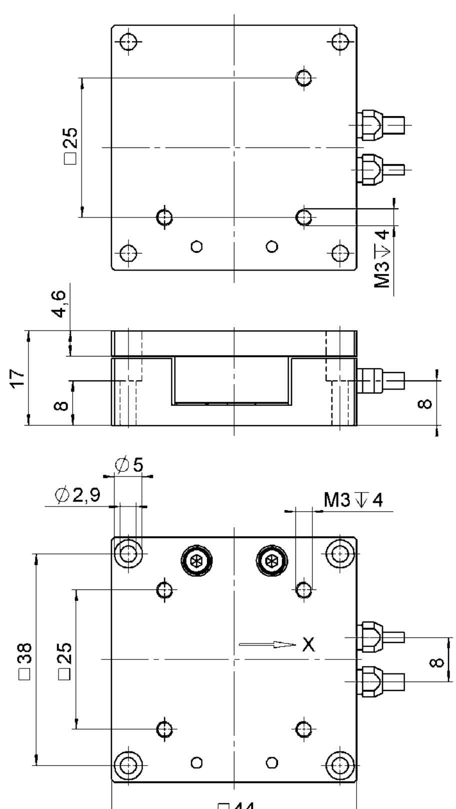
High Reliability and Long Lifetime

The compact P-611 systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and thus offer better performance and reliability than conventional piezo actuators. Actuators, guidance and sensors are maintenance-free and not subject to wear, and thus offer an extraordinary reliability.

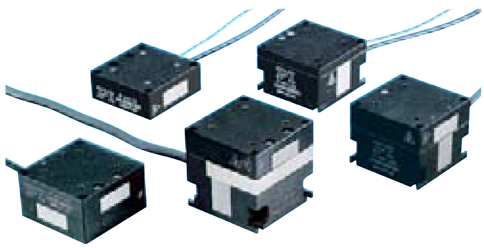
Ordering Information

P-611.10
Linear Nanopositioning System, 120 µm, No Sensor

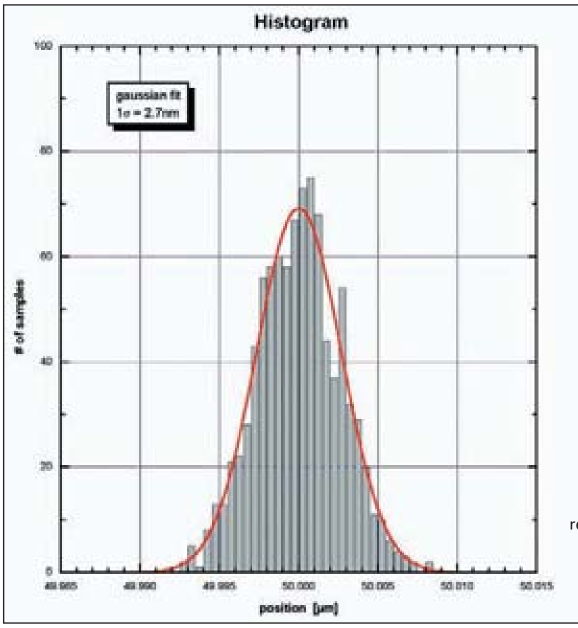
P-611.1S
Linear Nanopositioning System, 100 µm, SGS-Sensor



P-611.1S dimensions in mm



The whole P-611 family: X, Z, XY, XZ and XYZ stages



P-611.1S repeatability equals 2.7 nm

System properties	
System configuration	P-611.1S and E-665.SR controller, 30 g load
Closed-loop amplifier bandwidth, small signal	45 Hz
Settling time (10 % step width)	18 ms

Technical Data

Model	P-611.1S	P-611.10	Unit	Tolerance
Active axes	X	X		
Motion and positioning				
Integrated sensor	SGS	–		
Open-loop travel, -20 to 120 V	120	120	µm	min. (+20 %/0 %)
Closed-loop travel	100	–	µm	calibrated
Open-loop resolution	0.2	0.2	nm	typ.
Closed-loop resolution	2	–	nm	typ.
Linearity, closed-loop	0.1	–	%	typ.
Repeatability	<10	–	nm	typ.
Pitch	±5	±5	µrad	typ.
Yaw	±20	±20	µrad	typ.
Flatness	10	10	nm	typ.
Mechanical properties				
Stiffness in motion direction	0.2	0.2	N/µm	±20 %
Unloaded resonant frequency	400	400	Hz	±20 %
Resonant frequency @ 30 g	300	300	Hz	±20 %
Resonant frequency @ 100 g	195	195	Hz	±20 %
Push/pull force capacity in motion direction	15 / 10	15 / 10	N	Max.
Load capacity	15	15	N	Max.
Drive properties				
Ceramic type	PICMA® P-885	PICMA® P-885		
Electrical capacitance	1.5	1.5	µF	±20 %
Dynamic operating current coefficient	1.9	1.9	µA/(Hz • µm)	±20 %
Miscellaneous				
Operating temperature range	-20 to 80	-20 to 80	°C	
Material	Aluminum, steel	Aluminum, steel		
Dimensions	44 x 44 x 17	44 x 44 x 17	mm	
Mass	0.135	0.135	kg	±5 %
Cable length	1.5	1.5	m	±10 mm
Voltage connection	LEMO	LEMO		
Sensor connector	LEMO	–		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Noise equivalent motion with E-503 amplifier (p. 2-146).
Dynamic Operating Current Coefficient in µA per Hz and µm. Example: Sinusoidal scan of 50 µm at 10 Hz requires approximately 0.9 mA drive current.

Recommended controller / amplifier
E-610 servo controller / amplifier (p. 2-110), E-625 servo controller, bench-top (p. 2-114), E-665 powerful servo controller, bench-top (p. 2-116), for open-loop systems:
E-660 bench-top (p. 2-119) for multiple independent axes:
E-621 controller module (p. 2-160)

P-620.1 – P-629.1 PIHera® Piezo Linear Stage

Compact Nanopositioning System Family with Long Travel Ranges

PIHera® piezo nanopositioning systems feature travel ranges from 50 to 1800 µm

- **Travel Ranges 50 to 1800 µm**
- **High-Precision, Cost-Efficient**
- **Resolution to 0.1 nm**
- **Direct Metrology with Capacitive Sensors**
- **0.02 % Positioning Accuracy**
- **Frictionless, High-Precision Flexure Guiding System**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **X-, XY-, Z-, XYZ Versions**
- **Vacuum-Compatible Versions Available**

Single-axis PIHera® systems are piezo-nanopositioning stages featuring travel ranges from 50 to 1800 µm. Despite the increased travel ranges, the units are extremely compact and provide rapid response and high guiding precision. This and the long travel range is achieved with a friction-free and extremely stiff flexure system.

Application Examples

- Interferometry
- Microscopy
- Nanopositioning
- Biotechnology
- Quality assurance testing
- Semiconductor technology

The PIHera® piezo nanopositioning series also includes Z- and XY-stages (see p. 2-40, p. 2-54).

Nanometer Precision in Milliseconds

One of the advantages of PIHera® stages over motor-driven positioning stages is the rapid response to input changes and the fast and precise settling behavior. The P-622.1CD, for example, can settle to an accuracy of 10 nm in only 30 msec (other PI stages provide even faster response)!

Superior Accuracy With Direct-Metrology Capacitive Sensors

A choice of tasks such as optical path adjustment in interferometry, sample positioning in microscopy, precision alignment or optical tracking require the relatively long scanning ranges and nanometer precision offered by PIHera® nanopositioning stages.

PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz.

Designed for Precision

High stiffness is achieved with the FEA-optimized design of the frictionless flexure elements, which assure excellent guiding accuracy and dynamics. A straightness and flatness in the nanometer range is achieved.

Ordering Information

P-620.1CD* / P-620.1CL*
PIHera® Precision Piezo Linear Nanopositioning System, 50 µm, Direct Metrology, Capacitive Sensor

P-621.1CD* / P-621.1CL*
PIHera® Precision Piezo Linear Nanopositioning System, 100 µm, Direct Metrology, Capacitive Sensor

P-622.1CD* / P-622.1CL*
PIHera® Precision Piezo Linear Nanopositioning System, 250 µm, Direct Metrology, Capacitive Sensor

P-625.1CD* / P-625.1CL*
PIHera® Precision Piezo Linear Nanopositioning System, 500 µm, Direct Metrology, Capacitive Sensor

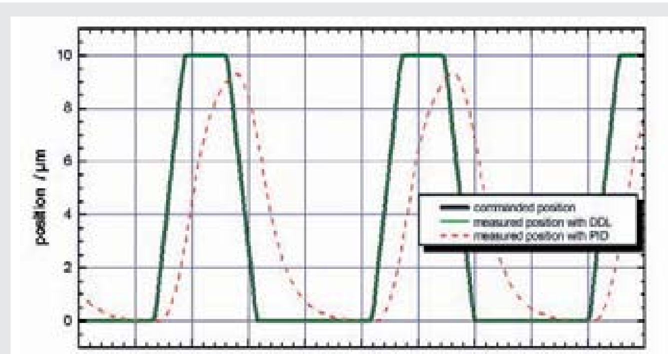
P-628.1CD* / P-628.1CL*
PIHera® Precision Piezo Linear Nanopositioning System, 800 µm, Direct Metrology, Capacitive Sensor

P-629.1CD* / P-629.1CL*
PIHera® Precision Piezo Linear Nanopositioning System, 1500 µm, Direct Metrology, Capacitive Sensor

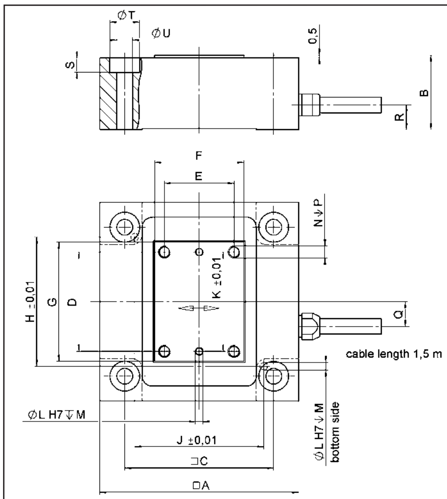
*.1CD with Sub-D Connector
*.1CL with LEMO Connector

Open-loop versions are available as P-62x.10L.
Vacuum versions to 10^{-9} hPa are available as P-62x.1UD.

System properties	
System configuration	P-625.1CD and E-500 modular piezo controller system with E-505.00F amplifier and E-509.C1A servo controller; 250 g load
Closed-loop amplifier bandwidth, large signal	30 Hz
Settling time (full travel)	31 ms



Rapid scanning motion of a P-621.1CD (commanded rise time 5 ms) with the E-710 controller ##600300 and Digital Dynamic Linearization (DDL) option. DDL virtually eliminates the tracking error (<20 nm) during the scan. The improvement over a classical PI controller is up to 3 orders of magnitude, and increases with the scanning frequency



	A	B	C	D	E	F	G	H	J	K	ØL	M	N	P	Q	R	S	ØT	ØU
P-620.1CD / 10L	30	12	24	15	12	15	18	19	24	15	1,01	1,5	M2	4	4,5	6	2	4,4	2,2
P-621.1CD / 10L	40	15	30	20	14	18	24	26	26	20	1,51	2,5	M2,5	5	5	5	3	6	3,2
P-622.1CD / 10L	50	15	40	24	20	25	30	35	35	24	1,51	2,5	M2,5	5	5,5	5	3	6	3,2
P-625.1CD / 10L	60	15	50	40	27	32	44,5	46	46	40	1,51	2,5	M2,5	5	5,5	5	3	6	3,2
P-628.1CD / 10L	80	17	70	58	41	45	63	66	66	58	1,51	2,5	M2,5	5	5,5	5	3	6	3,2

P-62x.1CD/.1CL/.10L dimensions in mm

PIHera® XYZ combination, P-62x.2 XY piezo stage (see p. 2-54), P-62x.Z vertical stage (see p. 2-40)

Linear Actuators & Motors
Nanopositioning / Piezoelectrics
Piezo Flexure Stages / High-Speed Scanning Systems
Linear
Vertical & Tip/Tilt
2- and 3-Axis
6-Axis
Fast Steering Mirrors / Active Optics
Piezo Drivers / Servo Controllers
Single-Channel
Multi-Channel
Modular
Accessories
Piezoelectrics in Positioning
Nanometrology
Micropositioning
Index

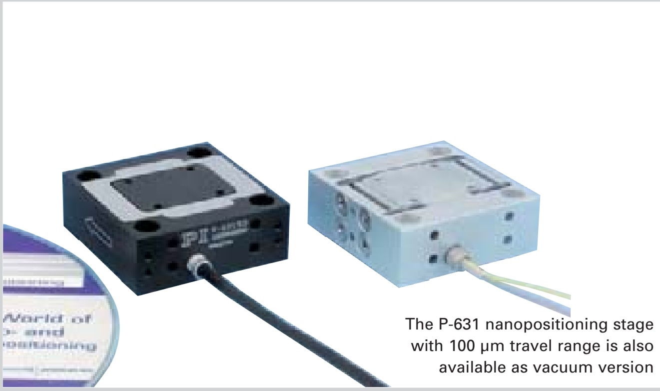
Technical Data

Model	P-620.1CD/ P-620.1CL	P-621.1CD/ P-621.1CL	P-622.1CD/ P-622.1CL	P-625.1CD/ P-625.1CL	P-628.1CD/ P-628.1CL	P-629.1CD/ P-629.1CL/	P-62x.10L open-loop version	Units	Tolerance
Active axes	X	X	X	X	X	X	X		
Motion and positioning									
Integrated sensor	Capacitive	Capacitive	Capacitive	Capacitive	Capacitive	Capacitive	–		
Open-loop travel, -20 to +120 V	60	120	300	600	950	1800	as P-62x.1CD	µm	min. (+20 %/-0 %)
Closed-loop travel	50	100	250	500	800	1500	–	µm	calibrated
Closed-loop / open-loop resolution	0.1 / 0.2	0.2 / 0.4	0.4 / 0.7	0.5 / 1.4	0.5 / 1.8	2 / 3	as P-62x.1CD	nm	typ.
Linearity, closed-loop	0.02	0.02	0.02	0.02	0.03*	0.03**	–	%	typ.
Repeatability	±1	±1	±1	±5	±10	±14	–	nm	typ.
Pitch / yaw	±3	±3	±3	±6	±6	±10	as P-62x.1CD	µrad	typ.
Mechanical properties									
Stiffness in motion direction	0.42	0.35	0.2	0.1	0.12	0.13	as P-62x.1CD	N/µm	±20 %
Unloaded resonant frequency	1100	800	400	215	125	125	as P-62x.1CD	Hz	±20 %
Resonant frequency @ 20 g	550	520	340	180	115	120	as P-62x.1CD	Hz	±20 %
Resonant frequency @ 120 g	260	240	185	110	90	110	as P-62x.1CD	Hz	±20 %
Push/pull force capacity in motion direction	10	10	10	10	10	10	as P-62x.1CD	N	Max.
Load capacity	10	10	10	10	10	10	as P-62x.1CD	N	Max.
Lateral Force	10	10	10	10	10	8	as P-62x.1CD	N	Max.
Drive properties									
Ceramic type	PICMA® P-883	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-887	PICMA® P-888	as P-62x.1CD		
Electrical capacitance	0.35	1.5	3.1	6.2	19	52	as P-62x.1CD	µF	±20 %
Dynamic operating current coefficient	0.9	1.9	1.9	1.6	3	4.3	as P-62x.1CD	µA/(Hz • µm)	±20 %
Miscellaneous									
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 150	°C	
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum		
Dimensions	30 x 30 x 12	40 x 40 x 15	50 x 50 x 15	60 x 60 x 15	80 x 80 x 17	100 x 100 x 22.5	as P-62x.1CD	mm	
Mass	0.11	0.16	0.2	0.24	0.38	0.72	as P-62x.1CD	kg	±5 %
Cable length	1.5	1.5	1.5	1.5	1.5	1.5	1.5 m	±10 mm	
Sensor / voltage connection	CD version: Sub-D special CL version: LEMO	CD version: Sub-D special CL version: LEMO	CD version: Sub-D special CL version: LEMO	CD version: Sub-D special CL version: LEMO	CD version: Sub-D special CL version: LEMO	CD version: Sub-D special CL version: LEMO	LEMO (no sensor)		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. The value given is noise equivalent motion with E-710 controller (p. 2-128).
*With digital controller. For analog controller 0.05 %.
**With digital controller. For analog controller 0.07 %.
Recommended controller / amplifier
CD version: E-610 servo controller / amplifier (p. 2-110), E-625 servo controller, bench-top (p. 2-114), E-665 powerful servo controller, bench-top (p. 2-116)
Single-channel digital controller: E-753 (bench-top) (p. 2-108)
CL version: E-500 modular piezo controller system (p. 2-142) with E-505 amplifier module (high power) p. 2-147 and E-509 controller (p. 2-152)
Open-loop version: E-500 modular piezo controller system (p. 2-142) with E-505 amplifier module (high power) (p. 2-147)

P-631 Compact Piezo Nanopositioning System

Cost-Effective, Scalable Design for High-Volume Applications



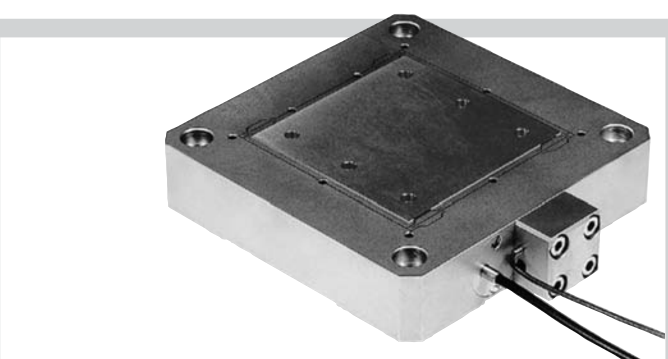
The P-631 nanopositioning stage with 100 µm travel range is also available as vacuum version

- Cost-Effective, Compact Design for High-Volume Applications
- Travel Range 100 µm, Longer Ranges on Request
- Direct Metrology with Capacitive Sensors
- Resolution to 0,2 nm
- Outstanding Lifetime Due to PICMA® Piezo Actuators
- Mechanically Compatible to P-621 PIHera® Nanopositioning Stages

Model	Closed-loop / open-loop travel @ -20 to +120 V	Closed-loop / openloop resolution	Linearity	Pitch / yaw	Load capacity
P-631.1CD	120 / 100 µm	0.2 / 0.4 nm	0.02 %	25 µrad	10 N

P-750 Piezo Nanopositioning System

Dynamic High-Load Nanopositioning Stages with Direct Metrology



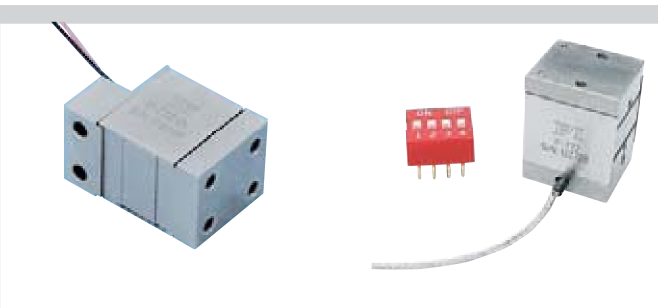
The P-750.10 piezo stage is equipped with high-precision capacitive position sensors

- 1 nm Lateral Guiding Accuracy
- Frictionless, High-Precision Flexure Guiding System
- Load Capacity 10 kg
- Resolution <1 nm
- Superior Accuracy With Direct-Metrology Capacitive Sensors
- Direct Drive for Faster Response
- 75 µm Travel Range
- Outstanding Lifetime Due to PICMA® Piezo Actuators

Model	Closed-loop / open-loop travel	Closed-loop / open-loop resolution	Load capacity	Rotation around θ_X, θ_Y	Unloaded resonant frequency
P-750.00	– /75 µm	– / 0.4 nm	100 N	±10 µrad	600 Hz
P-750.20 with capacitive sensor	75 / 75 µm	1 / 0.4 nm	100 N	±10 µrad	600 Hz

P-772 Miniature Nanopositioning System

High Dynamics and Direct Position Measurement



The P-772 piezo nanopositioning system is available with capacitive sensors for closed-loop operation (left) or as open-loop version (right). DIP switch for size comparison.

- Smallest Stage with Direct Metrology
- Frictionless, High-Precision Flexure Guiding System
- Resolution <0.1 nm
- Travel Range to 12 µm
- Closed-Loop and Open-Loop Versions
- Rapid Response and Settling
- Outstanding Lifetime Due to PICMA® Piezo Actuators

Modell	Closed-loop / open-loop travel @ 0 to +100 V	Closed-loop / open-loop resolution	Linearity	Unloaded resonant frequency	Load capacity
P-772.1CD / P-772.1CL	10 / 12 µm	0.05 / 0.05 nm	0.03 %	1.7 kHz	5 N
P-772.0L	– />10 µm	– / 0.05 nm	–	1.7 kHz	5 N

P-720 PIFOC® Piezo Nanofocusing Systems

Compact High-Dynamics Scanner for Small Objectives

The P-720 objective nanofocusing / scanning drive (objective not included) was designed for small objectives. Similar PIFOC® systems are available for large objectives and with position sensors

- **Travel Range 100 µm**
- **Rapid Response & Settling Behavior**
- **Scans and Positions Objectives with Sub-nm Resolution**
- **Frictionless, High-Precision Flexure Guiding System**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**

Model	Max. objective diameter	Travel	Open-loop, resolution	Stiffness	Push/pull force capacity	Rotation around θ_X, θ_Y
P-720.00	25 mm	100 µm	0.5 nm	0.2 N/µm	100 / 20 N	13 µrad

P-721K PIFOC® Nosepiece Nanopositioner

Compact Design, Sub-Nanometer Resolution

P-721KTPZ Compact Nosepiece Nanopositioner

- **Positioning and Scanning of Microscope Turrets**
- **Direct-Metrology Capacitive Sensors for Highest Linearity, Stability and Control Dynamics**
- **Frictionless, High-Precision Flexure Guiding System for Better Focus Stability**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**

Model	Travel	Closed-loop/ open-loop resolution	Resonant frequency (fully loaded)	Dimensions
P-721KTPZ Turret-PIFOC®	80 µm	10 / 0.5 nm	215 Hz	44.5 x 42 x 53 mm (W x L x H)

P-721K Power-PIFOC® Nosepiece Nanopositioner

For High-Resolution Microscopy. High-Load Capacity, Capacitive Feedback

The P-721KPTZ high-load PIFOC® allows precision positioning of a complete microscope turret

- **Scans and Positions Objectives with Sub-nm Resolution**
- **Travel Ranges to 150 µm, Millisecond Settling Time**
- **Parallel Flexure Guiding for Minimized Objective Offset**
- **Direct Metrology with Capacitive Sensors for Highest Linearity**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**

Model	Load capacity	Closed-loop travel	Resonant frequency	Mass
P-721KPTZ	20 N	to 150 µm	410 Hz (no load)	1.5 kg

P-721 PIFOC® Piezo Flexure Objective Scanner

Fast Nanopositioner and Scanner for Microscope Objectives

P-721.CLQ piezo objective nanopositioning system with P-721.12Q QuickLock option and objective (adapter and objective not included)

- **Scans and Positions Objectives with Sub-nm Resolution**
- **Travel Ranges to 140 µm, Millisecond Settling Time**
- **Significantly Faster Response and Higher Lifetime than Motorized Z-Stages**
- **Parallel Precision Flexure Guiding for Better Focus Stability**
- **Choice of Position Sensors: Capacitive Direct Metrology (Higher Performance) or Strain Gauge (Lower Cost)**
- **Compatible with Metamorph™ Imaging Software**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **QuickLock Adapter for Easy Attachment**

P-721 PIFOCs® are high-speed, piezo-driven microscope objective nanofocusing/scanning devices, providing a positioning and scanning range of 100 µm with sub-nanometer resolution and very high motion of linearity up to 0.03 %.

Application Examples

- 3D-Imaging
- Z Stack Acquisition
- Screening
- Interferometry
- Metrology
- Disc-drive-testing
- Autofocus systems
- Confocal microscopy
- Biotechnology
- Semiconductor testing

PIFOCs® are also available with up to 460 µm travel (P-725 p. 2-28), and for exceptional dynamic and step performance (models P-726 p. 2-32 and P-725.SDD p. 2-30).

Superior Accuracy With Direct-Metrology Capacitive Sensors

Capacitive position feedback is used in the top-of-the-line models. PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz.

Alternatively, strain gauge sensor (SGS) models are available. The sensors are connected in a bridge configuration to eliminate thermal drift, and assure optimal position stability in the nanometer range.

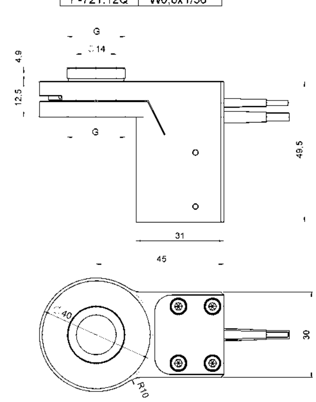
Open-loop models are available for applications where fast response and very high resolution are essential. Here, specifying or reporting absolute position values is either not required or is handled by external sensors, such as interferometers, a vision system or photodiode PSD (position sensitive detector). These models retain the inherent piezo advantages such as high resolution and speed.

Simple Installation with QuickLock Thread Options

The PIFOC® is mounted between the turret and the objective with the QuickLock thread adapter. After threading the adapter into the turret, the Quick Lock is affixed in the desired position. Because the PIFOC® body need not to be rotated, cable wind-up is not an issue.

QuickLock Adapter

	G
P-721.02Q	M26x0,75
P-721.03Q	M27x0,75
P-721.04Q	M28x0,75
P-721.05Q	M32x0,75
P-721.06Q	M26x1/36"
P-721.08Q	M19x0,75
P-721.11Q	M25x0,75
P-721.12Q	W0,8x1/36"



P-721.CLQ, .CDQ, .SL2 dimensions in mm (adapter to be ordered separately)

Ordering Information

P-721.CDQ
Fast PIFOC® Piezo Nanofocusing Z-Drive, 100 µm, Direct Metrology, Capacitive Sensor, Sub-D Connector, for Quick Lock Thread Adapters

P-721.CLQ
Fast PIFOC® Piezo Nanofocusing Z-Drive, 100 µm, Direct Metrology, Capacitive Sensor, LEMO Connector, for Quick Lock Thread Adapters

P-721.SL2
Fast PIFOC® Piezo Nanofocusing Z-Drive, 100 µm, SGS-Sensor, LEMO Connector, for Quick Lock Thread Adapters

P-721.0LQ
Fast PIFOC® Piezo Nanofocusing Z-Drive, 100 µm, No Sensor, LEMO Connector, for Quick Lock Thread Adapters

Extension Tubes for Objectives

P-721.90Q
Extens. Tube, 12.5 mm, Thread W0.8 x 1/36"

P-721.91Q
Extens. Tube, 12.5 mm, Thread M25 x 0.75

P-721.92Q
Extens. Tube, 12.5 mm, Thread M26 x 0.75

P-721.93Q
Extens. Tube, 12.5 mm, Thread M27 x 0.75

P-721.94Q
Extens. Tube, 12.5 mm, Thread M28 x 0.75

P-721.95Q
Extens. Tube, 12.5 mm, Thread M32 x 0.75

P-721.96Q
Extens. Tube, 12.5 mm, Thread M26 x 1/36"

P-721.98Q
Extens. Tube, 12.5 mm, Thread M19 x 0.75

QuickLock Thread Adapters see figure

High Reliability and Long Lifetime

The compact PIFOC® systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and thus offer better performance and reliability than conventional piezo actuators. Actuators, guidance and sensors are maintenance-free and not subject to wear, and thus offer an extraordinary reliability.

Choice of Controllers

A large choice of analog and digital piezo controllers as OEM, bench-top and 19-inch-rackmount versions is available.

QuickLock P-721.12Q thread adapter exploded view with microscope objective and PIFOC® P-721.CLQ (mounting tools are included, QuickLock adapter and objective not included)

Technical Data

Model	P-721.CLQ	P-721.CDQ	P-721.SL2	P-721.0LQ	Units	Tolerance
Active axes	Z	Z	Z	Z		
Motion and positioning						
Integrated sensor	Capacitive	Capacitive	SGS	–		
Open-loop travel, -20 to +120 V	140	140	140	140	µm	min. (+20 %/-0%)
Closed-loop travel	100	100	100	–	µm	calibrated
Open-loop resolution	0.5	0.5	0.5	0.5	nm	typ.
Closed-loop resolution	0.7	0.7	5	–	nm	typ.
Linearity, closed-loop	0.03	0.03	0.2	–	%	typ.
Repeatability	±5	±5	±10	–	nm	typ.
Runout θX, θY	13	13	13	13	µrad	typ.
Crosstalk X, Y	100	100	100	100	nm	typ.
Mechanical properties						
Stiffness in motion direction	0.3	0.3	0.3	0.3	N/µm	±20 %
Unloaded resonant frequency	580	580	580	550	Hz	±20 %
Resonant frequency @ 120 g	235	235	235	235	Hz	±20 %
Resonant frequency @ 200 g	180	180	180	180	Hz	±20 %
Push/pull force capacity in motion direction	100 / 20	100 / 20	100 / 20	100 / 20	N	Max.
Drive properties						
Ceramic type	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885		
Electrical capacitance	3.1	3.1	3.1	3.1	µF	±20 %
Dynamic operating current coefficient	3.9	3.9	3.9	3.9	µA/(Hz•µm)	±20 %
Miscellaneous						
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	°C	
Material	Aluminum	Aluminum	Aluminum	Aluminum		
Mass	0.24	0.24	0.22	0.22	kg	±5 %
Max. objective diameter	39	39	39	39	mm	
Cable length	1.5	1.5	1.5	1.5	m	±10 mm
Sensor / voltage connection	LEMO	Sub-D Special	LEMO	LEMO (no sensor)		
Recommended controller / amplifier	E-610 servo controller/amplifier (p. 2-110), modular piezo controller system E-500 (p. 2-142) with amplifier module E-505 (high performance) (p. 2-147) and E-509 servo controller (p. 2-152)	E-625 servo controller, bench top (p. 2-114), E-665 powerful servo controller, bench-top (p. 2-116), Single-channel digital controller: E-753 (bench-top) (p. 2-108)	E-610 servo controller/amplifier, E-625 servo controller, bench-top, E-665 powerful servo controller, bench-top	E-610 servo controller/amplifier		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E-503 amplifier (p. 2-144)

P-725 PIFOC® Long-Travel Objective Scanner

High-Precision Positioner / Scanner for Microscope Objectives

P-725.2CL with QuickLock option
P-721.12Q for W0.8 x 1/36" threads
and objective (QuickLock adapter
and objective not included)

- **Travel Ranges to 460 µm**
- **Significantly Faster Response and Higher Lifetime than Motorized Z-Stages**
- **Scans and Positions Objectives with Sub-nm Resolution**
- **Direct Metrology with Capacitive Sensors for Highest Linearity**
- **Parallel Precision Flexure Guiding for Better Focus Stability**
- **Compatible with Metamorph™ Imaging Software**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **QuickLock Adapter for Easy Attachment**

P-725 PIFOC® nanofocus systems are long-travel, high-speed, piezo-driven microscope objective nanofocusing/ scanning devices. Despite the increased travel ranges (up to 460 µm), they are 20 % shorter than P-721 units (p. 2-25) while providing sub-nanometer resolution. The innovative, frictionless, flexure guiding system provides enhanced precision for superior focus stability with fast response for rapid settling and scanning.

Application Examples

- 3D-Imaging
- Screening
- Interferometry
- Metrology
- Disc-drive-testing
- Autofocus systems
- Confocal microscopy
- Biotechnology
- Semiconductor testing

Fastest Step-and-Settle: 25 Milliseconds for 250 Microns

The P-725.2CL can perform a 250 µm step to 1 % accuracy in only 25 ms (E-665.CR controller, no load) and in 50 ms with a load of 150 g.

Superior Accuracy With Direct-Metrology Capacitive Sensors

Cpacitive position feedback is used in the top-of-the-line models. PI's proprietary capacitive position sensors measure the actual motion of the moving part relative to the stationary base (direct metrology). Errors in the drive train, actuator, lever arm or in guiding system do not influence the measurements. The result is exceptional motion linearity, higher long-term stability and a stiffer, more-responsive servo loop, because external influences are immediately recognized by the sensor.

Open-loop models are available for applications where fast response and very high resolution are essential. Here, specifying or reporting absolute position values is either not required or is handled by external sensors, such as interferometers, vision system or photodiode PSD (position sensitive detector). These models retain the inherent piezo advantages as high resolution and speed.

Simple Installation with QuickLock Thread Options

The PIFOC® is mounted between the turret and the objective with the QuickLock thread adapter. After threading the adapter into the turret, the Quick Lock is affixed in the desired position. Because the PIFOC® body need not to be rotated, cable wind-up is not an issue.

High Reliability and Long Lifetime

The compact PIFOC® systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and thus offer better performance and reliability than conventional piezo actuators. Actuators, guidance and sensors are maintenance-free and not subject to wear, and thus offer an extraordinary reliability.

Ordering Information

P-725.1CD
PIFOC® Piezo Nanofocusing Z-Drive for Long Scanning Ranges, 100 µm, Capacitive Sensors, Sub-D Connector, for Quick Lock Thread Adapters

P-725.1CL*
PIFOC® Piezo Nanofocusing Z-Drive for Long Scanning Ranges, 100 µm, Capacitive Sensors, LEMO Connector, for Quick Lock Thread Adapters

P-725.2CD
PIFOC® Piezo Nanofocusing Z-Drive for Long Scanning Ranges, 250 µm, Capacitive Sensors, Sub-D Connector, for Quick Lock Thread Adapters

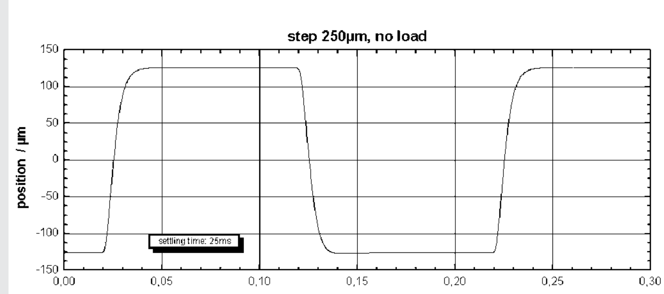
P-725.2CL*
PIFOC® Piezo Nanofocusing Z-Drive for Long Scanning Ranges, 250 µm, Capacitive Sensors, LEMO Connector, for Quick Lock Thread Adapters

P-725.4CD
PIFOC® Piezo Nanofocusing Z-Drive for Long Scanning Ranges, 400 µm, Capacitive Sensors, Sub-D Connector, for Quick Lock Thread Adapters

P-725.4CL*
PIFOC® Piezo Nanofocusing Z-Drive for Long Scanning Ranges, 400 µm, Capacitive Sensors, LEMO Connector, for Quick Lock Thread Adapters

*Also available w/o sensor (open-loop): P-725.10L, P-725.20L and P-725.40L

Accessories
QuickLock thread adapters and extension tubes for objectives (see p. 2-26)

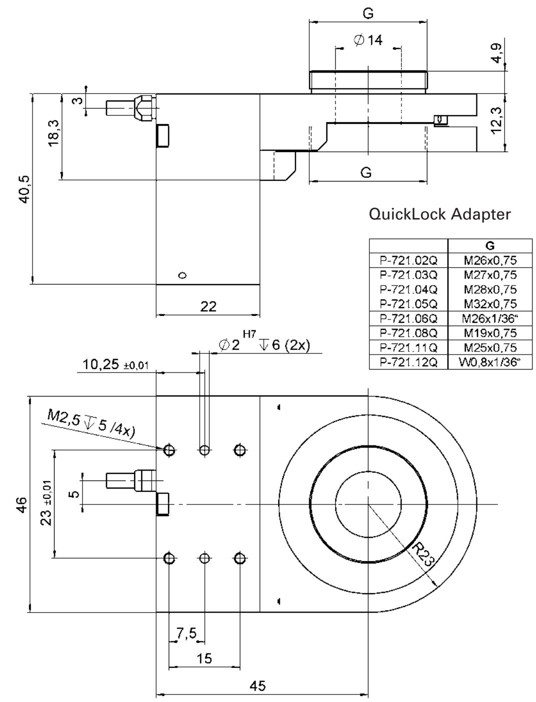


Top dynamic performance of the P-725.2CL PIFOC®: only 25 ms for a 250 µm step

Specimen Stages & Faster Scanners

For the highest dynamics, the P-726 (see p. 2-32) and P-725.DD (see p. 2-30) models are also available. Alternatively, the sample can be moved into focus: The P-737 piezo Z specimen stage features a large aperture for a variety of sample holders.

P-721.12Q QuickLock thread adapter, exploded view with microscope objective and PIFOC® (mounting tools are included, QuickLock adapter and objective not included)



P-725 dimensions in mm (thread adapter ordered separately)

Technical Data

Model	P-725.1CL, P-725.1CD	P-725.2CL, P-725.2CD	P-725.4CL, P-725.4CD	Units	Tolerance
Active axes	Z	Z	Z		
Motion and positioning					
Integrated sensor	Capacitive	Capacitive	Capacitive		
Open-loop travel, -20 to +120 V	150	330	460	µm	min. (+20 %/0 %)
Closed-loop travel	100	250	400	µm	calibrated
Open-loop resolution	0.3	0.4	0.5	nm	typ.
Closed-loop resolution	0.65	0.75	1.25	nm	typ.
Linearity, closed-loop	0.03	0.03	0.03	%	typ.
Repeatability	±5	±5	±5	nm	typ.
Runout Θ_X	1	6	10	µrad	typ.
Runout Θ_Y	20	45	45	µrad	typ.
Crosstalk in X	20	20	60	nm	typ.
Crosstalk in Y	20	40	60	nm	typ.
Mechanical properties					
Stiffness in motion direction	0.23	0.17	0.12	N/µm	±20 %
Unloaded resonant frequency	470	330	230	Hz	±20 %
Resonant frequency @ 150 g	185	140	120	Hz	±20 %
Push/pull force capacity in motion direction	100 / 20	100 / 20	100 / 20	N	Max.
Drive properties					
Ceramic type	PICMA® P-885	PICMA® P-885	PICMA® P-885		
Electrical capacitance	4.2	6.2	6.2	µF	±20 %
Dynamic operating current coefficient	5.2	3.1	1.9	µA/(Hz • µm)	±20 %
Miscellaneous					
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	°C	
Material	Aluminum	Aluminum	Aluminum		
Max. objective diameter	39	39	39	mm	
Mass	0.215	0.23	0.23	kg	±5 %
Sensor / voltage connection	CL-version: LEMO CD-version: Sub-D special	CL-version: LEMO CD-version: Sub-D special	CL-version: LEMO CD-version: Sub-D special		

Recommended controller / amplifier
"CL"-versions:
E-610 servo controller / amplifier (p. 2-110); E-500 modular piezo controller system (p. 2-142) with E-505 high-performance amplifier module (p. 2-147) and E-509 controller (p. 2-152)
"CD"-versions:
E-621 controller module (p. 2-160), E-625 servo controller, bench-top (p. 2-114), E-665 display servo controller, with digital interface, bench-top (p. 2-116)
Single-channel digital controller: E-753 (bench-top) (p. 2-108)

P-725.xDD PIFOC® High-Dynamics Piezo Scanner

Nanopositioning and Scanning System for Microscope Objectives

P-725.CDD direct-drive version for high-dynamics focusing

- Fastest Settling Time under 5 ms with Microscope Objective
- 20 µm Travel Range
- Scans and Positions Objectives with Sub-nm Resolution
- Parallel Flexure Guiding for Minimized Objective Offset
- Choice of Position Sensors: Capacitive Direct Metrology (Higher Performance) or Strain Gauges (Lower Cost)
- Compatible with Metamorph™ Imaging Software
- Outstanding Lifetime Due to PICMA® Piezo Actuators
- QuickLock Adapter for Easy Attachment

Direct Drive for Ultra-Fast Scanning and Positioning

The P-725.xDD objective positioners were designed for extremely fast motion over relatively short travel ranges up to 20 µm. Their ultra-stiff direct piezo drive (1.2 kHz resonant frequency) enables the highest scanning rates and response times of only 5 msecs – essential for time-critical tasks.

Application Exampels

- 3D-Imaging
- Screening
- Interferometry
- Metrology
- Disc-drive-testing
- Autofocus systems
- Confocal microscopy
- Biotechnology
- Semiconductor testing

Superior Accuracy With Direct-Metrology Capacitive Sensors

Capacitive position feedback is used in the top-of-the-line model. PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz.

Alternatively compact, more cost-efficient strain gauge sensors (SGS) featuring nanometer resolution are implemented. Absolute-measuring SGS-sensors are applied to appropriate places on the drive train and thus measure the displacement of the moving part of the stage relative to the base.

Simple Installation with QuickLock Thread Options

The PIFOC® is mounted between the turret and the objective with the QuickLock thread adapter. After threading the adapter into the turret, the QuickLock is affixed in the desired position. Because the PIFOC® body need not to be rotated, cable wind-up is not an issue.

High Reliability and Long Lifetime

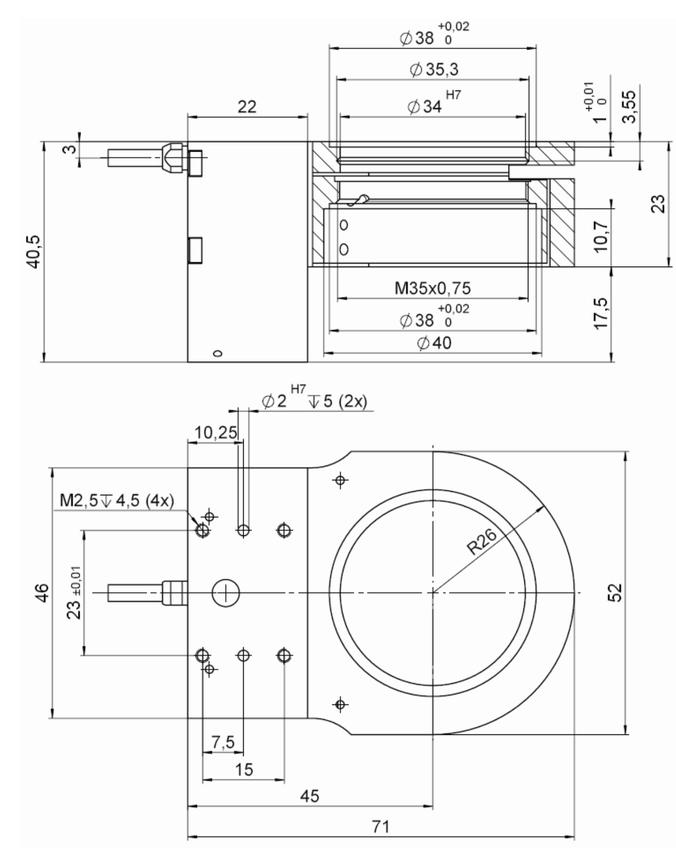
The compact PIFOC® systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and thus offer better performance and reliability than conventional piezo actuators. Actuators, guidance and sensors are maintenance-free and not subject to wear, and thus offer an extraordinary reliability.

Ordering Information

P-725.CDD
Fast PIFOC® Piezo Nanofocusing Z-Drive, 20 µm, Capacitive Sensor, Sub-D Connector, for QuickLock Thread Adapters

P-725.SDD
Fast PIFOC® Piezo Nanofocusing Z-Drive, 20 µm, SGS-Sensor, LEMO Connector, for QuickLock Thread Adapters

Ask about custom designs!



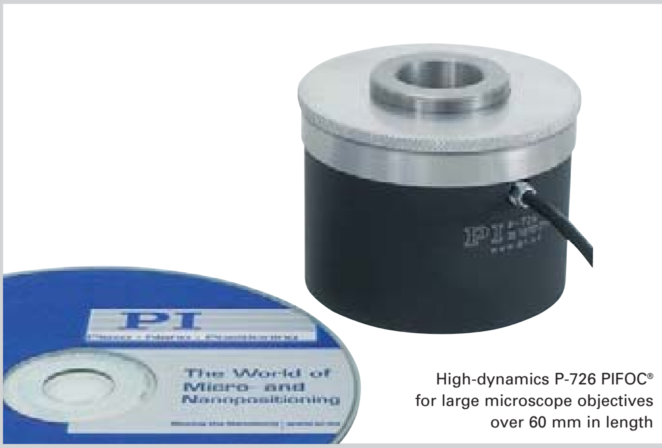
P-725.xDD dimensions in mm

Model	P-725.CDD	P-725.SDD	Units	Tolerance
Active axes	Z	Z		
Motion and positioning				
Integrated sensor	Capacitive	SGS		
Open-loop travel, -20 to +120 V	20	20	µm	min. (+20 %/-0 %)
Closed-loop travel	20	20	µm	calibrated
Open-loop resolution	0.2	0.2	nm	typ.
Closed-loop resolution	0.2	0.2	nm	typ.
Linearity, closed-loop	0.04	0.5	%	typ.
Repeatability	±1.5	±5	nm	typ.
Runout θ_X, θ_Y	2	2	µrad	typ.
Crosstalk in X, Y	150	150	nm	typ.
Mechanical properties				
Stiffness in motion direction	1.5	1.5	N/µm	±20 %
Unloaded resonant frequency	1180	1180	Hz	±20 %
Resonant frequency @ 200 g	450	450	Hz	±20 %
Push/pull force capacity in motion direction	100 / 20	100 / 20	N	Max.
Drive properties				
Ceramic type	PICMA® P-887	PICMA® P-887		
Electrical capacitance	3.1	3.1	µF	±20 %
Dynamic operating current coefficient	19.4	19.4	µA/(Hz • µm)	±20 %
Miscellaneous				
Operating temperature range	-20 to 80	-20 to 80	°C	
Material	Aluminum	Aluminum		
Mass	0.21	0.2	kg	±5 %
Cable length	1.5	1.5	m	±10 mm
Sensor / voltage connection	Sub-D Special	LEMO		

Recommended controller
E-610 servo controller / amplifier (p. 2-110), E-625 servo controller, bench-top (p. 2-114), E-665 high-power servo controller, bench-top (p. 2-116)
Single-channel digital controller: E-753 (bench-top) (p. 2-108)

P-726 PIFOC® High-Load Objective Scanner

High-Dynamic Piezo Z Scanner for Heavy Objectives



High-dynamics P-726 PIFOC® for large microscope objectives over 60 mm in length

- High-Dynamics Positioning and Scanning for Large Objectives
- 1120 Hz Resonant Frequency, 560 Hz with 210 g Load
- Typical Settling Time about 6 ms
- Travel Range 100 µm
- Direct-Metrology Capacitive Sensors for Best Linearity, Stability and Control Dynamics
- Resolution to 0.3 nm
- Frictionless, High-Precision Flexure Guiding System for Better Focus Stability

The P-726 PIFOC® Nanofocusing system was developed to achieve the fastest possible stepping time with the heavy, high-numerical-aperture objectives used in many of today's high-resolution microscopy applications. Its extremely stiff design offers excellent settling time and scanning frequency values even when objectives of several hundred grams are moved. High stiffness is achieved with the rotationally symmetric arrangement of multiple piezo drives and the optimized design of the flexure and lever elements, which assure the excellent guiding accuracy and dynamics.

Furthermore, like other members of the PIFOC® family, the P-726 is equipped with direct metrology capacitive position sensors that allow resolutions far below one nanometer.

Application Examples

- 3-D Imaging
- Screening
- Autofocus systems
- Microscopy
- Confocal microscopy
- Surface analysis
- Wafer inspection

Direct Metrology with Capacitive Sensors for Highest Stability and Accuracy

PI's proprietary capacitive position sensors measure the actual motion of the moving part relative to the stationary base (direct metrology). Errors in the drive train, actuator, lever arm or in guiding system do not influence the measurements. The result is exceptional motion linearity, higher long-term stability and a stiffer, more-responsive servo loop, because external influences are immediately recognized by the sensor. Due to this sensor principle, the P-726 features a resolution of under 0.4 nm in closed-loop and a linearity of 0.02 %.

Simple Installation with QuickLock Thread Options

The PIFOC® is mounted between the turret and the objective with the QuickLock thread adapter. After threading the adapter into the turret, the QuickLock is affixed in the desired position. Because the PIFOC® body need not to be rotated, cable wind-up is not an issue.

Ceramic Insulated Piezo Actuators Provide Long Lifetime

Highest possible reliability is assured by the use of award-winning PICMA® multilayer piezo actuators. PICMA® actuators are the only actuators on the market with ceramic-only insulation, which makes them resistant to ambient humidity and leakage-current failures. They are thus far superior to conventional actuators in reliability and lifetime.

Ordering Information

P-726.1CD
High-Dynamics PIFOC® Piezo Nanofocusing Z-Drive, 100 µm, Capacitive Sensor

QuickLock Thread Adapter as Accessories:

P-726.04
P-726 PIFOC® Thread Adapter M28 x 0.75

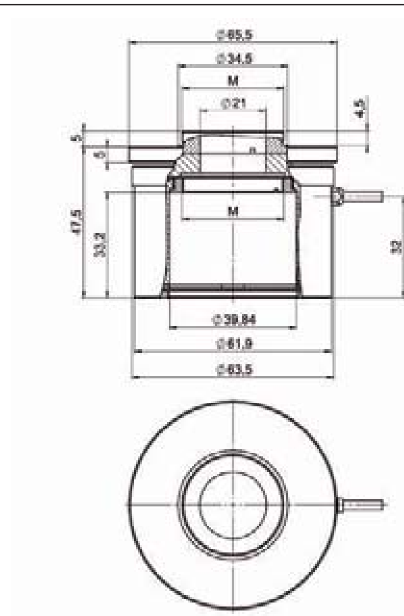
P-726.05
P-726 PIFOC® Thread Adapter M32 x 0.75

P-726.06
P-726 PIFOC® Thread Adapter M26 x 1/36"

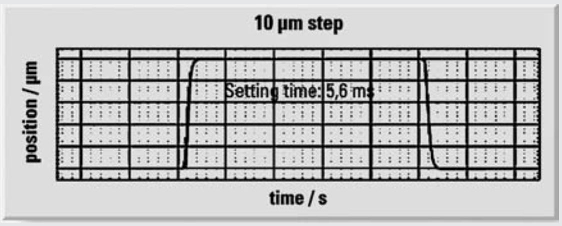
P-726.11
P-726 PIFOC® Thread Adapter M25 x 0.75

P-726.12
P-726 PIFOC® Thread Adapter W0.8 x 1/36"

Ask about custom designs!



P-726 dimensions in mm with P-726.05 M32 QuickLock adapter



P-726 settling time under load

Technical Data

	P-726.1CD	Tolerance
Active axes	Z	
Motion and positioning		
Integrated sensor	Capacitive, direct metrology	
Closed-loop travel	100 µm	calibrated
Closed-loop resolution	0.4 nm	typ.
Open-loop resolution	0.3 nm	typ.
Linearity, closed-loop	0.02 %	typ.
Repeatability	±3 nm	typ.
Runout Θ_X, Θ_Y	±5 µrad	typ.
Crosstalk X, Y	50 nm	typ.
Mechanical properties		
Stiffness in motion direction	3.4 N/µm	±20 %
Unloaded resonant frequency	1120 Hz	±20 %
Resonant frequency under load	560 Hz @ 210 g	±20 %
Resonant frequency under load	480 Hz @ 310 g	±20 %
Push/pull force capacity in motion direction	100 / 50 N	Max.
Drive properties		
Piezo ceramic type	PICMA® P-885	
Electrical capacitance	6 µF	±20 %
Dynamic operating current coefficient	7.5 µA/(Hz • µm)	±20 %
Miscellaneous		
Operating temperature range	-20 to 80 °C	
Material	Aluminum, steel	
Dimensions	Diameter: 65 mm, Height: 50.7 mm	
Max. objective diameter	M32	
Mass	575 g	±5 %
Cable length	1.5 m	±10 mm
Sensor / voltage connection	Sub-D Special	
Recommended controller / amplifier	Single-channel digital controller: E-753 (bench-top) (p. 2-108) E-625 bench-top controller (p. 2-114), E-665 high-power bench-top controller (p. 2-116) E-500 modular piezo controller system (p. 2-142) with E-505 high-power amplifier module (p. 2-147) and E-509 servo-controller (p. 2-152)	
System properties		
System configuration	E-500 modular piezo controller system with E-505 high-power amplifier module and E-509 servo-controller 310 g load (objective mass)	
Closed-loop amplifier bandwidth, small signal, 10 µm	130 Hz	
Closed-loop amplifier bandwidth, large signal	70 Hz	

Linear Actuators & Motors
Nanopositioning / Piezoelectrics
Piezo Flexure Stages / High-Speed Scanning Systems
Linear
Vertical & Tip/Tilt
2- and 3-Axis
6-Axis
Fast Steering Mirrors / Active Optics
Piezo Drivers / Servo Controllers
Single-Channel
Multi-Channel
Modular
Accessories
Piezoelectrics in Positioning
Nanometrology
Micropositioning
Index

P-726 QuickLock thread adapter exploded view with P-726 PIFOC® (mounting tools included)

P-737 PIFOC® Specimen-Focusing Z Stage

Low-Profile, Long-Range Piezo Z Nanopositioner for Microscopy Samples

P-737 piezo Z-stage for high-resolution microscopy

- **High-Speed Piezo Z Motion with Travel Ranges to 250 µm (Up to 500 µm on Request)**
- **Nanometer Resolution**
- **Large Clear Aperture to Accommodate Specimen Holders**
- **Perfect Mechanical Fit with XY OEM Manual or Motorized Stages**
- **Response Times in the Millisecond Range**

PIFOC® P-737 high-speed vertical positioning systems are designed for use with XY microscopy stages–OEM manual stages as well as aftermarket motorized stages.

While the XY stage positions the sample, the piezo-actuator-based P-737 moves the sample along the optical axis to quickly and precisely adjust the focus. Vertical stepping with an accuracy in the nanometer range takes only a few milliseconds.

The large aperture is designed to accommodate a variety of specimen holders including slides or multiwell plates.

Application Examples

- Fluorescence microscopy
- Confocal microscopy
- Biotechnology
- Autofocus systems
- 3D Imaging
- Medical technology

High-Speed Z Steps for Fast Focus Control and Z Stack Acquisition

The immediate response of the solid-state piezo drives enables rapid Z-steps with typically 10 to 20 times faster step & settle times than classical stepper motor drives. This leads to higher image acquisition speed and throughput.

Closed-Loop Position Control for High-Precision and Stability

For high stability and repeatability, P-737 stages are equipped with position feedback. High-resolution, fast-responding, strain gauge sensors (SGS) are applied to appropriate locations on the drive train and provide a high-bandwidth, nanometer-precision position feedback signal to the controller. The sensors are connected in a full-bridge configuration to eliminate thermal drift, and assure optimal position stability in the nanometer range.

Excellent Guiding Accuracy

Flexures optimized with Finite Element Analysis (FEA) are used to guide the stage. FEA techniques are used to give the design the highest possible stiffness in, and perpendicular to, the direction of motion, and to minimize linear and angular runout. Flexures allow extremely high-precision motion, no matter how minute, as they are completely free of play and friction.

Ordering Information

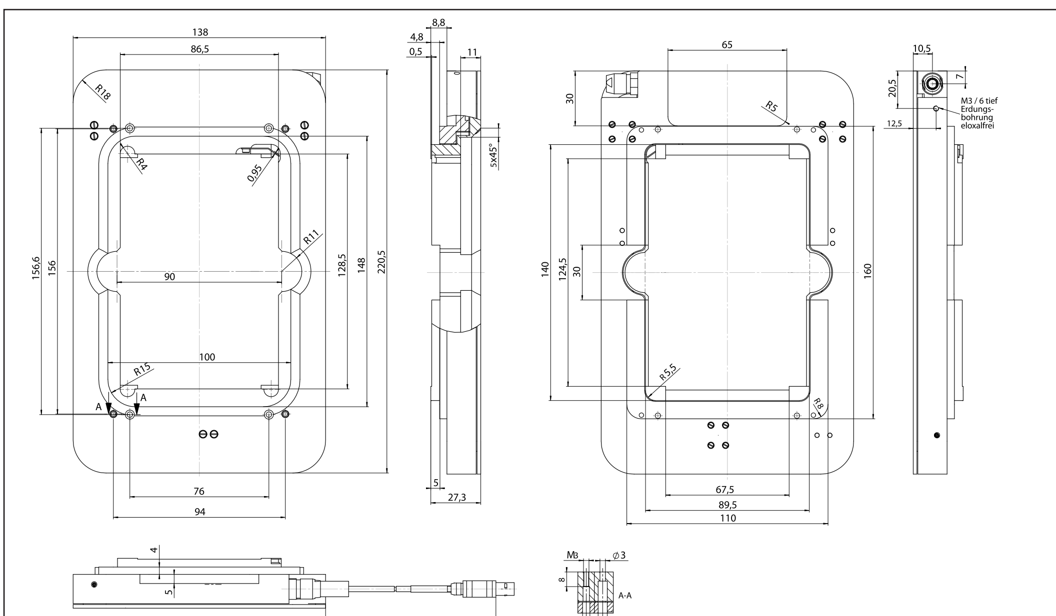
P-737.1SL
PIFOC® Nanofocusing Z-Stage for Microscope Sample Holder, 100 µm, SGS, LEMO Connector, for Märzhäuser Microscope Stages

P-737.2SL
PIFOC® Nanofocusing Z-Stage for Microscope Sample Holder, 250 µm, SGS, LEMO Connector, for Märzhäuser Microscope Stages

Versions with up to 500 µm travel or with direct-measuring, high-resolution capacitive sensors on request.

Ceramic Insulated Piezo Actuators Provide Long Lifetime

Highest possible reliability is assured by the use of award-winning PICMA® multilayer piezo actuators. PICMA® actuators are the only actuators on the market with ceramic-only insulation, which makes them resistant to ambient humidity and leakage-current failures. They are thus far superior to conventional actuators in reliability and lifetime.



P-737 dimensions in mm

Linear Actuators & Motors
Nanopositioning / Piezoelectrics
Piezo Flexure Stages / High-Speed Scanning Systems
Linear
Vertical & Tip/Tilt
2- and 3-Axis
6-Axis
Fast Steering Mirrors / Active Optics
Piezo Drivers / Servo Controllers
Single-Channel
Multi-Channel
Modular
Accessories
Piezoelectrics in Positioning
Nanometrology
Micropositioning
Index

The P-737 piezo Z-stage (shown with multiwell plate) is compatible with motorized microscope XY stages like the one shown from Märzhäuser

Instead of moving the sample, it is also possible to move the objective. The P-725 PIFOC® Objective Scanner offers travel ranges over 400 µm with nanometer resolution and response times in the millisecond range

Technical Data

Model	P-737.1SL	P-737.2SL	Units	Tolerance
Active axes	Z	Z		
Motion and positioning				
Integrated sensor	SGS	SGS		
Open-loop travel, -20 to +120 V	150	280	µm	min. (+20 %/-0 %)
Closed-loop travel	100	250	µm	
Open-loop resolution	0.8	1	nm	typ.
Closed-loop resolution	2.5	4	nm	typ.
Linearity, closed-loop	0.2	0.2	%	typ.
Repeatability	6	12	nm	typ.
Runout X	±36	±36	µrad	typ.
Runout Y	±36	±140	µrad	typ.
Mechanical properties				
Unloaded resonant frequency	270	210	Hz	±20 %
Resonant frequency @ 100 g	230	180	Hz	±20 %
Resonant frequency @ 200 g	210	155	Hz	±20 %
Push/pull force capacity in motion direction	50 / 20	50 / 20	N	Max.
Drive properties				
Ceramic type	PICMA® P-885	PICMA® P-885		
Electrical Capacitance	6.3	9.3	µF	±20 %
Dynamic operating current coefficient	7.9	4.6	µA/(Hz • µm)	±20 %
Miscellaneous				
Operating temperature range	-20 to 80	-20 to 80	°C	
Material	Aluminum	Aluminum		
Dimensions	220.5 x 138 x 27.3	220.5 x 138 x 27.3	mm	
Mass	0.7	0.7	kg	±5 %
Cable length	2	2	m	±10 mm
Sensor / voltage connection	LEMO	LEMO		
System properties				
System configuration	E-500 System with E-503 amplifier (6 W) E-509 servo module	E-500 System with E-503 amplifier (6 W) E-509 servo module		
Closed-loop amplifier bandwidth, small signal	60	30	Hz	typ.
Settling time (10 % step width)	24	30	ms	typ.

Recommended controller / amplifier
Single-channel: E-610 servo controller / amplifier (p. 2-110), E-625 servo controller, bench-top (p. 2-114), E-665 powerful servo controller, bench-top (p. 2-116)

P-611.Z Piezo Z-Stage

Compact Nanopositioner

P-611 Z-axis nanopositioning stage, 100 µm closed-loop travel, resolution to 0.2 nm

- **Compact: Footprint Only 44 x 44 mm**
- **Travel Range to 120 µm**
- **Resolution to 0.2 nm**
- **Cost-Effective Mechanics/Electronics System Configurations**
- **Frictionless, High-Precision Flexure Guiding System**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **X, XY, XZ and XYZ Versions also Available**

P-611 Z stages are piezo-based nanopositioning systems with 100 µm closed-loop travel range featuring a compact footprint of only 44 x 44 mm. The stages described here are part of the P-611 family of positioners available in 1- to 3-axis configurations. Equipped with ceramic-encapsulated piezo drives and a stiff, zero-stiction, zero-friction flexure guiding system, all P-611 piezo stages combine millisecond responsiveness with nanometric precision and extreme reliability.

The P-611.Z versions described here are ideally suited for use in applications such as microscopy, auto-focusing and photonics packaging.

Application Examples

- Photonics / integrated optics
- Micromachining
- Micromanipulation
- Semiconductor testing

Closed-Loop and Open-Loop Versions

High-resolution, fast-responding, strain gauge sensors (SGS) are applied to appropriate locations on the drive train and provide a high-bandwidth, nanometer-precision position feedback signal to the controller. The sensors are connected in a full-bridge configuration to eliminate thermal drift, and assure optimal position stability in the nanometer range.

The open-loop models are ideal for applications where fast response and very high resolution are essential, but absolute positioning is not important. They can also be used when the position is controlled by an external feedback system such as an interferometer, a PSD (position sensitive diode), CCD chip / image processing system, or the eyes and hands of an operator.

Versatility & Combination with Motorized Stages

The P-611 family of piezo stages comprises a variety of single- and multi-axis versions (X, XY, Z, XZ and XYZ) that can be easily combined with a number of very compact manual or motorized micropositioning systems to form coarse/fine positioners with longer travel ranges (see p. 2-20, p. 2-50 *ff*).

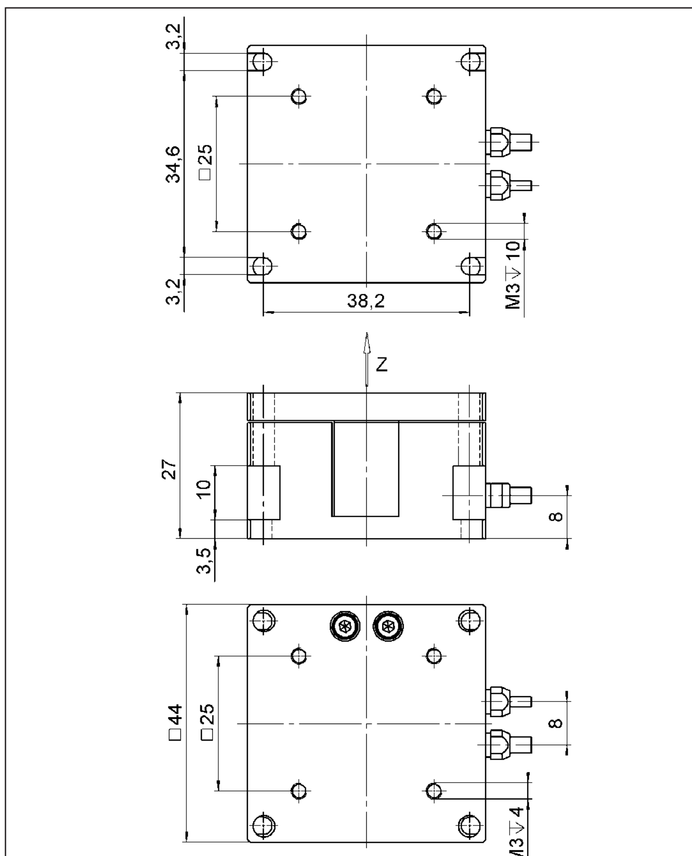
High Reliability and Long Lifetime

The compact P-611 systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and thus offer better performance and reliability than conventional piezo actuators. Actuators, guidance and sensors are maintenance-free and not subject to wear, and thus offer an extraordinary reliability.

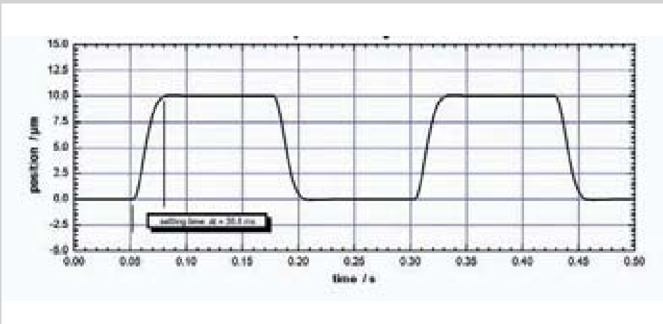
Ordering Information

P-611.Z0
Vertical Nanopositioning Stage, 120 µm, No Sensor

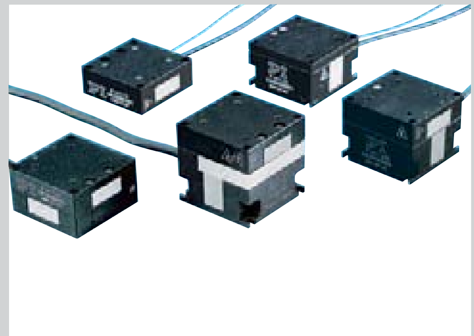
P-611.ZS
Vertical Nanopositioning Stage, 100 µm, SGS-Sensor



P-611.ZS dimensions in mm



The settling time of a P-611.Z with a load of 30 g is 26 ms for a 10 µm step. Measured with interferometer



The whole P-611 family: X, Z, XY, XZ and XYZ stages

Technical Data

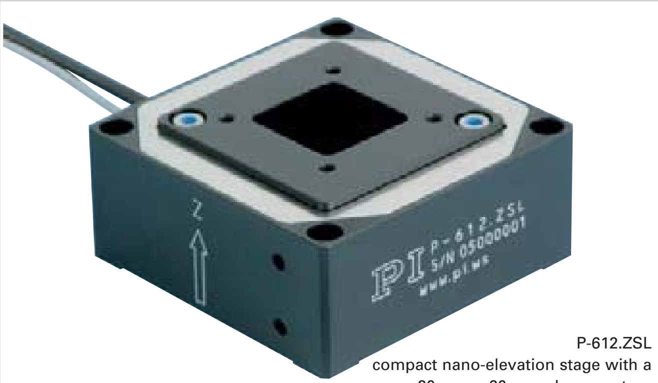
Model	P-611.ZS	P-611. Z0	Unit	Tolerance
Active axes	Z	Z		
Motion and positioning				
Integrated sensor	SGS	-		
Open-loop travel, -20 to +120 V	120	120	µm	min. (+20 %/0 %)
Closed-loop travel	100	-	µm	
Open-loop resolution	0.2	0.2	nm	typ.
Closed-loop resolution	2	-	nm	typ.
Linearity	0.1	-	%	typ.
Repeatability	<10	-	nm	typ.
Runout θZ (Z motion)	±5	±5	µrad	typ.
Runout θX (Z motion)	±20	±20	µrad	typ.
Runout θY (Z motion)	±5	±5	µrad	typ.
Mechanical properties				
Stiffness	0.45	0.45	N/µm	±20 %
Unloaded resonant frequency	460	460	Hz	±20 %
Resonant frequency @ 30 g	375	375	Hz	±20 %
Resonant frequency @ 100 g	265	265	Hz	±20 %
Push/pull force capacity	15 / 10	15 / 10	N	Max.
Drive properties				
Ceramic type	PICMA® P-885	PICMA® P-885		
Electrical capacitance	1.5	1.5	µF	±20 %
Dynamic operating current coefficient	1.9	1.9	µA/(Hz • µm)	±20 %
Miscellaneous				
Operating temperature range	-20 to 80	-20 to 80	°C	
Material	Aluminum, steel	Aluminum, steel		
Dimensions	44 x 44 x 27	44 x 44 x 27	mm	
Mass	176	176	g	±5 %
Cable length	1.5	1.5	m	±10 mm
Sensor connector	LEMO	LEMO		
Voltage connection	LEMO	LEMO		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E -503 amplifier (p. 2-146)
Recommended controller / amplifier
E-610 servo controller / amplifier (p. 2-110), E-625 servo controller, bench-top (p. 2-114), E-665 powerful servo controller, bench-top (p. 2-116), E-660 bench-top for open-loop systems (p. 2-119)

System properties	
System Configuration	P-611.1S and E-665.SR controller, 30 g load
Amplifier bandwidth, small signal	40 Hz
Settling time (10 % step width)	25 ms

P-612.Z Piezo Z Stage

Compact Nanopositioning Stage with Aperture



P-612.ZSL
compact nano-elevation stage with a
20 mm x 20 mm clear aperture

- **Travel Range 100 µm**
- **Resolution to 0.2 nm**
- **Linearity 0.2 %**
- **Compact: Footprint 60 x 60 mm**
- **Very Cost-Effective Controller/Piezomechanics Systems**
- **Frictionless, High-Precision Flexure Guiding System**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**

These elevation stages are cost-effective, compact, piezo-based positioning systems with travel ranges of 100 µm. The space-saving design features a footprint of only 60 x 60 mm. The 20 x 20 mm clear aperture makes them ideally suited for sample positioning in microscopy. Equipped with PICMA® piezo drives and zero-stiction, zero-friction flexure guiding system, the series provides nanometer-range resolution and millisecond response time.

Application Examples

- Interferometry
- Scanning microscopy
- Nanopositioning
- Biotechnology
- Quality assurance testing
- Semiconductor fabrication

Position Servo-Control with Nanometer Resolution

High-resolution, broadband, strain gauge sensors (SGS) are applied to appropriate locations on the drive train and measure the displacement of the moving part of the stage relative to the base. The SGS sensors assure optimum position stability in the nanometer range and fast response.

The open-loop models are ideal for applications where fast response and very high resolution are essential, but absolute positioning is not important. They can also be used when the position is controlled by an external sensor such as an interferometer, a PSD (position sensitive detector), CCD chip / image processing system, or the eyes and hands of an operator.

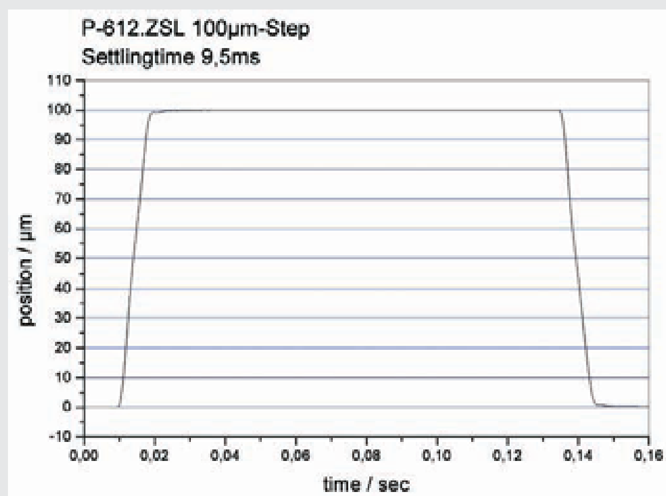
High Reliability and Long Lifetime

The compact P-612 systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and thus provide better performance and reliability than conventional piezo actuators. Actuators, guiding system and sensors are maintenance-free, not subject to wear and offer an extraordinary reliability.

Ordering Information

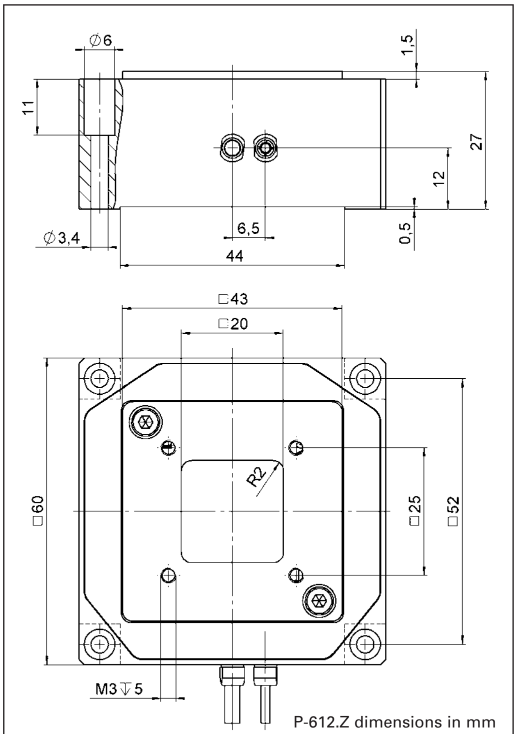
P-612.ZSL
Vertical Nanopositioning Stage, 100 µm, 20 x 20 mm Aperture, SGS-Sensor

P-612.Z0L
Vertical Nanopositioning Stage, 100 µm, 20 x 20 mm Aperture, No Sensor



Settling takes less than 10 ms over the entire travel range in closed-loop operation

P-612s are available as XY-scanners (P-612.2SL, on the left) and vertical stages (P-612.ZSL, on the right) providing a travel range of 100 µm per axis



P-612.Z dimensions in mm

System properties	
System configuration	P-612.ZSL and E-625.SR controller, 30 g load
Closed-loop amplifier small signal bandwidth	110 Hz
Closed-loop amplifier large signal bandwidth	80 Hz
Settling time (10 % step width)	8 ms

Technical Data

Model	P-612.ZSL	P-612.Z0L	Units	Tolerance
Active axes	Z	Z		
Motion and positioning				
Integrated sensor	SGS	–		
Open-loop travel, -20 to +120 V	110	110	µm	min. (+20 %/-0 %)
Closed-loop travel	100	–	µm	calibrated
Open-loop resolution	0.2	0.2	nm	typ.
Closed-loop resolution	1.5	–	nm	typ.
Linearity, closed-loop	0.2	–	%	typ.
Repeatability	±4	–	nm	typ.
Runout θ_X, θ_Y	±10	±10	µrad	typ.
Crosstalk X, Y	±20	±20	µm	typ.
Mechanical properties				
Stiffness in motion direction	0.63	0.63	N/µm	±20 %
Unloaded resonant frequency	490	490	Hz	±20 %
Resonant frequency under load	420 (30 g)	420 (30 g)	Hz	±20 %
Load capacity	15 / 10	15 / 10	N	Max.
Drive properties				
Ceramic type	PICMA® P-885	PICMA® P-885		
Electrical capacitance	3	3	µF	±20 %
Dynamic operating current coefficient	3.8	3.8	µA/(Hz • µm)	±20 %
Miscellaneous				
Operating temperature range	-20 to 80	-20 to 80	°C	
Material	Aluminum	Aluminum		
Mass	0.28	0.275	kg	±5 %
Cable length	1.5	1.5	m	±10 mm
Sensor / voltage connection	LEMO	LEMO (no sensor)		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E-503 amplifier. (p. 2-146)
Recommended controller / amplifier
E-610 servo controller / amplifier card (p. 2-110), E-625 servo-controller, bench-top (p. 2-114), E-665 high-power servo-controller with display, bench-top (p. 2-116), E-660 bench-top for open-loop systems (p. 2-119)

P-620.Z – P-622.Z PIHera® Precision Z-Stage

Nanopositioning System Family with Direct Metrology and Long Travel Ranges

P-620.ZCL, P-621.ZCL and P-622.ZCL (from left) PIHera® piezo nano-elevation stages, 50 to 400 µm (CD for size comparison)

- **Vertical Travel Range 50 to 400 µm**
- **High-Precision, Cost-Efficient**
- **Resolution to 0.1 nm**
- **Direct Metrology with Capacitive Sensors**
- **0,02 % Positioning Accuracy**
- **Frictionless, High-Precision Flexure Guiding System**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **X-, XY-, Z- XYZ-Versionen**
- **Vacuum-Compatible Versions Available**

Z-axis PIHera® systems are cost-efficient piezo nanopositioning stages featuring travel ranges up to 400 µm and provide sub-nanometer resolution. Despite the increased travel ranges, the units are extremely compact and provide sub-nanometer resolution. The long travel range is achieved with a friction-free and extremely stiff flexure system, which also offers rapid response and excellent guiding accuracy.

Application Examples

- Interferometry
- Microscopy
- Nanopositioning
- Biotechnology
- Quality assurance testing
- Semiconductor technology

PIHera® piezo nanopositioning stages are also available as X- and XY-stages (see p. 2-22 and p. 2-54).

Nanometer Precision in Milliseconds

One of the advantages of PIHera® stages over motor-driven positioning stages is the rapid response to input changes and the fast and precise settling behavior. The P-622.1CD, for example, can settle to an accuracy of 10 nm in only 30 msec (other PI stages provide even faster response)!

Superior Accuracy With Direct-Metrology Capacitive Sensors

A choice of tasks such as optical path adjustment in interferometry, sample positioning in microscopy, precision alignment or optical tracking require the relatively long scanning ranges and nanometer precision offered by PIHera® nanopositioning stages.

PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz.

Designed for Precision

High stiffness is achieved with the FEA-optimized design of the frictionless flexure elements, which assure excellent guiding accuracy and dynamics. A straightness and flatness in the nanometer range is achieved.

Ordering Information

P-620.ZCD
PIHera® Precision Vertical Nanopositioning Stage, 50 µm, Capacitive Sensor, Sub-D Connector

P-620.ZCL
PIHera® Precision Vertical Nanopositioning Stage, 50 µm, Capacitive Sensor, LEMO Connector

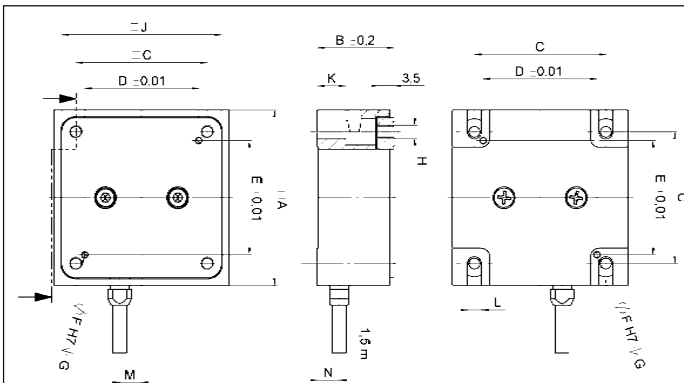
P-621.ZCD
PIHera® Precision Vertical Nanopositioning Stage, 100 µm, Capacitive Sensor, Sub-D Connector

P-621.ZCL
PIHera® Precision Vertical Nanopositioning Stage, 100 µm, Capacitive Sensor, LEMO Connector

P-622.ZCD
PIHera® Precision Vertical Nanopositioning Stage, 250 µm, Capacitive Sensor, Sub-D Connector

P-622.ZCL
PIHera® Precision Vertical Nanopositioning Stage, 250 µm, Capacitive Sensor, LEMO Connector

Open-loop versions are available as P-62x.Z0L



	A	B	C	D	E	∅ F
P-620.ZCD / Z0L	30	15	24	19	24	1,01
P-621.ZCD / Z0L	40	17,5	30	26	26	1,51
P-622.ZCD / Z0L	50	17,5	40	35	35	1,51

	G	H	J	K	L	M	N
P-620.ZCD / Z0L	2	M2	28	5	2,2	4,5	6
P-621.ZCD / Z0L	2,5	M3	36,5	6,5	3,2	5	5
P-622.ZCD / Z0L	2,5	M3	46,5	6,5	3,2	5	5

P-62x.ZCD / .ZCL / .Z0L dimensions in mm

System properties	
System configuration	P-621.ZCD with E-753 digital controller and 30 g load
Amplifier bandwidth, small signal	25 Hz
Amplifier bandwidth, large signal	25 Hz
Settling time (full travel)	15 ms

PIHera® XYZ combination

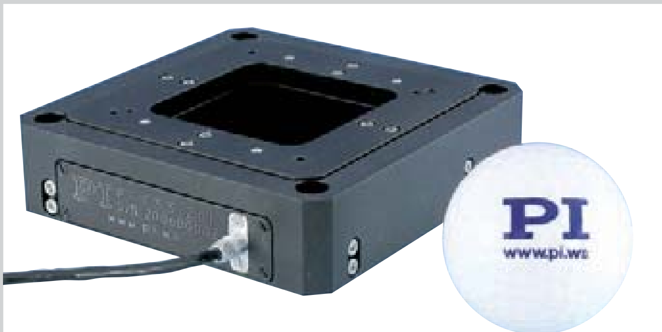
Technical Data

Model	P-620.ZCD P-620.ZCL	P-621.ZCD P-621.ZCL	P-622.ZCD P-622.ZCL	P-62x.Z0L Open-loop versions	Units	Tolerance
Active axes	Z	Z	Z	Z		
Motion and positioning						
Integrated sensor	Capacitive	Capacitive	Capacitive	–		
Open-loop travel, -20 to +120 V	65	140	400	as P-62x.ZCD	µm	min. (+20 %/-0 %)
Closed-loop travel	50	100	250	–	µm	
Open-loop resolution	0.1	0.2	0.5	as P-62x.ZCD	nm	typ.
Closed-loop resolution	0.2	0.3	1	–	nm	typ.
Linearity	0.02	0.02	0.02	–	%	typ.
Repeatability	±1	±1	±1	–	nm	typ.
Runout θ_X, θ_Y)	<20	<20	<80	as P-62x.ZCD	µrad	typ.
Mechanical properties						
Stiffness	0.5	0.6	0.24	as P-62x.ZCD	N/µm	±20 %
Unloaded resonant frequency	1000	790	360	as P-62x.ZCD	Hz	±20 %
Resonant frequency @ 30 g	690	500	270	as P-62x.ZCD	Hz	±20 %
Push/pull force capacity	0 / 5	10 / 8	10 / 8	as P-62x.ZCD	N	Max.
Load capacity	10	10	10	as P-62x.ZCD	N	Max.
Lateral Force	10	10	10	as P-62x.ZCD	N	Max.
Drive properties						
Ceramic type	PICMA® P-883	PICMA® P-885	PICMA® P-885	as P-62x.ZCD		
Electrical capacitance	0.7	3	6.2	as P-62x.ZCD	µF	±20 %
Dynamic operating current coefficient	1.8	3.8	3.1	as P-62x.ZCD	µA/(Hz • µm)	±20 %
Miscellaneous						
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 150	°C	
Material	Aluminum	Aluminum	Aluminum	Aluminum		
Mass	0.12	0.17	0.24	as P-62x.ZCD	g	±5 %
Cable length	1.5	1.5	1.5	as P-62x.ZCD	m	±10 mm
Sensor / voltage connection	Sub-D special (CD-version) CL-version: LEMO	Sub-D special (CD-version) CL-version: LEMO	Sub-D special (CD-version) CL-version: LEMO	LEMO (no sensor)		

Recommended controller
CD-Versions:
E-610 servo controller / amplifier (p. 2-110), E-625 servo controller, bench-top (p. 2-114), E-665 powerful servo controller, bench-top (p. 2-116)
Single-channel digital controller: E-753 (bench-top) (p. 2-108)
CL-Versions:
Modular piezo controller system E-500 (p. 2-142) with amplifier module E-505 (high performance) (p. 2-147) and E-509 controller (p. 2-152)
Open-loop versions: modular piezo controller system E-500 (p. 2-142) with amplifier module E-505 (high performance) (p. 2-147)

P-733.Z High-Dynamics Z-Nanopositioner / Scanner

Direct Position Metrology and Clear Aperture



P-733.ZCD Piezo Z-Stage

- **Travel Range 100 µm**
- **Direct Metrology with Capacitive Sensors**
- **Resolution to 0.3 nm, Closed-Loop**
- **Clear Aperture 50 x 50 mm**
- **Versions with Additional Degrees of Freedom Available**
- **XY and XYZ Versions Also Available**
- **Vacuum-Compatible Versions Available**

P-733.Z piezo vertical stages offer a positioning and scanning range of 100 µm with sub-nanometer resolution. The 50 x 50 mm clear aperture is ideal for applications such as scanning or confocal microscopy. Their fast settling time of less than 10 ms allows high throughput rates.

Application Examples

- Scanning microscopy
- Confocal microscopy
- Mask / wafer positioning
- Surface measurement technique
- Nano-imprinting
- Micromanipulation
- Image processing / stablilization
- Nanopositioning with high flatness & straightness

Capacitive Sensors for Highest Accuracy

PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz. The resolution of the P-733.Z is better than 0.3 nm.

Because of the direct measurement of the actual distance between the fixed frame and the moving part of the stage, errors in the drive train, actuator, lever arm or in guiding system do not influence the measuring accuracy. The result is exceptional motion linearity, higher long-term stability and a stiffer, more-responsive control loop, because external influences are immediately recognized by the sensor. The capacitive sensor non-linearity is typically less than 0.03 %, the repeatability of the P-733.Z is better than 2 nm.

Ceramic Insulated Piezo Actuators Provide Long Lifetime

Highest possible reliability is assured by the use of award-winning PICMA® multilayer piezo actuators. PICMA® actuators are the only actuators on the market with ceramic-only insulation, which makes them resistant to ambient humidity and leakage-current failures. They are thus far superior to conventional actuators in reliability and lifetime.

Large Variety of Models for a Broad Range of Applications

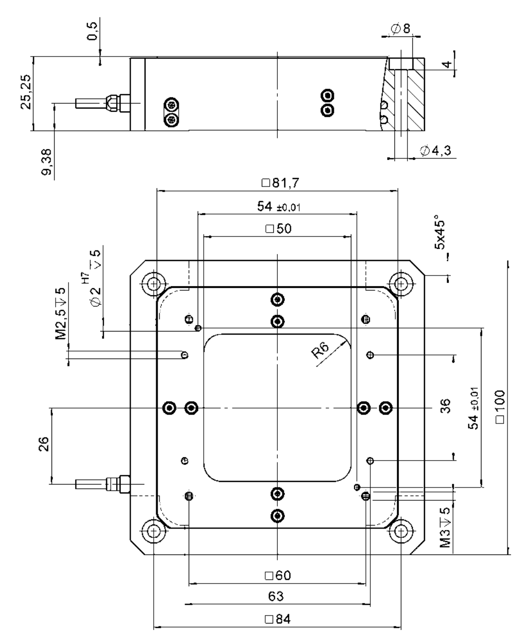
For scanning and positioning tasks in XY, the P-733.2CD and .3CD versions are available with a travel range of 100 x 100 µm. For high-dynamics applications, the P-733.2DD and P-733.3DD models can be offered with direct drive and reduced travel range (see p. 2-62).

For ultra-high-vacuum applications down to 10^{-9} hPa, nanopositioning systems as well as comprehensive accessories, such as suitable feedthroughs, are available.

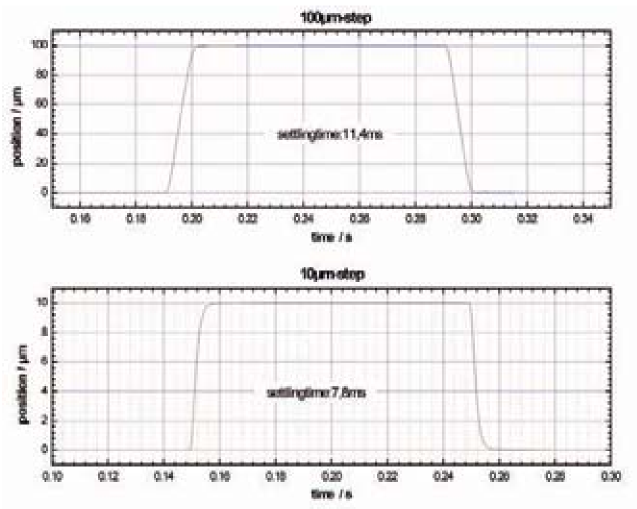
Ordering Information

P-733.ZCD
Compact Precision Nanopositioning Vertical Stage, 100 µm, Capacitive Sensor, Sub-D Connector

P-733.ZCL
Compact Precision Nanopositioning Vertical Stage, 100 µm, Capacitive Sensor, LEMO Connector



P-733.Z dimensions in mm



Step response of the P-733.ZCD. Settling time is in the 10 ms range

System properties	
System configuration	E-500 modular system with E-503 amplifier and E-509 sensor module; 20 g load
Amplifier bandwidth, small signal	96 Hz
Settling time (10 % step width)	8 ms

Technical Data

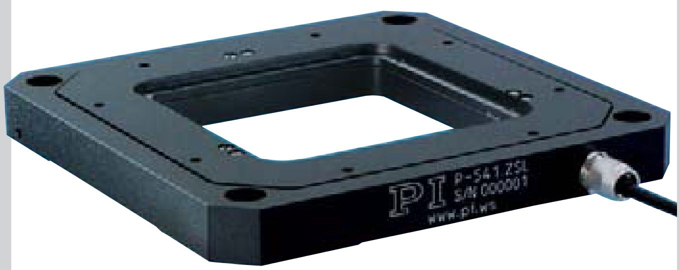
Model	P-733.ZCD P-733.ZCL	Tolerance
Active axes	Z	
Motion and positioning		
Integrated sensor	Capacitive	
Open-loop travel, -20 to +120 V	115 µm	min. (+20 %/-0 %)
Closed-loop travel	100 µm	
Open-loop resolution	0.2 nm	typ.
Closed-loop resolution	0.3 nm	typ.
Linearity	0.03 %	typ.
Repeatability	<2 nm	typ.
Rotation around Z	<10 µrad	typ.
Rotation around X	<5 µrad	typ.
Rotation around Y	<5 µrad	typ.
Mechanical properties		
Stiffness	2.5 N/µm	±20 %
Unloaded resonant frequency	700 Hz	±20 %
Resonant frequency @ 120 g	530 Hz	±20 %
Resonant frequency @ 200 g	415 Hz	±20 %
Push/pull force capacity	50 / 20 N	Max.
Drive properties		
Ceramic type	PICMA® P-885	
Electrical capacitance	6 µF	±20 %
Dynamic operating current coefficient	7.5 µA/(Hz • µm)	±20 %
Miscellaneous		
Operating temperature range	20 to 80 °C	
Material	Aluminum	
Dimensions	100 x 100 x 25 mm	
Mass	580 g	±5 %
Cable length	1,5 m	±10 mm
Sensor connection	Sub-D special (CD-version); 2x LEMO (CL-version)	
Voltage connection	Sub-D special (CD-version); 1 x LEMO (CL-version)	

Dynamic Operating Current Coefficient in µA per Hz and mrad. Example: Sinusoidal scan of 10 µm at 10 Hz requires approximately 3 mA drive current.
Recommended controller
One channel: E-610 controller / amplifier (p. 2-110), E-625 bench-top controller (p. 2-114), E-621 modular controller (p. 2-160)
Multi-channel: modular piezo controller system E-500 (p. 2-142) with amplifier module E-503 (three channels) (p. 2-146) or E-505 (1 per axis, high-power) (p. 2-147) and E-509 controller (p. 2-152)
Single-channel digital controller: E-753 (bench-top) (p. 2-108)

Piezo • Nano • Positioning

P-541.Z Piezo Z and Z/Tip/Tilt Stages

Low Profile, Large Aperture



P-541 series nanopositioning Z-stages and Z-tip/tilt stages offer travel ranges of 100 µm with sub-nanometer resolution. They feature a very low profile of 16.5 mm and a large 80 x 80 mm aperture. Versions with strain gauge and capacitive position feedback sensors are available

- **Low Profile for Easy Integration: 16.5 mm; 80 x 80 mm Clear Aperture**
- **Vertical and Z/Tip/Tilt Stages**
- **100 µm Travel Range, 1 mrad Tilt**
- **Parallel-Kinematics / Metrology for Enhanced Responsiveness / Multi-Axis Precision**
- **Choice of Sensors: Strain Gauge (Lower Cost) or Capacitive Sensors (Higher Performance)**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **Combination with Long-Travel M-686 Microscopy Stages**

Low Profile, Optimized for Microscopy Applications

The P-541 Z stages and Z/tip/tilt stages are for ideal alignment, nano-focusing or metrology tasks in the nanometer range. They feature a very low profile of 16.5 mm, a large 80 x 80 mm aperture, and offer highly accurate motion with sub-nanometer resolution.

Application Examples

- Scanning microscopy
- Mask / wafer positioning
- Interferometry
- Metrology
- Biotechnology
- Micromanipulation

A variety of P-541 XY scanning stages with the same footprint are also available (see p. 2-60). Due to the low-profile design, the stages can easily be integrated in high-resolution microscopes.

Choice of Position Sensors

PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz.

Alternatively, economical strain gauge sensors are available. PI uses a bridge configuration to eliminate thermal drift, and assure optimal position stability in the nanometer range.

Active and Passive Guidance for Nanometer Flatness and Straightness

Flexures optimized with Finite Element Analysis (FEA) are completely free of play and friction to allow extremely high-precision motion. The FEA techniques also optimize straightness and flatness and provide for the highest possible stiffness in, and perpendicular to, the direction of motion.

Due to the parallel-kinematics design there is only one common moving platform for all axes, minimizing mass, enabling identical dynamic behaviour and eliminiating cumulative errors. Parallel kinematics also allows for a more compact construction and faster response compared to stacked or nested designs.

Ordering Information

P-541.ZCD
Vertical Nanopositioning Stage with Large Aperture, 100 µm, Direct Metrology, Capacitive Sensors

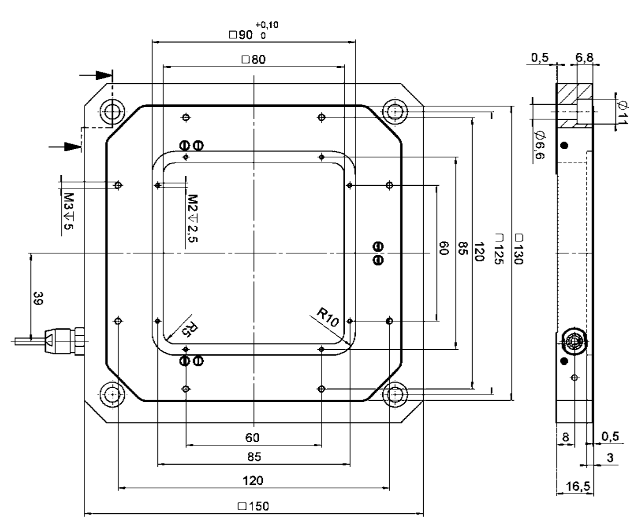
P-541.TCD
Vertical Tip / Tilt Nanopositioning Stage with Large Aperture, 100 µm / 1 mrad, Parallel Metrology, Capacitive Sensors

P-541.ZSL
Vertical Nanopositioning Stage with Large Aperture, 100 µm, Strain Gauge Sensors

P-541.TSL
Vertical Tip / Tilt Nanopositioning Stage with large Aperture, 100 µm, Strain Gauge Sensors

Ceramic Insulated Piezo Actuators Provide Long Lifetime

Highest possible reliability is assured by the use of award-winning PICMA® multilayer piezo actuators. PICMA® actuators are the only actuators on the market with ceramic-only insulation, which makes them resistant to ambient humidity and leakage-current failures. They are thus far superior to conventional actuators in reliability and lifetime.



P-541.Z dimensions in mm

Linear Actuators & Motors
Nanopositioning / Piezoelectrics
Piezo Flexure Stages / High-Speed Scanning Systems
Linear
Vertical & Tip/Tilt
2- and 3-Axis
6-Axis
Fast Steering Mirrors / Active Optics
Piezo Drivers / Servo Controllers
Single-Channel
Multi-Channel
Modular
Accessories
Piezoelectrics in Positioning
Nanometrology
Micropositioning
Index

M-686 open-frame stage with P-541 piezo scanner on top makes an ideal combination for microscopy tasks. The system height is only 48 mm

System properties	
System configuration	P-541.ZCD and E-500 modular system with E-503 amplifier and E-509 sensor module, 20 g load
Amplifier bandwidth, small signal	60 Hz
Settling time (10 % step width)	9 ms

Technical Data

Models	P-541.ZCD	P-541.TCD*	P-541.ZSL	P-541.TSL	P-541.T0L*	P-541.Z0L	Units	Tolerane
Active axes	Z	Z, θ_X, θ_Y	Z	Z, θ_X, θ_Y	Z	Z, θ_X, θ_Y		
Motion and positioning								
Integrated sensor	Capacitive	Capacitive	SGS	SGS	Open-loop	Open-loop		
Open-loop Z-travel, -20 to +120 V	150	150	150	150	150	150	µm	min. (+20 %/0 %)
Open-loop tip/tilt angle, -20 to +120 V	–	±0.6	–	±0.6	–	±0.6	mrad	min. (+20 %/0 %)
Closed-loop Z-travel	100	100	100	100	–	–	µm	
Closed-loop tip/tilt angle	–	±0.4	–	±0.4	–	–	mrad	
Open-loop Z-resolution	0.2	0.2	0.2	0.2	0.2	0.2	nm	typ.
Open-loop tip/tilt angle resolution	–	0.001	–	0.001	–	0.001	µrad	typ.
Closed-loop Z-resolution	0.5	0.5	2.5	2.5	–	–	nm	typ.
Closed-loop tip/tilt resolution	–	0.002	–	0.002	–	–	µrad	typ.
Linearity Z, θ_X, θ_Y	0.03	0.03	0.2	0.2	–	–	%	typ.
Repeatability Z	<2	<2	<10	<10	–	–	nm	typ.
Repeatability θ_X, θ_Y	–	0.01	–	0.05	–	–	µrad	typ.
Runout θ_X, θ_Y	<±5	<±5	<±5	<±5	<±5	<±5	µrad	typ.
Mechanical properties								
Stiffness Z	0.8	0.8	0.8	0.8	0.8	0.8	N/µm	±20 %
Unloaded resonant frequency (Z)	410	410	410	410	410	410	Hz	±20 %
Unloaded resonant frequency (θ_X, θ_Y)	–	330	–	330	–	330	Hz	±20 %
Resonant frequency @ 200 g (Z)	250	250	250	250	250	250	Hz	±20 %
Resonant frequency @ 200 g (θ_X, θ_Y)	–	270	–	270	–	270	Hz	±20 %
Push/pull force capacity	50 / 20	50 / 20	50 / 20	50 / 20	50 / 20	50 / 20	N	Max.
Drive properties								
Ceramic type	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885		
Electrical capacitance	6.3	6.3	6.3	6.3	6.3	6.3	µF	±20 %
Dynamic operating current coefficient	7.9	7.9	7.9	7.9	7.9	7.9	µA / (Hz • µm)	±20 %
Miscellaneous								
Operating temperature range	20 to 80	20 to 80	20 to 80	20 to 80	20 to 80	20 to 80	°C	
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum		
Mass	750	750	730	730	700	700	g	±5 %
Cable length	1.5	1.5	1.5	1.5	1.5	1.5	m	±10 mm
Sensoranschluss	Sub-D Special	Sub-D Special	LEMO	3 x LEMO	–	–		
Voltage connection	Sub-D Special	Sub-D Special	LEMO	3 x LEMO	LEMO	3 x LEMO		

*Parallel kinematics design; the maximum displacement for translation and tilt motion cannot be achieved at the same time

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E-503 (p. 2-146) or E-710 controller (p. 2-128).

Recommended controller / amplifier

Single-channel (1 per axis): E-610 servo controller / amplifier (p. 2-110), E-625 servo controller, bench-top (p. 2-114), E-621 controller module (p. 2-160)

Multi-channel: modular piezo controller system E-500 (p. 2-142) with amplifier module E-503 (three channels) (p. 2-146) or E-505 (1 per axis, high-power) (p. 2-147) and E-509 controller (p. 2-152)

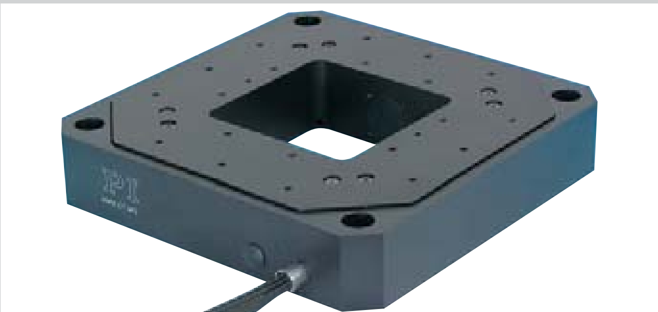
Single-channel digital controller: E-753 (bench-top) (p. 2-108)

Multi-channel digital controllers: E-710 bench-top (p. 2-128), E-712 modular (p. 2-140), E-725 high-power (p. 2-126), E-761 PCI board (p. 2-130)

PI Piezo • Nano • Positioning

P-518, P-528, P-558 Piezo Z/Tip/Tilt Stage

High-Dynamics with Large Clear Aperture



P-528 Z/tip/tilt piezo nanopositioning system

- **1- and 3-Axis Versions**
- **Closed-Loop Vertical / Tilt Range to 200 µm / 2 mrad (Open-Loop to 240 / 2.4)**
- **Parallel Kinematics / Metrology for Enhanced Responsiveness & Multi-Axis Precision**
- **Frictionless, High-Precision Flexure Guiding System**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **Clear Aperture 66 x 66 mm**
- **Capacitive Sensors for Highest Linearity**

P-5x8 series, Z/tip/tilt nanopositioners / scanners are open-frame, high-resolution, piezo-driven stages providing motion to 240 µm and 2.4 mrad with resolutions of up to 0.5 nm and 50 nrad. The 66 x 66 mm clear aperture is ideal for transmitted-light applications.

XY and XYZ multi-axis versions in the same form factor are also offered as P-517, P-527 (see p. 2-70) models with six degrees of freedom are available upon request.

Capacitive Position Sensors for Higher Accuracy

PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz.

Excellent Guiding Accuracy

Flexures optimized with Finite Element Analysis (FEA) are used to guide the stage. FEA techniques are used to give the design the highest possible stiffness in, and perpendicular to, the direction of motion, and to minimize linear and angular runout. Flexures allow extremely high-precision motion, no matter how minute, as they are completely free of play and friction.

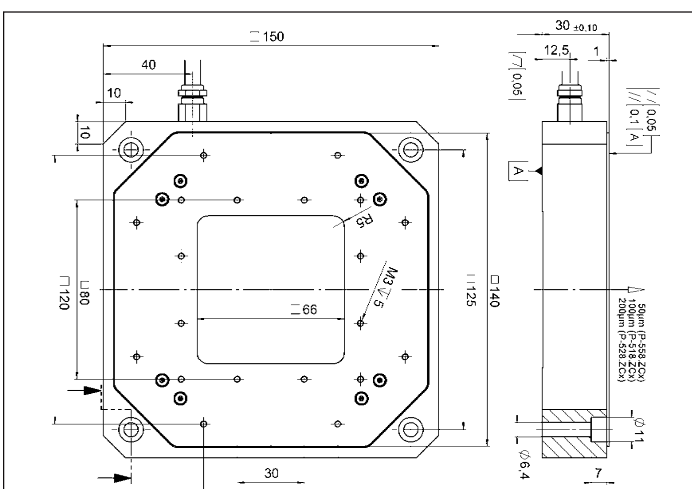
Flatness and Straightness is further enhanced by active trajectory control: Multi-axis nanopositioning systems equipped with both parallel kinematics and parallel direct metrology are able to measure platform position in all degrees of freedom against one common fixed reference. In such systems, undesirable motion from one actuator in the direction of another (cross-talk) is detected immediately and actively compensated by the servo-loops. This Active Trajectory Control Concept can keep deviation from a trajectory to under a few nanometers, even in dynamic operation.

Higher Precision in Periodic Motion

The highest dynamic accuracy in scanning applications is

Application Examples

- Metrology
- Interferometry
- Optics
- Lithography
- Scanning microscopy
- Mass storage device testing
- Laser technology
- Micromachining



P-558, P-518, P-528 dimensions in mm

Ordering Information

P-558.ZCD
Precision Nanopositioning Z-Stage, 50 µm, Direct Metrology, Capacitive Sensors, Sub-D Connector

P-558.ZCL
Precision Nanopositioning Z-Stage, 50 µm, Direct Metrology, Capacitive Sensors, LEMO Connector

P-518.ZCD
Precision Nanopositioning Z-Stage, 100 µm, Direct Metrology, Capacitive Sensors, Sub-D Connector

P-518.ZCL
Precision Nanopositioning Z-Stage, 100 µm, Direct Metrology, Capacitive Sensors, LEMO Connector

P-528.ZCD
Precision Nanopositioning Z-Stage, 200 µm, Direct Metrology, Capacitive Sensors, Sub-D Connector

P-528.ZCL
Precision Nanopositioning Z-Stage, 200 µm, Direct Metrology, Capacitive Sensors, LEMO Connector

P-558.TCD
Precision Nanopositioning Z/Tip/Tilt Stage, 50 µm, 0.6 mrad, Parallel Metrology, Capacitive Sensors, Sub-D Connector

P-518.TCD
Precision Nanopositioning Z/Tip/Tilt Stage, 100 µm, 1.4 mrad, Parallel Metrology, Capacitive Sensors, Sub-D Connector

P-528.TCD
Precision Nanopositioning Z/Tip/Tilt Stage, 200 µm, 2.4 mrad, Parallel Metrology, Capacitive Sensors, Sub-D Connector

made possible by the DDL algorithm, which is available in PI's modern digital controllers. DDL eliminates tracking errors, improving dynamic linearity and usable bandwidth by up to three orders of magnitude!

Ceramic Insulated Piezo Actuators Provide Long Lifetime

Highest possible reliability is assured by the use of award-winning PICMA® multilayer piezo actuators. PICMA® actuators are the only actuators on the market with ceramic-only insulation, which makes them resistant to ambient humidity and leakage-current failures. They are thus far superior to conventional actuators in reliability and lifetime.

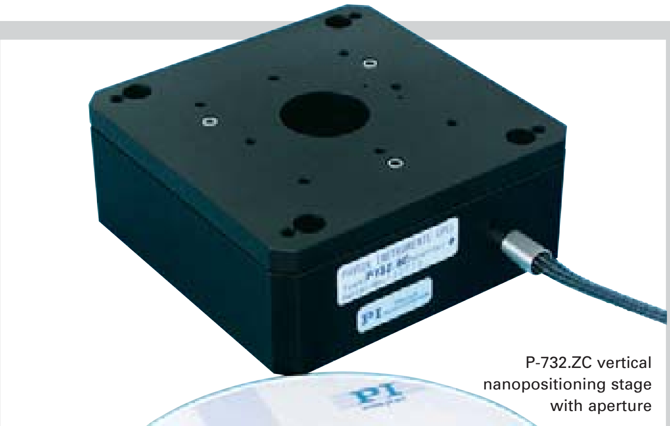
Technical Data

Model	P-558.ZCD/ P-558.ZCL	P-558.TCD	P-518.ZCD/ P-518.ZCL	P-518.TCD	P-528.ZCD/ P-528.ZCL	P-528.TCD	Units	Tolerance
Active axes	Z	Z, θ_x, θ_y	Z	Z, θ_x, θ_y	Z	Z, θ_x, θ_y		
Motion and positioning								
Integrated sensor	Capacitive	Capacitive	Capacitive	Capacitive	Capacitive	Capacitive		
Open-loop travel, -20 to +120 V	60	60	140	140	240	240	µm	min. (+20 %/-0 %)
Open-loop tip/tilt angle, -20 to +120 V	–	±0.3 mrad	–	±0.7 mrad	–	±1.2 mrad	mrad	min. (+20 %/-0 %)
Closed-loop travel	50	50	100	100	200	200	µm	
Closed-loop tip/tilt angle	–	±0.25 mrad	-	±0.5 mrad	–	±1 mrad	mrad	
Open-loop resolution	0.2	0.2	0.2	0.4	0.6	0.6	nm	typ.
Open-loop tip/tilt angle resolution	–	0.02	–	0.04	–	0.06	µrad	typ.
Closed-loop resolution	0.5	0.5	0.8	0.8	1	1	nm	typ.
Closed-loop tip/tilt resolution	–	0.05	–	0.05	–	0.1	µrad	typ.
Linearity θ_x, θ_y	–	0.03	–	0.03	–	0.03	%	typ.
Repeatability	±5	±5	±5	±5	±10	±10	nm	typ.
Repeatability θ_x, θ_y	–	±0.03	–	±0.05	–	±0.1	µrad	typ.
Runout θ_z (Z motion)	<10	<10	<10	<10	<20	<20	µrad	typ.
Runout θ_x, θ_y (Z motion)	<50	<50	<50	<50	<100	<100	µrad	typ.
Mechanical properties								
Stiffness	4	4	2.7	2.7	1.5	1.5	N/µm	±20 %
Unloaded resonant frequency (Z)	570	570	500	500	350	350	Hz	±20 %
Unloaded resonant frequency (θ_x, θ_y)	-	610	-	530	-	390	Hz	±20 %
Resonant frequency @ 30 g in Z	410	410	350	350	210	210	Hz	±20 %
Resonant frequency @ 500 g in X, Y	-	430	-	370	-	250	Hz	±20 %
Resonant frequency @2500 g in Z	245	245	200	200	130	130	Hz	±20 %
Resonant frequency @ 2500 g θ_x, θ_y	-	240	-	190	-	115	Hz	±20 %
Push/pull force capacity	100 / 50	100 / 50	100 / 50	100 / 50	100 / 50	100 / 50	N	Max.
Drive properties								
Ceramic type	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885		
Electrical capacitance	6	6	8.4	8.4	14.8	14.8	µF	±20 %
Dynamic operating current coefficient	15	15	10.5	10.5	9.2	9.2	µA/ (Hz•µm)	±20%
Miscellaneous								
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80	°C	
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum		
Dimensions	150 x 150 x 30	150 x 150 x 30	150 x 150 x 30	150 x 150 x 30	150 x 150 x 30	150 x 150 x 30	mm	
Mass	1380	1380	1400	1400	1420	1420	g	±5 %
Cable length	1.5	1.5	1.5	1.5	1.5	1.5	m	±10 mm
Sensor / voltage connection	CD-version: Sub-D special CL-version: LEMO	Sub-D Special	CD-version: Sub-D special CL-version: LEMO	Sub-D Special	CD-version: Sub-D special CL-version: LEMO	Sub-D Special		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E-503 (p. 2-146) or E-710 controller (p. 2-128)
Recommended controller
CD-Versions:
Single-channel (1 per axis): E-610 servo controller / amplifier (p. 2-110), E-625 servo controller, bench-top (p. 2-114)
Single-channel digital controller: E-753 (bench-top) (p. 2-108)
CL-Versions:
Single-channel: E-500 modular piezo controller system (p. 2-142) with E-505 (p. 2-147) high-power amplifier module and E-509 servo-controller (p. 2-152)
Multi-channel versions:
Multi-channel digital controllers: E-710 bench-top (p. 2-128), E-712 modular (p. 2-140), E-725 high-power (p. 2-126), E-761 PCI board (p. 2-130)

P-732 Piezo Z-Stage with Aperture

High-Dynamics Nanopositioner / Scanner



P-732.ZC vertical nanopositioning stage with aperture

- 15 µm Vertical Travel Range
- High Stiffness for Dynamic Operation
- <1 nm Resolution
- Straightness of Travel <10 µrad
- Clear Aperture with 25 mm Diameter

Model	Travel	Resolution	Linearity	Laod capacity	Rotation around θ_X, θ_Y
P-732.ZC	15 µm	0.1 nm	0.03 %	20 N	<10 µrad

P-915K Vacuum-Compatible Piezo-Z Stage

High-Load, High Dynamics and Large Clear Aperture

The direct-drive P-915KVPZ stage provides high stiffness for fast operation

- Travel Range 45 µm
- Large Clear Aperture 273 x 273 mm
- Direct Metrology with Capacitive Sensors
- Direct Drive for High Dynamics and Stiffness
- Vacuum Compatible up to 10^{-6} hPa
- Outstanding Lifetime Due to PICMA® Piezo Actuators

Model	Travel	Resolution	Push/ Pull force capacity	Material	Dimensions
P-915KVPZ Z Stage	45 µm	0.3 nm	20 N	Stainless stell	Moving platform: 375 x 375 mm Clear aperture: 273 x 273 mm

P-915K Low-Profile Piezo Objective Scanner

For High Scanning Frequencies

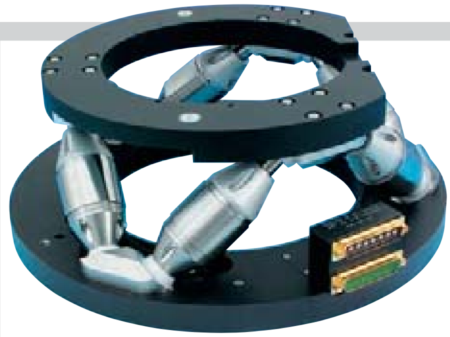
The P-915KLPZ objective scanner allows high scanning frequencies

- Very Low Profile of 15 mm
- Travel Range 75 µm
- Clear Aperture for Objectives with W0.8 x 1/36” Thread
- Frictionless, High-Precision Flexure Guiding System for Better Focus Stability and Minimized Runout
- Very Low Profile
- Outstanding Lifetime Due to PICMA® Piezo Actuators

Model	Active axes	Travel range	Resonant frequency @ 150 g	Dimensions
P-915KLPZ Objective Scanner	Z	75 µm	200 Hz	60 x 60 x 15 mm

N-515K Non-Magnetic Piezo Hexapod

6-Axis Precision Positioning System with NEXLINE® Linear Drives



6-axis parallel kinematics (Hexapod) with integrated N-215 NEXLINE® high-load actuators, suitable for applications in strong magnetic fields

- **Travel Ranges 10 mm Linear, 6° Rotation**
- **Large Clear Aperture Ø 202 mm**
- **Non-Magnetic**
- **Nanometer Resolution**
- **Low-Profile: 140 mm Height Only**
- **Parallel Kinematics for Enhanced Dynamics and Better Multi-Axis Accuracy**
- **Up to 500 N Force Generation**
- **Self Locking at Rest, No Heat Generation**

Model	Travel range	Load capacity	Dimensions
N-515KNPH NEXLINE® Piezo Hexapod	X, Y, Z: 10 mm θ_X, θ_Y, θ_Z: 6°	50 kg	Outer Ø baseplate, 380 mm Ø moved platform (top) 300 mm 140 mm height

N-510 High-Force NEXLINE® Z/Tip/Tilt Platform

Nanometer Precision for Semiconductor Industry, Wafer Alignment

Z, tip, tilt nanopositioning platform with 3 integrated drives (tripod design)

- **Self Locking at Rest, No Heat Generation**
- **Vacuum Compatible and Non-Magnetic Designs Feasible**
- **Parallel Kinematics for Enhanced Dynamics and Better Multi-Axis Accuracy**
- **NEXLINE® Piezo Walking Drive Free from Wear and Tear**
- **Load Capacity 200 N**
- **High Precision with Integrated 5 nm Incremental Sensors + Picometer Resolution Dithering Mode**

Model	Travel	Load capacity	Linear velocity	Dimensions
N-510 NEXLINE® Z, tip, tilt platform	1,3 mm vertical range 10 mrad tilt angle	200 N	0.2 mm/s	Ø 300 mm (12´´) Clear aperture 250 mm

N-510K High-Stiffness NEXLINE® Z Stage

High-Precision Positioning, with Capacitive Sensors

The N-510KHFS hybrid-drive nanopositioner offers maximum accuracy for semiconductor inspection applications

- **Self Locking at Rest, No Heat Generation**
- **Hybrid Drive: PiezoWalk® plus PICMA®**
- **Travel Range: 400 µm Coarse + 40 µm Fine**
- **2 µm Closed-Loop Resolution**
- **Direct Metrology: One Single Control Loop with Capacitive Sensors**
- **High Push and Holding Force to 25 N**
- **Piezo Walking Drive w/o Wear and Tear & Outstanding Lifetime due to PICMA® Piezo Actuators**

Model	Vertical travel	Velocity	Bidirectional repeatability	Load capacity	Dimensions
N-510KHFS Hybrid-Focus System	400 µm coarse 40 µm fine	1 mm/sec	50 nm (full travel)	25 N	Ø 300 mm 68.5 mm height

P-611.XZ · P-611.2 XZ & XY Nanopositioner

Compact 2-Axis Piezo System for Nanopositioning Tasks

P-611 XY- and XZ-nanopositioning systems (from left), 100 µm travel, resolution to 0.2 nm

- **Compact: Footprint 44 x 44 mm**
- **Travel Range to 120 x 120 µm**
- **Resolution to 0.2 nm**
- **Cost-Effective Mechanics/Electronics System Configurations**
- **Frictionless, High-Precision Flexure Guiding System**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **X, Z and XYZ Versions also Available**

P-611 piezo stages are flexure-guided nanopositioning systems featuring a compact footprint of only 44 x 44 mm. The XY- and XZ-versions described here are part of a family of positioners available in 1 to 3 axis configurations. Despite their small dimensions the systems provide up to 120 µm travel with sub-nanometer resolution. They are ideally suited for planar positioning tasks such as optical-path length correction in interferometry, sample positioning in microscopy or scanning applications, for autofocus and photonics applications. Both versions are available with 100 µm travel per axis. Equipped with ceramic-encapsulated piezo drives and a stiff, zero-stiction, zero-friction flexure guiding system, all P-611 piezo stages combine millisecond responsiveness with nanometric precision and extreme reliability.

Application Examples

- Fiber positioning
- Semiconductor testing
- Micromachining
- Micromanipulation
- MEMS fabrication/testing
- Photonics / integrated optics

Closed-Loop and Open-Loop Versions

High-resolution, fast-responding, strain gauge sensors (SGS) are applied to appropriate locations on the drive train and provide a high-bandwidth, nanometer-precision position feedback signal to the controller. The sensors are connected in a full-bridge configuration to eliminate thermal drift, and assure optimal position stability in the nanometer range.

The open-loop models are ideal for applications where fast response and very high resolution are essential, but absolute positioning is not important. They can also be used when the position is controlled by an external linear position sensor such as an interferometer, a PSD (position sensitive diode), CCD chip / image processing system, or the eyes and hands of an operator.

Versatility & Combination with Motorized Stages

The P-611 family of piezo stages comprises a variety of single- and multi-axis versions (X, XY, Z, XZ and XYZ) that can be easily combined with a number of very compact manual or motorized micropositioning systems to form coarse/fine positioners with longer travel ranges (see p. 2-20, p. 2-36 and p. 2-50).

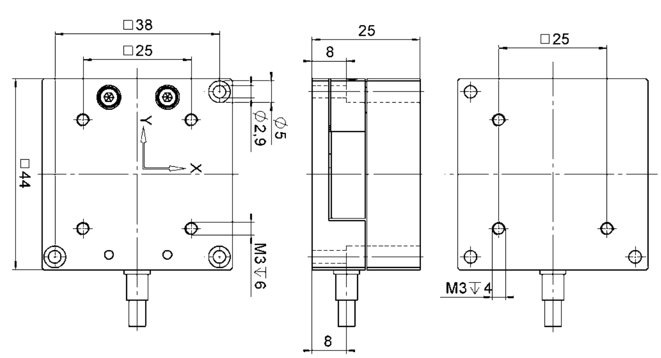
Ordering Information

P-611.2S
XY Nanopositioning System, 100 x 100 µm, SGS-Sensor

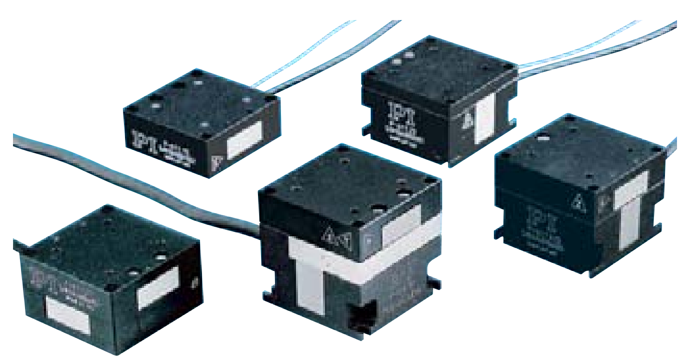
P-611.20
XY Nanopositioning System, 100 x 100 µm, No Sensor

P-611.XZS
XZ Nanopositioning System, 100 x 100 µm, SGS-Sensor

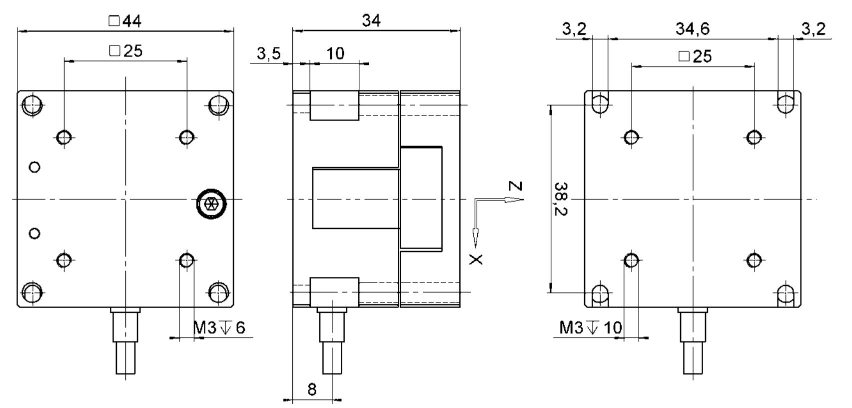
P-611.XZ0
XZ Nanopositioning System, 100 x 100 µm, No Sensor



P-611.2S dimensions in mm



The whole P-611 family: X, Z, XY, XZ and XYZ stages



P-611.XZS dimensions in mm

Technical Data

Models	P-611.2S	P-611.20	P-611.XZS	P-611.XZ0	Units	Tolerance
Active axes	X, Y	X, Y	X, Z	X, Z		
Motion and positioning						
Integrated sensor	SGS	–	SGS	–		
Open-loop travel, -20 to +120 V	120	20	120	120	µm	min. (+20 %/0 %)
Closed-loop travel	100	–	100	–	µm	
Open-loop resolution	0.2	0.2	0.2	0.2	nm	typ.
Closed-loop resolution	2	–	2	–	nm	typ.
Linearity	0.1	–	0.1	–	%	typ.
Repeatability	<10	–	<10	–	nm	typ.
Pitch in X,Y	±5	±5	±5	±5	µrad	typ.
Runout θ_X (Z motion)	–	–	±10	±10	µrad	typ.
Yaw in X	±20	±20	±20	±20	µrad	typ.
Yaw in Y	±10	±10	–	–	µrad	typ.
Runout θ_Y (Z motion)	–	–	±10	+/-10	µrad	typ.
Mechanical properties						
Stiffness	0.2	0.2	0.2 Z: 0.35	0.2 Z: 0.35	N/µm	±20 %
Unloaded resonant frequency	X: 345; Y: 270	X: 345; Y: 270	X: 365; Z: 340	X: 365; Z: 340	Hz	±20 %
Resonant frequency @ 30 g	X: 270; Y: 225	X: 270; Y: 225	X: 280; Z: 295	X: 280; Z: 295	Hz	±20 %
Resonant frequency @ 100 g	X: 180; Y: 165	X: 180; Y: 165	X: 185; Z: 230	X: 185; Z: 230	Hz	±20 %
Push/pull force capacity in motion direction	15 / 10	15 / 10	15 / 10	15 / 10	N	Max.
Load capacity	15	15	15	15	N	Max.
Drive properties						
Ceramic type	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885		
Electrical capacitance	1.5	1.5	1.5	1.5	µF	±20 %
Dynamic operating current coefficient	1.9	1.9	1.9	1.9	µA/(Hz • µm)	±20 %
Miscellaneous						
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	°C	
Material	Aluminum, steel	Aluminum, steel	Aluminum, steel	Aluminum, steel		
Dimensions	44 x 44 x 25	44 x 44 x 25	44 x 44 x 34	44 x 44 x 34	mm	
Mass	0.235	0.235	0.27	0.27	kg	±5 %
Cable length	1.5	1.5	1.5	1.5	m	±10 mm
Sensor connection	LEMO	–	LEMO	–		
Voltage connection	LEMO	LEMO	LEMO	LEMO		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E-503 amplifier (p. 2-146)
Dynamic Operating Current Coefficient in µA per Hz and µm. Example: Sinusoidal scan of 50 µm at 10 Hz requires approximately 0.9 mA drive current.
Recommended controller / amplifier
Single-channel (1 per axis): E-610 servo controller / amplifier (p. 2-110), E -625 servo controller, bench-top (p. 2-114), E-621 controller module (p. 2-160)
Multi-channel: modular piezo controller system E-500 (p. 2-142) with amplifier module E-503 (three channels) (p. 2-146) or E-505 (1 per axis, high-power) (p. 2-147) and E-509 controller (p. 2-152)

P-611.3 NanoCube® XYZ Piezo Stage

Compact Multi-Axis Piezo System for Nanopositioning and Fiber Alignment

NanoCube® XYZ-nanopositioning system, 100 x 100 x 100 µm closed-loop travel range, resolution 1 nm

- **Up to 120 x 120 x 120 µm Travel Range**
- **Very Compact: 44 x 44 x 44 mm**
- **Resolution to 0.2 nm, Rapid Response**
- **Frictionless, High-Precision Flexure Guiding System**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **Fast Multi-Axis Scanning**
- **Version with Integrated Fiber Adapter Interface**
- **Cost-Effective Mechanics/Electronics System Configurations**

The P-611 NanoCube® piezo stage is a versatile, multi-axis piezo-nanopositioning system. Its 100 x 100 x 100 µm positioning and scanning range comes in an extremely compact package of only 44 x 44 x 44 mm. Equipped with a stiff, zero-stiction, zero-friction guiding system, this NanoCube® provides motion with ultra-high resolution and settling times of only a few milliseconds. The minimal moved masses and the stiff piezo drive make it ideal for high-throughput applications such as fiber alignment where it enables significantliy faster device characterization than achievable with conventional motorized drives.

Application Examples

- Photonics / integrated optics
- Micromanipulation
- Biotechnology
- Semiconductor testing
- Fiber positioning

Closed-Loop and Open-Loop Versions

High-resolution, fast-responding, strain gauge sensors (SGS) are applied to appropriate locations on the drive train and provide a high-bandwidth, nanometer-precision position feedback signal to the controller. The sensors are connected in a full-bridge configuration to eliminate thermal drift, and assure optimal position stability in the nanometer range.

The open-loop models are ideal for applications where fast response and very high resolution are essential, but absolute positioning is not important, e.g. in tracking or fiber positioning. They can also be used when the position is controlled by an external linear position sensor such as an interferometer, a PSD (position sensitive diode), CCD chip / image processing system, or the eyes and hands of an operator.

Versatility & Combination with Motorized Stages

The P-611 family of piezo stages comprises a variety of single- and multi-axis versions (X, XY, Z, XZ and XYZ) that can be easily combined with a number of very compact manual or motorized micropositioning systems to form coarse/fine positioners with longer travel ranges (see p. 2-20, p. 2-36 and p. 2-50). For fiber positioning tasks, several fiber, waveguide and optics adapters are available for mounting on the NanoCube® P-611.3SF (e.g. for combination with the F-206.S nanoalignment system see p. 4-12).

High Reliability and Long Lifetime

The compact P-611 systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and thus offer better performance and reliability than conventional piezo actuators. Actuators, guidance and sensors are maintenance-free and not subject to wear, and thus offer an extraordinary reliability.

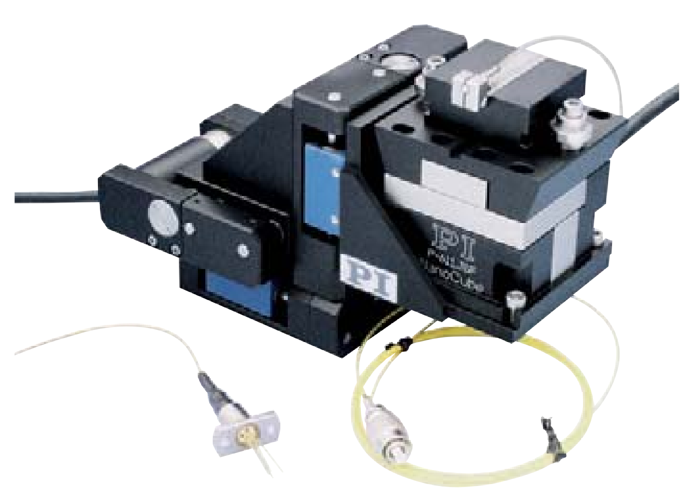
Ordering Information

P-611.3S
NanoCube® XYZ Nanopositioning System, 100 x 100 x 100 µm, Strain Gauge Sensors

P-611.30
NanoCube® XYZ Nanopositioning System, 100 x 100 x 100 µm, Open-Loop

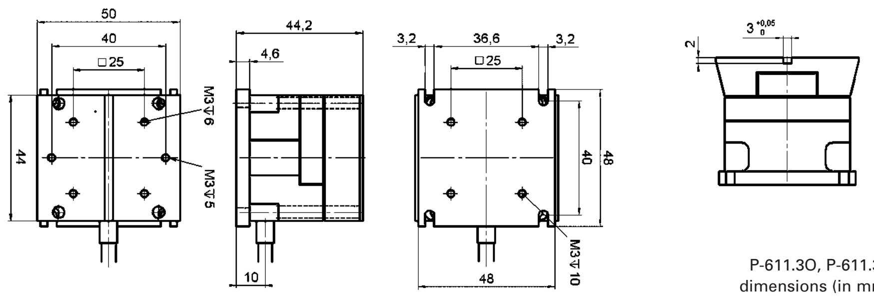
P-611.3SF
NanoCube® XYZ Nanopositioning System, 100 x 100 x 100 µm, Strain Gauge Sensors, Fiber Adapter Interface

P-611.30F
NanoCube® XYZ Nanopositioning System, 100 x 100 x 100 µm, Open-Loop, Fiber Adapter Interface



Combination of P-611.3SF NanoCube® XYZ Nanopositioning System, 100 x 100 x 100 µm and M-111 XYZ MicroPositioner 15 x 15 x 15 mm

Linear Actuators & Motors
Nanopositioning / Piezoelectrics
Piezo Flexure Stages / High-Speed Scanning Systems
Linear
Vertical & Tip/Tilt
2- and 3-Axis
6-Axis
Fast Steering Mirrors / Active Optics
Piezo Drivers / Servo Controllers
Single-Channel
Multi-Channel
Modular
Accessories
Piezoelectrics in Positioning
Nanometrology
Micropositioning
Index



P-611.3O, P-611.3S dimensions (in mm)

Technical Data

Model	P-611.3S P-611.3SF	P-611.3O P-611.3OF	Units	Tolerance
Active axes	X, Y, Z	X, Y, Z		
Motion and positioning				
Integrated sensor	SGS			
Open-loop travel, -20 to +120 V	120 / axis	120 / axis	µm	min. (+20 %/0 %)
Closed-loop travel	100 / axis	–	µm	
Open-loop resolution	0.2	0.2	nm	typ.
Closed-loop resolution	1	–	nm	typ.
Linearity	0.1	–	%	typ.
Repeatability	<10	–	nm	typ.
Pitch in X,Y	±5	±5	µrad	typ.
Runout θ_X (Z motion)	±10	±10	µrad	typ.
Yaw in X	±20	±20	µrad	typ.
Yaw in Y	±10	±10	µrad	typ.
Runout θ_Y (Z motion)	±10	±10	µrad	typ.
Mechanical properties				
Stiffness	0.3	0.3	N/µm	±20 %
Unloaded resonant frequency X / Y / Z	350 / 220 / 250	350 / 220 / 250	Hz	±20 %
Resonant frequency @ 30 g X / Y / Z	270 / 185 / 230	270 / 185 / 230	Hz	±20 %
Resonant frequency @ 100 g X / Y / Z	180 / 135 / 200	180 / 135 / 200	Hz	±20 %
Push/pull force capacity in motion direction	+15 / -10	+15 / -10	N	Max.
Load capacity	15	15	N	Max.
Drive properties				
ceramic type	PICMA® P-885	PICMA® P-885		
Electrical capacitance	1.5	1.5	µF	±20 %
Dynamic operating current coefficient	1.9	1.9	µA/(Hz • µm)	±20 %
Miscellaneous				
Operating temperature range	-20 to 80	-20 to 80	°C	
Material	Aluminum, steel	Aluminum, steel		
Dimensions	44 x 44 x 43.2 SF-version: 44 x 50 x 44.2	44 x 44 x 43.2 OF-version: 44 x 50 x 44.2	mm	
Mass	0.32	0.32	kg	±5 %
Cable length	1.5	1.5	m	±10 mm
Sensor connector	Sub-D	–		
Voltage connection	Sub-D	Sub-D		
Recommended controller / amplifier	E-664 Nanocube® Controller (p. 2-137)	3 x E-610.00F OEM amplifier modules (p. 2-110); E-663 3-channel amplifier, bench-top (p. 2-136)		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E-503 amplifier (p. 2-146)
Dynamic Operating Current Coefficient in µA per Hz and µm. Example: Sinusoidal scan of 50 µm at 10 Hz requires approximately 0.8 mA drive current.
Adapter cable with LEMO connectors for sensor and operating voltage available.

P-620.2 - P-629.2 PIHera® XY Piezo Stage

High-Precision Nanopositioner Family–Compact and Long Travel Ranges

PIHera® XY-Nanopositioniersysteme mit Stellwegen von 50 x 50 µm bis 1800 x 1800 µm

- **Travel Ranges 50 to 1800 µm**
- **High-Precision, Cost-Efficient**
- **Resolution to 0.1 nm**
- **Frictionless, High-Precision Flexure Guiding System**
- **0,02 % Positioning Accuracy**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **X-, XY-, Z- and XYZ-Versions**
- **Vacuum-Compatible Versions Available**

Two-axis (XY) PIHera® systems are piezo-nanopositioning stages featuring travel ranges from 50 to 1800 µm. Despite the increased travel ranges, the units are extremely compact and provide rapid response and high guiding precision. This, and the long travel range is achieved with a friction-free and extremely stiff flexure system sub-nanometer resolution. The PIHera® piezo nanopositioning series also includes Z and X stages (see p. 2-22 and p. 2-40).

Application Examples

- Interferometry
- Microscopy
- Nanopositioning
- Biotechnology
- Quality assurance testing
- Semiconductor technology

Nanometer Precision in Milliseconds

One of the advantages of PIHera® stages over motor-driven positioning stages is the rapid response to input changes and the fast and precise settling behavior. The P-622.1CD, for example, can settle to an accuracy of 10 nm in only 30 msec (other PI stages provide even faster response)!

Superior Accuracy With Direct-Metrology Capacitive Sensors

A choice of tasks such as optical path adjustment in interferometry, sample positioning in microscopy, precision alignment or optical tracking require the relatively long scanning ranges and nanometer precision offered by PIHera® nanopositioning stages.

PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz.

Designed for Precision

High stiffness is achieved with the FEA-optimized design of the frictionless flexure elements, which assure excellent guiding accuracy and dynamics. A straightness and flatness in the nanometer range is achieved.

Ordering Information

P-620.2CD* / P-620.2CL*
PIHera® Precision XY Nanopositioning System, 50 x 50 µm, Direct Metrology, Capacitive Sensors

P-621.2CD* / P-621.2CL*
PIHera® Precision XY Nanopositioning System, 100 x 100 µm, Direct Metrology, Capacitive Sensors

P-622.2CD* / P-622.2CL*
PIHera® Precision XY Nanopositioning System, 250 x 250 µm, Direct Metrology, Capacitive Sensors

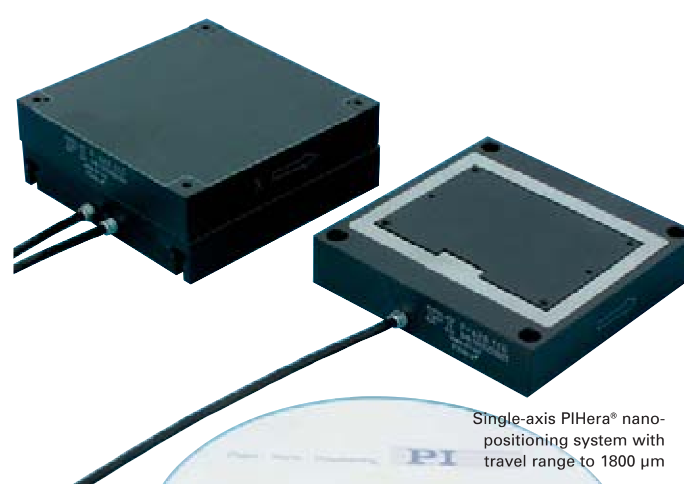
P-625.2CD* / P-625.2CL*
PIHera® Precision XY Nanopositioning System, 500 x 500 µm, Direct Metrology, Capacitive Sensors

P-628.2CD* / P-628.2CL*
PIHera® Precision XY Nanopositioning System, 800 x 800 µm, Direct Metrology, Capacitive Sensors

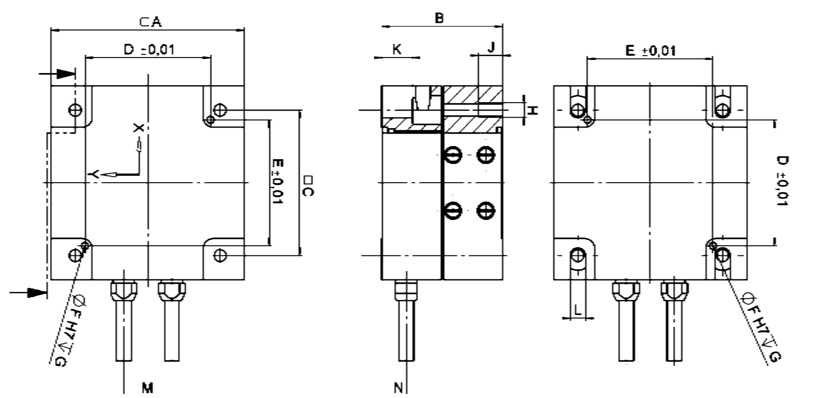
P-629.2CD* / P-629.2CL*
PIHera® Precision XY Nanopositioning System, 1500 x 1500 µm, Direct Metrology, Capacitive Sensors

*.2CD with Sub-D Connector
*.2CL with LEMO Connector

Open-loop versions are available as P-62x.20L.
Vacuum versions to 10^{-9} hPa are available as P-62x.2UD.



Single-axis PIHera® nanopositioning system with travel range to 1800 µm



	A	B	C	D	E	ØF	G
P-620.2CD / .20L	30	21,5	24	24	19	1,01	1,5
P-621.2CD / .20L	40	25	30	26	26	1,51	2,5
P-622.2CD / .20L	50	25	40	35	35	1,51	2,5
P-625.2CD / .20L	60	25	50	46	46	1,51	2,5
P-628.2CD / .20L	80	30	70	66	66	1,51	2,5

	H	J	K	L	M	N
P-620.2CD / .20L	M2	3,5	5,1	2,2	9	6
P-621.2CD / .20L	M3	5	6,25	3,2	10	5
P-622.2CD / .20L	M3	5	6,25	3,2	11	5
P-625.2CD / .20L	M3	6	6,25	3,2	11	5
P-628.2CD / .20L	M3	6	6,75	3,2	11	5

P-62x.2CD/.2CL/.20L Abmessungen in mm

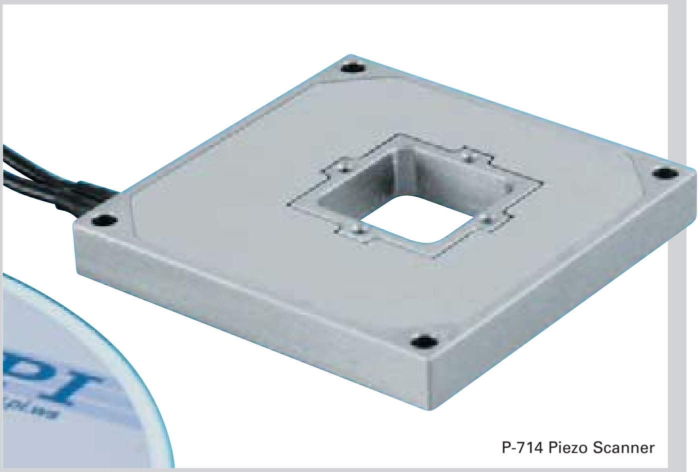
Technical Data

Model	P-620.2CD/ P-620.2CL	P-621.2CD/ P-621.2CL	P-622.2CD/ P-622.2CL	P-625.2CD/ P-625.2CL	P-628.2CD/ P-628.2CL	P-629.2CD P-629.2CL	P-62x.20L open-loop versions	Units	Tolerance
Active axes	X, Y	X, Y	X, Y	X, Y	X, Y	X, Y	X, Y		
Motion and positioning									
Integrated sensor	Capacitive	Capacitive	Capacitive	Capacitive	Capacitive	Capacitive	–		
Open-loop travel X, Y, -20 to +120 V	60	120	300	600	950	1800	as P-62x.2CD	µm	min. (+20 %/-0 %)
Closed-loop travel	50	100	250	500	800	1500	–	µm	
Open-loop resolution	0.1	0.2	0.4	0.5	0.5	2	as P-62x.2CD	nm	typ.
Closed-loop resolution	0.2	0.4	0.7	1.4	3.5	3.5	–	nm	typ.
Linearity	0.02	0.02	0.02	0.03	0.03	0.03	–	%	typ.
Repeatability	±2	±2	±2	±5	±10	±14	as P-62x.2CD	nm	typ.
Pitch / yaw	±3	±3	±3	±3	±20	±30	as P-62x.2CD	µrad	typ.
Mechanical properties									
Stiffness	0.22	0.25	0.2	0.1	0.05	0.1	as P-62x.2CD	N/µm	±20 %
Unloaded resonant frequency in X,	575	420	225	135	75	60	as P-62x.2CD	Hz	±20 %
Unloaded resonant frequency in Y	800	535	300	195	105	100	as P-62x.2CD	Hz	±20 %
Resonant frequency in X @ 50 g	270	285	180	120	60	55	as P-62x.2CD	Hz	±20 %
Resonant frequency in Y @ 50 g	395	365	215	150	85	85	as P-62x.2CD	Hz	±20 %
Resonant frequency in X @ 100 g	285	220	160	105	55	50	as P-62x.2CD	Hz	±20 %
Resonant frequency in Y @ 100 g	300	285	175	125	75	80	as P-62x.2CD	Hz	±20 %
Push/pull force capacity in motion direction	10 / 5	10 / 8	10 / 8	10 / 8	10 / 8	10 / 8	as P-62x.2CD	N	Max.
Load capacity	10	10	10	10	10	10	as P-62x.2CD	N	Max.
Lateral Force	10	10	10	10	10	10	as P-62x.2CD	N	Max.
Drive properties									
Ceramic type	PICMA® P-883	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-887	PICMA® P-888	as P-62x.2CD		
Electrical Capacitance	0.35	1.5	3.1	6.2	19	52	as P-62x.2CD	µF	±20 %
Dynamic operating current coefficient	0.9	1.9	1.9	1.6	3	4.3	as P-62x.2CD	µA/(Hz•µm)	±20 %
Miscellaneous									
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 150	°C	
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum		
Mass	0.195	0.295	0.348	0.43	0.7	1.37	as P-62x.2CD	kg	±5 %
Cable length	1.5	1.5	1.5	1.5	1.5	1.5	1.5	m	±10 mm
Sensor / voltage connection	CD version: 2x Sub-D special CL version: LEMO	CD version: 2x Sub-D special CL version: LEMO	CD version: 2x Sub-D special CL version: LEMO	CD version: 2x Sub-D special CL version: LEMO	CD version: 2x Sub-D special CL version: LEMO	CD version: 2x Sub-D special CL version: LEMO	2x LEMO (no sensor)		

Lower axis: X; upper axis: Y.
Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. The value given is noise equivalent motion with E-710 controller (p. 2-128)
Recommended controller
CD version: E-610 servo controller / amplifier (p. 2-110), E-625 servo controller, bench-top (p. 2-114), E-665 powerful servo controller, bench-top (p. 2-116)
Multi-channel digital controllers: E-710 bench-top (p. 2-128), E-712 modular (p. 2-140), E-725 high-power (p. 2-126), E-761 PCI board (p. 2-140)
CL version: E-500 modular piezo controller system (p. 2-142) with E-505 amplifier module (1 per axis, high power) (p. 2-147) and E-509 controller (p. 2-152)
Open-loop versions: E-500 modular piezo controller system (p. 2-142) with E-505 amplifier module (1 per axis, high power) (p. 2-147)

P-713 · P-714 XY Piezo Scanner

Cost-Effective OEM System with Low Profile



P-714 Piezo Scanner

- Ideal for Pixel Sub-Stepping in Image Enhancement
- Small Footprint and Low Profile: 45 x 45 x 6 mm with Clear Aperture
- Very Cost-Effective Design
- Travel Ranges to 20 x 20 µm
- Parallel Kinematics for Better Multi-Axis Accuracy and Dynamics

P-713 / P-714 family piezo scanners and positioners with travel ranges of 15 x 15 µm feature especially compact designs. Ideal applications for the P-713 and P-714 are high-dynamics scanning or tracking tasks such as sub-stepping methods for enhancing image resolution. Such tasks involve moving to specific positions in a small area (e. g. marked cells or CCD photosites) and from there following or performing motion with an amplitude of a few microns. The resonant frequency of up to over 2 kHz makes for settling times of a few milliseconds, even after a full-range move, all with closed-loop repeatability of under 5 nm.

A single-axis version with similar footprint is available as P-712 (see p. 2-14) and XY versions with longer travel ranges are available on request.

Application Examples

- Pixel dithering / sub-stepping image resolution enhancement
- Quality assurance testing
- Optical Metrology
- Microscopy
- Imaging
- CCD / CMOS camera technology

Flexibility

P-713 and P-714 nanopositioners are offered in different versions for different applications. The lowest-cost, basic version of the P-713 offers guiding accuracy in the motion plane of 50 µrad, a value generally good enough for dithering and interlacing tasks in scanning patterns of a few microns. For more demanding applications, the P-714 offers greater accuracy, typically 5 µrad or <10 nm absolute.

Nanometer Position Servo-Control

If servo-control is required and no external position sensor is available, the P-714.2SL version, equipped with high-resolution strain gauge sensors (SGS) can provide nanometer-range resolution.

High-resolution, broadband, strain gauge sensors (SGS) are applied to appropriate locations on the drive train and measure the displacement of the moving part of the stage relative to the base indirectly. The SGS sensors assure optimum position stability in the nanometer range and fast response.

Ceramic Insulated Piezo Actuators Provide Long Lifetime

Highest possible reliability is assured by the use of award-winning PICMA® multilayer piezo actuators. PICMA® actuators are the only actuators on the market with ceramic-only insulation, which makes them resistant to ambient humidity and leakage-current failures. They are thus far superior to conventional actuators in reliability and lifetime.

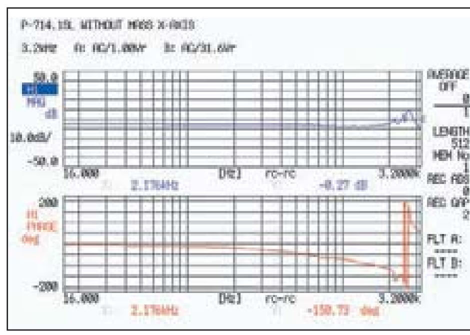
Ordering Information

P-713.20L
Low-Profile OEM XY Nanoscanner, 15 x 15 µm, No Sensor, LEMO Connector

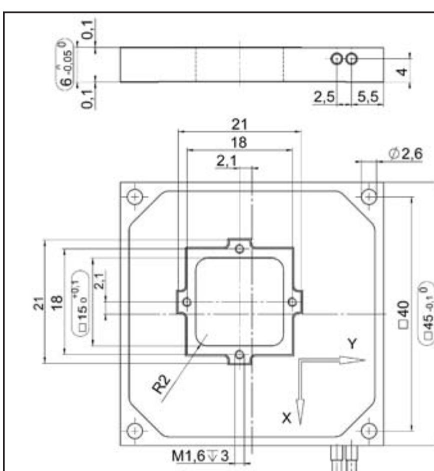
P-714.20L
Low-Profile OEM XY Nanoscanner, 15 x 15 µm, Improved Guiding Accuracy, No Sensor, LEMO Connector

P-713.2SL
Low-Profile OEM XY Nanoscanner, 15 x 15 µm, SGS-Sensor, LEMO Connector

P-714.2SL
Low-Profile OEM XY Nanoscanner, 15 x 15 µm, Improved Guiding Accuracy, SGS-Sensor, LEMO Connector



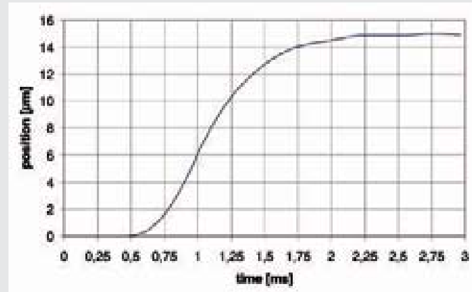
The resonant frequency of an unloaded P-713 / P-714 scanner is over 2 kHz



P-713/P-714 dimensions in mm

See the "Selection Guide" for comparison with other nanopositioning systems (see p. 2-4 *ff*).

System properties	
System controller	P-714.2SL with modular system E-500 (E-503 amplifier and E-509 sensor module); 20 g load
Bandwidth, small signal	300 Hz
Bandwidth, large signal	220 Hz
Settling time (10 % step width)	3.1 ms
Settling time (full travel)	4.5 ms



Settling time for the P-713/P-714 at 15 µm is in the 2 ms range

Technical Data

Model	P-713.20L	P-713.2SL	P-714.20L	P-714.2SL	Units	Tolerance
Active axes	X, Y	X, Y	X, Y	X, Y		
Motion and positioning						
Integrated sensor	-	SGS	-	SGS		
Open-loop travel, -20 to +120 V	20	20	20	20	µm	min. (+20 %/0 %)
Closed-loop travel	-	15	-	15	µm	
Open-loop resolution	0.1	0.1	0.1	0.1	nm	typ.
Closed-loop resolution	-	1	-	1	nm	typ.
Linearity	-	0.3	-	0.3	%	typ.
Repeatability	-	<4	-	<4	nm	typ.
Pitch	typ. ±1 max. ±5	typ. ±1 max. ±5	typ. ±1 max. ±5	typ. ±1 max. ±5	µrad	typ.
Yaw	typ. ±40 max. ±50	typ. ±40 max. ±50	typ. ±40 max. ±50	typ. ±40 max. ±50	µrad	µrad
Mechanical properties						
Stiffness	0.8	0.8	0.8	0.8	N/µm	±20 %
Unloaded resonant frequency	2250	2250	2250	2250	Hz	±20 %
Resonant frequency under load	1310 (20 g) 1020 (50 g) 460 (100 g)	1310 (20 g) 1020 (50 g) 460 (100 g)	1310 (20 g) 1020 (50 g) 460 (100 g)	1310 (20 g) 1020 (50 g) 460 (100 g)	Hz	±20 %
Push/pull force capacity in motion direction	5 / 5	5 / 5	5 / 5	5 / 5	N	Max.
Load capacity	2	2	2	2	N	Max.
Drive properties						
Ceramic type	PICMA® P-882	PICMA® P-882	PICMA® P-882	PICMA® P-882		
Electrical capacitance in X , Y	0.31	0.31	0.31	0.31	µF	±20 %
Dynamic operating current coefficient (DOCC) in X, Y	2.5	2.5	2.5	2.5	µA/(Hz • µm)	±20 %
Miscellaneous						
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	°C	
Material	Stainless steel, ferromagnetic	Stainless steel, ferromagnetic	Stainless steel, ferromagnetic	Stainless steel, ferromagnetic		
Dimensions	45 x 45 x 6	45 x 45 x 6	45 x 45 x 6	45 x 45 x 6		
Mass	0.1	0.1	0.1	0.1	kg	±5 %
Cable length	1.5	1.5	1.5	1.5	m	±10 mm
Sensor connection	-	LEMO	-	LEMO		
Voltage connection	LEMO	LEMO	LEMO	LEMO		

Resolution of PI piezo nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E-503 amplifier (p. 2-146)

Dynamic Operating Current Coefficient in µA per Hz and µm. Example: Sinusoidal scan of 10 µm at 100 Hz requires approximately 2.5 mA drive current.

Recommended controller / amplifier

Single-channel (1 per axis): E-610 servo controller / amplifier (p. 2-110), E-625 servo controller, bench-top (p. 2-114), E-621 controller module (p. 2-160)

Multi-channel: modular piezo controller system E-500 (p. 2-142) with amplifier module E-503 (three channels) (p. 2-146) or E-505 (1 per axis, high-power) (p. 2-147) and E-509 controller (p. 2-152)

P-612 XY Piezo Nanopositioning System

Compact, Clear Aperture

P-612.2SL XY piezo stage (CD for size comparison)

- Compact: Footprint 60 x 60 mm
- 100 x 100 µm Closed-Loop Travel Range (130 x 130 Open-Loop)
- For Cost-Sensitive Applications
- Clear Aperture 20 x 20 mm
- Parallel-Kinematics for Enhanced Responsiveness / Multi-Axis Precision
- Outstanding Lifetime Due to PICMA® Piezo Actuators
- Z-Stage Also Available

The P-612.2SL is a piezo-based nanopositioning system featuring a compact footprint of only 60 x 60 mm and a height of 18 mm. Due to the 20 x 20 mm open aperture, the system is excellently suited for sample positioning in microscopy or scanning applications. Equipped with piezo drives and zero-stiction, zero-friction flexure guiding system, the series provides nanometer-range resolution and millisecond response time. A Z stage with the same form factor is available for vertical positioning applications (see P-612.ZSL p. 2-36).

Cost-Effective Design

Flexures optimized with Finite Element Analysis (FEA) are used to guide the compact, low-cost stage. Flexures allow extremely high-precision motion, no matter how minute, as they are completely free of play and friction. They also optimize stiffness in and perpendicular to the direction of motion.

Position Servo-Control with Nanometer Resolution

High-resolution, broadband, strain gauge sensors (SGS) are applied to appropriate locations on the drive train and measure the displacement of the moving part of the stage relative to the base directly. The SGS sensors assure optimum position stability in the nanometer range and fast response.

The open-loop models are ideal for applications where fast response and very high resolution are essential, but absolute positioning is not important. They can also be used in applications where the position is controlled by an external linear position sensor such as an interferometer, a PSD (position sensitive diode), CCD chip / image processing system, or the eyes and hands of an operator.

Ceramic Insulated Piezo Actuators Provide Long Lifetime

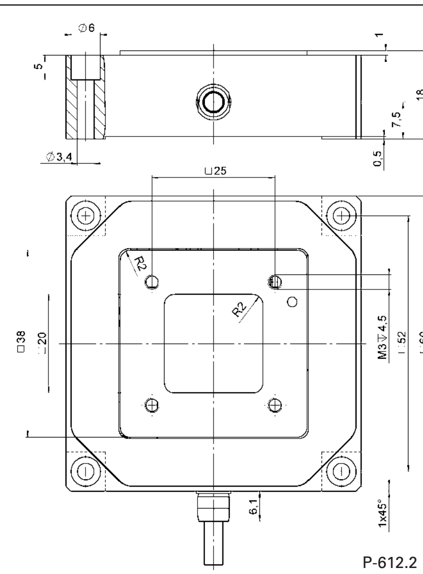
Highest possible reliability is assured by the use of award-winning PICMA® multilayer piezo actuators. PICMA® actuators are the only actuators on the market with ceramic-only insulation, which makes them resistant to ambient humidity and leakage-current failures. They are thus far superior to conventional actuators in reliability and lifetime.

Ordering Information

P-612.2SL
XY Nanopositioning System with 20 x 20 mm Aperture, 100 x 100 µm, Strain Gauge Sensors

P-612.20L
XY Nanopositioning System with Aperture 20 x 20 mm, 100 x 100 µm, Open-Loop

System properties	
System configuration	P-612.2 SL and E-500 modular system with E-503 amplifier and E-509 sensor module, 100 load
Amplifier bandwidth, small signal	45 Hz
Settling time (10 % step width)	15 ms



P-612.2 dimensions in mm

P-612 are available as XY-scanners (P-612.2SL, on the left) and vertical stages (P-612.ZSL, on the right) providing a travel range of 100 µm per axis

Technical Data

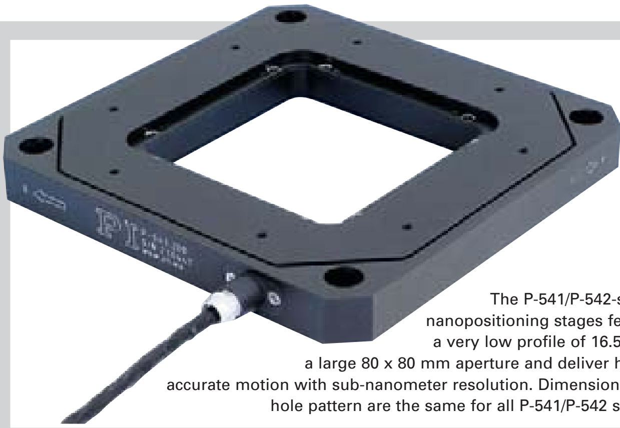
Model	P-612.2SL	P-612.20L	Units	Tolerance
Active axes	X, Y	X, Y		
Motion and positioning				
Integrated sensor	SGS	–		
Open-loop travel, -20 to +120 V	130	130	µm	min. (+20 %/-0 %)
Closed-loop travel	100	–		µm
Open-loop resolution	0.8	0.8	nm	typ.
Closed-loop resolution	5	–	nm	typ.
Linearity	0.4	–	%	typ.
Repeatability	<10	–	nm	typ.
Pitch	±10	±10	µrad	typ.
Yaw in X/ Y	±10 / ±50	±10 / ±50	µrad	typ.
Mechanical properties				
Stiffness	0.15	0.15	N/µm	±20 %
Unloaded resonant frequency	400	400	Hz	±20 %
Resonant frequency @ 100 g	200	200	Hz	±20 %
Push/pull force capacity in motion direction	15 / 5	15 / 5	N	Max.
Load capacity	15	15	N	Max.
Drive properties				
Ceramic type	PICMA® P-885	PICMA® P-885		
Electrical capacitance	1.5	1.5	µF	±20 %
Dynamic operating current coefficient	1.9	1.9	µA/(Hz • µm)	±20 %
Miscellaneous				
Operating temperature range	-20 to 80	-20 to 80	°C	
Material	Aluminum, steel	Aluminum, steel		
Mass	105	105	g	±5 %
Cable length	1.5	1.5	m	±10 mm
Sensor connector	LEMO connector	–		
Voltage connection	LEMO connector	LEMO connector		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Noise equivalent motion with E-503 amplifier (p. 2-146)
Recommended controller
Single-channel (1 per axis): E-610 servo-controller / amplifier (p. 2-110) , E-625 servo-controller, bench-top (p. 2-114), E-621 controller module (p. 2-160)
Multi-channel: modular piezo controller system E-500 (p. 2-142) with amplifier module E-503 (three channels) (p. 2-146) or E-505 (1 per axis, high-power) (p. 2-147) and E-509 controller (p. 2-152)

Piezo • Nano • Positioning

P-541.2 – P-542.2 Piezo XY-Stage

Low-Profile XY Nanopositioning System with Large Aperture



The P-541/P-542-series nanopositioning stages feature a very low profile of 16.5 mm, a large 80 x 80 mm aperture and deliver highly accurate motion with sub-nanometer resolution. Dimensions and hole pattern are the same for all P-541/P-542 stages

- **Low Profile for Easy Integration: 16.5 mm; 80 x 80 mm Clear Aperture**
- **Up to 200 x 200 µm Travel Range**
- **Parallel-Kinematics / Metrology for Enhanced Responsiveness & Multi-Axis Precision**
- **High-Dynamics Direct-Drive Version**
- **Choice of Sensors: Strain Gauge (Lower Cost) or Capacitive Sensors (Higher Performance)**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **Combination with Long Travel Microscopy Stages or Longer Stroke**

Low Profile, Optimized for Microscopy Applications

P-541/P-542 nanopositioning and scanning stages are designed for easy integration into high-resolution microscopes. They feature a very low profile of 16.5 mm, a large 80 x 80 mm aperture, and offer highly accurate motion with sub-nanometer resolution. A variety of Z stages and Z-tip/tilt stages with the same footprint are also offered to suit a wide range of applications (p. 2-44). They are ideal for alignment, nano-focusing or metrology tasks.

Application Examples

- Laser technology
- Scanning microscopy
- Mask / wafer positioning
- Interferometry
- Metrology
- Biotechnology
- Micromanipulation

Choice of Drives: Long Range or High-Speed Direct Drive

Lever-amplified XY systems with 100 and 200 µm travel and direct-driven XY scanners with 45 µm travel are available. Their high resonant frequencies of 1.5 kHz in both axes allow for faster step response and higher scanning rates, needed for example in single-molecule microscopy, or in other time-critical applications.

Parallel Kinematics for Fast Response

In a parallel kinematics multi-axis system, all actuators act di - rectly on one moving platform. This means that all axes move the same minimized mass and can be designed with identical dynamic properties. Systems with parallel kinematics and metrology have additional advantages over serially stacked or nested systems, including more-compact construction and no cumulative error from the different axes.

Parallel kinematics systems can be operated with up to six degrees of freedom with low inertia and excellent dynamic performance. Multi-axis nanopositioning systems equipped with both parallel kinematics and parallel, direct metrology are able to measure platform position in all degrees of freedom against one common fixed reference. In such systems, undesirable motion from one actuator in the direction of another (cross talk) is detected immediately and actively compensated by the servo-loops.

Tailored Position Measurement

Integrated high-resolution position sensors provide fast response and positional stability in the nanometer range. Top-of-the-line models use capacitive sensors. They measure displacement directly and without physical contact (direct metrology) enabling superior linearity. Alternatively, versions with cost-effective strain gauge sensors (SGS) are also available.

Ordering Information

P-541.2DD
XY Nanopositioning System with large Aperture, High-Speed Direct Drive, 45 x 45 µm, Parallel Kinematics, Capacitive Sensors

P-541.2CD
XY Nanopositioning System with large Aperture, 100 x 100 µm, Parallel Kinematics, Capacitive Sensors

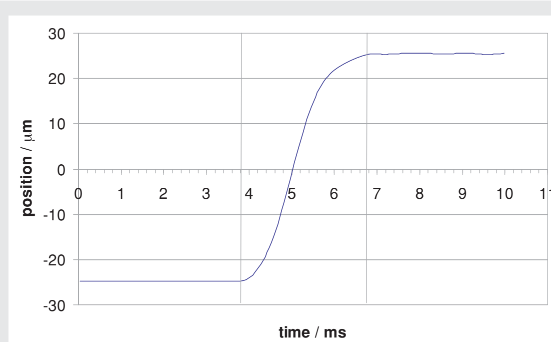
P-542.2CD
XY Nanopositioning System with large Aperture, 200 x 200 µm, Parallel Kinematics, Capacitive Sensors

P-541.2SL
XY Nanopositioning System with large Aperture, 100 x 100 µm, Strain Gauge Sensors

P-542.2SL
XY Nanopositioning System with large Aperture, 200 x 200 µm, Strain Gauge Sensors

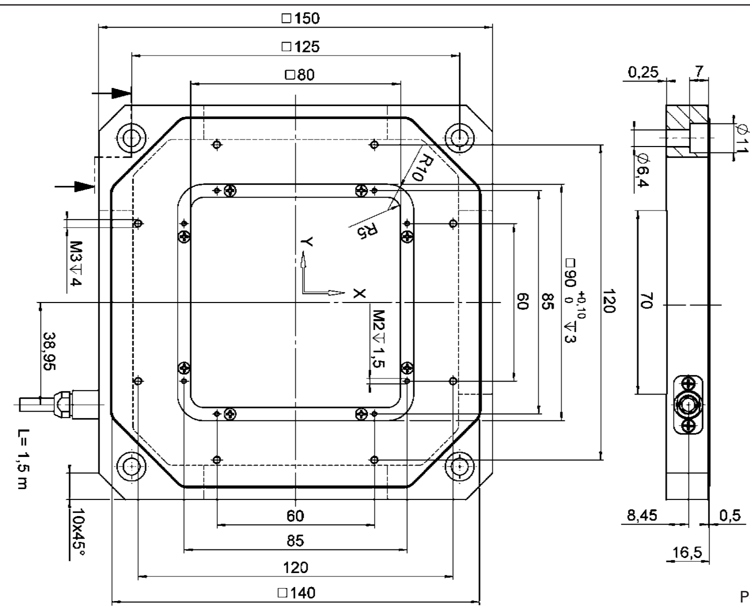
P-541.20L
XY Nanopositioning System with large Aperture, 100 x 100 µm, Open Loop

P-542.20L
XY Nanopositioning System with large Aperture, 200 x 200 µm, Open Loop



The settling time of a P-541.2DD stage is only 3 ms for a 50 µm step

System properties	
System configuration	P-541.2CD and E-500 modular system with E-503 amplifier and E-509 sensor module, 200 g load
Amplifier bandwidth, large signal	35 Hz
Settling time (full travel)	28 ms



P-541.2 and P-542.2, dimensions in mm

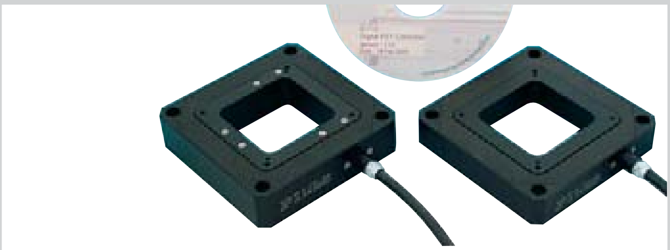
Technical Data

Model	P-541.2CD	P-542.2CD	P-541.2DD	P-541.2SL	P-542.2SL	P-541.20L	P-542.20L	Units	Tolerance
Active axes	X, Y	X, Y	X, Y	X, Y	X, Y	X, Y	X, Y		
Motion and positioning									
Integrated sensor	Capacitive	Capacitive	Capacitive	SGS	SGS	–	–		
Open-loop travel, -20 to +120 V	175 x 175	290 x 290	60 x 60	175 x 175	290 x 290	175 x 175	290 x 290	µm	min. (+20 %/0 %)
Closed-loop travel	100 x 100	200 x 200	45 x 45	100 x 100	200 x 200	–	–	µm	
Closed-loop / open-loop resolution	0.2 / 0.3	0.4 / 0.7	0.1 / 0.3	0.2 / 2.5	0.4 / 4	0.2 / –	0.4 / –	nm	typ.
Linearity	0.03	0.03	0.03*	0.2	0.2	–	–	%	typ.
Repeatability	<5	<5	<5	<10	<10	–	–	nm	typ.
Pitch	<±5	<±5	<±3	<±5	<±5	<±5	<±5	µrad	typ.
Yaw	<±10	<±10	<±3	<±10	<±10	<±10	<±10	µrad	typ.
Mechanical properties									
Stiffness in motion direction	0.47	0.4	10	0.47	0.4	0.47	0.4	N/µm	±20 %
Unloaded resonant frequency	255	230	1550	255	230	255	230	Hz	±20 %
Resonant frequency @ 100 g	200	190	–	200	190	200	190	Hz	±20 %
Resonant frequency @ 200 g	180	–	1230	180	–	180	–	Hz	±20 %
Resonant frequency @ 300 g	150	145	–	150	145	150	145	Hz	±20 %
Push/pull force capacity in motion direction	100 / 30	100 / 30	100 / 30	100 / 30	100 / 30	100 / 30	100 / 30	N	Max.
Load capacity	20	20	20	20	20	20	20	N	Max.
Drive properties									
Ceramic type	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885		
Electrical capacitance per axis	4.2	7.5	9	4.2	7.5	4.2	7.5	µF	±20 %
Dynamic operating current coefficient per axis	5.2	4.8	25	5.2	4.8	5.2	4.8	µA/(Hz • µm)	±20 %
Miscellaneous									
Operating temperature range	20 to 80	20 to 80	20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80	°C	
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum		
Mass	1100	1150	1210	1050	1100	1050	1100	kg	±5 %
Cable length	1.5	1.5	1.5	1.5	1.5	1.5	1.5	m	±10 mm
Sensor connection	Sub-D Special	Sub-D Special	Sub-D Special	LEMO	LEMO	–	–		
Voltage connection	Sub-D Special	Sub-D Special	Sub-D Special	LEMO	LEMO	LEMO	LEMO		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E-503 (p. 2-146) or E-710 controller (p. 2-128).
Dynamic Operating Current Coefficient in µA per Hz and µm. Example: Sinusoidal scan of 10 µm at 10 Hz requires approximately 0.48 mA drive current for the P-542.2CD.
*With digital controller. Non-linearity of direct drive stages measured with analog controllers is up to 0.1 % typ.
Recommended controller / amplifier
Single-channel (1 per axis): E-610 servo controller / amplifier (p. 2-110), E-625 servo controller, bench-top (p. 2-114), E-621 controller module (p. 2-160)
Multi-channel: modular piezo controller system E-500 (p. 2-142) with amplifier module E-503 (three channels) (p. 2-146) or E-505 (1 per axis, high-power) (p. 2-147) and E-509 controller (p. 2-152) (for systems with sensors)
Multi-channel digital controllers: E-710 bench-top (p. 2-128), E-712 modular (p. 2-140), E-725 high-power (p. 2-126), E-761 PCI board (p. 2-130)

P-733.2 · P-733.3 XY(Z) Piezo-Nanopositioning Stage

High-Precision XY(Z) Scanner Family with Aperture



P -733.3 DD (left) and P -733.2 DD, high-speed, direct drive XY(Z) scanning stages are the fastest scanning stages with large aperture currently available (2.2 kHz resonant frequency!). Both units feature a footprint of only 100 x 100 mm. CD for size comparison.

- **Travel Ranges to 100 x 100 µm in X,Y & to 10 µm in Z**
- **Resolution to 0.1 nm with Capacitive Sensors**
- **High-Speed Versions with Direct Drive**
- **Vacuum and Non-Magnetic Versions**
- **Parallel Kinematics for Better Multi-Axis Accuracy and Dynamics**
- **Parallel Metrology for Active Trajectory Control**
- **Frictionless, High-Precision Flexure Guiding System**
- **Clear Aperture 50 x 50 mm for Transmitted-Light Applications**

P-733 XY and XYZ piezo driven stages are fast and highly accurate nanopositioning and scanning systems. They provide a positioning and scanning range of 100 x 100 (x10) µm together with sub-nanometer resolution and are equipped with parallel-metrology capacitive position feedback for superior multi-axis linearity and repeatability. The guiding accuracy minimizes runout to under 10 nm over the whole travel range. In addition, the high-speed Z-axis of the P-733.3CD can actively compensate any out-of-plane Z-axis deviation during XY motion.

Application Examples

- Image processing / stablilization
- Scanning microscopy
- Surface inspection
- Metrology / interferometry
- Biotechnology
- Semiconductor testing
- Mask / wafer positioning
- Micromanipulation
- Nanopositioning with high flatness & straightness

Fastest Multi-Axis Systems / Direct Drive, Low Profile and Large Apertures

P-733.2DD / .3DD multi-axis piezo nanopositioning systems are the fastest ultra-high-precision, open-frame stages for scanning microscopy. They provide a positioning and scanning range of 30 x 30 (x10) µm. P-733 nanopositioning and scanning stages feature very low profiles, as low as 20 mm (0.8 inch). The novel, high-stiffness direct drive gives the systems resonant frequencies as high as 2.2 kHz (4 x that of other comparable systems), enabling millisecond scanning rates with sub-nanometer resolution.

Parallel-Kinematics / Metrology for Enhanced Responsiveness

In a parallel kinematics multi-axis system, all actuators act directly on one moving platform. This means that all axes move the same minimized mass and can be designed with identical dynamic properties. Multi-axis nanopositioning systems equipped with both parallel kinematics and parallel, direct metrology are able to measure platform position in all degrees of freedom against one common fixed reference. In such systems, undesirable motion from one actuator in the direction of another (cross talk) is detected immediately and actively compensated by the servo-loops.

Capacitive Sensors for Subnanometer Resolution

PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz. The closed-loop resolution is 0.3 nm for the X and Y axes and 0.2 nm for the optional Z-axis. The direct drive versions are rated to 0.1 nm resolution for every axis.

Large Variety of Models for a Broad Range of Applications

For Z-axis scanning applications, the P-733.ZCD (see p. 2-42) version is available with a travel range of 100 µm. For ultra-high-vacuum applications down to 10^{-9} hPa, nanopositioning systems as well as comprehensive accessories, such as suitable feedthroughs, are available.

Ordering Information

P-733.2DD
High-Dynamics High-Precision XY Nanopositioning System, 30 x 30 µm, Direct Drive, Capacitive Sensors, Parallel Metrology, Sub-D Connector

P-733.3DD
High-Dynamics Precision XYZ Nanopositioning System, 30 x 30 x 10 µm, Direct Drive, Capacitive Sensors, Parallel Metrology, Sub-D Connector

P-733.2CD* / P-733.2CL*
High-Precision XY Nanopositioning System, 100 x 100 µm, Capacitive Sensors, Parallel Metrology

P-733.3CD* / P-733.3CL*
Precision XYZ Nanopositioning System, 100 x 100 x 10 µm, Capacitive Sensors, Parallel Metrology

P-733.2VL* / P-733.2VD*
High-Precision XY Nanopositioning System, 100 x 100 µm, Capacitive Sensors, Parallel Metrology, Vacuum Compatible to 10-6 hPa

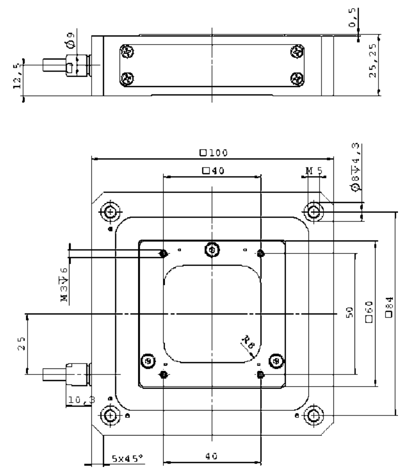
P-733.2UD
High-Precision XY Nanopositioning System, 100 x 100 µm, Capacitive Sensors, parallel metrology, Sub-D Connector, Vacuum Compatible to 10-9 hPa

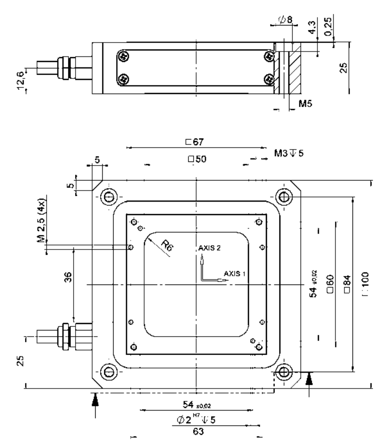
*.xxD with Sub-D Connector

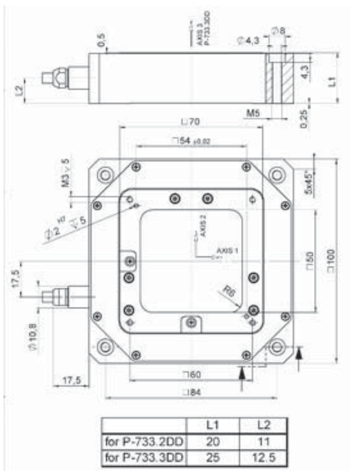
*.xxL with LEMO Connector

Ask about custom designs

P-733.2UD non-magnetic XY scanning stage for UHV to 10^{-9} hPa


P-733.2 dimensions in mm


P-733.3 dimensions in mm



P-733.xDD dimensions in mm

Technical Data

Model	P-733.2CD P-733.2CL	P-733.3CD P-733.3CL	P-733.2DD	P-733.3DD	Units	Tolerance
Active axes	X, Y	X, Y, Z	X, Y	X, Y, Z		
Motion and positioning						
Integrated sensor	Capacitive	Capacitive	Capacitive	Capacitive		
Open-loop travel, -20 to +120 V	115 x 115	115 x 115 x 12	33 x 33	33 x 33 x 14	µm	min. (+20 %/-0 %)
Closed-loop travel	100 x 100	100 x 100 x 10	30 x 30	30 x 30 x 10	µm	
Open-loop resolution	0.2	0.2 (0.1 in Z)	0.1	0.1	nm	typ.
Closed-loop resolution	0.3	0.3 (0.2 in Z)	0.1	0.1	nm	typ.
Linearity (X, Y)	0.03	0.03	0.03*	0.03*	%	typ.
Linearity (Z)	–	0.03	–	0.03*	%	typ.
Repeatability (X, Y)	<2	<2	<2	<2	nm	typ.
Repeatability (Z)	–	<1	–	<1	nm	typ.
Pitch (X,Y)	<±3	<±3	<±5	<±5	µrad	typ.
Yaw (X, Y)	<±10	<±10	<±10	<±10	µrad	typ.
Runout θZ (motion in Z)		<±5		<±5	µrad	typ.
Mechanical properties						
Stiffness	1.5	1.4 (9 in Z)	20	4 (10 in Z)	N/µm	±20 %
Unloaded resonant frequency	500	460 (1400 in Z)	2230	1200 (1100 in Z)	Hz	±20 %
Resonant frequency @ 120 g	370	340 (1060 in Z)	-	-	Hz	±20 %
Resonant frequency @ 200 g	340	295 (650 in Z)	1550	530 (635 in Z)	Hz	±20 %
Push/pull force capacity in motion direction	50/20	50/20	50/20	50/20	N	Max.
Drive properties						
Ceramic type	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885		
Electrical capacitance	6	6 (2.4 in Z)	6.2	6.2 (3.3 in Z)	µF	±20 %
Dynamic operating current coefficient	7.5	7.5 (30 in Z)	25	25 (41 in Z)	µA	(Hz • µm) ±20 %
Miscellaneous						
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	°C	
Material	Aluminum	Aluminum	Aluminum	Aluminum		
Mass	0.58	0.675	0.58	0.675	kg	±5 %
Cable length	1.5	1.5	1.5	1.5	m	±10 mm
Sensor/ voltage connection	Sub-D special (CD-version) LEMO (CL-version)	Sub-D special (CD-version) LEMO (CL-version)	Sub-D special	Sub-D special		

*With digital controller. Non-linearity of direct drive stages measured with analog controllers is up to 0.1 % typ.

Recommended controller:
Single-channel (1 per axis): E-610 servo controller / amplifier (p. 2-110), E -625 servo controller, bench-top (p. 2-114), E-621 controller module (p. 2-160)
Multi-channel: modular piezo controller system E-500 (p. 2-142) with amplifier module E-503 (three channels) (p. 2-146) or E-505 (1 per axis, high-power) (p. 2-147) and E-509 controller (p. 2-152)
Multi-channel digital controllers: E-710 bench-top (p. 2-128), E-712 modular (p. 2-140), E-725 high-power (p. 2-126), E-761 PCI board (p. 2-130)

PI Piezo • Nano • Positioning

P-734 XY Piezo Scanner

High-Dynamics System with Minimum Runout & Clear Aperture

P-734 low-bow flexure nanopositioning stage with ultra-precise trajectory control

- **Ultra-Precision Trajectory Control, Ideal for Surface Analysis and Scanning Microscopy**
- **Parallel-Kinematics / Metrology for Enhanced Responsiveness / Multi-Axis Precision**
- **Travel Range 100 x 100 µm, Clear Aperture 56 x 56 mm**
- **Capacitive Sensors for Resolution <0,4 nm**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**

P-734 high-dynamics, XY piezo nanopositioning stages feature linear travel ranges to 100 x 100 µm with sub-nanometer resolution and maximum flatness of motion.

Flatness in the Low Nanometer Range

P-734 open-frame XY nanopositioning and scanning stages are ideal for nanometrology tasks that require extreme flatness of scanning. These stages feature an ultra-precise, flexure guiding system which confines motion to the XY plane and reduces runout in Z to a few nanometers or less. This unsurpassed trajectory precision is fundamental for highest-precision surface metrology applications. These stages provide a positioning and scanning range of 100 x 100 µm with accuracy and resolution in the nanometer and sub-nanometer range.

Application Examples

- Scanning microscopy
- Metrology / interferometry
- Semiconductor testing
- Mask/wafer positioning
- Image processing / stablilization
- Biotechnology
- Micromanipulation
- Nanopositioning

Excellent Guiding Accuracy

Flexures optimized with Finite Element Analysis (FEA) are used to guide the stage. FEA techniques are used to give the design the highest possible stiffness in, and perpendicular to, the direction of motion, and to minimize linear and angular runout. Flexures allow extremely high-precision motion, no matter how minute, as they are completely free of play and friction.

Higher Precision in Periodic Motion

The highest dynamic accuracy in scanning applications is made possible by the DDL algorithm, which is available in PI's modern digital controllers. DDL eliminates tracking errors, improving dynamic linearity and usable bandwidth by up to three orders of magnitude!

Direct Position Measurement with Sub-Nanometer Accuracy

PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz.

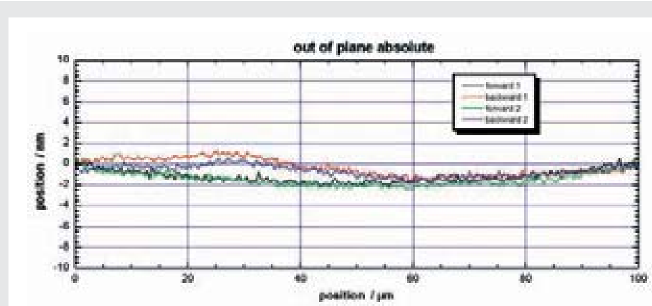
Parallel Kinematics and Metrology with Capacitive Sensors for High Trajectory Fidelity

In a parallel kinematics multi-axis system, all actuators act directly on one moving platform. This means that all axes move the same minimized mass and can be designed with identical dynamic properties. Systems with parallel kinematics and metrology have additional advantages over serially stacked or nested systems, including more-compact construction and no cumulative error from the different axes. Parallel kinematics systems can be operated with up to six degrees of freedom with low inertia and excellent dynamic performance. Multi-axis nanopositioning systems equipped with both parallel kinematics and parallel, direct metrology are able to measure platform position in all degrees of freedom against one common fixed reference. In such systems, undesirable motion from one actuator in the direction of another (cross talk) is detected immediately and actively compensated by the servo-loops. This Active Trajectory Control Concept can keep deviation from a trajectory to under a few nanometers, even in dynamic operation.

Ordering Information

P-734.2CD
High-Precision XY Nanopositioning System with Minimum Runout, 100 x 100 µm, Capacitive Sensors, Parallel Metrology, Sub-D Connector

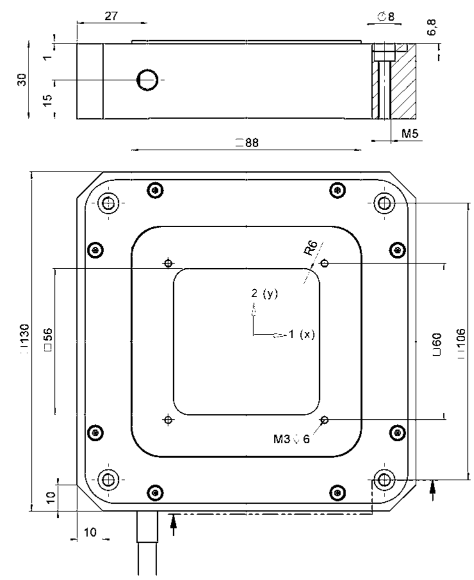
P-734.2CL
High-Precision XY Nanopositioning System with Minimum Runout, 100 x 100 µm, Capacitive Sensors, Parallel Metrology, LEMO Connector



Typical flatness of P-734 motion is in the low nanometer range

Ceramic Insulated Piezo Actuators Provide Long Lifetime

Highest possible reliability is assured by the use of award-winning PICMA® multilayer piezo actuators. PICMA® actuators are the only actuators on the market with ceramic-only insulation, which makes them resistant to ambient humidity and leakage-current failures. They are thus far superior to conventional actuators in reliability and lifetime.



P-734 dimensions in mm

Technical Data

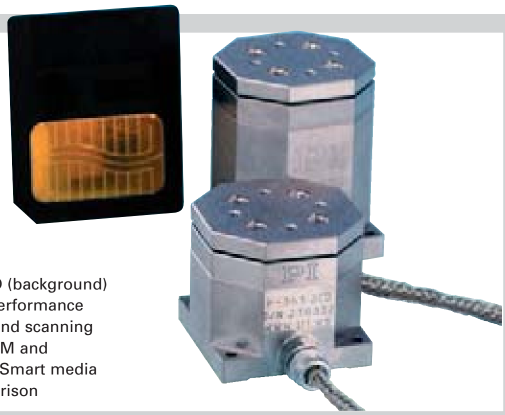
Models	P-734.2CL	P-734.2CD	Units	Tolerance
Active axes	X, Y	X, Y		
Motion and positioning				
Integrated sensor	Capacitive	Capacitive		
Open-loop travel, -20 to +120 V	110 x 110	110 x 110	µm	min. (+20 %/-0 %)
Closed-loop travel	100 x 100	100 x 100	µm	
Open-loop resolution	0.2	0.2	nm	typ.
Closed-loop resolution	0.3	0.3	nm	typ.
Linearity	0.03	0.03	%	typ.
Repeatability	<2.5	<2.5	nm	typ.
Pitch	<3	<3	µrad	typ.
Yaw	<10	<10	µrad	typ.
Flatness	typ. <5, max. <10	typ. <5, max. <10	nm	typ.
Mechanical properties				
Stiffness	3	3	N/µm	±20 %
Unloaded resonant frequency	500	500	Hz	±20 %
Resonant frequency @ 200 g	350	350	Hz	±20 %
Resonant frequency @ 500 g	250	250	Hz	±20 %
Push/pull force capacity in motion direction	300 / 100	300 / 100	N	Max.
Load capacity	20	20	N	Max.
Drive properties				
Ceramic type	PICMA® P-885	PICMA® P-885		
Electrical Capacitance	6.2	6.2	µF	±20%
Dynamic operating current coefficient	7.8	7.8	µA/(Hz • µm)	±20%
Miscellaneous				
Operating temperature range	-20 to 80	-20 to 80	°C	
Material	Aluminum	Aluminum		
Mass (with cables)	1.04	1.04	kg	±5 %
Cable length	1.5	1.5	m	±10 mm
Sensor connection	2x LEMO	Sub-D Special		
Voltage connection	4x LEMO	Sub-D Special		

Dynamic Operating Current Coefficient in µA per Hz and µm. Example: Sinusoidal scan of 10 µm at 10 Hz requires approximately 7.8 mA drive current.

Recommended controller / amplifier
P-734.2CL (p. 2-64): E-500 modular piezo controller system (p. 2-142) with amplifier module E-503 (three channels) (p. 2-146) or E-505 (1 per axis, high performance) (p. 2-147) and E-509 controller (p. 2-152)
P-734.2CD (p. 2-64): Multi-channel digital controllers: E-710/E-725 bench-top (p. 2-128, p. 2-126), E-712 modular (p. 2-140), E-761 PCI board (p. 2-130)

P-363 PicoCube™ XY(Z) Piezo Scanner

High-Dynamics Nanoscanner for Scanning Probe Microscopy



P-363.2CD and .3CD (background) PicoCube™, high-performance piezo positioning- and scanning systems or AFM/STM and nanomanipulation. Smart media card for size comparison

- **Ultra-High-Performance Closed-Loop Scanner for AFM/SPM**
- **Compact Manipulation Tool for Bio/Nanotechnology**
- **Resonant Frequency 9.8 kHz**
- **Capacitive Sensors for Highest Accuracy**
- **Parallel-Motion Metrology for Automated Compensation of Guiding Errors**
- **50 Picometer Resolution**
- **5 x 5 x 5 µm Travel Range**
- **Vacuum-Compatible Versions**

The P-363 PicoCube™ XY/XYZ is an ultra-high-performance closed-loop piezo scanning system. Designed for AFM, SPM and nanomanipulation applications, it combines an ultra-low inertia, high-speed XY/XYZ piezo scanner with non-contact, direct-measuring, parallel-metrology capacitive feedback capable of 50 picometers resolution. On top of being extremely precise, the PicoCube™ system is also very small and rugged. Measuring only 30 x 30 x 40 mm (with removable top plate, 30 x 30 x 28 mm for XY version), it is easy to integrate in any scanning apparatus.

Application Examples

- Scanning microscopy (SPM)
- Biotechnology
- Micromanipulation
- Nanopositioning
- Nano-imprinting
- Nanometrology
- Nanolithography

SPM, AFM, STM, Nanolithography, Nanoimprinting, Nanometrology

The PicoCube™ was specifically developed to overcome the limitations of the open-loop scanners currently available for SPM, AFM and STM. In addition to these applications, the PicoCube™ is also the ideal scanning and manipulation tool for nanoimprinting, nanolithography, ultra-high-resolution, near-field, scanning optical microscopy and nano-surface-metrology applications.

Higher Precision Through Parallel-Motion Metrology w/ Capacitive Sensors

The PicoCube™ is based on a proprietary, ultra-fast, piezo-driven scanner design equipped with direct-measuring, capacitive position sensors (parallel metrology). Unlike conventional sensors, they measure the actual distance between the fixed frame and the moving part of the stage. This results in higher-motion linearity, long-term stability, phase fidelity, and—because external disturbances are seen by the sensor immediately—a stiffer, faster-responding servo-loop.

Multi-axis nanopositioning systems equipped with parallel direct metrology are able to measure the platform position in all degrees of freedom against one fixed reference. In such systems, undesirable motion from one actuator in the direction of another (cross-talk) is detected immediately and actively compensated by the servo-loops. This Active Trajectory Control Concept can keep deviation from a trajectory to under a few nanometers, even in dynamic operation.

Ordering Information

P-363.3CD
PicoCube™ High-Precision XYZ Nanopositioning System, 5 x 5 x 5 µm, Parallel Metrology, Capacitive Sensors, Sub-D Connector

P-363.3UD
PicoCube™ High-Precision XYZ Nanopositioning System, 5 x 5 x 5 µm, Parallel Metrology, Capacitive Sensors, Sub-D Connector, Vacuum Compatible to 10^{-9} hPa

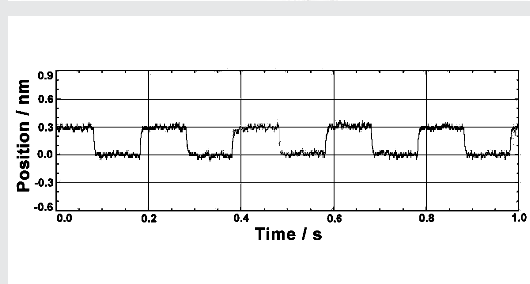
P-363.2CD
PicoCube™ High-Precision XY Nanopositioning System, 5 x 5 µm, Parallel Metrology, Capacitive Sensors, Sub-D Connector

P-363.2UD
PicoCube™ High-Precision XY Nanopositioning System, 5 x 5 µm, Parallel Metrology, Capacitive Sensors, Sub-D Connector, Vacuum Compatible to 10^{-9} hPa

P-363.3CL
PicoCube™ High-Precision XYZ Nanopositioning System, 5 x 5 x 5 µm, Parallel Metrology, Capacitive Sensors, LEMO Connector

P-363.2CL
PicoCube™ High-Precision XY Nanopositioning System, 5 x 5 µm, Parallel Metrology, Capacitive Sensors, LEMO Connector

The P-363 settles to within 1 nm in 1 ms (100 nm step, X and Y motion; faster response in Z)



300 picometer steps (0.3 nm) performed with the P-363, measured with an external high-resolution, capacitive measurement system

Nanometer Accuracy in 1 Millisecond with 30-Picometer Resolution

PicoCube™ systems provide resolution of 30 picometers and below. The ultra-fast XY/XYZ piezo drives offer resonant frequencies of 9.8 kHz in Z and >3 kHz in X and Y! The high resonant frequency and high-bandwidth capacitive feedback allow step and settle to 1% accuracy in as little as one millisecond.

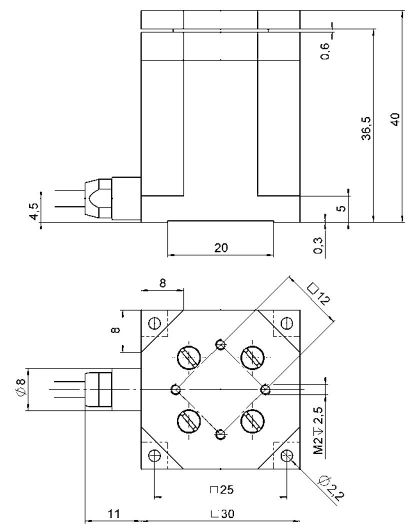
Rugged Design

In spite of its ability to move and position on an atomic scale, the PicoCube™ boasts a rugged design for real-world applications. For extra-high stability and reduced mass, the body is precision machined from heat-treated and stress-relieved titanium. The sophisticated frictionless design also ensures that the (moving) top plate protects the internal actuator/sensor unit from contamination.

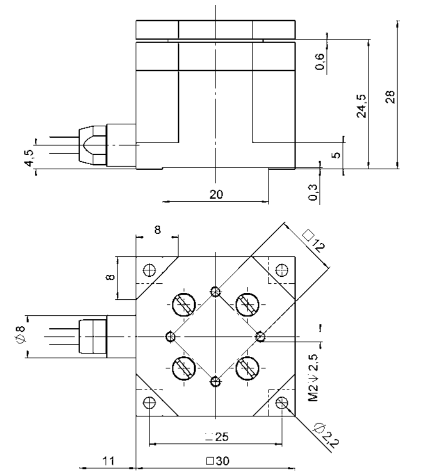
Controller

For dynamic scanning operation the E-725.3CM high-power digital controller offers advanced linearization algorithms for sub-nanometer precision (see p. 2-126).

Alternatively the analog E-536 PicoCube™ controller (see p. 2-134) comes in different versions optimized for resolution or power. An optional E-517 24-bit interface module is also available (see p. 2-156).



P-363.3Cx dimensions in mm. Removable top plate



P-363.2Cx dimensions in mm. Removable top plate

Technical Data

Model	P-363.3CD	P-363.2CD	Units
Active axes	X, Y, Z	X, Y	
Motion and positioning			
Integrated sensor	Capacitive	Capacitive	
Open-loop travel X, Y, -250 to +250 V	±3	±3	µm
Open-loop travel, -250 to +250 V	±2.7	–	µm
Closed-loop travel X, Y	±2.5	±2.5	µm
Closed-loop travel	±2.5	–	µm
Open-loop resolution	0.03*	0.03*	nm
Closed-loop resolution	0.1	0.1nm	
Linearity	0.05	0.05	%
Repeatability	1**	1**	nm
Pitch / yaw in X, Y	0.5	0.5	µrad
Runout X, Y (Z motion)	0.2	–	µrad
Straightness in X, Y	3	3	nm
Flatness in X, Y	<10	<10	nm
Crosstalk X, Y (Z motion)	5	–	nm
Mechanical properties			
Unloaded resonant frequency in X, Y	3.1	4.2	kHz
Unloaded resonant frequency (Z)	9.8	–	kHz
Resonant frequency in X, Y	1.5 (20 g)	2.1 (20 g)	kHz
Load capacity	10	10	N
Ceramic type	PICA™, PICA™ Shear	PICA™ Shear	
Miscellaneous			
Operating temperature range	-20 to 80	-20 to 80	°C
Material	Titanium	Titanium	
Dimensions	30 x 30 x 40	30 x 30 x 28	mm
Mass	225	190	g
Cable length	1.5	1.5	m
Sensor / voltage connection***	Sub-D connector PicoCube™	Sub-D connector PicoCube™	
Recommended controller	E-536 PicoCube™ Controller	E-536 PicoCube™ Controller	

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E-536 controller (p. 2-134)
*With E-536.3xH Controller
**for 10% travel in Z; 50 nm for 100% travel in Z
***P-363.xCL versions with LEMO connectors

System properties

System configuration	P-363.3CD (Z-axis) with 20 g load and E-536 servo controller
Settling time	(10% step width) 1 ms

P-615 NanoCube® XYZ Piezo System

Long-Travel Multi-Axis Piezo Stage for Precision Alignment Applications

P-615NanoCube® XYZ Nanopositioning System provides up to 420 x 420 x 300 µm travel range

- **Up to 420 x 420 x 300 µm Travel Range**
- **Resolution 1 nm**
- **Parallel-Kinematics / Metrology for Enhanced Responsiveness / Multi-Axis Precision**
- **Clear Aperture of 10 mm Ø, Ideal for Alignment and Photonics Packaging Applications**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **Open- & Closed-Loop Versions**
- **Vacuum-Compatible Versions to 10^{-9} hPa**
- **Frictionless, High-Precision Flexure Guiding System**

The P-615 NanoCube® is a multi-axis piezo nanopositioning and alignment system. Its 420 x 420 x 300 µm, XYZ positioning and scanning range comes in a compact package. Equipped with a zero-stiction, zero-friction guidance system, this NanoCube® provides motion with ultra-high resolution and settling times of only a few milliseconds.

Fiber Positioning

The P-615 NanoCube® is equipped with a fiber adapter interface similar to the P-611.3SF and accommodates all F-603-series fiber holders and accessories. Fiber optics handling is facilitated by the clear aperture.

Application Examples

- Micromanipulation
- Biotechnology
- Semiconductor testing
- Photonics / integrated optics

Double Stiffness for Fast Response

The P-615's unique flexure design has double the stiffness in the vertical axis than in X and Y, providing faster response and higher operating frequencies under load. For example, the settling time to reach a commanded position with 1 % accuracy is only 15 ms in the Z-axis with 100 g load (as opposed to 10 ms without load).

Open-Loop and Closed-Loop Operation

The open-loop basic model P-615.30L is ideal for applications where fast response and very high resolution are essential but specifying or reporting absolute position values is either not required or is handled by external sensors, e. g. in tracking or fiber positioning tasks. In open-loop mode, the piezo displacement is roughly proportional to the applied voltage (see p. 2-184).

Capacitive Sensors for Highest Accuracy

The P-615.3C models are equipped with high-accuracy, capacitive position sensors. PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz.

Active and Passive Guidance for Nanometer Flatness and Straightness

Wire-cut flexures optimized with Finite Element Analysis (FEA) are used to guide the stage. The FEA techniques give the design the highest possible stiffness and minimize linear and angular runout. Further enhancement is achieved by active trajectory control: multi-axis nanopositioning systems equipped with parallel metrology are able to measure platform position in all degrees of freedom against a common, fixed reference. In such systems, undesirable motion from one actuator in the direction of another (cross-talk) is detected immediately and actively compensated by the servo-loops. This can keep deviation from a trajectory to under a few nanometers, even in dynamic operation.

Ordering Information

P-615.3CD
NanoCube® XYZ Nanopositioning System with Long Travel Range, 350 x 350 x 250 µm, Parallel Metrology, Capacitive Sensors, Sub-D Connector

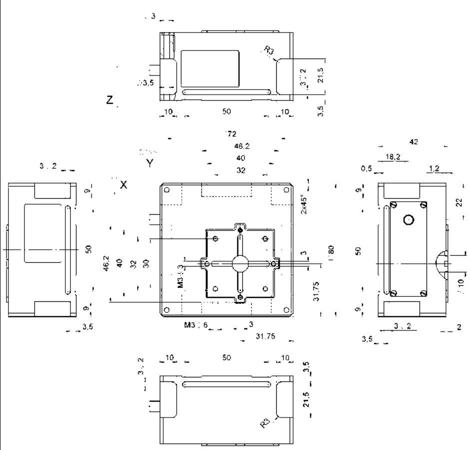
P-615.3CL
NanoCube® XYZ Nanopositioning System with Long Travel Range, 350 x 350 x 250 µm, Parallel Metrology, Capacitive Sensors, LEMO Connector

P-615.30L
NanoCube® XYZ Nanopositioning System with Long Travel Range, 420 x 420 x 300 µm, Parallel Metrology, Open-Loop, LEMO Connector

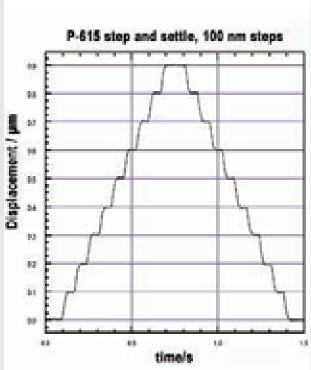
P-615.3UD
NanoCube® XYZ Nanopositioning System with Long Travel Range, 350 x 350 x 250 µm, Parallel Metrology, Capacitive Sensors, Sub-D Connector, Vacuum Compatible to 10^{-9} hPa

Ceramic Insulated Piezo Actuators Provide Long Lifetime

Highest possible reliability is assured by the use of award-winning PICMA® multilayer piezo actuators. PICMA® actuators are the only actuators on the market with ceramic-only insulation, which makes them resistant to ambient humidity and leakage-current failures. They are thus far superior to conventional actuators in reliability and lifetime.



P-615 dimensions in mm.
The clear aperture has a diameter of 10 mm.



P-615, X-axis with 100 g load performing 100 nm steps in rapid sequence without overshoot. Settling time for the Z-axis to reach a commanded position with 1 % accuracy is only 15 ms.

P-615 with optional fiber holder F-603.22

Technical Data

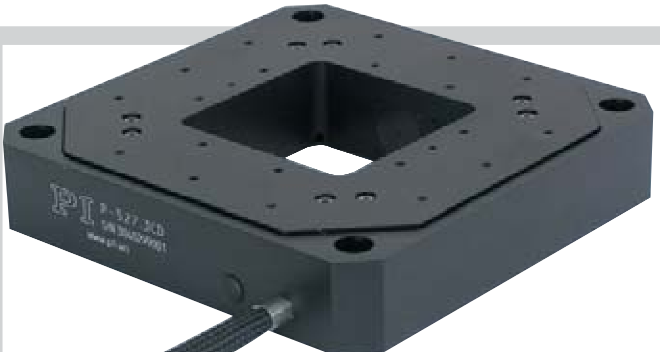
Model	P-615.3CD / P-615.3CL	P-615.30L	Units	Tolerance
Active axes	X, Y, Z	X, Y, Z		
Motion and positioning				
Integrated sensor	Capacitive	–		
Open-loop travel in X/Y/Z, -20 to +120 V	420 / 420 / 300	420 / 420 / 300	µm	min. (+20 %/-0 %)
Closed-loop travel X/Y/Z	350 / 350 / 250	–	µm	
Open-loop resolution X/Y/Z	0.5	0.5	nm	typ.
Closed-loop resolution X/Y/Z	1	–	nm	typ.
Linearity X/Y/Z	0.02	–	%	typ.
Repeatability in X, Y, Z	±7.5 / ±7.5 / ±5	–	nm	typ.
Pitch in X,Y	100	100	µrad	typ.
Yaw in X, Y	50	50	µrad	typ.
Runout θ_X, θ_Y (Z motion)	10	10	µrad	typ.
Mechanical properties				
Stiffness X / Y / Z	0.13 / 0.13 / 0.35	0.13 / 0.13 / 0.35	N/µm	±20 %
Unloaded resonant frequency in X / Y / Z	210 / 210 / 250	210 / 210 / 250	Hz	±20 %
Resonant frequency @ 100 g in X / Y / Z	125 / 125 / 200	125 / 125 / 200	Hz	±20 %
Push/pull force capacity in motion direction	20 / 10	20 / 10	N	Max.
Load capacity	20	20	N	Max.
Drive properties				
Ceramic type	PICMA® P-885	PICMA® P-885		
Electrical capacitance in X / Y / Z	3.7 / 3.7 / 6.2	3.7 / 3.7 / 6.2	µF	±20 %
Dynamic operating current coefficient (DOCC) in X / Y / Z	1.3 / 1.3 / 3.1	1.3 / 1.3 / 3.1	µA/(Hz·µm)	±20 %
Miscellaneous				
Operating temperature range	-20 to 80	-20 to 80	°C	
Material	Aluminum	Aluminum		
Mass	0.58	0.57	kg	±5 %
Cable length	1.5	1.5	m	±10 mm
Sensor / voltage connection	Sub-D special (CD-version); LEMO (CL-version)	LEMO (no sensor)		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E-503 amplifier (p. 2-146).

Recommended controller
Multi-channel digital controllers: E-710 bench-top (p. 2-128), E-712 modular (p. 2-140), E-725 high-power (p. 2-126), E-761 PCI board (p. 2-130)
Multi-channel:
E-500 modular piezo controller system (p. 2-142) with E-509 servo-controller (p. 2-152) (optional) and as amplifier either E-503 (three channels) (p. 2-146) or E-505 (1 per axis, high-power, p. 2-147)
modules P-615.30L (p. 2-68): E-610 controller / amplifier (p. 2-110) (1 per axis)

P-517 · P-527 Multi-Axis Piezo Scanner

High-Dynamics Nanopositioner / Scanner with Direct Position Metrology


P-527.2CL parallel-kinematic nanopositioning system

- **Travel Ranges to 200 µm**
- **Sub-Nanometer Resolution**
- **Frictionless, High-Precision Flexure Guiding System**
- **Capacitive Sensors for Highest Linearity**
- **Parallel-Kinematics / Metrology for Enhanced Responsiveness / Multi-Axis Precision**
- **Clear Aperture 66 x 66 mm**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**

P-517 and P-527 high-dynamics, multi-axis piezo-nanopositioning stages are available in XY ΘZ, XY and XYZ configurations featuring linear travel ranges to 200 x 200 x 20 µm and rotation ranges to 4 mrad. The 66 x 66 mm clear aperture is ideal for transmitted-light applications.
Z/tip/tilt versions in the same form factor are also offered as models P-518, P-528, P-558 (see p. 2-46) and as custom versions with up to six degrees of freedom.

Capacitive Sensors for Highest Accuracy

PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz.

Application Examples

- Metrology
- Interferometry
- Optics
- Lithography
- Nanopositioning
- Scanning microscopy
- Mass storage device testing
- Laser technology
- Micromachining

Technical Data

Models	P-517.2CL	P-527.2CL	P-517.3CL/ P-517.3CD	P-527.3CL/ P-527.3CD	P-517.RCD	P-527.RCD
Active axes	X, Y	X, Y	X, Y, Z	X, Y, Z	X, Θ_Y, Θ_Z	Θ_Y, Θ_Z
Motion and positioning						
Integrated sensor	Capacitive	Capacitive	Capacitive	Capacitive	Capacitive	Capacitive
Open-loop travel, -20 to +120 V	130	250	130; Z: 25	250; Z: 25	130; Θ_Z: ±1.3 mrad	250; Θ_Z: ±2.5 mrad
Closed-loop travel	100	200	100; Z: 20	200; Z: 20	100; Θ_Z: ± 1 mrad	200; Θ_Z: ± 2 mrad
Open-loop resolution	0.3	0.5	0.3; Z: 0.1	0.5; Z: 0.1	0.3; Θ_Z: 0.1 µrad	0.5; Θ_ZZ: 0.1 µrad
Closed-loop resolution	1	2	1; Z: 0.1	2; Z: 0.1	1; Θ_Z: 0.3 µrad	2; Θ_Z: 0.3 µrad
Linearity	0.03	0.03	0.03	0.03	0.03	0.03
Repeatability	±5	±10	±5; Z: ±1	±10; Z: ±1	±5; Z: ±0.5 µrad	±10
Mechanical properties						
Stiffness	2	1	2; Z: 15	1; Z: 15	2	1
Unloaded resonant frequency	450	350	450; Z: 1100	350; Z: 1100	450; Z: 400	350; Z: 300
Resonant frequency @ 500 g X, Y	250	190	250	190	250	190
Resonant frequency @ 2500 g X, Y	140	110	140	110	140	110
Push/pull force capacity in motion direction	50 / 30	50 / 30	50 / 30	50 / 30	50 / 30	50 / 30
Drive properties						
Ceramic type	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885
Electrical capacitance	9.2	9.2	9; Z: 6	9; Z: 6	9	9
Dynamic operating current coefficient (DOCC)	11.5	5.8	11.5; Z: 37	5.5; Z: 37	11.5	5.5
Miscellaneous						
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
Mass	0.14	0.14	0.145	0.145	0.14	0.14
Sensor / voltage connection	LEMO	LEMO	Sub-D special (CD-version) LEMO (CL-version)	; Sub-D special (CD-version) LEMO (CL-version)	Sub-D Special	Sub-D Special

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E -503 or E-710 controller (p. 2-146 or p. 2-128)
Linear Dynamic Operating Current Coefficient in µA per Hz and µm. Example for P-527.2xx: Sinusoidal scan of 30 µm at 10 Hz requires approximately 1.8 mA drive current (p. 2-70). Electrical capacitance and DOCC of the rotatic stated.
Recommended controller
Versions with LEMO connectors: Single-channel (1 per axis): E-610 servo-controller / amplifier (p. 2-110), E-625 servo-controller, bench-top (p. 2-114), E-621 controller module (p. 2-160) Multi-channel: modular piezo controller sy (three channels) (p. 2-146) or E-505 (1 per axis, high-power) (p. 2-147) and E-509 controller (p. 2-152)
Versions with Sub-D connectors: Multi-channel digital controllers: E-710 bench-top (p. 2-128), E-712 modular (p. 2-140), E-725 high-power (p. 2-126), E-761 PCI board (p. 2-130)

Active and Passive Guidance for Nanometer Flatness and Straightness

Flexures optimized with Finite Element Analysis (FEA) are used to guide the stage. The FEA techniques provide for the highest possible stiffness in, and perpendicular to, the direction of motion, and minimize linear and angular runout. Flexures allow extremely high-precision motion, no matter how minute, as they are completely free of play and friction. Due to the parallel kinematics design there is only one common moving platform for all axes, minimizing mass, enabling identical dynamic behavior and eliminating cumulative errors. Parallel kinematics also allows for a more compact construction and faster response compared to stacked or nested designs. The high precision due to flexure guidance is further enhanced by Active Trajectory Control: Multi-axis nanopositioning systems equipped with both parallel kinematics and parallel direct metrology are able to measure platform position in all degrees of freedom against one common fixed reference. In such systems, undesirable motion from one actuator in the direction of another (cross-talk) is detected immediately and actively compensated by the servo-loops. This Active Trajectory Control Concept can keep deviation from a trajectory to under a few nanometers, even in dynamic operation.

Ceramic Insulated Piezo Actuators Provide Long Lifetime

Highest possible reliability is assured by the use of award-winning PICMA® multilayer piezo actuators. PICMA® actuators are the only actuators on the market with ceramic-only insulation, which makes them resistant to ambient humidity and leakage-current failures. They are thus far superior to conventional actuators in reliability and lifetime.

Units	Tolerance
µm	min.(+20%/0%)
µm	
nm	typ.
nm	typ.
%	typ.
nm	typ.
N/µm	±20%
Hz	±20%
Hz	±20%
Hz	±20%
N	Max.
µF	±20%
µA/(Hz • µm)	±20%
°C	
kg	±5%

on axes base upon differential motion in X, Y; therefore not

stem E-500 (p. 2-142) with amplifier module E-503

Ordering Information

P-517.2CL
Precision XY Nanopositioning System, 100 x 100 µm, Capacitive Sensors, Parallel Metrology, LEMO Connector

P-527.2CL
Precision XY Nanopositioning System, 200 x 200 µm, Capacitive Sensors, Parallel Metrology, LEMO Connector

P-517.3CL
Precision XYZ Nanopositioning System, 100 x 100 x 20 µm, Capacitive Sensors, Parallel Metrology, LEMO Connector

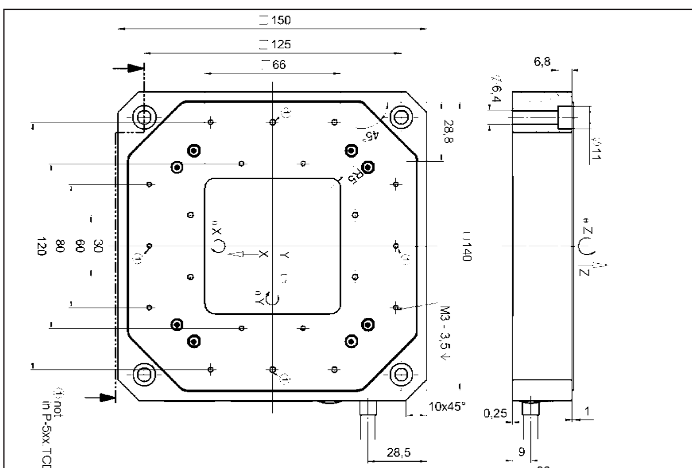
P-517.3CD
Precision XYZ Nanopositioning System, 100 x 100 x 20 µm, Capacitive Sensors, Parallel Metrology, Sub-D Connector

P-527.2CL
Precision XY Nanopositioning System, 200 x 200 µm, Capacitive Sensors, Parallel Metrology, LEMO Connector

P-527.3CD
Precision XYZ Nanopositioning System, 200 x 200 x 20 µm, Capacitive Sensors, Parallel Metrology, Sub-D Connector

P-517.RCD
Precision XY / rotation nanopositioning system, 100 x 100 µm, 2 mrad, Capacitive Sensors, Parallel Metrology, Sub-D Connector

P-527.RCD
Precision XY / rotation nanopositioning system, 200 x 200 µm, 4 mrad, Capacitive Sensors, Parallel Metrology, Sub-D Connector



P-517, P-527 dimensions in mm, cable length 1.5 m

P-561 · P-562 · P-563 PIMars™ XYZ Piezo System

High-Precision Nanopositioning Stage, 3 to 6 Axes

P-562 PIMars™ multi-axis, parallel-kinematics nanopositioning stages are available with up to 340 µm travel per axis. Custom versions to 6 DOF are available

- **Parallel-Kinematics / Metrology for Enhanced Responsiveness / Multi-Axis Precision**
- **Travel Ranges to 340 x 340 x 340 µm**
- **Capacitive Sensors for Highest Linearity**
- **Frictionless, High-Precision Flexure Guiding System**
- **Excellent Scanning Flatness**
- **High-Dynamics XYZ Version Available; Custom Versions to 6-DOF**
- **Clear Aperture 66 x 66 mm**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **UHV Versions to 10^{-9} hPa**

PIMars™ open-frame piezo stages are fast and highly accurate multi-axis scanning and nanopositioning systems with flatness and straightness in the nanometer range.

The 66 x 66 mm clear aperture is ideal for transmitted-light applications such as near-field scanning or confocal micro-scopy and mask positioning.

Large Variety of Models

PIMars™ multi-axis nanopositioners are offered in a large variety of configurations. Standard models include long-travel systems (to 300 x 300 x 300 µm), high-speed and vacuum versions. Custom six-axis designs with rotation to 6 mrad are available on request.

PI offers versions specially designed for applications in ultra-high vacuum with vacuum-qualified components only. The integrated ceramic-encapsulated PICMA® actuators allow high bakeout temperatures and assure minimal outgassing rates. A non-magnetizable version is available on request.

Application Examples

- Scanning microscopy
- Mask/wafer positioning
- Interferometry
- Metrology
- Biotechnology
- Micromanipulation

Direct Drive for Ultra-Fast Scanning and Positioning

The P-561.3DD versions have resonant frequencies to 1.0 kHz, enabling millisecond scanning rates with sub-nanometer resolution.

Capacitive Sensors for Highest Accuracy and Position Stability

PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz.

Active and Passive Guidance for Nanometer Flatness and Straightness

Wire-cut flexures optimized with Finite Element Analysis (FEA) are used to guide the stage. The FEA techniques give the design the highest possible stiffness and minimize linear and angular runout. Further enhancement is achieved by active trajectory control: multi

Ordering Information

P-561.3CD
PIMars™ XYZ Piezo-Nano-positioning System, 100 x 100 x 100 µm, Parallel Metrology

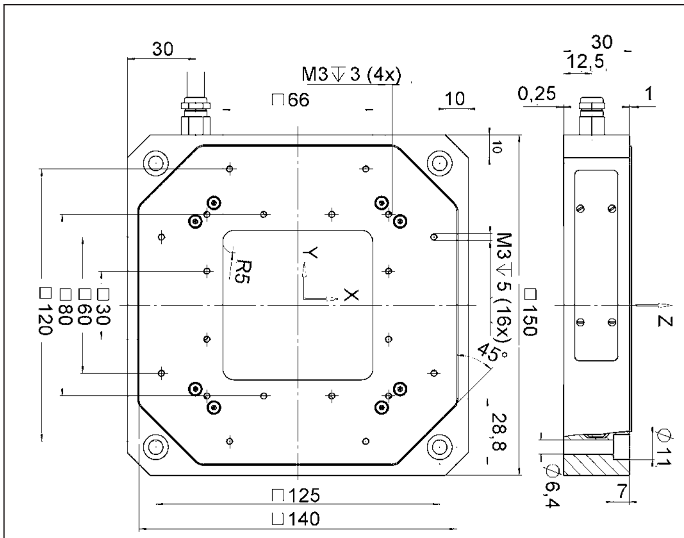
P-562.3CD
PIMars™ XYZ Piezo-Nano-positioning System, 200 x 200 x 200 µm, Parallel Metrology

P-563.3CD
PIMars™ XYZ Piezo-Nanopositioning System, 300 x 300 x 300 µm, Parallel Metrology

P-561.3DD
PIMars™ High-Dynamics XYZ Nanopositioning System, 45 x 45 x 15 µm, Parallel Metrology, Direct Drive

Vacuum-compatible versions to 10^{-6} hPa for the P-561.3CD, P-562.3CD and P-563.3CD models are available as P-561.3VD, P-562.3VD and P-563.3VD; versions to 10^{-9} hPa as P-561.3UD, P-562.3UD and P-563.3UD.

Super-invar & titanium versions are available, 6-DOF versions on request.

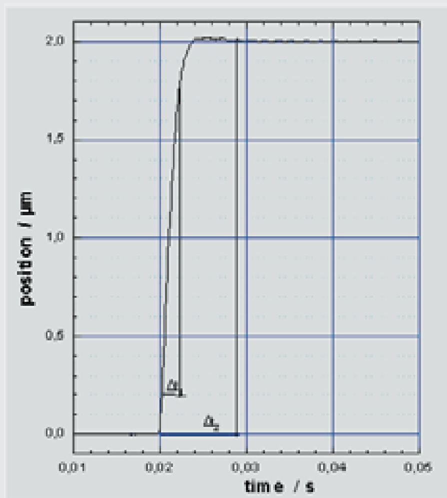


P-561, P-562, P-562 dimensions in mm

System properties

System Configuration	P-561.3CD with E-710 digital controller, 330 g load
Amplifier bandwidth, small signal	25 Hz in X, Y; 35 Hz in Z
Settling time (10 % step)	20 ms

axis nanopositioning systems equipped with parallel metrology are able to measure platform position in all degrees of freedom against a common, fixed reference. In such systems, undesirable motion from one actuator in the direction of another (cross-talk) is detected immediately and actively compensated by the servo-loops. This can keep deviation from a trajectory to under a few nanometers, even in dynamic operation.



P-562.3CD (unloaded) step and settle is faster than 10 ms in X, Y and Z

Technical Data

Model	P-561.3CD	P-562.3CD	P-563.3CD	P-561.3DD	Units	Tolerance
Active axes	X, Y, Z	X, Y, Z	X, Y, Z	X, Y, Z		
Motion and positioning						
Integrated sensor	Capacitive	Capacitive	Capacitive	Capacitive		
Open-loop travel, -20 to +120 V	150 x 150 x 150	300 x 300 x 300	340 x 340 x 340	58 x 58 x 18	µm	min. (+20 %/0 %)
Closed-loop travel	100 x 100 x 100	200 x 200 x 200	300 x 300 x 300	45 x 45 x 15	µm	
Open-loop resolution	0.2	0.4	0.5	0.1	nm	typ.
Closed-loop resolution	0.8	1	2	0.2	nm	typ.
Linearity	0.03	0.03	0.03	0.01*	%	typ.
Repeatability in X, Y, Z	2 / 2 / 2	2 / 2 / 4	2 / 2 / 4	2 / 2 / 2	nm	typ.
Pitch in X,Y	±1	±2	±2	±3	µrad	typ.
Runout θ_x, θ_y (Z motion)	±15	±20	±25	±3	µrad	typ.
Yaw in X, Y	±6	±10	±10	±3	µrad	typ.
Flatness in X, Y	±15	±20	±25	±10	nm	typ.
Crosstalk X, Y (Z motion)	±30	±50	±50	±20	nm	typ.
Mechanical properties						
Unloaded resonant frequency in X / Y / Z	190 / 190 / 380	160 / 160 / 315	140 / 140 / 250	920 / 920 / 1050**	Hz	±20 %
Resonant frequency @ 100 g in X / Y / Z	-	145 / 145 / 275	120 / 120 / 215	860 / 860 / 950	Hz	±20 %
Resonant frequency @ 30 g in X / Y / Z	140 / 140 / 300	130 / 130 / 195	110 / 110 / 170	500 / 500 / 470	Hz	±20 %
Push force capacity in motion direction in X / Y / Z	200 / 200 / 50	120 / 120 / 50	100 / 100 / 50	200 / 200 / 50	N	Max.
Pull force capacity in motion direction in X / Y / Z	30 / 30 / 30	30 / 30 / 30	30 / 30 / 30	30 / 30 / 30		
Load capacity	50	50	50	50	N	Max.
Drive properties						
Ceramic type	PICMA® P-885	PICMA® P-885	PICMA® P-885	PICMA® P-885 in Z, P-888 in XY		
Electrical capacitance in X / Y / Z	5.2 / 5.2 / 10.4	7.4 / 7.4 / 14.8	7.4 / 7.4 / 14.8	38 / 38 / 6	µF	±20 %
Dynamic operating current coefficient (DOCC) in X / Y / Z	6.5 / 6.5 / 13	4.6 / 4.6 / 9.25	3.1 / 3.1 / 6.1	106 / 106 / 50	µA/ (Hz • µm)	±20 %
Miscellaneous						
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	°C	
Material	Aluminum	Aluminum	Aluminum	Aluminum		
Mass	1.45	1.45	1.45	1.55	kg	±5 %
Cable length	1.5	1.5	1.5	1.5	m	±10 mm
Sensor / voltage connection	Sub-D Special	Sub-D Special	Sub-D Special	Sub-D Special		

Resolution of PI Piezo Nanopositioners is not limited by friction or stiction. Value given is noise equivalent motion with E-710 (p. 2-128) controller.
*With digital controller. Non-linearity of direct drive stages measured with analog controllers is typically up to 0.1 %.

Recommended controller
Multi-channel digital controllers: E-710 bench-top (p. 2-128), E-712 modular (p. 2-140), E-725 high-power (p. 2-126), E-761 PCI board (p. 2-130)

P-915K XY-Theta-Z Piezo Stage

3 Degrees of Freedom in the XY Plane

The P-915KPPS is equipped with FEA-modeled flexures for higher stiffness in all three directions of motion

- **Travel Ranges 250 x 250 µm, 16 mrad**
- **Frictionless, High-Precision Flexure Guiding System**
- **High Stiffness >1 N/µm**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**

Model	Travel	Resolution	Load capacity	Settling (system combination with E-621	Dimensions
P-915KPPS XY-Rot-Z-Piezo Stage	250 x 250 µm ±8 mrad	3 nm 15 µrad	2 kg	45 ms (250 µm) 28 ms (16 mrad)	60 x 60 x 100 mm

P-313 PicoCube™ XY(Z) Piezo Scanner

Picometer Precision, High Bandwidth, No Servo Lag, for Scanning Probe Microscopy

A new drive concept allows high-linearity positioning in open-loop operation

- **Ultra-High-Performance Scanner for AFM/SPM**
- **20 Picometers Resolution, <1 nm Hysteresis**
- **Very High Bandwidth with no Servo Lag Due to New Drive Concept**
- **Compact Manipulation Tool for Bio-/Nanotechnology**
- **Resonant Frequency 4.0 kHz (X, Y), 11 kHz (Z)**
- **1 x 1 x 0.8 µm Travel Range**

Model	Travel range (±250 V)	Resolution	Dimensions
P-313.30 PicoCube™ XYZ Scanner	1 x 1 µm (X,Y) 0.8 µm (Z)	0.02 nm (X, Y) 0.14 nm (Z)	30 x 30 x 29.4 mm Moved platform 20 x 20 mm

P-628K Long-Travel XY Piezo Stage with Nanometer Flatness

Novel Active Z-Axis Design Provides Real Time Runout Compensation

The P-628KHFS with an active Z-axis provides an improved straightness of travel with only 9.5 mm added height compared to an P-628.2 nanopositioning stage

- **Closed-Loop Travel Range 800 x 800 µm (up to 1500 µm Possible)**
- **Improved Straightness of Travel <1nm**
- **High-Precision, Cost-Efficient**
- **Resolution to 0.1 nm, 0.02 % Positioning Accuracy**
- **Frictionless, High-Precision Flexure Guiding System**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**

Model	Travel ranges	Unload resonant frequency	Load capacity	Dimensions
P-628KHFS High Flatness XY Stage	800 x 800 µm (X, Y)	75 Hz (X), 105 Hz (Y)	10 N	80 x 80 x (9.5 + 30) mm

P-915K Fast XY Piezo Scanner

Cost-Effective OEM Slide for Imaging

The fast P-915KXYS open-loop XY scanner is ideally suited for image enhancement e.g. for CCD chips

- For Pixel Sub-Stepping to Enhance Image Resolution
- Compact Design: 40 x 60 x 7 mm
- Highly Cost-Efficient Open-Loop Design
- Travel Ranges to 4 x 4 µm
- Parallel Kinematics for Enhanced Dynamics and Better Multi-Axis Accuracy

Model	Travel	Resolution	Load capacity	Dimensions
P-915KXYS XY Scanner	4 x 4 µm	0.4 nm	50 g	40 x 60 x 7 mm

P-915K High-Dynamics XY Piezo Scanner

Cost-Effective OEM Slide with Large Aperture for Imaging Applications

The P-915KHDS XY scanning stage is driven by 4 PICMA® piezo actuators to provide high stiffness, high dynamics and superior lifetime

- Direct Drive for High Dynamics
- Scanning Stage for Pixel Sub-Stepping: Enhances Image Resolution
- Cost-Efficient Design
- 15 x 15 µm Travel Range
- Load Capacity to 5 N
- Clear Aperture 30 x 45 mm

Model	Travel range	Resolution	Resonant frequency	Dimensions
P-915KHDS High-Dynamics XY Scanner	15 x 15 µm	0.1 nm	1850 Hz	Baseplate 85 x 54 mm Moved platform 69 x 69 mm Clear aperture 30 x 45 mm

P-915K Vacuum Compatible XYZ Piezo Scanner

Large Clear Aperture, High-Dynamics, High-Load Nanopositioner

The P-915KLVS high-dynamics scanner offers a very large clear aperture of 200 x 200 mm

- Vacuum Compatible to 10^{-6} hPa
- Direct Metrology with Capacitive Sensors
- Excellent Straightness: <0.1 µrad Runout
- Frictionless, High-Precision Flexure Guiding System
- Direct Metrology with Capacitive Sensors

Model	Travel	Re-solution	Resonant frequency	Load capacity	Dimensions
P-915KLVS Large XYZ Scanner	100 x 100 x 100 µm	1 nm	110 Hz (X,Y) 230 Hz (Z)	50 kg	340 x 340 x 60 mm Clear aperture 200 x 200 mm

P-587 6-Axis Precision Piezo Stage

Long Scanning Range, Direct Position Measurement

P-587 piezo-driven parallel-kinematics nanopositioning / scanning stage with E-710.6CD 6-axis digital controller

- **For Surface Metrology, Scanning and Positioning in all Six Degrees of Freedom**
- **800 x 800 x 200 µm Linear Range**
- **Up to 1 mrad Rotational Range**
- **Parallel-Kinematics / Metrology for Enhanced Responsiveness / Multi-Axis Precision**
- **Direct Metrology with Capacitive Sensors for Highest Linearity**
- **Outstanding Lifetime Due to PICMA® Piezo Actuators**
- **Frictionless, High-Precision Flexure Guiding System**
- **Active Trajectory Control in All 6 Degrees of Freedom**

The P-587.6CD is a unique, highly accurate, 6-axis scanning and positioning system based on piezo flexure drives. It provides a linear travel range of 800 x 800 x 200 µm and rotation ranges up to 1 mrad.

Application Examples

- Interferometry
- Metrology
- Nano-imprinting
- Semiconductor testing
- Semiconductor fabrication

Direct Position Measurement with Sub-Nanometer Accuracy

PI's proprietary capacitive sensors measure position directly and without physical contact. They are free of friction and hysteresis, a fact which, in combination with the positioning resolution of well under 1 nm, makes it possible to achieve very high levels of linearity. A further advantage of direct metrology with capacitive sensors is the high phase fidelity and the high bandwidth of up to 10 kHz.

Excellent Guiding Accuracy

Flexures optimized with Finite Element Analysis (FEA) are used to guide the stage. FEA techniques are used to give the design the highest possible stiffness in, and perpendicular to, the direction of motion, and to minimize linear and angular runout. Flexures allow extremely high-precision motion, no matter how minute, as they are completely free of play and friction. A flatness and straightness in the low nanometer range is achieved, important for surface metrology applications.

Parallel Kinematics and Metrology with Capacitive Sensors for High Trajectory Fidelity

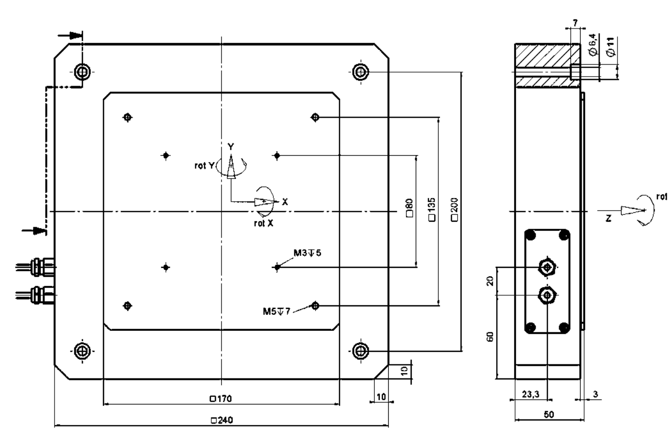
In a parallel kinematics multi-axis system, all actuators act directly on one moving platform. This means that all axes move the same minimized mass and can be designed with identical dynamic properties. Parallel kinematics systems have additional advantages over serially stacked systems, including more-compact construction and no cumulative errors from the individual axes. Multiaxis nanopositioning systems equipped with direct metrology are able to measure platform position in all degrees of freedom against one common reference. In such systems, undesirable motion from one actuator in the direction of another (cross-talk) is detected immediately and actively compensated by the servo-loops. This Active Trajectory Control Concept can keep deviation from a trajectory to under a few nanometers, even in dynamic operation.

Ordering Information

P-587.6CD
6-Axis Nanopositioning System with Long Travel Range, 800 x 800 x 200 µm, ±0.5 mrad, Parallel Metrology, Capacitive Sensors

Automatic Configuration

PI digital piezo controllers and nanopositioning stages with ID-Chip can be operated in any combination, supported by the AutoCalibration function of the controller. Individual stage data and optimized servo-control parameters are stored in the ID-Chip and are read out automatically by the digital controllers.



P-587 dimensions in mm

Technical Data

Model	P-587.6CD	Tolerance
Active axes	X, Y, Z, θ_X, θ_Y, θ_Z	
Motion and positioning		
Integrated sensor	Capacitive	
Closed-loop travel X, Y	800 µm	
Closed-loop travel	200 µm	
Closed-loop tip/tilt angle	±0.5 mrad	
Closed-loop θZ angle	±0.5 mrad	
Closed-loop / open-loop resolution X, Y	0.9 / 2.2 nm	typ.
Closed-loop / open-loop resolution Z	0.4 / 0.7 nm	typ.
Closed-loop / open-loop resolution θ_X, θ_Y	0.05 / 0.1 µrad	typ.
Closed-loop / open-loop resolution θ_Z	0.1 / 0.3 µrad	typ.
Linearity X, Y, Z	0.01 %	typ.
Linearity θ_X, θ_Y, θ_Z	0.1 %	typ.
Repeatability X, Y	±3 nm	typ.
Repeatability	±2 nm	typ.
Repeatability θ_X, θ_Y	±0.1 µrad	typ.
Repeatability θ_Z	±0.15 µrad	typ.
Flatness	<15 nm	typ.
Mechanical properties		
Stiffness X / Y / Z	0.55 / 0.55 / 1.35 N/µm	
Unloaded resonant frequency in X / Y / Z	103 / 103 / 235 Hz	±20 %
Resonant frequency @ 500 g in X / Y / Z	88 / 88 / 175 Hz	±20 %
Resonant frequency @ 2000 g in X / Y / Z	65 / 65 / 118 Hz	±20 %
Push/pull force capacity in motion direction	50 / 10 N	Max.
Drive properties		
Ceramic type	PICMA®	
Electrical capacitance in X / Y / Z	81 / 81 / 18.4 µF	±20 %
Dynamic operating current coefficient (DOCC) in X, Y, θ_Z	12.6 µA/(Hz • µm)	±20 %
Dynamic operating current coefficient (DOCC) Z, θ_X, θ_Y	11.5 µA/(Hz • µm)	±20 %
Miscellaneous		
Operating temperature range	-20 to 80 °C	
Material	Aluminum	
Dimensions	240 x 240 x 50 mm	
Mass	7.2 kg	±5 %
Cable length	1.5 m	±10 mm
Sensor / voltage connection	2 x Sub-D Special	
Recommended controller / amplifier	E-710.6CD (p. 2-128) or E-712.6CD (p. 2-140) digital controller	

The maximum rotational angle in θ_Z is 8 mrad, the tilt angles around X and Y rate 3 mrad.
Due to parallel kinematics linear motion is not possible when the stage is in extreme position.

Notes on Specifications for Piezo Stages, Systems and Actuators

Motion and positioning

Performance specifications are valid for room temperature (22 ±3 °C) and closed-loop systems are calibrated at this temperature (specifications for different operating temperatures on request). Recalibration is recommended for operation at a significantly higher or lower temperature. Custom designs for ultra-low or ultra-high temperatures on request.

Integrated feedback sensor

Absolute measuring capacitive and SGS sensors are used to provide position information to the controller. For details see the tutorial "Piezoelectrics in Positioning" section (see p. 2-188 *ff*).

Open-loop travel for PICMA® Ceramic Equipped Piezo Stages and Actuators

Typical open-loop travel at 0 to 100 V operating voltage. Max. recommended operating voltage range is -20 to +120 V (extremes for short durations only).

Open-loop travel for PICA™ Ceramic Equipped Piezo Actuators

Typical open-loop travel of high-voltage piezo actuators at 0 to +1000 V operating voltage. Voltages in excess of +750 V should not be applied for long durations. Operation in the range of -200 to +750 V is recommended for maximum lifetime and displacement.

Closed-loop travel for PICMA® Ceramic Equipped Piezo Stages and Actuators

Travel provided in closed-loop operation. PI piezo amplifiers have an output voltage range of -20 to +120 V or -30 to +135 V to provide enough margin for the servo-controller to compensate for load changes, etc.

Open-loop / closed-loop resolution

Resolution of piezo flexure stages is basically infinitesimal because it is not limited by stiction or friction. Instead of resolution, the noise-equivalent motion is specified. Values are typical results (RMS, 1 σ), measured with E-503/E-508) amplifier module in E-500/501 chassis.

Full-range repeatability (typ.)

Typical values in closed-loop mode (RMS, 1 σ). Repeatability is a percentage of the total distance or angle traveled. For small ranges, repeatability is significantly better.

Pitch / Yaw / Roll / Rotational Runout

Typical rotational off-axis error; sometimes associated with a particular motion axis, as in "Rotational runout (Z motion)".

Straightness / Flatness / Crosstalk

Typical linear off-axis error; sometimes associated with a particular motion axis, as in "Crosstalk (Z motion)".

Mechanical properties

Stiffness

Static large-signal stiffness of the stage in operating direction at room temperature. Small-signal stiffness and dynamic stiffness may differ because of effects caused by the active nature of piezoelectric material, compound effects, etc. For details see the tutorial "Piezoelectrics in Positioning" section (see p. 2-171 *ff*).

Unloaded resonant frequency

Lowest resonant frequency in operating direction (does not specify the maximum operating frequency). For details see the tutorial "Piezoelectrics in Positioning" section (see p. 2-171 *ff*).

Resonant frequency with load

Resonant frequency of the loaded system.

Push/pull force capacity (in operating direction)

Specifies the maximum forces that can be applied to the system along the active axis. Limited by the piezoceramic material and the flexure design. If larger forces are applied, damage to the piezoceramic, the flexures or the sensor can occur. The force limit must also be considered in dynamic applications.

Example: the dynamic forces generated by sinusoidal operation at 500 Hz, 20 µm peak-to-peak, 1 kg moved mass, are approximately ±100 N. For details see the tutorial "Piezoelectrics in Positioning" section (see p. 2-171 *ff*).

Load capacity

Maximum vertical load, when the stage is mounted horizontally. Limited by the flexures or the load capacity of the piezo actuators.

Lateral force limit

Maximum lateral force orthogonal to the operating direction. Limited by the piezoceramics and the flexures. For XY stages the push/pull force capacity of the other module (in its operating direction) limits the lateral force that can be tolerated.

Torque limit (θ_X, θ_Y, θ_Z)

Maximum torque that can be applied to the system before damage occurs. Limited by the piezo ceramics and the flexures

Drive properties

Electrical capacitance

The piezo capacitance values indicated in the technical data tables are small-signal values (measured at 1 V, 1000 Hz, 20 °C, no load). Large-signal values at room temperature are 30 to 50 % higher. The capacitance of piezoceramics changes with amplitude, temperature, and load, up to 200 % of the unloaded, small-signal capacitance at room temperature. For detailed information on power requirements, refer to the amplifier frequency-response graphs in the "Piezo Drivers / Servo Controllers" (see p. 2-99 *ff*) section of this catalog.

Dynamic Operating Current Coefficient (DOCC)

Average electrical current (supplied by the amplifier) required to drive a piezo actuator per unit frequency and unit displacement (sine-wave operation). For example to find out if a selected amplifier can drive a given piezo stage at 50 Hz with 30 µm amplitude, multiply DOC coefficient by 50 x 30 and check if the result is smaller or equal to the output current of the selected amplifier. For details see the tutorial "Piezoelectrics in Positioning" section (see p. 2-169 *ff*).

Miscellaneous

Operating temperature range

Typically -20 to +80 °C, the temperature range indicates where the piezo stage may be operated without damage. Nevertheless, recalibration or zero-point-adjustment may be required if the system is operated at different temperatures. Performance specifications are valid for room temperature range.

Material

Flexure stages are usually made of anodized aluminum or stainless steel. Small amounts of other materials may be used internally (for spring preload, piezo coupling, mounting, thermal compensation, etc.).

Al: Aluminum
N-S: Non-magnetic stainless steel
S: Ferromagnetic stainless steel
I: Invar
T: Titanium

Voltage connection

Standard operating voltage connectors are LEMO and sub-D type connectors.

Low-voltage piezos :
LEMO FFA.00.250, male. Cable: coaxial, RG 178, Teflon coated, 1 m

Sub-D special connectors include lines for stage ID information used by digital controllers with AutoCalibration function

Sensor connection

Standard sensor connectors are LEMO and sub-D type connectors.
Sub-D special connectors contain both piezo voltage and sensor connections.

For extension cables and adapters, see "Accessories" p. 2-89 *ff*, in the "Piezo Drivers / Servo Controllers" section.

Fast Steering Mirrors / Active Optics

Selection Guide: Piezo Steering Mirrors

Fast Steering Mirrors (FSM), Tip/Tilt Platform & Active Optics

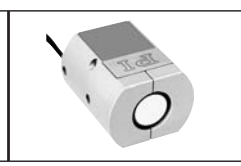
Piezo-driven tip/tilt platforms and scanners (steering mirrors, beam deflectors, phase shifters) provide higher accelerations and bandwidth than other actuators such as voice-coils or galvos. All are flexure-guided for zero friction and stiction and excellent guiding accuracy. Multiaxis models are parallel-kinematic designs with coplanar axes. Open- and closed-loop models with strain gauge and capacitive sensors (highest precision) are available.

PI FSM's provide resolution down to nanoradians and excellent position stability. They can perform optical beam steering over ranges of up to 120 mrad, and have extremely low response times (milliseconds to microseconds). They are ideal for dynamic operation (e. g. tracking, scanning, drift and vibration cancellation) as well as static positioning of optics and samples.

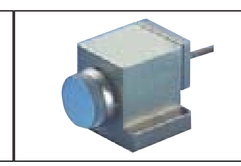
Models	Description	Axes	Tilt Angle / opt Deflection [mrad]	Linear Travel [µm]	Sensor	Page
S-310, S-316	Clear aperture, 5 models, open- and closed-loop, Z-actuators and Z/tip/tilt versions, for optics to 1" diameter	1 & 3	0.6 / 1.2 or 1.2 / 2.4	6 / 12	SGS	2-94
S-325	3-axis (tripod) Z/tip/tilt platform for optics to 1" diameter	3	5 / 10	30	SGS	2-92
S-334	Ultra-compact 2-axis FSM with largest optical deflection to 120 mrad. With 10 mm mirror	2	60 / 120		SGS	2-90
S-330	High-dynamics tip/tilt FSM with two orthogonal axes, for optics to 2" diameter. 3 models	2	2 / 4, 5 / 10, 10/ 20	–	SGS	2-88
S-224, S-226	With mirror, compact, very fast, available with sensor or without	1	to 2.2 / 4.4	–	SGS	2-96
S-303	Phase Shifters. Extremely precise, 25 kHz resonant frequency, optional sensors	1	–	3	Capacitive	2-96
S-323	Z/tip/tilt platform, high dynamics	2	3 / 6	30	Capacitive	2-96
P-541.Z	Low-profile Z & Z/tip/tilt platform, 80 x 80 mm aperture	3	1	100	Capacitive / SGS	2-44
P-528	Z-axis and tip/tilt piezo stage platforms 66 x 66 mm clear aperture	3	4	200	Capacitive	2-46
N-510	Tripod Z-tip/tilt Nanopositioning Platform	3	10 / 20	1300	Linear encoder	1-17

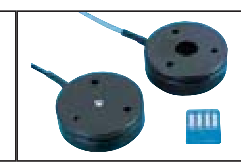

S-310, S-316 Z/tip/tilt platforms with aperture


S-325 Z/Tip/tilt platform

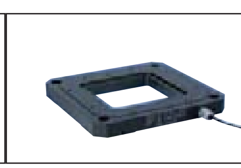

S-334 2-Axis FSM, very large optical deflection

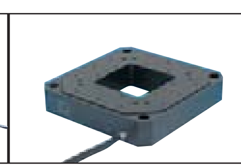

S-330 Tip/tilt steering mirror platforms, high dynamics, 1" diameter


S-224, S-226 With mirror, compact, fast


S-303 Phase shifters, 3 µm, picometer resolution


S-323: Z/tip/tilt platform with capacitive sensors


P-541.Z Low-profile large aperture Z/tip/tilt piezo stage


P-528 Large aperture Z/tip/tilt piezo stage


N-510 Tripod Z/tip/tilt nanopositioning platform


Astronomy: High bandwidth 8" secondary steering mirror and long range 6-axis alignment system

More tip/tilt piezo stages see p. 2-25 *ff*
Notes on specifications see p. 2-97 *ff*

Piezo Tip/Tilt Mirrors Fundamentals

Single Axis Designs

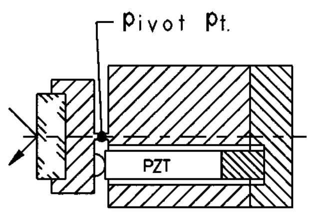


Fig. 1. Single-flexure, single-piezo actuator tilt platform design

Single-Axis Systems / Scanners

Two designs of single-axis (θ_x) tilt platforms are available:

I. Single-Flexure, Single-Actuator Tilt Platform

Examples: S-224 and S-226.

The platform is supported by one flexure and pushed by one linear piezo actuator (see Fig. 1). The flexure determines the pivot point and doubles as a preload for the piezo actuator. The advantages of the single-flexure, single-actuator design are the straightforward construction, low cost and small size. If angular stability over a wide temperature range is a critical issue, the differential piezo drive is recommended.

II. Differential-Piezo-Drive Tilt Platform

This design features two piezo actuators operating in push/pull mode supporting the platform (see Fig. 2). The actuators are wired in a bridge which is supplied with a constant and a variable drive voltage. The case features integrated zero-friction, zero-stiction flexures which assure excellent guiding accuracy.

The differential design exhibits excellent angular stability over a wide temperature range. With this arrangement, temperature changes only affect the vertical position of the platform (piston motion) and have no influence on the angular position. In the closed-loop models, availability of two sensor signals permits better linearity and resolution.

A variety of single- and multi-axis implementations is possible.

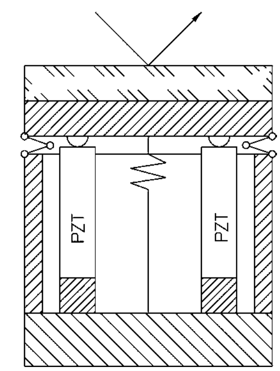


Fig. 2. Design of a differential-piezo-drive tilt platform

Multi-Axis Tip/Tilt Systems / Scanners

PI offers two standard designs, both using parallel kinematics. Parallel kinematics systems have the following advantages over serial systems: only one moving platform, fixed pivot point, better dynamics, smaller form-factor. In addition, the design offers better linearity than attainable with two single-axis systems (e.g. two galvoscanners) in a stacked configuration.

I. Piezo Tripod Z/Tip/Tilt Platform

Examples: S-315 and S-316, S-325.

The platform is supported by three piezo actuators spaced at 120° intervals. Because expansion of an individual actuator affects both θ_x and θ_Y, more complex control algorithms are required. With coordinate transformation, platform position commands can be resolved into targets for individual actuators (see the equations and Fig. 3 for details). The piezo tripod has one advantage over the differential drive: in addition to tilt motion, it allows active vertical control (piston motion) of the platform—an important feature for applications involving optical path-length adjustment (phase-shifting).

Also, the design allows for a central clear aperture, ideal for transmitted-light applications. As with the differential drives, temperature changes have no effect on the angular stability.

II. Differential-Piezo-Drive Tip/Tilt Platform

Examples:
S-334, S-330, S-340.

The platform is driven by two pairs of piezo actuators arranged at 90° angles. Each pair is controlled as a unit in push-pull mode. The four actuators are connected in a bridge circuit and supplied with one fixed and two variable voltages. Because each actuator pair is parallel to one of the orthogonal tip/tilt axes θ_x and θ_Y, no coordinate transformation is required.

Like the piezo tripod design, the differential drive exhibits excellent angular stability over a wide temperature range. In the closed-loop models, availability of two sensor signals permits better linearity and resolution.

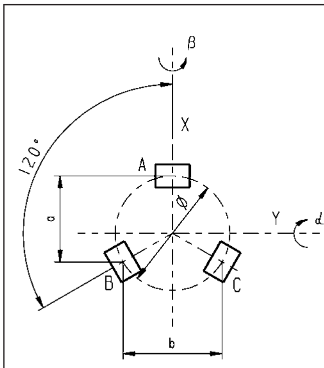


Fig. 3. Piezo tripod drive: A, B, C are the linear displacements of the respective actuators

$$\alpha = \frac{2A - (B+C)}{2a}$$

$\beta = (B-C) / b$

$z = (A+B+C) / 3$

Example:
S-315 tip/tilt platform (see page 3-16).
Ø = 13.9 mm
a = 10.4 mm
b = 12.0 mm
A, B, C 0 to 12 µm

Dynamic Behavior of Piezo Steering Mirrors

The maximum operating frequency of a tilt platform is heavily dependent on its mechanical resonant frequency. The performance characteristics of the amplifier, servo-controller and sensors are also very important. To estimate the effective resonant frequency of the tilt mirror system (platform + mirror), the moment of inertia of the mirror substrate must first be calculated.

Moment of inertia of a rotationally symmetric mirror:

$$I_M = m\left[\frac{3R^2 + H^2}{12} + \left(\frac{H}{2} + T\right)^2\right]$$

Moment of inertia of a rectangular mirror:

$$I_M = m\left[\frac{L^2 + H^2}{12} + \left(\frac{H}{2} + T\right)^2\right]$$

where:

m = mirror mass [g]

I_M = moment of inertia of the mirror [g · mm²]

L = mirror length perpendicular to the tilt axis [mm]

H = mirror thickness [mm]

T = distance, pivot point to platform surface (see technical data table for individual model) [mm]

R = mirror radius [mm]

Using the resonant frequency of the unloaded platform (see individual technical data table) and the moment of inertia of the mirror substrate, the system resonant frequency is calculated according to the following equation:
Resonant frequency of a tilt platform/mirror system

$$f' = \frac{f_0}{\sqrt{1 + I_M/I_0}}$$

where:

f' = resonant frequency of platform with mirror [Hz]

f_0 = resonant frequency of unloaded platform [Hz]

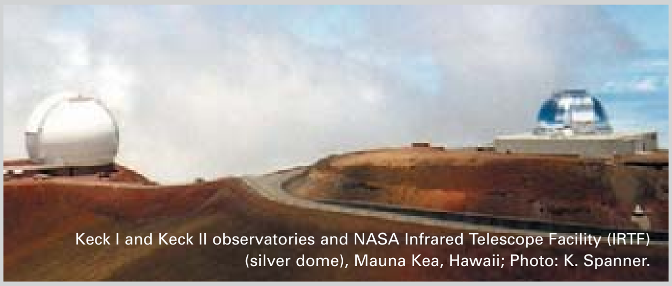
I_0 = moment of inertia of the platform (see technical data table for the individual model) [g · mm²]

I_M = moment of inertia of the mirror [g · mm²]

For more information on static and dynamic behavior of piezo actuators, see pp. 2-196 *ff.*

Custom Systems for Telescopes

PI Steering Mirrors and Alignment Systems in Astronomy


Keck I and Keck II observatories and NASA Infrared Telescope Facility (IRTF) (silver dome), Mauna Kea, Hawaii; Photo: K. Spanner.


The Horsehead Nebula; Photo: Brian Lula.

Resolution in large earthbound telescopes is limited by atmospheric turbulence and vibrations. During the last 15 years PI has designed several large-aperture tip/tilt systems for image stabilization. Piezoelectrically driven active secondary mirrors can improve the effective resolution up to 1000 % by correcting for these image shifts in real time, especially during long integrations with weak light sources.

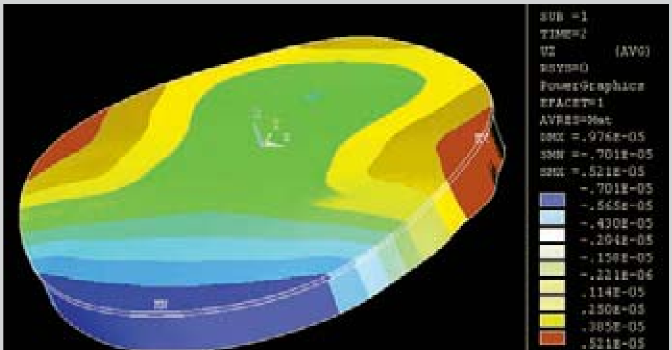
Momentum Compensation
Due to the inertia of the large mirrors and the high accelerations required to correct for image fluctuations, significant forces can be induced in the telescope structure, causing unwanted vibrations. PI has developed momentum compensation systems integrated into the tip/tilt platforms which cancel undesirable vibrations and thus offer significantly better stabilization than uncompensated systems.


Active tip/tilt mirror system for the Keck Outrigger telescope in Hawaii. The units are controlled by a high-performance digital controller with a fiber optic interface (not shown).
Mirror diameter: 250 mm
Tip/tilt range: ±150 µrad
Resolution: nanoradian range
Position measurement: capacitive

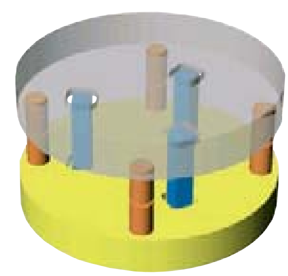
Example of a combined high-speed piezo tip/tilt plaftform with a long range, low-speed 6-axis hexapod alignment system

High-Resolution Linear Actuators
273 PI actuators are used for tip/tilt/piston movement of segmented mirror panels in the SALT Telescope.
Features: 16 nm design resolution; 0.15 µm minimum incremental motion; non-rotating tip, compact design.

Active Optics / Steering Mirrors



FEA analysis of a mirror platform shows nanometer-range deformation due to gravity.



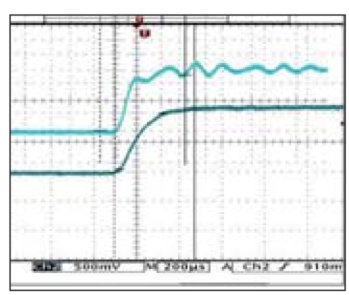
Basic design of a piezo tip/tilt platform featuring three actuators and four sensors. Large platforms handle optics to Ø500 mm

Fast Steering Mirrors: Why Piezo?

- Faster and more precise than conventional actuators
- Better stability through differential drive designs
- Stiff mechanical interface, 1 DOF only
- Tip/tilt & piston movements
- Up to Ø50 cm apertures

Applications of Fast Steering Mirrors

- Fast beam steering, alignment, switching
- Image resolution enhancement (pixel multiplication, dithering)
- Optical path length stabilization
- Vibration cancellation (laser systems, imaging)
- Interferometry, Fabry-Perot filters
- Image stabilization, high speed background subtraction
- Laser beam stabilization (resonators, optical setups)
- Laser beam scanning (lithography, optical setups)
- Laser beam steering and tracking (telecommunication satellites, etc.)
- Bore-sight systems
- Dynamic error correction (e. g. in polygon scanning mirrors)
- Mass storage device testing and manufacture



Fast: 200 µs step response. Standard (top), optimized amplifier (bottom), 0.2 µrad steps

Test & Metrology Protocol for Piezo Systems
Getting What You Bargained For

Linear Actuators & Motors

Nanopositioning / Piezoelectrics

Piezo Flexure Stages / High-Speed Scanning Systems
Linear
Vertical & Tip/Tilt
2- and 3-Axis
6-Axis

Fast Steering Mirrors / Active Optics

Piezo Drivers / Servo Controllers
Single-Channel
Multi-Channel
Modular
Accessories

Piezoelectrics in Positioning

Nanometrology

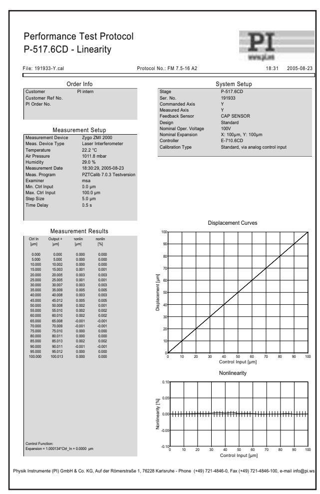
Micropositioning

Index

Piezo nanopositioning systems are significant investments and PI believes in optimizing the performance of every customer's system. PI individually tests every stage and optimizes the static and dynamic performance for the customer's application. The metrology test protocol is part of the system's delivery package. It shows the customer what the performance of the system was at the time of delivery and which system components belong together. For PI every metrology procedure and its recording is a quality assurance instrument, and only nanopositioning systems which meet their specifications will leave the premises.

Furthermore, PI makes significant continuing investments in improved-quality, higher-performance nanometrology equipment so that we can deliver better value to our customers.

Because a nanomechanism can only be as accurate as the equipment it was tuned and tested with, PI closed-loop stages are measured exclusively with prestigious Zygo interferometers. PI's nanometrology metrology laboratories are seismically, electromagnetically and thermally isolated, with temperatures controlled to better than 0.25 °C / 24 hrs. We are confident that our metrology capabilities and procedures are the benchmark for the industry.



Performance Test Protocol
P-517.6CD - Linearity

File: 191933-Y.cal | Protocol No.: FM 7.5-16 A2 | 18:31 2005-08-23

Order Info

Customer	PI intern
Customer Ref No.	
PI Order No.	

System Setup

Stage	P-517.6CD
Ser. No.	191933
Commanded Axis	Y
Measured Axis	Y
Feedback Sensor	CAP SENSOR
Design	Standard
Nominal Oper. Voltage	100V
Nominal Expansion	X: 100µm, Y: 100µm
Controller	E-710.6CD
Calibration Type	Standard, via analog control input

Measurement Setup

Measurement Device	Zygo ZMI 2000
Meas. Device Type	Laser Interferometer
Temperature	22.2 °C
Air Pressure	1011.8 mbar
Humidity	29.0 %
Measurement Date	18:30:29, 2005-08-23
Meas. Program	PZTCalib 7.0.3 Testversion
Examiner	msa
Min. Ctrl Input	0.0 µm
Max. Ctrl Input	100.0 µm
Step Size	5.0 µm
Time Delay	0.5 s

Measurement Results

Ctrl In [µm]	Output + [µm]	nonlin [µm]	nonlin [%]
0.000	0.000	0.000	0.000
5.000	5.000	0.000	0.000
10.000	10.002	0.000	0.000
15.000	15.003	0.001	0.001
20.000	20.005	0.003	0.003
25.000	25.005	0.001	0.001
30.000	30.007	0.003	0.003
35.000	35.009	0.005	0.005
40.000	40.008	0.003	0.003
45.000	45.012	0.005	0.005
50.000	50.008	0.002	0.001
55.000	55.010	0.002	0.002
60.000	60.010	0.002	0.002
65.000	65.008	-0.001	-0.001
70.000	70.009	-0.001	-0.001
75.000	75.010	0.000	0.000
80.000	80.011	0.000	0.000
85.000	85.013	0.002	0.002
90.000	90.011	-0.001	-0.001
95.000	95.012	0.000	0.000
100.000	100.013	0.000	0.000

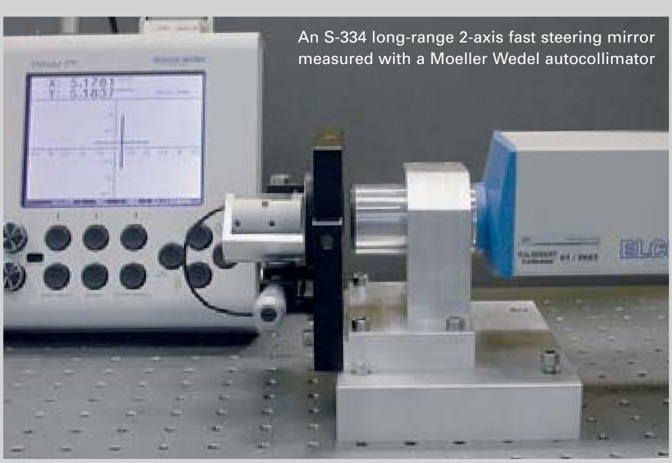
Control Function:
Expansion = 1.000134*Ctrl_In + 0.0000 µm

Displacement Curves

Nonlinearity

Physik Instrumente (PI) GmbH & Co. KG, Auf der Römerstraße 1, 76228 Karlsruhe - Phone: (+49) 721-4846-0, Fax (+49) 721-4846-100, e-mail info@pi.ws

All PI nanopositioning systems come with extensive system performance documentation



An S-334 long-range 2-axis fast steering mirror measured with a Moeller Wedel autocollimator

An S-340 2-axis fast steering mirror platform measured with a Zygo interferometer

S-330 Piezo Tip/Tilt-Platform

High-Dynamics, Large-Angle Piezo Tip/Tilt Platforms for Fast Steering Mirrors

S-330 tip/tilt platforms with optical beam deflection angles of 4, 10 and 20 mrad

- **Resolution to 20 nrad, Excellent Position Stability**
- **Optical Beam Deflection to 20 mrad (>1°)**
- **Higher Dynamics, Stability & Linearity Through Parallel-Kinematics Design**
- **Sub-Millisecond Response**
- **For Mirrors up to 50 mm Diameter**
- **Closed-Loop Versions for Better Linearity**
- **Excellent Temperature Stability**

S-330 piezo tip/tilt platforms are fast and compact tip/tilt units, providing precise angular motion of the top platform around two orthogonal axes.

Application Examples

- Image processing / stabilization
- Interlacing, dithering
- Laser scanning / beam steering
- Optics
- Optical filters / switches
- Beam stabilization

These flexure-guided, piezoelectric platforms can provide higher accelerations than other implementations, enabling step response times in the sub-millisecond range. Closed-loop and open-loop versions with 3 different tilt ranges up to 10 mrad (20 mrad optical deflection) are available.

Parallel-kinematics design for improved stability, linearity and dynamics

PI piezo tip/tilt mirror systems are based on a parallel-kinematics design with coplanar axes and a single moving platform. Two pairs of differentially-driven piezo actuators are employed to provide the highest possible angular stability over a wide temperature range. Compared to stacked, (two-stage) piezo or galvo scanners, the single-platform design provides several advantages: smaller package size, identical dynamic performance in both axes, faster response and better linearity. It also prevents polarization rotation.

Fast Piezo Ceramic Drives

Frictionless, flexure-guided piezo ceramic drives provide higher accelerations than other actuators, such as voice-coils, and enable response in the millisecond range and below. Piezo actuators do not require energy to hold a position. The resulting low heat signature is a great advantage in infrared imaging systems like those used in astronomy.

Closed Loop Operation

For high stability and repeatability, absolute-measuring strain gauge sensors (SGS) are applied to appropriate locations on the drive train. They provide a high-bandwidth, position feedback signal to the controller. The sensors are connected in a bridge configuration to eliminate thermal drift, and assure optimal position stability. Open-loop systems are also available.

Ordering Information

S-330.2SL
High-Dynamics Piezo Tip/Tilt Platform, 2 mrad, SGS, LEMO Connector

S-330.2SD
High-Dynamics Piezo Tip/Tilt Platform, 2 mrad, SGS, Sub-D Connector

S-330.20L
High-Dynamics Piezo Tip/Tilt Platform, 2 mrad, Open-Loop, LEMO Connector

S-330.4SL
High-Dynamics Piezo Tip/Tilt Platform, 5 mrad, SGS, LEMO Connector

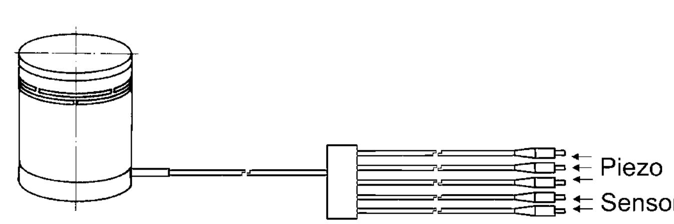
S-330.4SD
High-Dynamics Piezo Tip/Tilt Platform, 5 mrad, SGS, Sub-D Connector

S-330.40L
High-Dynamics Piezo Tip/Tilt Platform, 5 mrad, Open-Loop, LEMO Connector

S-330.8SL
High-Dynamics Piezo Tip/Tilt Platform, 10 mrad, SGS, LEMO Connector

S-330.8SD
High-Dynamics Piezo Tip/Tilt Platform, 10 mrad, SGS, Sub-D Connector

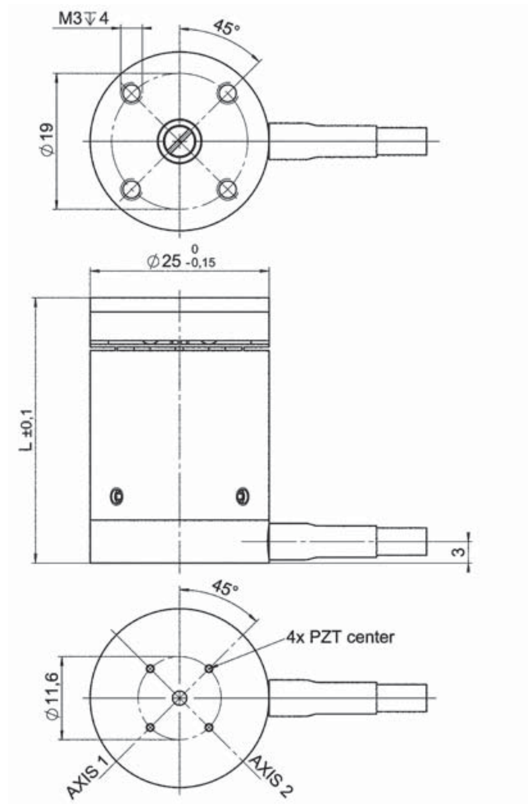
S-330.80L
High-Dynamics Piezo Tip/Tilt Platform, 10 mrad, Open-Loop, LEMO Connector



Circuit diagram and cable configuration of the S-330.xSL closed-loop versions. The S-330.xSD models feature a single Sub-D connector and can be operated by the E-616 controller.

Ceramic Insulated Piezo Actuators Provide Long Lifetime

Highest possible reliability is assured by the use of award-winning PICMA® multilayer piezo actuators. PICMA® actuators are the only actuators on the market with ceramic-only insulation, which makes them resistant to ambient humidity and leakage-current failures. They are thus far superior to conventional actuators in reliability and lifetime.



S-330 dimensions in mm

Technical Data

Model	S-330.2SL	S-330.4SL	S-330.8SL	S-330.2SD S-330.4SD S-330.8SD	S-330.20L S-330.40L S-330.80L	Units	Tolerance
Active axes	Θ_X, Θ_Y	Θ_X, Θ_Y	Θ_X, Θ_Y	Θ_X, Θ_Y	Θ_X, Θ_Y		
Motion and positioning							
Integrated sensor	SGS	SGS	SGS	SGS	–		
Open-loop tip/tilt angle, -20 to +120 V	3.5	7	15	as SL version	as SL version	mrad	min.
Closed-loop tip/tilt angle	2	5	10	as SL version	–	mrad	
Open-loop tip/tilt angle resolution	0.02	0.1	0.2	as SL version	as SL version	µrad	typ.
Closed-loop tip/tilt resolution	0.05	0.25	0.5	as SL version	–	µrad	typ.
Linearity in Θ_X, Θ_Y	0.1	0.2	0.25	as SL version	–	%	typ.
Repeatability Θ_X, Θ_Y	0.15	0.5	1	as SL version	–	µrad	typ.
Mechanical properties							
Unloaded resonant frequency (Θ_X, Θ_Y)	3.7	3.3	3.1	as SL version	as SL version	kHz	±20%
Resonant frequency loaded in Θ_X, Θ_Y (with 25 x 8 mm glass mirror)	2.6	1.6	1.0	as SL version	as SL version	kHz	±20%
Distance of pivot point to platform surface	6	6	6	6	6	mm	±1 mm
Platform moment of inertia	1530	1530	1530	1530	1530	g x mm²	±20%
Drive properties							
Ceramic type	PICMA®	PICMA®	PICMA®	PICMA®	PICMA®		
Electrical capacitance	3/axis	6/axis	12.5/axis	as SL	as SL	µF	±20%
Dynamic operating current coefficient	0.22/axis	0.4/axis	0.8/axis	as SL	as SL	µA/(Hz • mrad)	±20%
Miscellaneous							
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80	°C	
Material case	Stainless steel	Stainless steel	Stainless steel	Stainless steel	Stainless steel		
Material platform	Invar	Invar	Invar	Invar	Invar		
Mass	0.2	0.38	0.7	as SL version	as SL version	kg	±5%
Cable length	1.5	1.5	1.5	1.5	1.5	m	±10 mm
Sensor / voltage connection	LEMO	LEMO	LEMO	Sub-D connector	LEMO		

Recommended controller / amplifier
Versions with LEMO connector: modular piezo controller system E-500 (p. 2-142) with amplifier module E-503.00S (three channels) (p. 2-146) or 1 x E-505.00S and 2 x E-505 (high speed applications) (p. 2-147) and E-509 controller (p. 2-152) (optional)
Open-loop: E-663 three channel amplifier (p. 2-136)
Versions with Sub-D connectors: E-616 servo controller for tip/tilt mirror systems (p. 2-132)

S-334 Miniature Piezo Tip/Tilt-Mirror

Fast Steering Mirror with up to 120 mrad Deflection

S-334 Tip/Tilt Mirror System / Scanner Provides Optical Deflection Angle up to 120 mrad

- **Miniature Design**
- **Optical Beam Deflection to 120 mrad (~ 6.8°)**
- **Coplanar Axes & Fixed Pivot Point Eliminate Polarization Rotation**
- **Factory Installed Mirror**
- **Millisecond Response, Resolution to 0.5 µrad**
- **Closed-loop Position Servo-Control for High Accuracy**
- **For Mirrors up to 12.5 mm (0.5") Diameter**
- **Frictionless, High-Precision Flexure Guiding System**
- **Parallel Kinematics for Enhanced Dynamics and Better Multi-Axis Accuracy**

S-334 piezo tip/tilt mirrors / scanners provide extremely large deflection angles in a miniaturized package. These fast steering mirror systems are based on a sophisticated parallel-kinematics design with two coplanar, orthogonal axes and a fixed pivot point.

Large Tip/Tilt Ranges with Excellent Motion Characteristics

The novel flexure/lever design with minimized inertia allows for the exceptionally large tip/tilt range of 60 mrad (50 mrad in closed-loop operation, which is equivalent to 100 mrad optical beam deflection) and very fast response in the millisecond range. These parameters make the system unique in the market of piezo driven tip/tilt mirror systems.

Sub-Microradian Resolution

In addition to the large angles and the high dynamics the S-334 provides sub-micro-radian resolution. The integrated high-resolution, full-bridge strain gauge sensors (SGS) provide absolute position control, excellent repeatability and high linearity, typically better than 0.25 % over the entire travel range.

Differential Drive for Improved Stability and Dynamics

The S-334 is based on a parallel-kinematics design with coplanar axes and a single moving platform. Two pairs of differentially-driven piezo actuators are employed to provide the highest dynamics and position stability over a wide temperature range.

Compared to stacked, (two-stage), piezo or galvo scanners, the single-platform design provides several advantages: smaller package size, identical dynamic performance in both axes, faster response and better linearity. It also prevents polarization rotation.

High Reliability and Long Lifetime

The compact S-334 systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and provide better performance and reliability than conventional piezo actuators. Actuators, guidance and sensors are maintenance-free, not subject to wear and offer extraordinary reliability.

Factory Installed Mirror

The S-334 is equipped with a factory-installed mirror 10 mm in diameter and 2 mm thick (flatness λ/5, reflectivity >98 % from 500 nm to 2 µm).

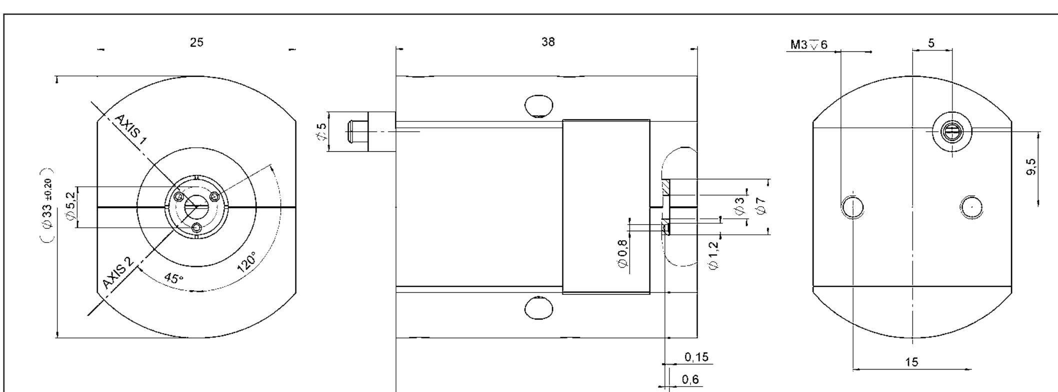
Ordering Information

S-334.2SD
High-Dynamics Piezo Tip/Tilt Platform, 50 mrad, SGS, Sub-D Connector, incl. Mirror

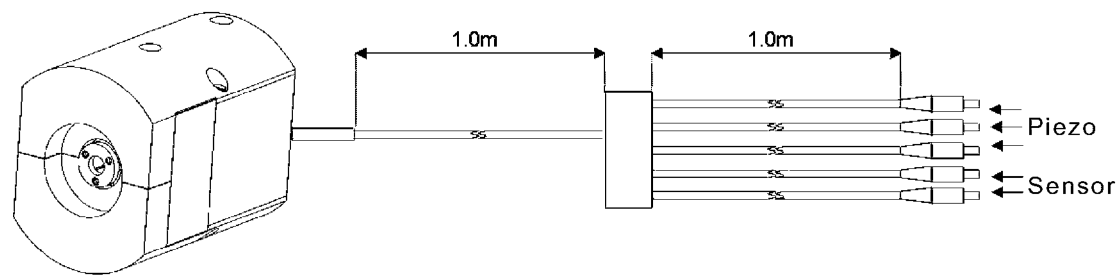
S-334.2SL
High-Dynamics Piezo Tip/Tilt Platform, 50 mrad, SGS, LEMO Connector, incl. Mirror

Application Examples

- Image processing / stablilization
- Interlacing, dithering
- Laser scanning / beam steering
- Optics
- Optical filters / switches
- Scanning microscopy
- Beam stabilization



S-334 dimensions in mm



S-334.2SL cable configuration

Technical Data

Model	S-334.2SL	S-334.2SD	Units	Tolerance
Active Axes	θ_X, θ_Y	θ_X, θ_Y		
Motion and positioning				
Integrated sensor	SGS	SGS		
*Open-loop tilt angle at -20 to +120 V	60	60	mrad	min. (+20 %/-0 %)
*Closed-loop tilt angle	50	50	mrad	
Open-loop resolution	0.5	0.5	µrad	typ.
Closed-loop resolution	5	5	µrad	typ.
Linearity	0.05	0.05	%	typ.
Repeatability	5	5	µrad	typ.
Mechanical properties				
Resonant frequency under load (with standard mirrors)	1.0	1.0	kHz	±20 %
Resonant frequency with 12.5 mm diam. x 2 mm glass mirror	0.8	0.8	kHz	±20 %
Load capacity	0.2	0.2	N	Max.
Distance of pivot point to platform surface	6	6	mm	±1 mm
Platform moment of inertia	1530	1530	g x mm²	±20 %
Standard mirror (mounted)	diameter: 10 mm, thickness: 2 mm, BK7, λ/5, R > 98 % (λ = 500 nm to 2 µm)	diameter: 10 mm, thickness: 2 mm, BK7, λ/5, R > 98 % (λ = 500 nm to 2 µm)		
Drive properties				
Ceramic type	PICMA® P-885	PICMA® P-885		
Electrical capacitance	6	6	µF	±20 %
Miscellaneous				
Operating temperature range	-20 to 80	-20 to 80	°C	
Material casing	Titanium	Titanium		
Mass	0.065	0.065	kg	±5 %
Cable length	2	2	m	±10 mm
Sensor / voltage connection	LEMO connector	25-pin sub-D connector		
Recommended controller / amplifier	Modular piezo controller system E-500 (p. 2-144) with amplifier module E-503.00S (three channels) (p. 2-146) or 1 x E-505.00S and 2 x E-505 (high speed applications) (p. 2-147) and E-509 servo controller (p. 2-152) Open-loop: E-663 three channel amplifier (p. 2-136)	E-616 controller for tip/tilt mirror systems (p. 2-132)		

Resolution of PI piezo tip/tilt platforms is not limited by friction or stiction. Noise equivalent motion with E-503 amplifier. (p. 2-146)
*Mechanical tilt, optical beam deflection is 120 mrad (open loop) and 100 mrad (closed-loop), respectively.

S-325 Piezo Z / Tip/Tilt Platform

High-Speed Tripod System for Mirrors and Optics


S-325.30L piezoelectric fast steering mirror platform / scanner

- **Optical Beam Deflection to 10 mrad, Resolution to 50 nrad**
- **Piston Movement up to 30 µm (for Path Length Adjustment)**
- **Compact Tripod Design with Coplanar Axes Eliminates Polarization Rotation**
- **Sub-Millisecond Responsiveness**
- **Closed-Loop Versions for Higher Precision**
- **For Mirrors up to 25 mm (1") Diameter**
- **Frictionless, High-Precision Flexure Guiding System**
- **Parallel Kinematics for Enhanced Dynamics and Better Multi-Axis Accuracy**

The S-325 Z/tip/tilt platforms and actuators provide high speed and precise movement of the platform in two tilt axes as well as sub-nanometer linear resolution with sub-millisecond response. The design is based on a parallel-kinematics direct-drive piezo tripod (see p. 2-83), and they are especially optimized for industrial applications where 1.000.000.000 motion cycles have to be performed without failure or performance degradation. The systems are designed for mirrors and optics up to 25 mm in diameter and can be mounted in any orientation.

The tripod drive offers optimum angular stability over a wide temperature range. Compared to stacked, (two-stage), piezo or galvo scanners, the single platform design provides several advantages: smaller package size, identical size, identical dynamic performance in all axes, faster response and better linearity. It also prevents polarization rotation.

All three piezo linear actuators can be driven individually (for tip/tilt movement) or in parallel (for vertical movement) by a three-channel amplifier.

High Resolution, Stability and Dynamics

The S-325 offers piston movement of up to 30 µm (ideal for path length adjustment) and mechanical tilt up to 5 mrad (equivalent to 10 mrad optical beam deflection). The zero-friction piezo drives and flexure guidance allow sub-nanometer linear resolution and sub-microradian angular resolution.

Ordering Information

S-325.3SD
High-Dynamics Piezo Z/Tip/Tilt Platform, 5 mrad, 30 µm, SGS, Sub-D Connector

S-325.3SL
High-Dynamics Piezo Z/Tip/Tilt Platform, 5 mrad, 30 µm, SGS, LEMO Connector

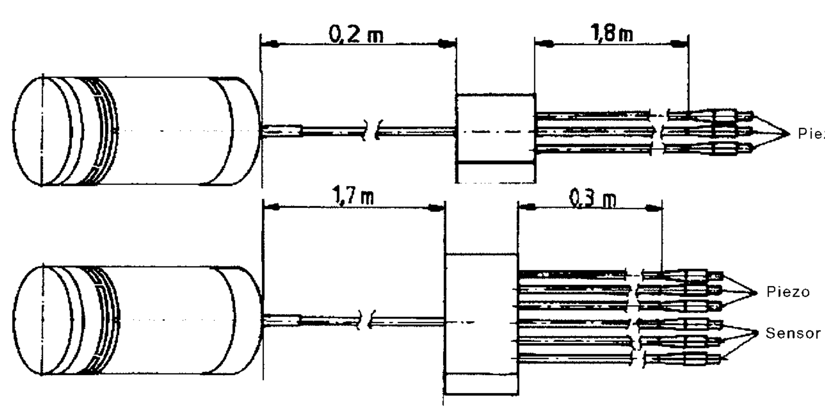
S-325.30L
High-Dynamics Piezo Z/Tip/Tilt Platform, 5 mrad, 30 µm, Open-Loop, LEMO Connector

Open-Loop and Closed-Loop Operation

In open-loop mode, the platform linear motion is roughly proportional to the applied voltage. The S-325.30L open-loop model is ideal for high-bandwidth, high-resolution applications where the absolute angular position is of secondary importance (e. g. for tracking) or where feedback is provided by an external sensor (e. g. CCD, PSD). The S-325.3SL model is equipped with high-resolution strain gauge sensors and provides absolute position control, high linearity and high repeatability. The new E-616 controller/driver module (see p. 2-132) is ideally suited for tip/tilt OEM applications.

Application Examples

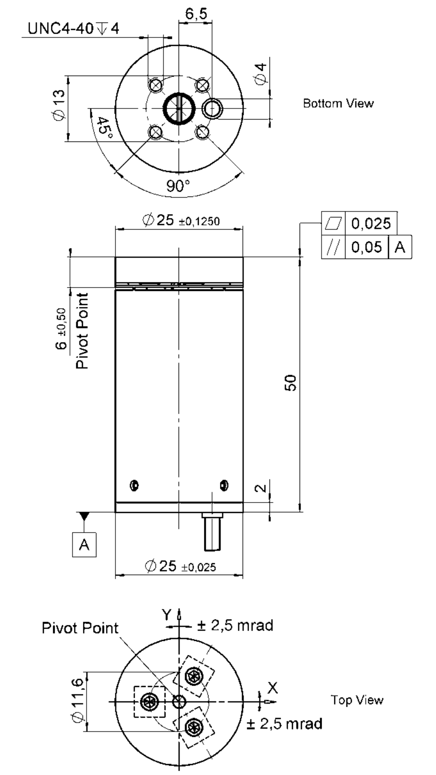
- Image processing / stablilization
- Optical trapping
- Laser scanning / beam steering
- Laser tuning
- Optical filters / switches
- Optics
- Beam stabilization



S-325 cable configuration (top: S-325.30L, bottom: S-325.3SL)

High Reliability and Long Lifetime

The compact S-325 systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and provide better performance and reliability than conventional piezo actuators. Actuators, guidance and sensors are maintenance-free, not subject to wear and offer extraordinary reliability.



S-325 dimensions in mm

Linear Actuators & Motors
Nanopositioning / Piezoelectrics
Piezo Flexure Stages / High-Speed Scanning Systems
Linear
Vertical & Tip/Tilt
2- and 3-Axis
6-Axis
Fast Steering Mirrors / Active Optics
Piezo Drivers / Servo Controllers
Single-Channel
Multi-Channel
Modular
Accessories
Piezoelectrics in Positioning
Nanometrology
Micropositioning
Index

Technical Data

Model	S-325.30L	S-325.3SL	S-325.3SD	Units	Tolerance
Active axes	Z, Θ_X, Θ_Y	Z, Θ_X, Θ_Y	Z, Θ_X, Θ_Y		
Motion and positioning					
Integrated sensor	–	SGS	SGS		
Open-loop travel, 0 to +100 V	30	30	30	µm	min. (+20 %/-0 %)
Open-loop tip/tilt angle, 0 to +100 V	5	5	5	mrad	min. (+20 %/-0 %)
Closed-loop travel	–	30	30	µm	
Closed-loop tip/tilt angle	–	4	4	mrad	
Open-loop resolution	0.5	0.5	0.5	nm	typ.
Open-loop tip/tilt angle resolution	0.05	0.05	0.05	µrad	typ.
Closed-loop linear resolution	–	0,6	0,6	nm	typ.
Closed-loop tip/tilt resolution	–	0.1	0.1	µrad	typ.
Mechanical properties					
Unloaded resonant frequency	2	2	2	kHz	±20 %
Resonant frequency (with 25 x 8 mm glass mirror)	1	1	1	kHz	±20 %
Distance of pivot point to platform surface	6	6	6	mm	±0.5 mm
Platform moment of inertia	515	515	515	g • mm²	±20 %
Drive properties					
Ceramic type	PICMA® P-885	PICMA® P-885	PICMA® P-885		
Electrical capacitance	9.3	9.3	9.3	µF	±20 %
Dynamic operating current coefficient	39	39	39	µA / (Hz • mrad)	±20 %
Miscellaneous					
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	°C	
Material casing	Aluminum	Aluminum	Aluminum		
Mass	0.065	0.065	0.065	kg	±5 %
Cable length	2	2	1.5	m	±10 mm
Sensor / voltage connection	LEMO	LEMO	Sub-D		

For maximum tilt range, all three piezo actuators must be biased at 50 V. Due to the parallel-kinematics design linear travel and tilt angle are interdependent. The values quoted here refer to pure linear / pure angular motion. See equations (p. 2-84).

Recommended controller / amplifier

Versions with LEMO connector: modular piezo controller system E-500 (p. 2-142) with amplifier module E-503.00S (three channels) (p. 2-146) or 1 x E-505.00S and 2 x E-505 (high speed applications) (p. 2-147) and E-509 controller (p. 2-152) (optional)

Single-channel (1 per axis): E-610 OEM servo controller / amplifier (p. 2-110), E-625 servo controller bench-top (p. 2-114)

Versions with Sub-D connectors: E-616 servo controller for tip/tilt mirror systems (p. 2-132)

S-310 – S-316 Piezo Z/Tip/Tilt Scanner

High-Speed System with Clear Aperture

S-310.10, S-316.10
piezo systems for scanning,
optics alignment and mirror shifter alignment

- **10 mm Clear Aperture**
- **Piezo Tripod Design**
- **Optical Beam Deflection to 2,4 mrad**
- **Piston Movement up to 12 µm (phase shifter)**
- **Sub-Millisecond Response, Sub-Microradian Resolution**
- **Closed-Loop Versions for Higher Precision**
- **For Optics, Mirrors or Other Components**
- **Frictionless, High-Precision Flexure Guiding System**
- **Parallel Kinematics for Enhanced Dynamics and Better Multi-Axis Accuracy**

S-310 to S-316 multi-axis tip/tilt platforms and Z-positioners are fast, compact units based on a piezo tripod design. They offer piston movement up to 12 µm and tilt movement up to 1.2 mrad (2.4 mrad optical beam deflection) with sub-millisecond response and settling.

Application Examples

- Image processing / stablilization
- Interferometry
- Laser scanning / beam steering
- Laser tuning
- Optical filters / switches
- Beam stabilization

The tripod design features optimum angular stability over a wide temperature range.

The systems are designed for mirrors and optics up to 25 mm in diameter and can be mounted in any orientation; the clear aperture is ideal for transmitted-light applications (e. g. for optical filters).

Open-Loop and Closed-Loop Operation

In open-loop mode, the tip/tilt angle is roughly proportional to the applied voltage. The S-310 to S-315 open-loop models are ideal for high-speed, high resolution applications where the absolute angular position is of secondary importance (e. g. for tracking) or where feedback is provided by an external sensor (e. g. CCD, PSD). The S-316.10 model is equipped with high-resolution strain gauge sensors and provides absolute position control, high linearity and high repeatability.

Available Versions

S-310.10, S-314.10

Open-loop Z-platforms; all three piezo linear actuators are electrically connected in parallel, providing vertical positioning (piston movement) of the top ring. Only one drive channel is required.

S-311.10, S-315.10

Open-loop Z/tip/tilt positioners; all three piezo linear actuators can be driven individually (or in parallel) by a three-channel amplifier. Vertical (piston movement) positioning and tip/tilt positioning are possible.

S-316.10

Closed-loop Z/tip/tilt positioner. All three piezo linear actuators are equipped with strain gauge position feedback sensors and can be driven individually (or in parallel) by a three-channel amplifier with a position servo-controller. Vertical positioning (piston movement) and tip/tilt positioning are possible. The integrated position feedback sensors provide sub-microradian resolution and high repeatability.

Ordering Information

S-310.10
Piezo Actuator, Clear Aperture, 6 µm, LEMO Connector

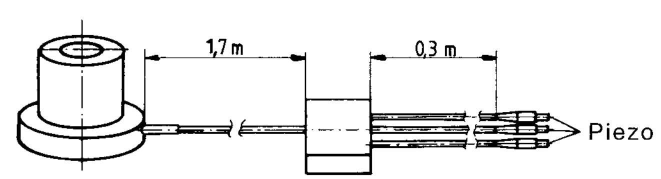
S-311.10
Piezo Z/Tip/Tilt Platform, Clear Aperture, 600 µrad, 6 µm, LEMO Connector

S-314.10
Piezo Actuator, Clear Aperture, 12 µm, LEMO Connector

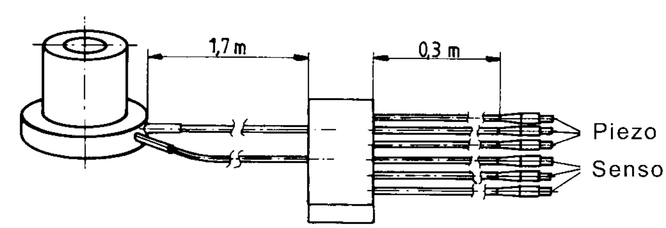
S-315.10
Piezo Z/Tip/Tilt Platform, Clear Aperture, 1.2 mrad, 12 µm, LEMO Connector

S-316.10
Piezo Z/Tip/Tilt Platform, Clear Aperture, 1.2 mrad, 12 µm, SGS, LEMO Connector

S-316.10
Piezo Z/Tip/Tilt Platform, Clear Aperture, 1.2 mrad, 12 µm, SGS, Sub-D Connector



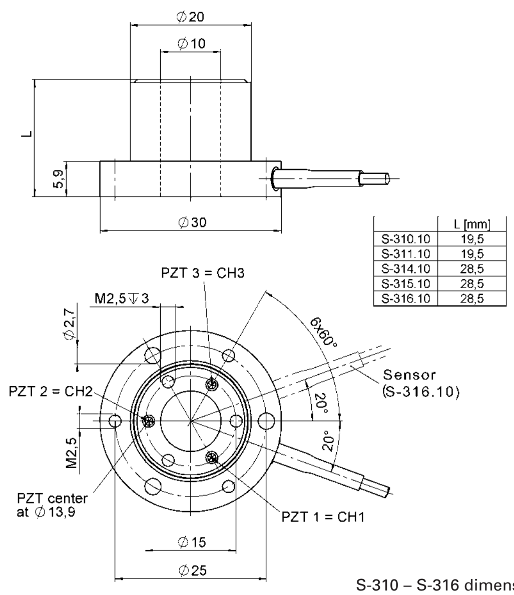
S-315 cable configuration



S-316 cable configuration

High Reliability and Long Lifetime

The compact S-310 - S-316 systems are equipped with preloaded PICMA® high-performance piezo actuators which are integrated into a sophisticated, FEA-modeled, flexure guiding system. The PICMA® actuators feature cofired ceramic encapsulation and provide better performance and reliability than conventional piezo actuators. Actuators, guidance and sensors are maintenance-free, not subject to wear and offer extraordinary reliability.



S-310 – S-316 dimensions (in mm)

Technical Data

Model	S-310.10	S-314.10	S-311.10	S-315.10	S-316.10	Units	Tolerance
Active axes	Z	Z	Z, Θ_X, Θ_Y	Z, Θ_X, Θ_Y	Z, Θ_X, Θ_Y		
Motion and positioning							
Integrated sensor	–	–	–	–	SGS		
Open-loop travel, 0 to +100 V	6 / –	12 / –	6 / –	12 / –	12 / 12	µm	min. (+20 %/-0 %)
*Open-loop tilt angle @ 0 to 100 V	–	–	600	1200	1200	µrad	min. (+20 %/-0 %)
Closed-loop travel	–	–	–	–	12	µm	
*Closed-loop tilt angle	–	–	–	–	1200	mrad	
Open-loop resolution	0.1	0.2	0.1	0.2	0.2	nm	typ.
Open-loop tip/tilt angle resolution			0.02	0.05	0.05	µrad	typ.
Closed-loop resolution	–	–	–	–	0.4	nm	typ.
Closed-loop tip/tilt resolution	–	–	–	–	0.1	µrad	typ.
Linearity	–	–	–	–	0.2	%	typ.
Mechanical properties							
Stiffness	20	10	20	10	10	N/µm	±20 %
Unloaded resonant frequency (Z)	9.5	5.5	9.5	5.5	5.5	kHz	±20 %
Resonant frequency (with 15 x 4 mm glass mirror)	6.5	4.4	6.5	4.1	4.1	kHz	±20 %
Resonant frequency (with 20 x 4 mm glass mirror)	6.1	4.2	6.1	3.4	3.4	kHz	±20 %
Distance of pivot point to platform surface	–	–	5	5	5	mm	±1 mm
Platform moment of inertia	–	–	150	150	150	g • mm²	±20 %
Drive properties							
Ceramic type	PICMA® P-882	PICMA® P-882	PICMA® P-882	PICMA® P-882	PICMA® P-882		
Electrical capacitance	0.39	0.93	0.39	0.93	0.93	µF	±20 %
Dynamic operating current coefficient	8	10	8	10	10	µA / (Hz • mrad)	±20 %
Miscellaneous							
Operating temperature range	-20 to 80	-20 to 80	-20 to 80	-20 to 80	-20 to 80	°C	
Material	Stainless steel	Stainless steel	Stainless steel	Stainless steel	Stainless steel		
Mass	0.45	0.55	0.45	0.55	0.55	kg	±5%
Cable length	2	2	2	2	2	m	±10 mm
Sensor connection	–	–	–	–	LEMO		
Voltage connection	LEMO	LEMO	LEMO	LEMO	LEMO		

Resolution of PI piezo tip/tilt platforms is not limited by friction or stiction. Noise equivalent motion with E-503 amplifier (p. 2-146).

*Mechanical tilt, optical beam deflection is twice as large. For maximum tilt range, all three piezo actuators must be biased at 50 V. Due to the parallel-kinematics design linear travel and tilt angle are interdependent. The values quoted here refer to pure linear / pure angular motion (equations p. 2-84).

Recommended controller / amplifier
Single-channel (1 per axis): E-610 servo-controller / amplifier (p. 2-110), E-625 servo-controller, bench-top (p. 2-114)

Multi-channel: modular piezo controller system E-500 (p. 2-142) with amplifier module E-503 (three channels) (p. 2-146) or E-505 (1 per axis, high-power) (p. 2-147) and E-509 controller (p. 2-152) (optional), E-517 interface module (p. 2-156) (optional)

S-323 Piezo Z/Tip/Tilt Platform

High Dynamics & Stability Nanopositioning System with Direct Metrology

The S-323 Z/tip/tilt platform integrates capacitive sensors for highest resolution and stability

- Optical Beam Deflection to 6 mrad
- Sub-μrad Resolution for High Positioning Stability
- Position Servo-Control with Capacitive Sensors
- Frictionless, High-Precision Flexure Guiding System
- System Combination with Digital Controllers for Highest Linearity

Model	Active axes	Travel range	Resolution	Unloaded resonant frequency
S-323.3CD	Z, θ_X, θ_Y	30 µm, ±1.5 mrad	0.1 nm, ±0.05 µrad	1.7 kHz

S-303 Piezo Phase Shifter

Highest Dynamics and Stability with Capacitive Feedback Sensor

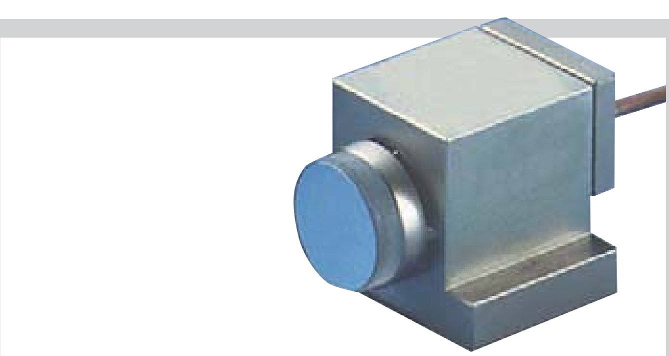
S-303 closed-loop model (left) and open-loop model (right). DIP switch for size comparison

- 25 kHz Resonant Frequency for Sub-Millisecond Dynamics
- Capacitive Sensor Option for Highest Linearity and Stability
- 3 µm Travel Range
- Compact Size: 30 mm Diameter x 10 mm
- Aperture with Open-Loop Versions
- Invar Option for Highest Thermal Stability

Model	Active axes	Closed-loop/ open-loop travel @ -20 to +120V	Closed-loop/ open-loop resolution	Unloaded resonant frequency
S-303.CD (closed-loop)/ S-302.0L (open-loop)	Z	2 / 3 µm	0.03 nm	25 kHz

S-224 -S-226 Piezo Tilt-Mirror

Fast Steering Mirror Combines Highest Dynamics and Compact Design



S-224 Piezo tip/tilt mirror for high-speed beam steering tasks and image stabilization applications

- Optical Beam Deflection to 4.4 mrad
- Sub-μrad Resolution, Sub-Millisecond Response
- Frictionless, High-Precision Flexure Guiding System
- Includes BK7 Mirror
- Optional Position Feedback Sensor
- Outstanding Lifetime Due to PICMA® Piezo Actuators

Model	Active axes	Open-loop tilt angle @ 0 to +100V	Closed-loop/ open-loop resolution	Unloaded resonant frequency
S-224.00 (open-loop)/ S-226.00 (closed-loop)	θ_X	2.0 / 2.2 mrad	0.05 / 0.1 µrad	9 kHz

Details on Specifications for Active Optics / Steering Mirrors

Motion and Positioning

Performance specifications are valid for room temperature (22° ±3 °C) and closed-loop systems are calibrated at this temperature (specifications for other operating temperatures on request). Recalibration is recommended for operation at a significantly higher or lower temperature. Custom designs for ultra-low or ultra-high temperatures on request.

Integrated feedback sensor

Absolute measuring capacitive and strain gauge (SGS) sensors are used to provide position information to the controller. For details see the tutorial "Piezoelectrics in Positioning" section (see p. 2-187).

Open-loop linear travel @ 0 to 100 V

Typical open-loop travel at 0 to 100 V operating voltage. Max. recommended operating voltage range is -20 to +120 V (extremes for short durations only).

Closed-loop linear travel

Travel provided in closed-loop operation. PI piezo amplifiers have an output voltage range of -20 to +120 V or -30 to +135 V to provide enough margin for the servo-controller to compensate for load changes, etc.

Open-Loop Tilt Angle @ 0 to 100 V

Typical open-loop tilt angle at 0 to 100 V operating voltage. For differential-drive tilt platforms, 0° is reached at 50 V drive voltage, the maximum negative angle at 0 V and the maximum positive angle at 100 V. Max. operating voltage range is -20 to +120 V (outside 0 to 100 V for short durations only).

Closed-Loop Travel

Tilt provided in closed-loop operation at room temperature. PI piezo amplifiers have an output voltage range of -20 to +120 V or -30 to 135 V to provide enough margin for the controller to compensate for load changes etc.

Open-loop / closed-loop resolution

Resolution of piezo flexure stages is basically infinitesimal because it is not limited by stiction or friction. Instead of resolution, the noise-equivalent motion is specified. Values are typical results (RMS, 1 σ), measured with E-503 amplifier module in E-500/501 chassis.

Full-range repeatability (typ.)

Typical values in closed-loop mode (RMS, 1 σ). Repeatability is a percentage of the total distance or angle traveled. For small ranges, repeatability is significantly better.

Pitch / Yaw / Roll / Rotational Runout

Typical rotational off-axis error; sometimes associated with a particular motion axis, as in "Rotational runout (Z motion)".

Straightness / Flatness / Crosstalk

Typical linear off-axis error; sometimes associated with a particular motion axis, as in "Crosstalk (Z motion)".

Mechanical Properties

Stiffness

Static large-signal stiffness of the piezo mechanics in operating direction at room temperature. Small-signal stiffness and dynamic stiffness may differ because of effects caused by the active nature of piezoelectric material, compound effects, etc. For details see the tutorial "Piezoelectrics in Positioning" section (see p. 2-189 *ff*).

Unloaded resonant frequency

Lowest tilt resonant frequency around active axis without mirror attached to platform (does not specify the maximum operating frequency). For details see the tutorial "Piezoelectrics in Positioning" Section (see p. 2-192 *ff*).

Resonant frequency with mirror

Example of how a load (mirror) attached to the platform affects the resonant frequency (calculated data). See "Dynamic Behavior" (p. 2-84) for further details.

Drive Properties

Electrical capacitance

The piezo capacitance values indicated in the technical data tables are small-signal values (measured at 1 V, 1000 Hz, 20 °C, no load). Large-signal values at room temperature are 30 to 50 % higher. The capacitance of piezo ceramics changes with amplitude, temperature, and load, up to 200 % of the unloaded, small-signal capacitance at room temperature. For detailed information on power requirements, refer to the amplifier frequency-response graphs in the "Piezo Drivers / Servo Controllers" (see p. 2-99 *ff*) section of this catalog.

Dynamic Operating Current Coefficient (DOCC)

Average electrical current (supplied by the amplifier) required to drive a piezo actuator per unit frequency and unit displacement (sine-wave operation). For example, to find out if a selected amplifier can drive a given piezo tilt platform at 50 Hz with 300 µrad amplitude, multiply the DOC coefficient by 50 and 300 and check if the result is less than or equal to the output current of the selected amplifier. For details see the tutorial "Piezoelectrics in Positioning" (see p. 2-195 *ff*) section.

Miscellaneous

Operating temperature range

Typically -20 to +80 °C, the temperature range indicates where the piezo stage may be operated without damage. Performance specifications are valid for room temperature (22 °C) and closed-loop systems are calibrated for optimum performance at this temperature (specifications for other operating temperatures on request). Recalibration is recommended for operation at a significantly higher or lower temperature. Custom designs for ultra-low or ultra-high temperatures on request.

Material

Flexure stages are usually made of anodized aluminum or stainless steel. Small amounts of other materials may be used internally (for spring preload, piezo coupling, mounting, thermal compensation, etc.).

- Al: Aluminum
- N-S: Non-magnetic stainless steel
- S: Ferromagnetic stainless steel
- I: Invar
- T: Titanium

Voltage connection

Standard operating voltage connectors are LEMO and sub-D type connectors.

LEMO connector: LEMO FFA. 00.250, male. Cable: coaxial, RG 178, Teflon coated, 1 m

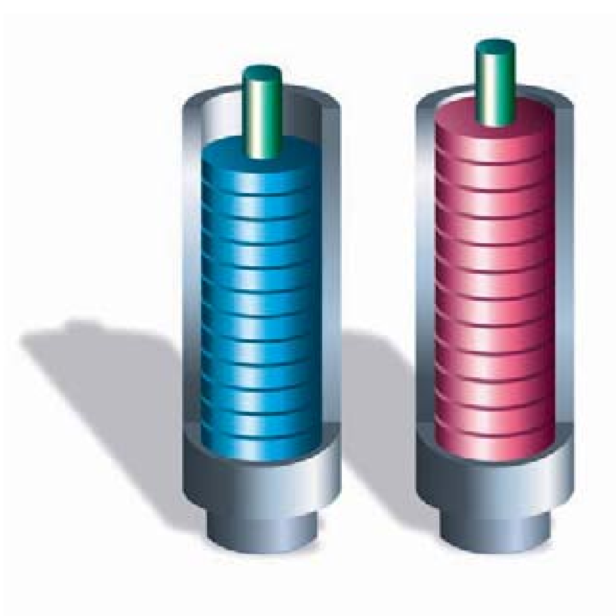
Sensor connection

Standard sensor connectors are LEMO and sub-D type connectors.

Sub-D special connectors contain both piezo voltage and sensor connections.

For extension cables and adapters, see "Accessories" (p. 2-168 *ff*), in the "Piezo Drivers / Servo Controllers" Section.

Piezoelectrics in Positioning



Contents

Piezoelectrics 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 & Components" 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

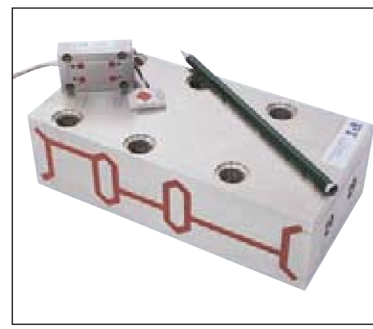
A piezo actuator has no moving parts like gears or bearings. Its displacement is based on solid state dynamics and shows no wear and tear. PI has conducted endurance tests on piezo actuators in which no measurable change in performance was observed after several billion cycles.

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 nanopositioning systems large (e.g. for precision machining), medium (e.g. for interferometry), small (e.g. for data storage medium testing)

Applications for Piezo 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

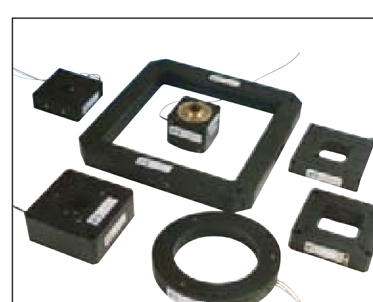
- Fast tool servos
- Non-circular grinding, drilling, turning
- Active vibration cancellation
- Structural deformation
- Tool adjustment
- Wear compensation
- Needle-valve actuation
- Micropumps
- Linear drives
- Knife edge control in extrusion tools
- Micro engraving systems
- Shock wave generation

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 Fundamentals Glossary (p. 4-128).

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.

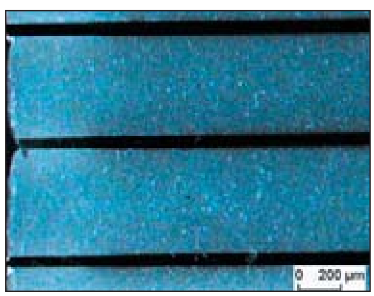
Creep:
An unwanted change in the displacement over time.

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.

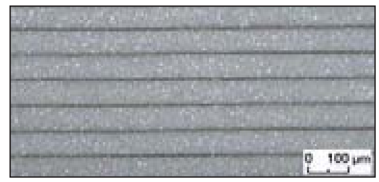
HVPZT:
Acronym for High-Voltage PZT (actuator).



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.

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



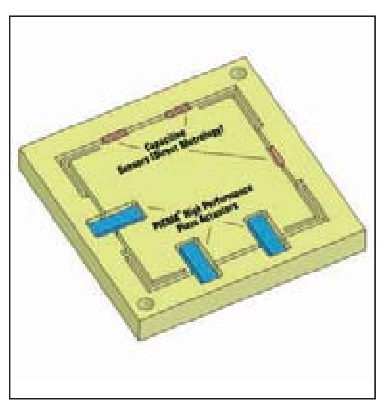
Piezoceramic layers in a monolithic actuator (LVPZT).

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.

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



Nanopositioning system featuring parallel kinematics and parallel metrology.

Linear Actuators & Motors
Nanopositioning / Piezoelectrics
Piezo Flexure Stages / High-Speed Scanning Systems
Linear
Vertical & Tip/Tilt
2- and 3-Axis
6-Axis
Fast Steering Mirrors / Active Optics
Piezo Drivers / Servo Controllers
Single-Channel
Multi-Channel
Modular
Accessories
Piezoelectrics in Positioning
Nanometrology
Micropositioning
Index

Glossary (cont.)

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:

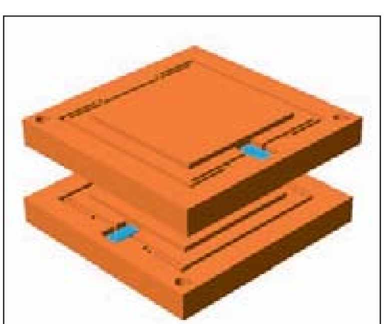
Acronym for plumbum (lead) zirconate titanate. Polycrystalline ceramic material with piezoelectric properties. Often also used to refer to a piezo actuator or translator.

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.



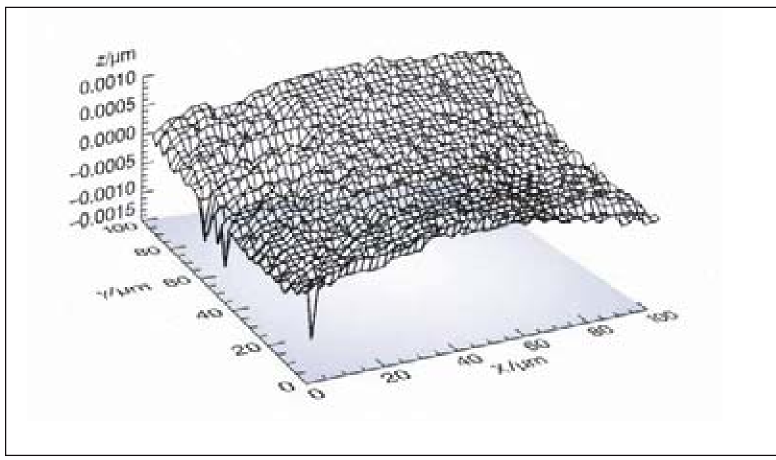
Design principle of a stacked XY piezo stage (serial kinematics).

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.

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. 2-181.

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 p. 2-207 *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. 1-3 *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

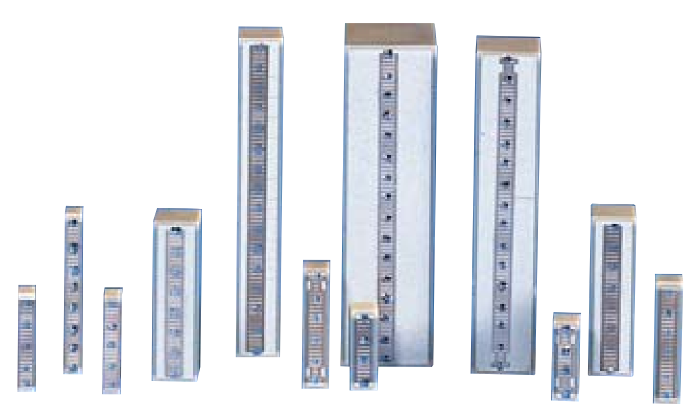


Fig. 1b. Selection of monolithic PICMA ® technology actuators

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. 2-189). 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 p. 2-183 *ff*.

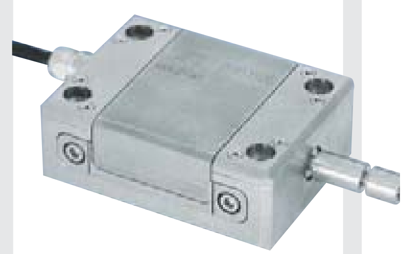


Fig. 2b. Custom linear drive with integrated NEXLINE® Piezo-Walk® piezomotor

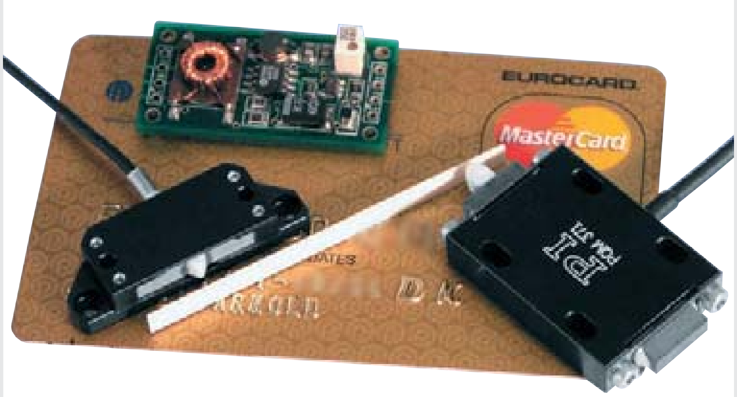


Fig. 2a. Ultrasonic piezo linear motors

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. 2-199). 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. 2-187 *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 p. 2-192 *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 p. 2-195 *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. 2-216). 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

Notes

The following pages give a detailed look at piezo actuator theory and their operation. For basic knowledge read “Quick Facts”, p. 2-178. For definition of units, dimensions and terms, see “Symbols and Units”, p. 2-217 and “Glossary”, p. 2-175.

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.

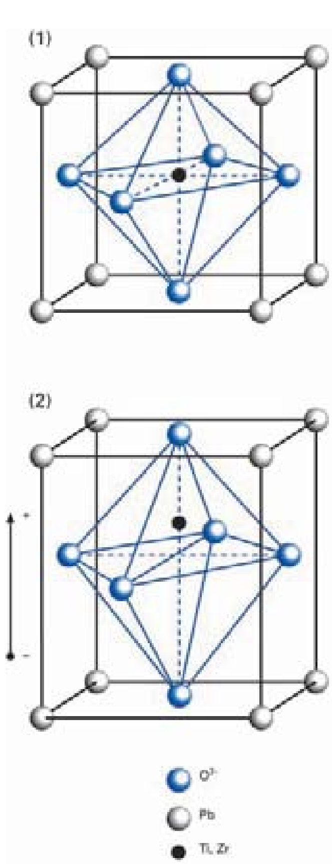


Fig. 5. PZT unit cell:
1) Perovskite-type lead zirconate titanate (PZT) unit cell in the symmetric cubic state above the Curie temperature
2) Tetragonally distorted unit cell below the Curie temperature

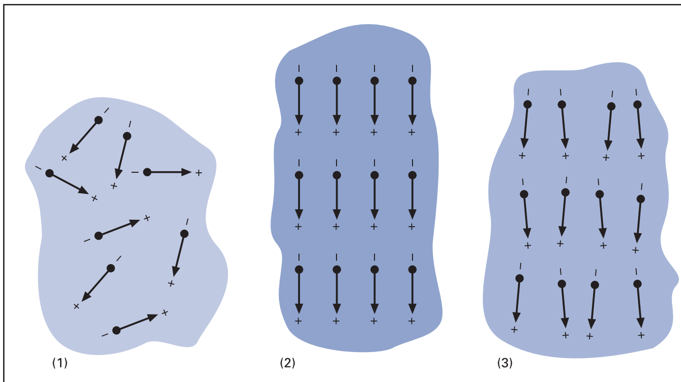


Fig. 6. Electric dipoles in domains; (1) unpoled ferroelectric ceramic, (2) during and (3) after poling (piezoelectric ceramic)

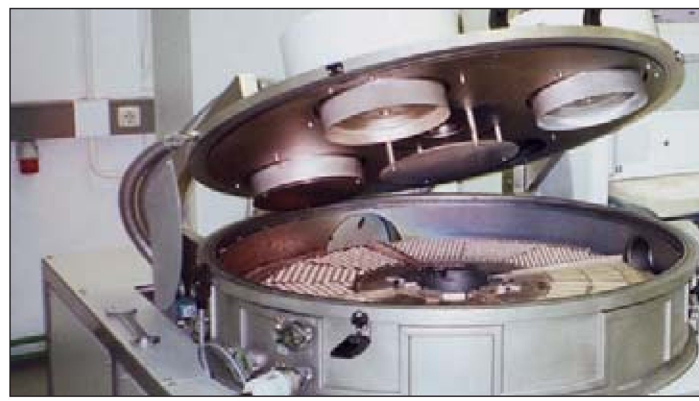
Fundamentals of Piezoelectricity (cont.)

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.

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.

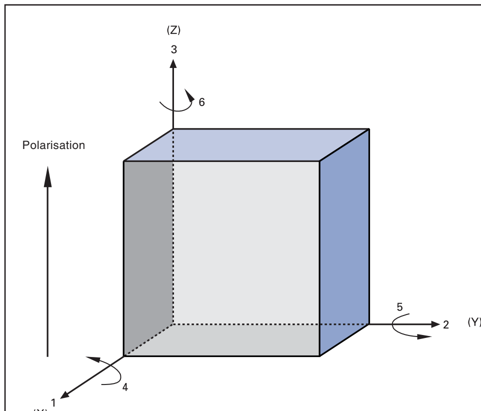


Fig. 7. Orthogonal system describing the properties of a poled piezoelectric ceramic. Axis 3 is the poling direction.

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. 2-10 and p. 2-199 *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.

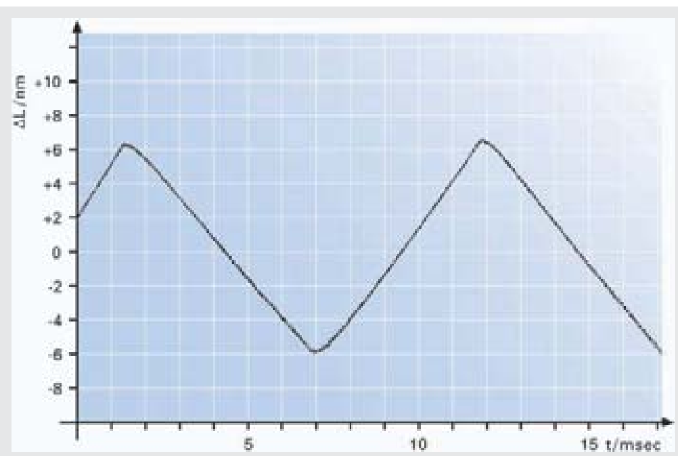


Fig. 8. Smooth response of a P-170 HVPZT translator to a 1 V, 200 Hz triangular drive signal. Note that one division is only 2 nanometers

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)

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

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. 2-210).

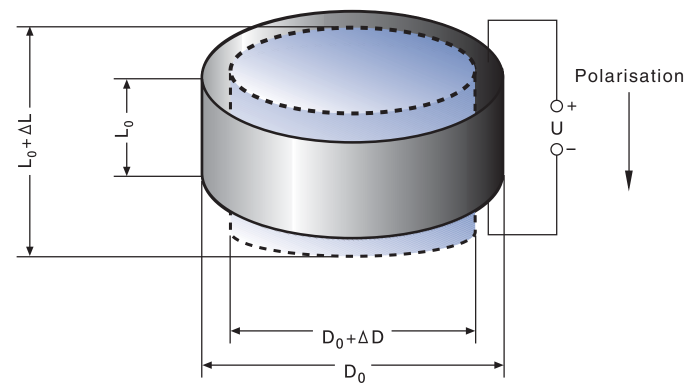


Fig. 9. Expansion and contraction of a piezoelectric disk in response to an applied voltage. Note that d_{31}, which describes the lateral motion, ΔD, is negative

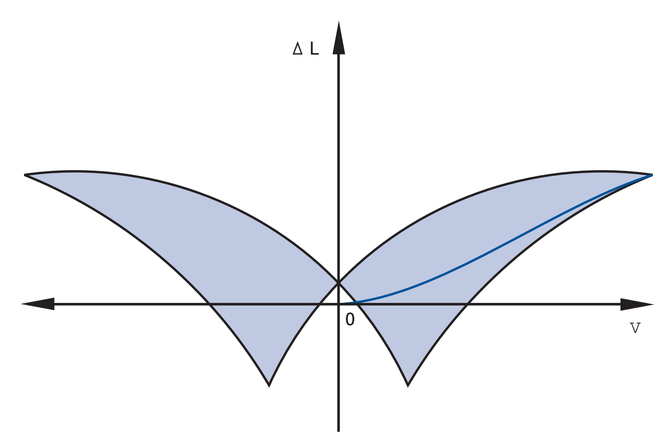


Fig. 10. Typical response of a "soft PZT" actuator to a bipolar drive voltage. When a certain threshold voltage negative to the polarization direction is exceeded, reversal of polarization can occur

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 p. 2-199 *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 p. 2-199 *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.

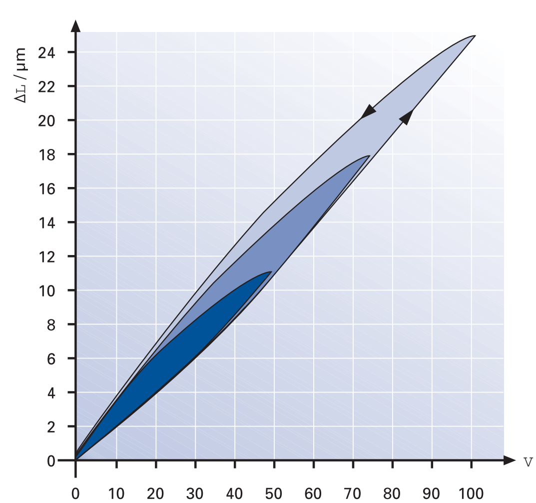


Fig. 11. Hysteresis curves of an open-loop piezo actuator for various peak voltages. The hysteresis is related to the distance moved, not to the nominal travel range

Fundamentals of Piezomechanics (cont.)

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]*
ΔL(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.

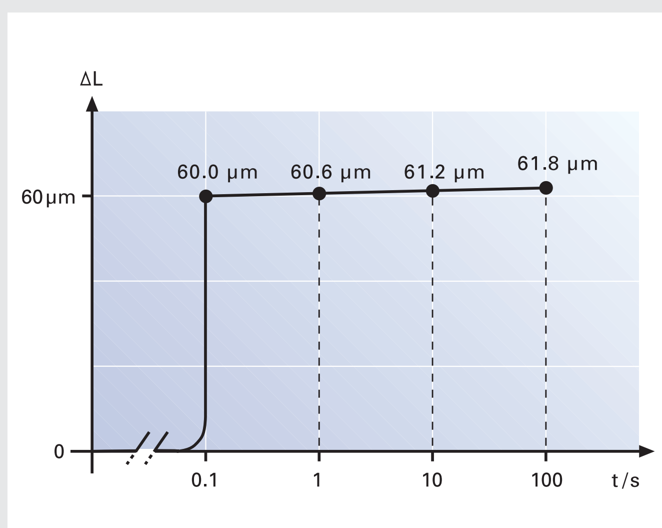


Fig. 12. Creep of open-loop PZT motion after a 60 µm change in length as a function of time. Creep is on the order of 1 % of the last commanded motion per time decade

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. 2-8 *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. 2-8 *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 & Components" section p. 1-61 *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 (cont.)


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

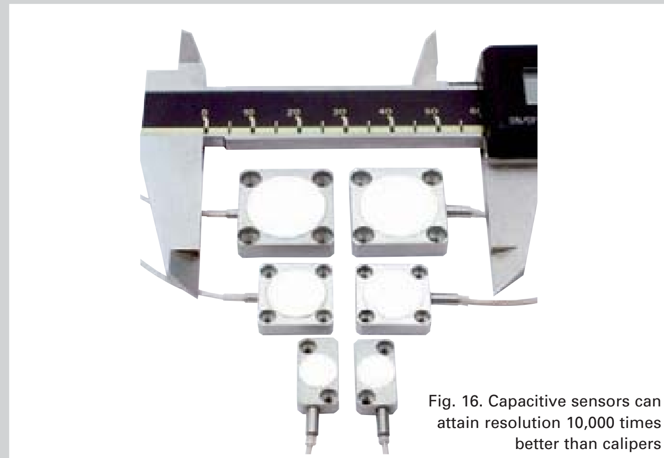


Fig. 16. Capacitive sensors can attain resolution 10,000 times better than calipers

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

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 "Nanometrology" section (p. 3-1 *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. 3-18) developed by PI.

Examples

P-733 parallel kinematic nanopositioning system with parallel metrology (see p. 2-62).
P-753 LISA NanoAutomation® actuators (see p. 2-16); additional examples in the "Piezo Flexure Stages / High-Speed Scanning Systems" section.

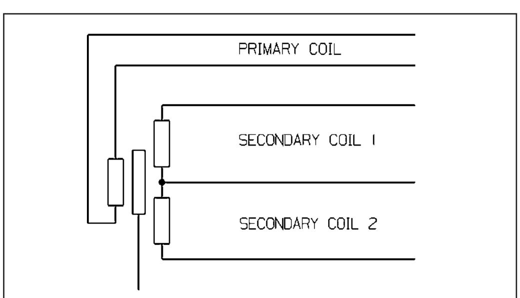


Fig. 15. Working principle of an LVDT sensor

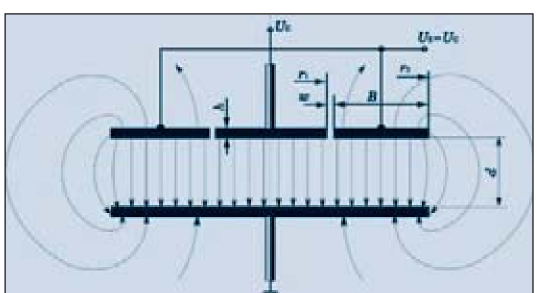


Fig. 17. Working principle of two-plate capacitive position sensors

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 all 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.

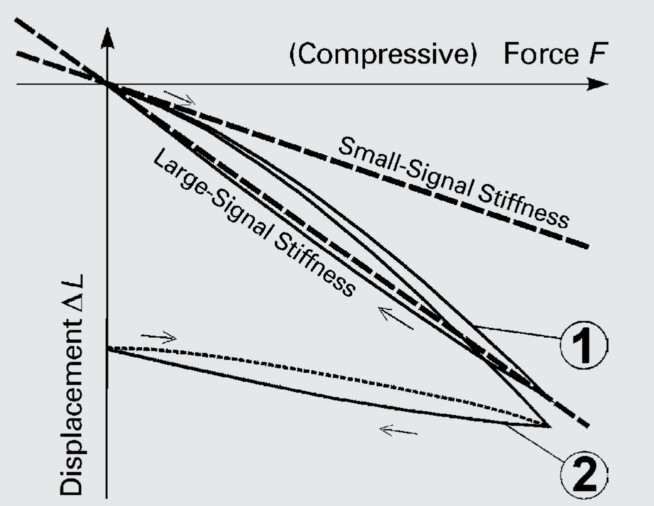


Fig. 18. Quasi-static characteristic mechanical stress/strain curves for piezo ceramic actuators and the derived stiffness values. Curve 1 is with the nominal operating voltage on the electrodes, Curve 2 is with the electrodes shorted (showing ceramics after depolarization)

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 (cont.)

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. 2-191). 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.

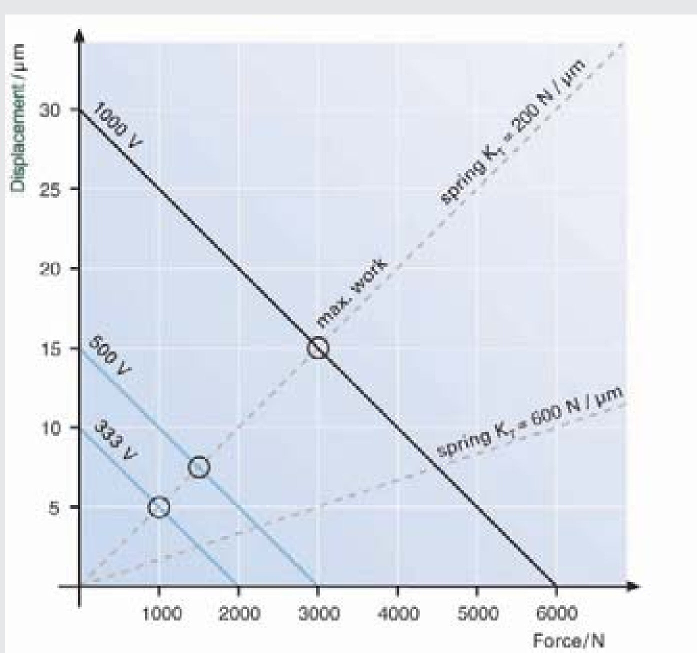


Fig. 19. Force generation vs. displacement of a piezo actuator (displacement 30 µm, stiffness 200 N/µm). Stiffness at various operating voltages. The points where the dashed lines (external spring curves) intersect the piezo actuator force/displacement curves determine the force and displacement for 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.

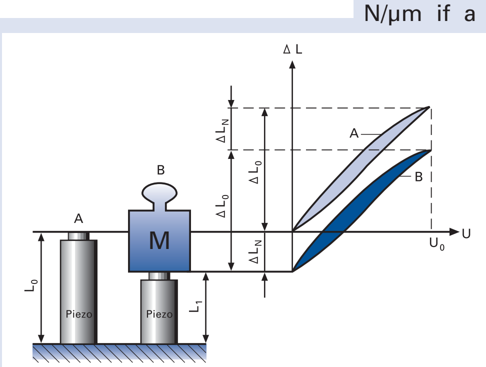


Fig. 20. Case a: Zero-point offset with constant force

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:

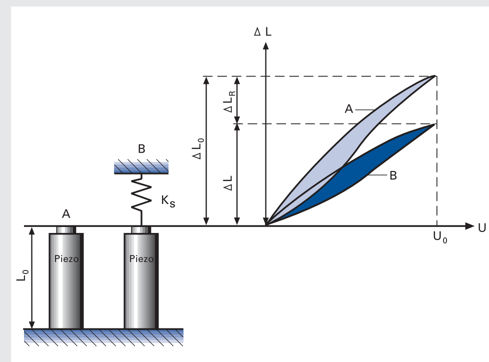


Fig. 21. Case b: Effective displacement of a piezo actuator acting against a spring load

(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.

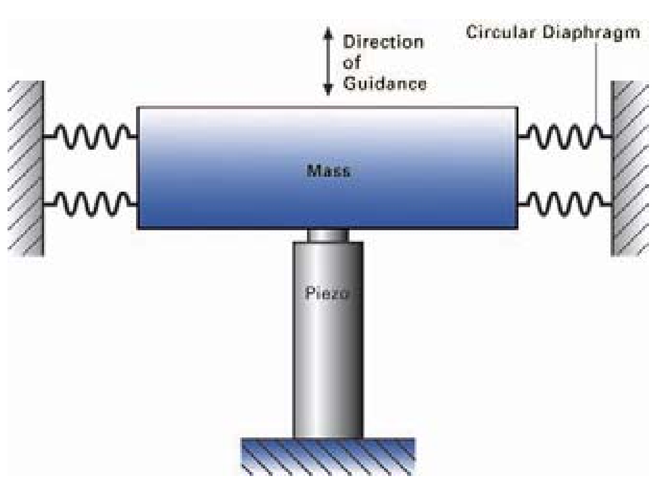


Fig. 22. Recommended guiding for large masses

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]*

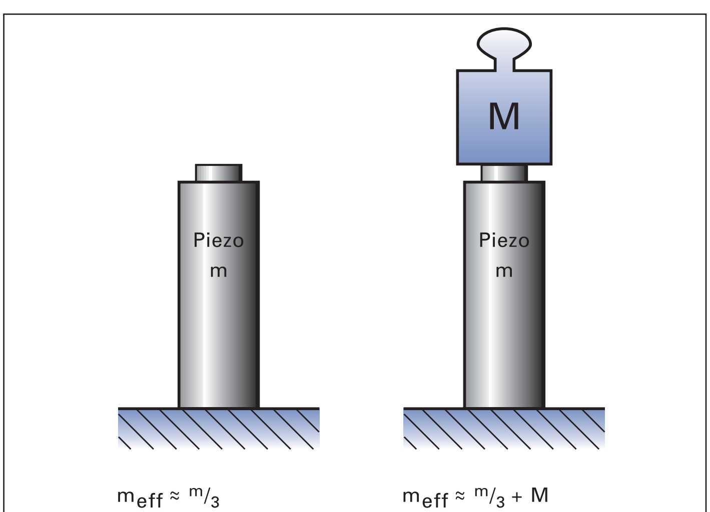


Fig. 23. Effective mass of an actuator fixed at one end

Dynamic Operation Fundamentals (cont.)

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. 2-201) 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.

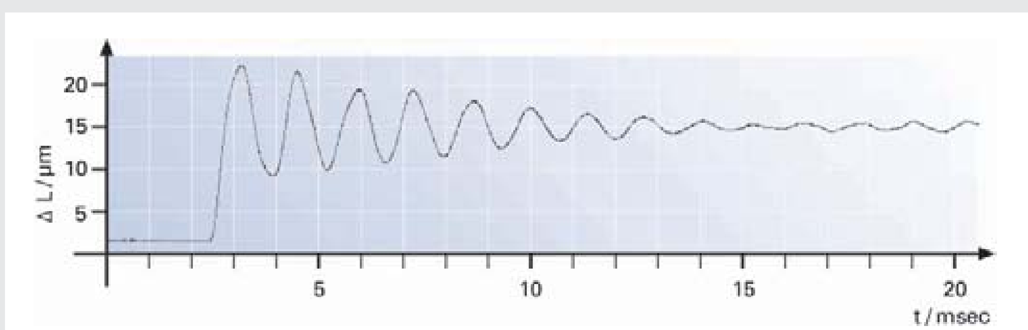


Fig. 24. Response of an undamped, lever-amplified piezo actuator (low resonant frequency) to a rapid drive-voltage change. This behavior can be prevented by intelligent control techniques or position servo-control

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 "Piezo Drivers / Servo Controllers" Selection Guide on p. 2-100 *ff*.

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 / Servo Controllers" (see p. 2-99 *ff*) section.

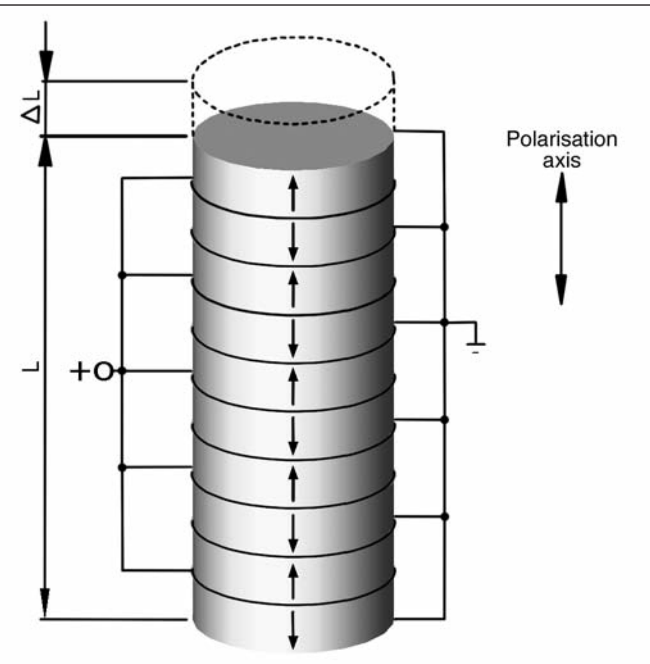


Fig. 25. Design of a piezo stack actuator

Piezo Actuator Electrical Fundamentals (cont.)

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. 2-192).
- 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 / Servo Controllers" section (p. 2-99 *ff*).

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)

$$P_{max} \approx \pi \cdot C \cdot U_{max} \cdot U_{p\text{-}p} \cdot f$$

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. 2-192).

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)

$$U(t) = U_0 + U_{p\text{-}p} \cdot (1 - e^{-t/RC})$$

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. 2-194).

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. 2-201) 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 (cont.)

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. 2-201 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. 1-88), 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.

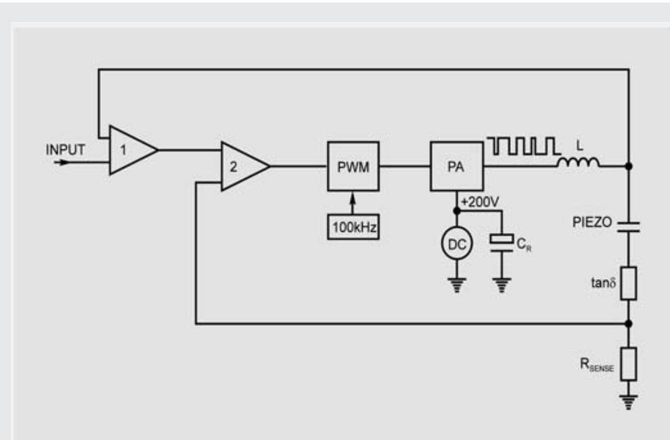


Fig. 26. Block diagram of an amplifier with energy recovery for higher frequency applications

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 "Nanometrology" p. 3-1 *ff*). Simpler, less accurate systems measure things like strain in drive elements.

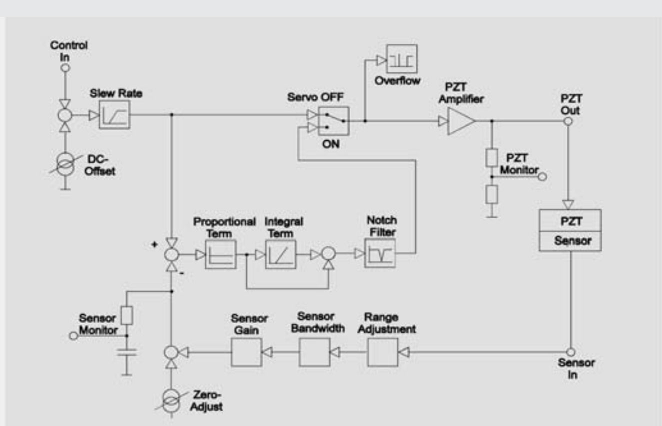


Fig. 28. Block diagram of a typical PI closed-loop piezo positioning system

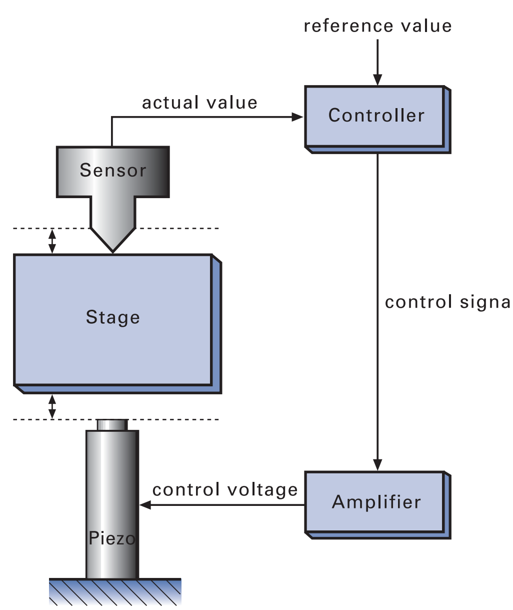


Fig. 29. Closed-loop position servo-control. For optimum performance, the sensor is mounted directly on the object to be positioned (direct metrology)

Linear Actuators & Motors
Nanopositioning / Piezoelectrics
Piezo Flexure Stages / High-Speed Scanning Systems
Linear
Vertical & Tip/Tilt
2- and 3-Axis
6-Axis
Fast Steering Mirrors / Active Optics
Piezo Drivers / Servo Controllers
Single-Channel
Multi-Channel
Modular
Accessories
Piezoelectrics in Positioning
Nanometrology
Micropositioning
Index

Control of Piezo Actuators and Stages (cont.)

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 Metrology Protocol

Each PI piezo position servo-controller is matched to the specific closed-loop piezo positioning system to achieve optimum displacement range, frequency response and settling time. The adjustment is performed at the factory and a report with plotted and tabulated positioning accuracy data is supplied with the system (see p. 2-87). To optimize the settings, information about the specific application is needed. For details see p. 2-11.

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

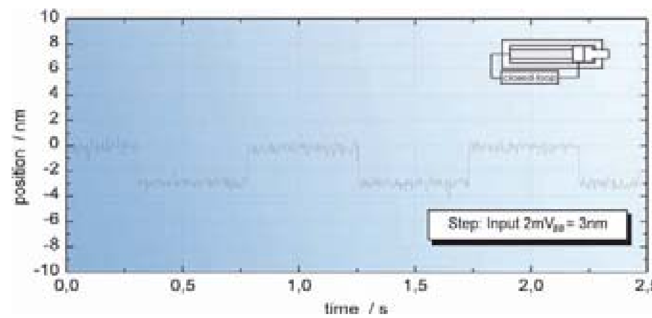


Fig. 30. Response of a closed-loop PI piezo actuator (P-841.10, 15 µm, strain gauge sensor) to a 3 nm peak-to-peak square-wave control input signal, measured with servo-control bandwidth set to 240 Hz and 2 msec settling time. Note the crisp, backlash-free behavior in the nanometer range

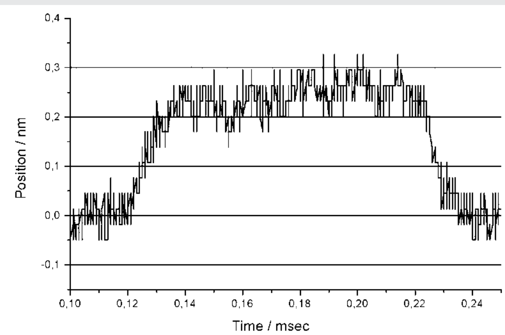


Fig. 31. PI piezo actuators with capacitive position sensors can achieve extremely high resolutions, as seen in the above result of a 250 picometer step by a S-303 phase corrector (Controller: E-509.C1A servo-controller and E-503 amplifier). The measurements were made with an ultra-sensitive capacitive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

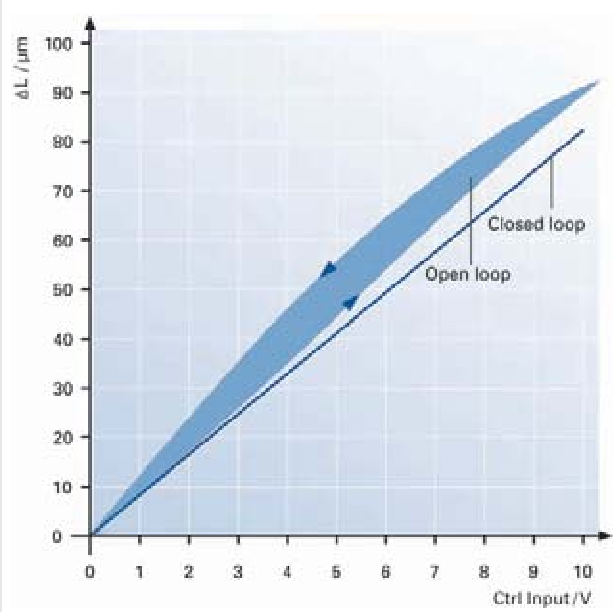


Fig. 32. Open-loop vs. closed-loop performance graph of a typical PI piezo actuator

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.

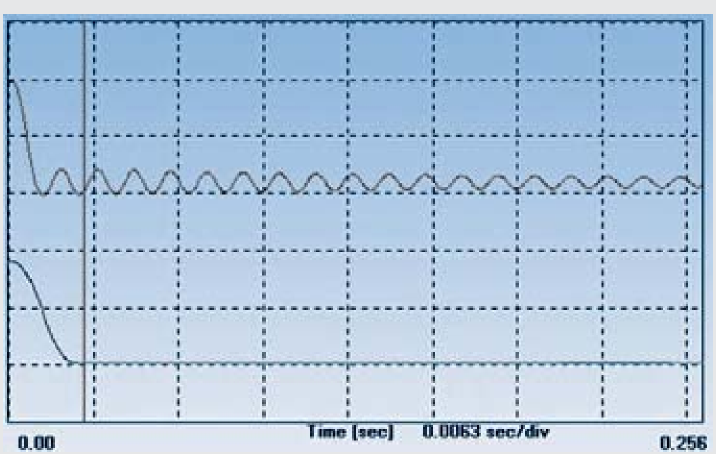


Fig. 33. InputShaping® eliminates the recoil-driven resonant reaction of loads and neighboring components due to rapid nanopositioner actuation.
Top: Polytec Laser Vibrometer reveals the resonant behavior of an undamped fixture when the nanomechanism is stepped.
Bottom: Same setup, same step, but with 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 (cont.)

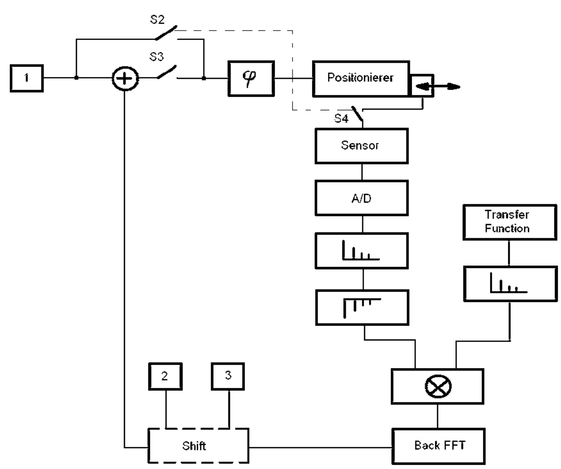


Fig. 34 a. Signal preshaping, phase 1

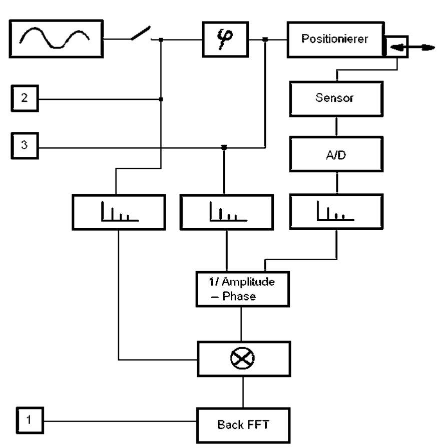


Fig. 34 b. Signal preshaping, phase 2

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.

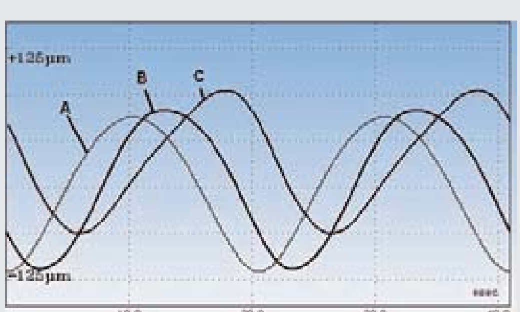


Fig. 35. No preshaping
A: Control input signal (expected motion)
B: Actual motion of system
C: Tracking error

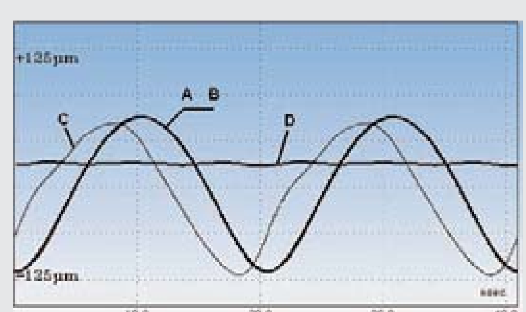


Fig. 36. Signal after preshaping phase 2
A: Expected Motion (old control signal)
B: Actual motion of system
C: New control input (producted by preshaping)
D: Tracking error

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 (see p. 2-108). 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.

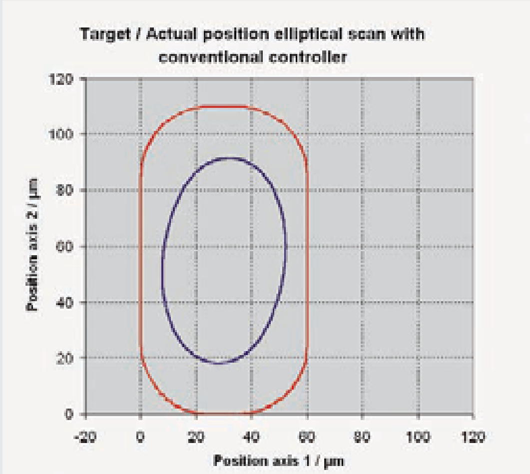


Fig. 37 a. Elliptical scan in a laser micro-drilling application with XY piezo scanning stage, conventional PID controller. The outer ellipse describes the target position, the inner ellipse shows the actual motion at the stage

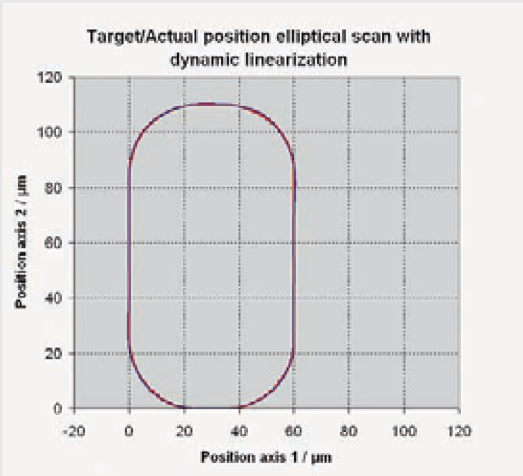


Fig. 37 b. Same scan as before, with a DDL controller. Target and actual data can hardly be discerned. The tracking error has been reduced to a few nanometers

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).

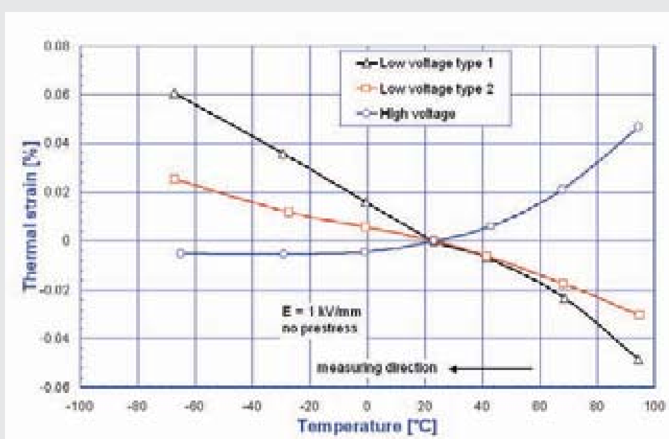


Fig. 38 a. Linear thermal expansion of different PZT ceramics

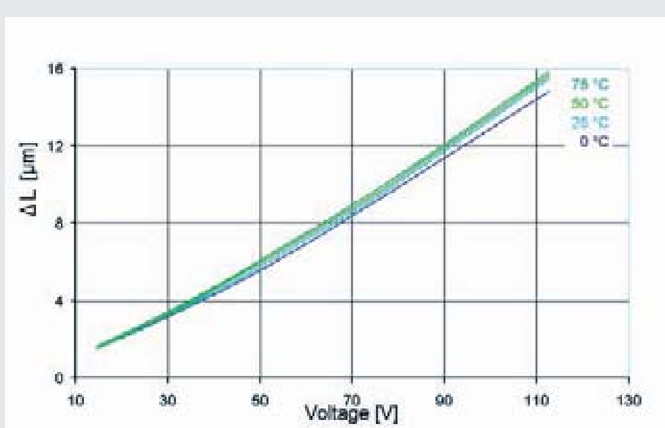


Fig. 38 b. The expansion of PICMA® piezoceramics is only slightly temperature dependent. This, and their low heat generation, makes them ideal for dynamic applications

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 & Components" sections, p. 2-104 *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

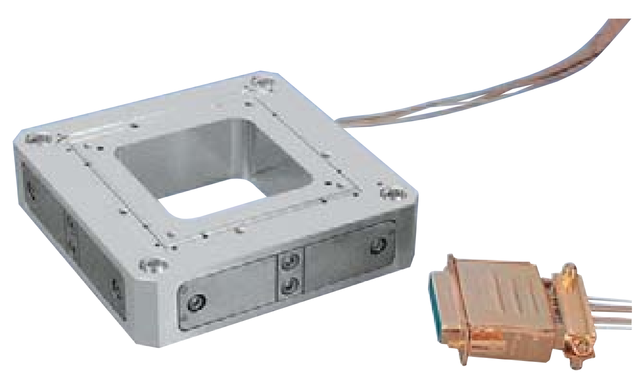


Fig. 39 b. P-733.UUD UHV-compatible XY stage for scanning microscopy applications. PICMA® ceramics are used here too. All materials used are optimized for minimal outgassing. Materials lists are available on request

Environmental Conditions and Influences (cont.)

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. 1-76 in the “Piezo Actuators & Components” 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.

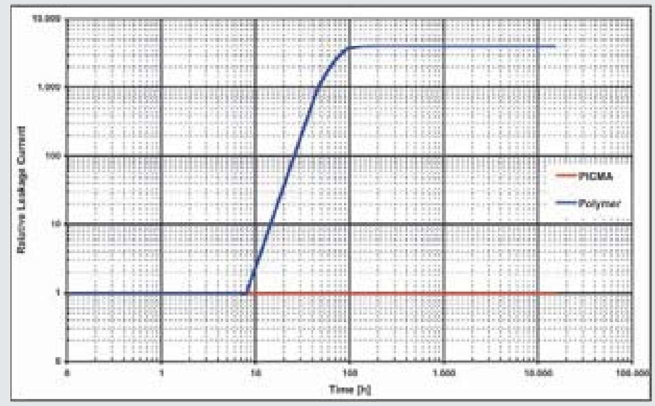


Fig. 39 c. PICMA® piezo actuators (lower curve) compared with conventional multi-layer piezo actuators with polymer insulation. PICMA® actuators are insensitve to high humidity in this test. In conventional actuators, the leakage current begins to rise after only a few hours—an indication of degradation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

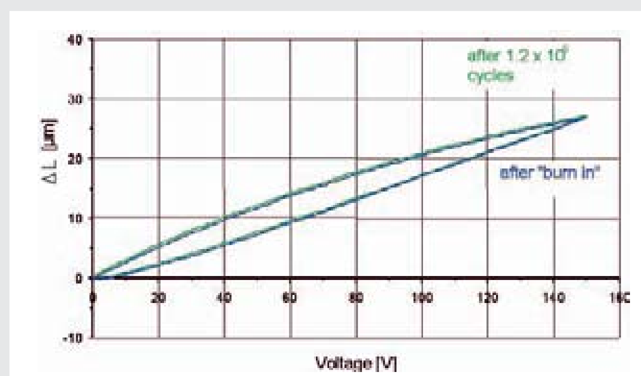


Fig. 39 d. P-885.50 PICMA® actuators with 15 MPa preload in dynamic motion test at 116 Hz. No observable wear after 1.2 billion (10^9) cycles

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. 2-189.

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. 1-76, etc. (see the “Piezo Actuators & Components” 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]

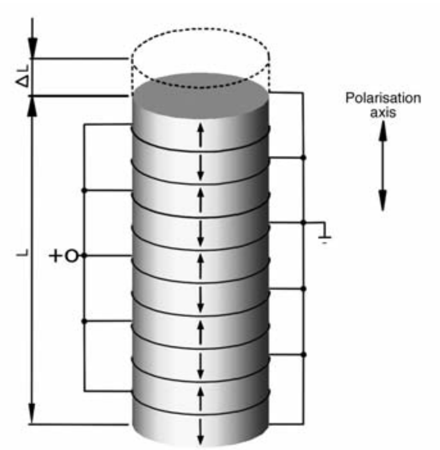


Fig. 40. Electrical design of a stack translator

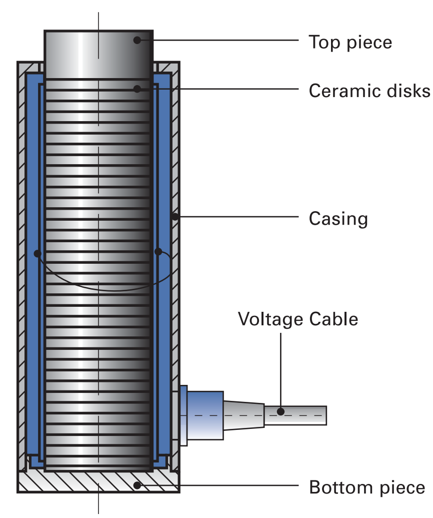


Fig. 41. Mechanical design of a stack translator

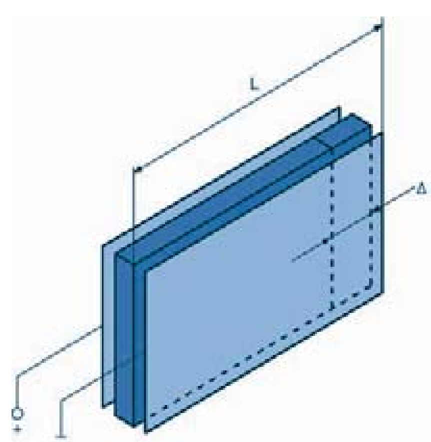


Fig. 42. Laminar actuator design

Basic Designs of Piezoelectric Positioning Drives/Systems (cont.)

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. 1-100).

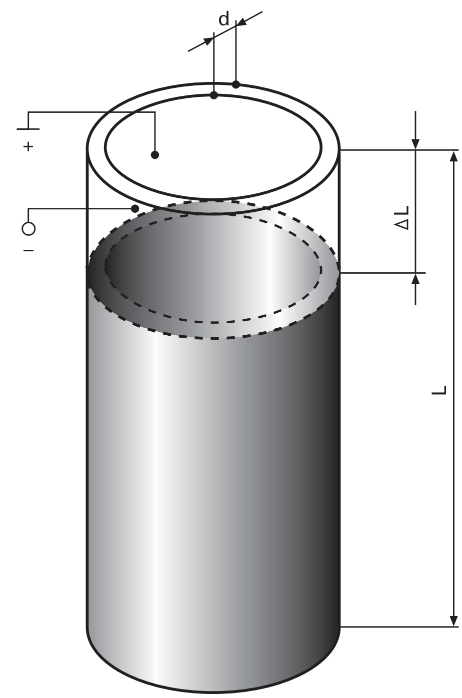


Fig. 43. Tube actuator design

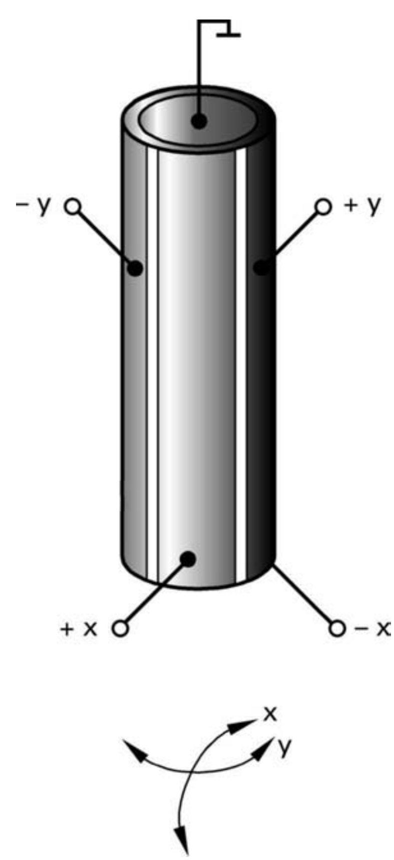


Fig. 44. Piezo scanner tube working principle

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:

PL122 multilayer bender actuators (p. 1-94).

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:

P-363 (p. 2-66),
N-214 NEXLINE® Piezo-Walk® motor (p. 1-10).

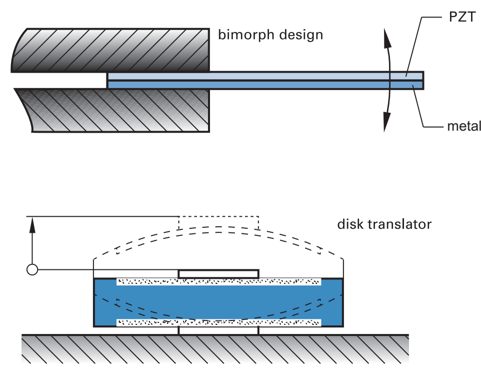


Fig. 45a. Bimorph design (strip and disk translator)

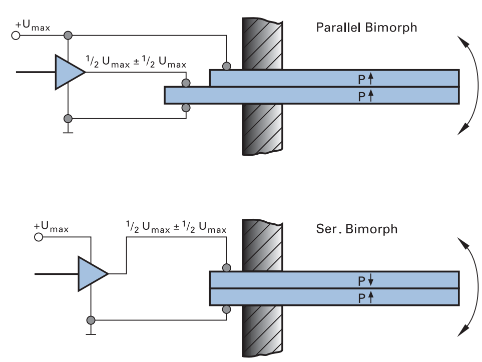


Fig. 45b. Bender Actuators: Serial and parallel bimorphs

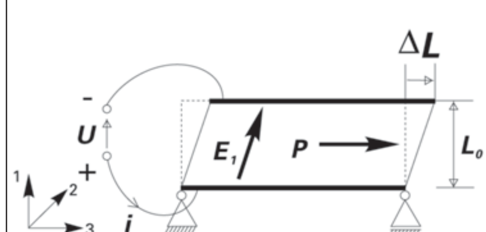


Fig. 46. Material deformation in a shear actuator

Basic Designs of Piezoelectric Positioning Drives/Systems (cont.)

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. 2-211).

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.

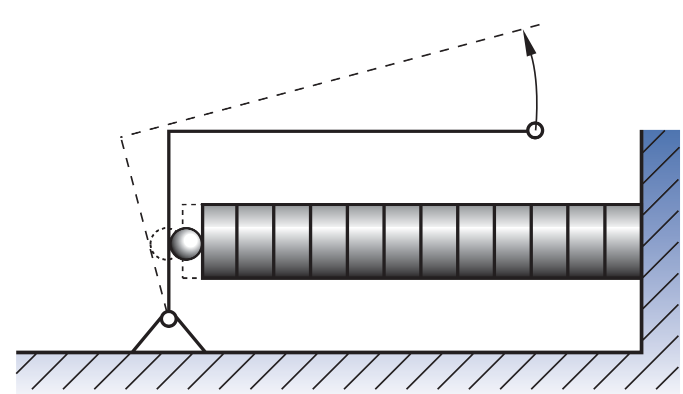


Fig. 47. Simple lever motion amplifier

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]

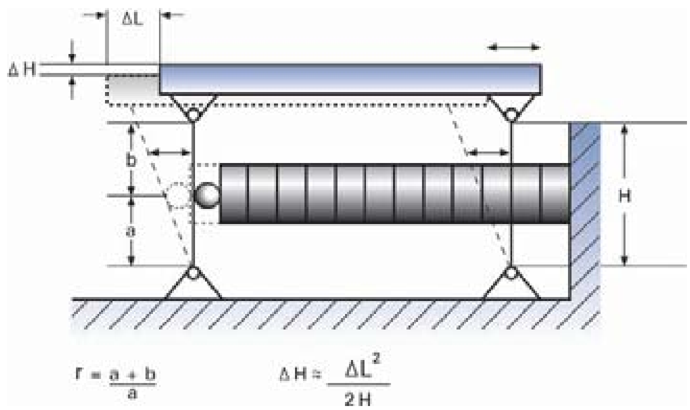


Fig. 48. Basic parallelogram flexure guiding system with motion amplification. The amplification r (transmission ratio) is given by (a+b)/a

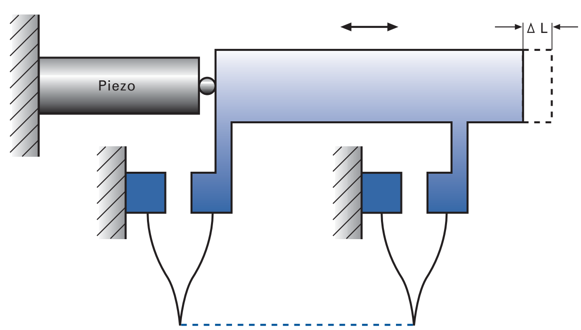


Fig. 49. Zero-arcuate-error multi-flexure guiding system

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.

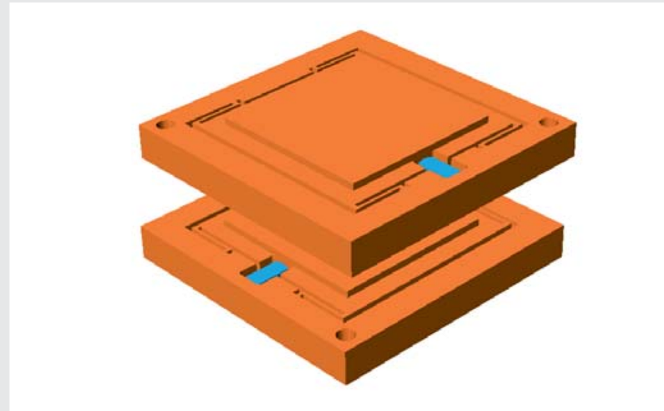


Fig. 50 a. Working principle of a stacked XY piezo stage (serial kinematics). Advantages: Modular, simple design. Disadvantages compared with parallel kinematics: More inertia, higher center of gravity, moving cables (can cause friction and hysteresis). Integrated parallel metrology and active trajectory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

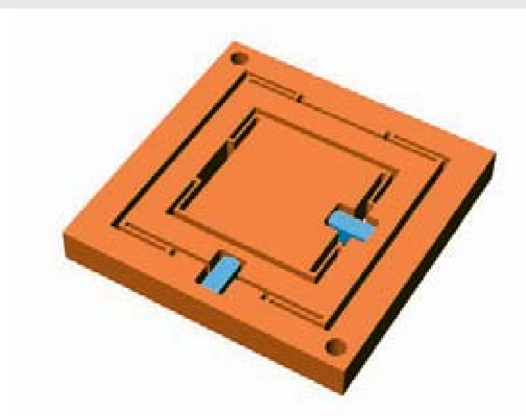


Fig. 50 b. Working principle of a nested XY piezo stage (serial kinematics). Lower center of gravity and somewhat better dynamics compared with stacked system, but retains all the other disadvantages of a stacked system, including asymmetric dynamic behavior of X and Y axes

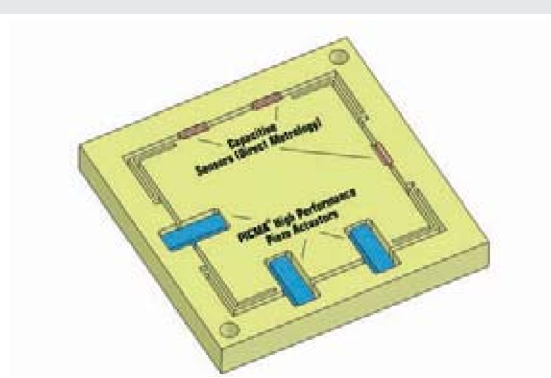


Fig. 50 c. Working principle of a monolithic XYΘ_Z parallel kinematics piezo stage. All actuators act directly on the central platform. Integrated parallel metrology keeps all motion in all controlled degrees of freedom inside the servo-loop. The position of the central, moving platform is measured directly 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. 2-64, p. 2-72) . in the “Piezo Flexure Stages / High-Speed Scanning Systems” section.

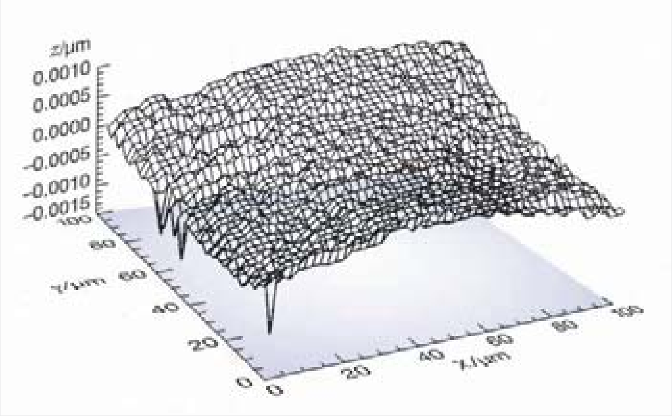


Fig. 51. Flatness (Z-axis) of a 6-axis nanopositioning system with active trajectory control over a 100 x 100 µm scanning range. The moving portion of this parallel metrology positioner is equipped with ultra-precise parallel metrology capacitive sensors in all six degrees of freedom. The sensors are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

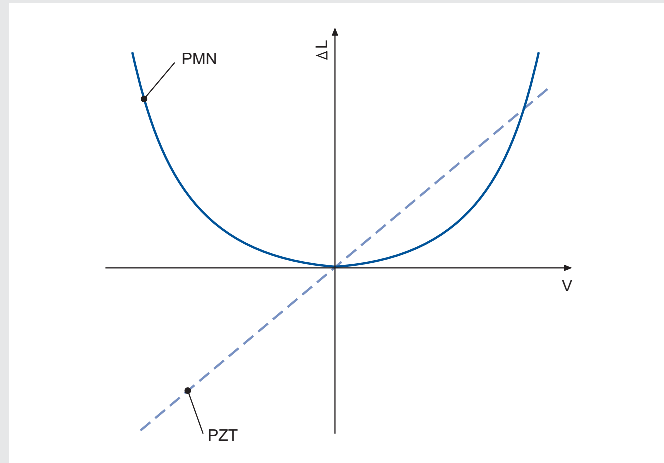


Fig. 52. Comparison of PMN and PZT material: displacement as a function of field strength (generalized)

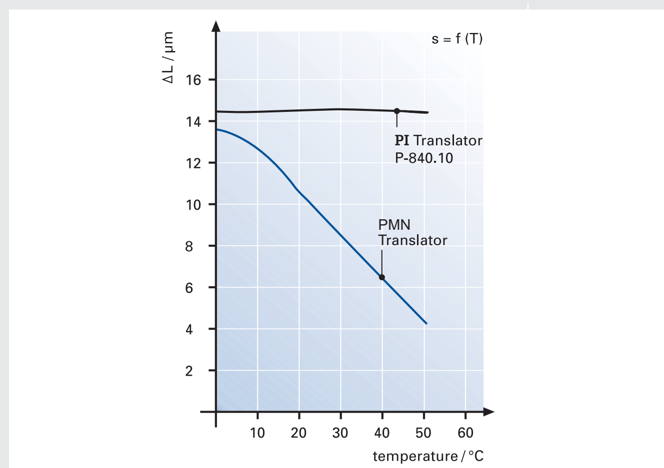


Fig. 53 a. Comparison of PMN and PZT material: displacement as a function of temperature

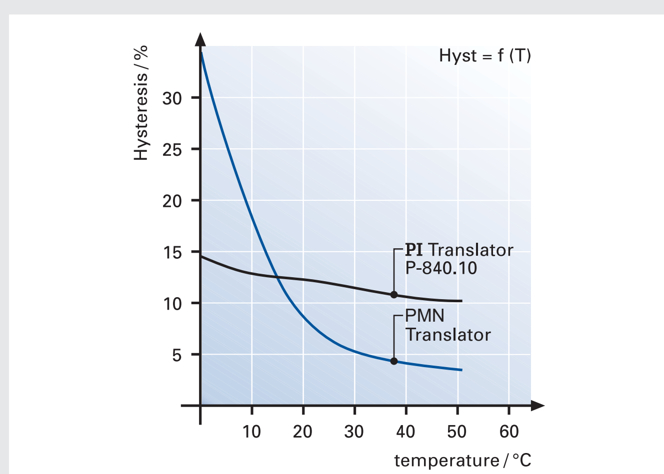


Fig. 53 b. Comparison of PMN and PZT material: hysteresis as a function of temperature

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.

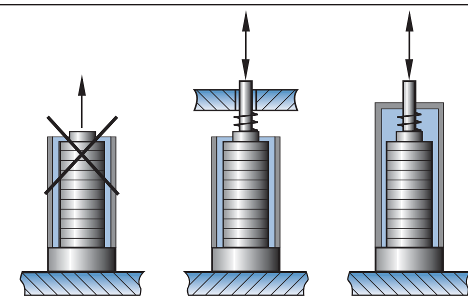
III. Piezoelectric stack actuators can be mounted by gluing them between even metal or ceramic surfaces by a cold or hot curing epoxy, respectively. Ground surfaces are preferred. Please, do not exceed the specified working temperature range of the actuator during curing.

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).

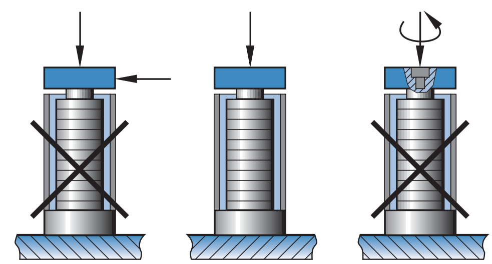
The combination of long-term high electric DC fields and high relative humidity values should be avoided with all piezoelectric actuators.

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.

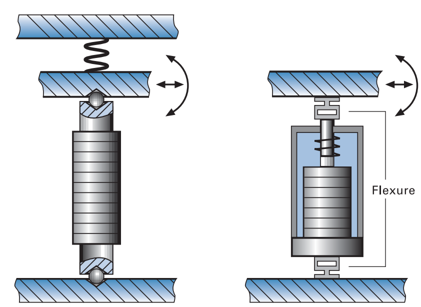
VI. Prevent any contamination of the piezo ceramic surfaces with conductive or corrosive substances. Isopropanol is recommended for cleaning. Avoid acetone and excessive ultrasonic cleaning at higher temperatures.



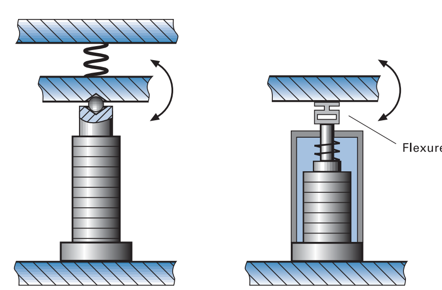
No pulling force without preload



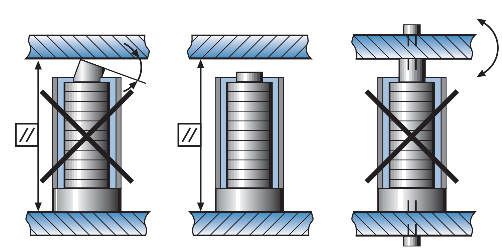
No lateral force or torque



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

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 [ΔL/L] (dimensionless)
t	Time [s] (second)
T_C	Curie temperature [° C]
U	Voltage [V] (volt)
U_{p-p}	Peak-to-peak voltage [V] (volt)