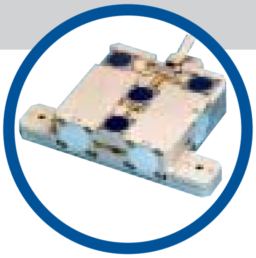
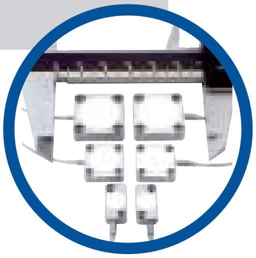
Piezo • Nano • Positioning

Capacitive Displacement Sensors & Nano-Metrology Solutions

Updated 05/2007





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Capacitive Displacement Sensors

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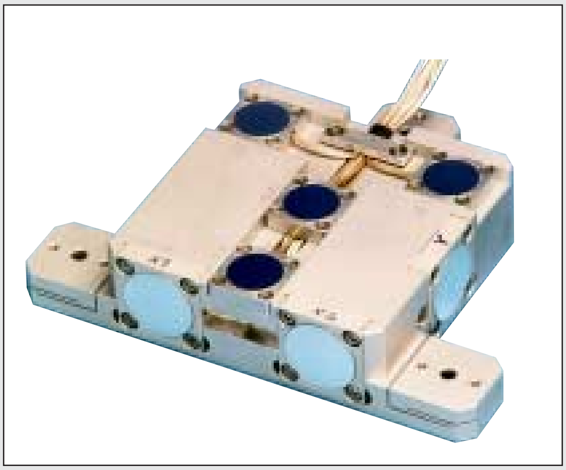
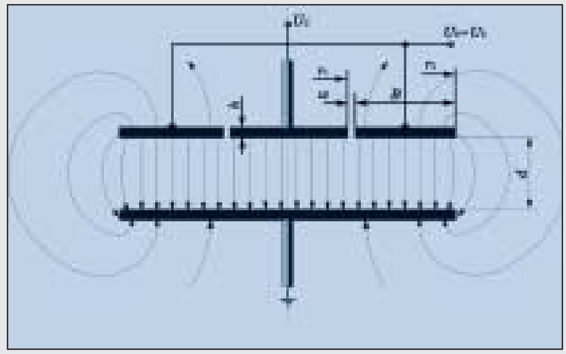
Capacitive Position Metrology

Overview



Capacitive position sensors in an ultra-high-accuracy, 6-degree-of freedom, scanning microscopy, nanopositioning system designed by PI for the German Institute of Standards (PTB)



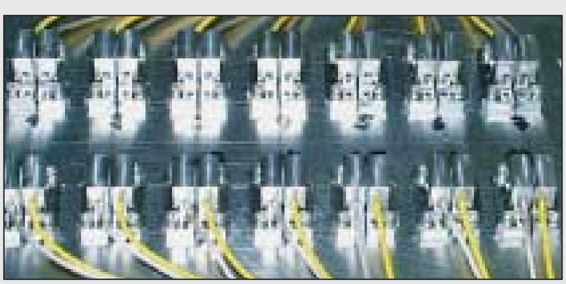
Two-plate capacitive sensor working principle

Properties of PI Capacitive Displacement Sensors

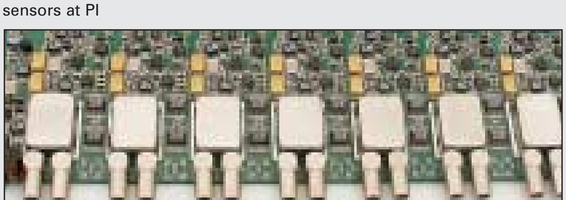
- Highest resolution (0.01 nanometer) of all commercially available position sensors
- Measuring ranges of up to 1 mm
- Ideal for parallel metrology applications
- Linearity to 0.003%
- Extremely high long-term stability (better than 0.1 nm / 3 hours)
- Vacuum compatible
- Bandwidth to 10 kHz
- Invar versions for highest temperature stability (5×10^{-6} / K)
- Multi-channel digital electronics available
- Compatible with PI nanopositioning system servo-controllers
- Two-plate and single-plate sensors
- Custom models

Reasons for Choosing PI

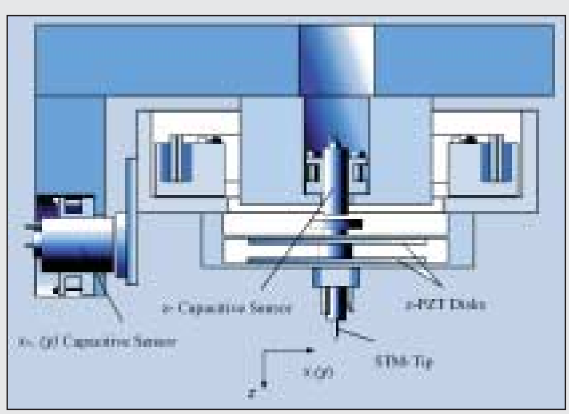
- Over 30 years experience in designing ultra-high-precision mechanics
- In-house design & manufacture of sensors and electronics
- State-of-the-art equipment for simulation, production and testing
- State-of-the-art metrology lab with multiple thermal, acoustic and seismic isolation for meaningful sub-nanometer measurements
- In-house controller development
- PI has the most-experienced nanopositioning systems development and production teams in the field
- ISO-9001 certified since 1994



Quality control and long-term stability testing of capacitive displacement sensors at PI



Custom, 7-channel, capacitive position sensor electronics



Working principle of STM (scanning tunneling microscope) with integrated capacitive position sensors.

D-510

PISeca™ Single-Electrode Capacitive Sensors for Sub-Nanometer Precision Measurements

PISeca™ capacitive displacement sensor probes with E-852 signal conditioner electronics. Sensor probes (from left): D-510.100 with 100 µm, D-510.050 with 50 µm, D-510.020 with 20 µm nominal measurement range

- **Non-Contact Measurement for Distance / Motion / Vibration**
- **Absolute Position Sensing**
- **Sub-Nanometer Resolution**
- **Measurement Ranges to 500 µm**
- **Easy Integration**
- **High Bandwidth**

The new PISeca™ single-electrode capacitive sensors from PI perform non-contact measurements of distance, position or motion against any kind of electrically conductive target. They feature the highest resolution and linearity available.

The PISeca™ single-electrode capacitive gauges are fundamentally very temperature stable, have excellent dynamics and are easy to work with.

Application Examples

- Semiconductor technology / test & measurement
- Data storage
- Automotive industry
- Metrology
- Precision machining

Capacitive Displacement Sensors for Highest Accuracy and Lifetime

Single-electrode capacitive (capacitance) sensors are direct metrology devices. They use an electric field to measure change of capacitance between the probe and a conductive target surface, without physical contact. This makes them free of friction and hysteresis and provides high phase fidelity and bandwidth.

In combination with suitable sensor electronics (E-852.10) resolutions down to the sub-nanometer range and bandwidths to 10 kHz can be achieved. For high-dynamics measurements, a bandwidth up to 10 kHz is possible, with a resolution still down to the 1-nm range. With sufficient mounting accuracy, excellent linearity can be attained (up to 0.1%).

Guard-Ring Capacitor Provides Higher Linearity

Sensor design has a strong influence on linearity because the operating principle is based on that of an ideal parallel-plate capacitor. The superior PI design uses a guard-ring electrode that shields the sensor electrode from boundary effects. This ensures a homogeneous electric field in the measurement zone and results in higher measuring linearity.

Easy Handling and Integration

All PISeca™ sensor probes feature an integrated LEMO connector for easy mounting and replacement in the field. The standardized shaft diameter allows compatibility and flexibility.

Factory Calibration for Improved Linearity

Highest possible linearity and accuracy are achieved with factory calibration of the sensor probe together with the signal conditioner electronics. Two measurement ranges can be calibrated at the same time for one particular sensor probe. Factory calibration also optimizes parameters like ILS (linearization), gain and offset and eliminates cable capacitance influences. The E-852.10 provides two calibrated, optionally extended measurement ranges are available.

High-Precision Machining

The measuring surfaces of the PISeca™ sensors are machined with diamond tools using sophisticated process control techniques. The result is the smooth, ultra-flat, mirrored surface required to obtain highest resolution. The standard material is stainless steel.

Ordering Information

D-510.020
PISeca™ Single-Electrode Capacitive Sensor Probe, 8 mm diameter, 20 µm nominal range

D-510.050
PISeca™ Single-Electrode Capacitive Sensor Probe, 12 mm diameter, 50 µm nominal range

D-510.100
PISeca™ Single-Electrode Capacitive Sensor Probe, 20 mm diameter, 100 µm nominal range

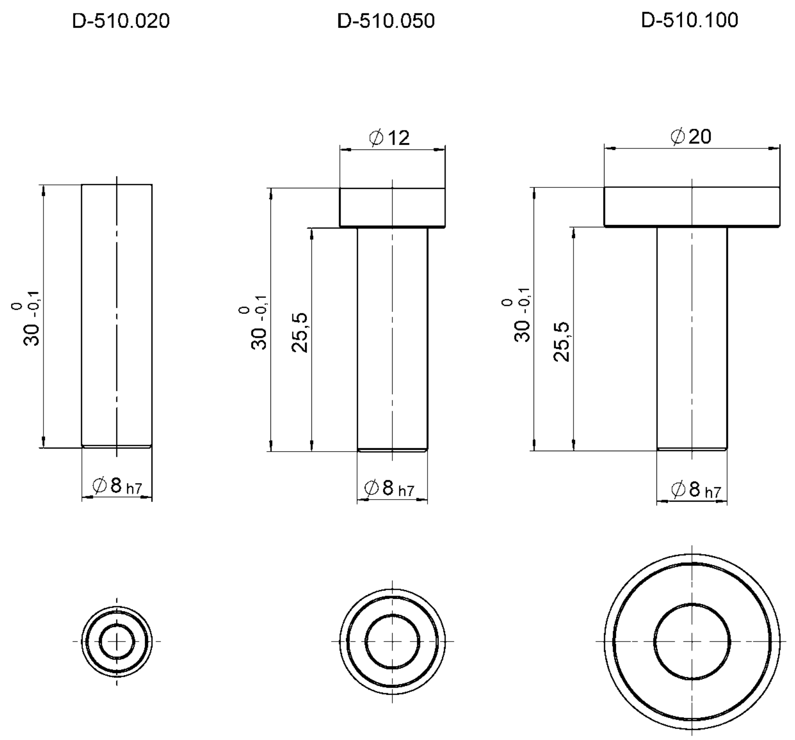
Ask about custom designs!

Custom Sensors / Two-Plate Sensors

In addition to the standard sensors listed here, PI can offer a variety of custom versions for different measuring ranges, geometries, materials match, etc. Systems with custom electronics are also available.

If ultimate performance is required, the D-100 series two-plate capacitive sensors are recommended, see page 5-4 *ff*.

D-510.050 with LEMO-connector for easy handling



D-510.020, D-510.050 and D-510.100 capacitive displacement sensor probes, dimensions in mm.
Sensor connection LEMO FFC00.650.CLA.543, triaxial, cable length 1 m

Technical Data

Models	D-510.020	D-510.050	D-510.100	Units	Tolerance
Sensor type	Single-electrode, capacitive	Single-electrode, capacitive	Single-electrode, capacitive		
Measurement accuracy					
Nominal measurement range*	20	50	100	µm	
Min. gap	10	25	50	µm	
Max. gap	150	375	750	µm	
Static resolution**	<0.001	<0.001	<0.001	% of measurement range	typical
Dynamic resolution**	<0.002	<0.002	<0.002	% of measurement range	typical
Linearity***	<0.2	<0.1	<0.1	%	
Mechanical properties					
Sensor active diameter	3.8	6	8.4	mm	
Sensor active area	11.2	27.9	56.1	mm^2	
Sensor diameter	8	12	20	mm	
Sensor area	50.3	113.1	314.0	mm^2	
Mounting shaft diameter	8	8	8	mm	
Miscellaneous					
Operating temperature range	-20 to +100	-20 to +100	-20 to +100	°C	
Material	Stainless steel	Stainless steel	Stainless steel		
Mass	8	10	16	g	±5%
Recommended signal conditioner electronics	E-852.10	E-852.10	E-852.10		

* Extended measurement ranges available for calibration with E-852 signal conditioner electronics
** Static resolution: bandwidth 10 Hz, dynamic: bandwidth 6.6 kHz, with E-852.10 signal conditioner electronics
*** Linearity over nominal measurement range

E-852

Signal Conditioner Electronics for PISeca™ Single-Electrode Capacitive Sensors

E-852 signal conditioner electronics with PISeca™ capacitive displacement sensor probes D-510.100, D-510.050, D-510.020 (from left)

- **Cost-Effective System Solution for PISeca™ Capacitive Displacement Sensor Probes**
- **Special Linearization System (ILS) for Maximum Linearity**
- **Bandwidth Adjustable from 10 Hz to 6.6 kHz**
- **Multiple Measurement Ranges per Probe**
- **LED-Bar Measuring-Range Display for Easy Setup & Sensor Installation**
- **External Synchronization for Multi-Channel Applications**

The economical E-852.10 signal conditioner electronics is specially designed for the PISeca™ D-510 series of single-electrode capacitive displacement sensor probes. It provides analog output with very high linearity, exceptional long-term-stability, sub-nanometer position resolution and bandwidths up to 6.6 kHz.

Measurement Principle of Capacitive Sensors

Single-electrode capacitive (capacitance) sensors are direct metrology devices. They use an electric field to measure change of capacitance between the probe and a conductive target surface, without physical contact. This makes them free of friction and hysteresis and provides high phase fidelity and bandwidth.

Application Examples

- Semiconductor technology / test & measurement
- Data storage
- Automotive industry
- Metrology
- Precision machining

Selectable Bandwidth and Measurement Range

The selectable bandwidth setting allows the user to adapt the system to different applications. For the highest accuracy and sub-nanometer resolution, the bandwidth can be limited to 10 Hz.

For high-dynamics measurements, a bandwidth up to 6.6 kHz is possible, with a resolution still down to the 1-nm range.

The user can choose a measurement range from 20 to 500 µm, depending on the nominal measurement range of the selected sensor. The E-852.10 provides different extended measuring ranges for each selected sensor.

Easy Sensor Installation

The simple installation of the single-electrode PISeca™ probes is facilitated by the E-852´s LED-bar indicating the optimum gap between probe and target.

Factory Calibration for Improved Linearity

Highest possible linearity and accuracy are achieved with factory calibration of the sensor probe together with the signal conditioner electronics. Two measurement ranges can be calibrated at the same time for one particular sensor probe. Factory calibration also optimizes parameters like ILS (linearization), gain and offset and eliminates cable capacitance influences.

Integrated Linearization System (ILS) for Highest Accuracy

A proprietary linearization circuit compensates the influences of parallelism errors between sensor and target and guarantees an excellent measuring linearity (to 0.1%).

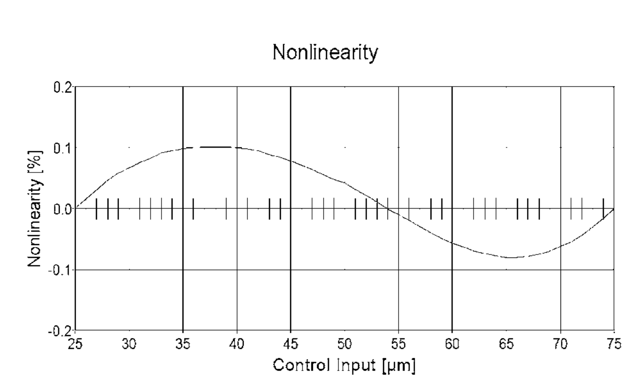
Multichannel Measurements

PISeca™ sensor electronics are equipped with I/O lines for the synchronization of multiple sensor systems.

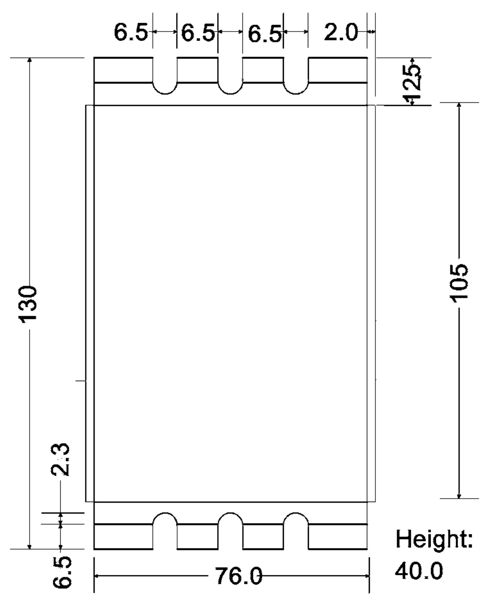
Ordering Information

E-852.10
PISeca™ Signal Conditioner Electronics for Single Electrode Capacitive Sensors, 1 Channel (with E-852.PS Power Supply)

Ask about custom designs!



Output linearity error of E-852 signal conditioner / D-510.050 sensor combination (nominal measurement range)



E-852.10, dimensions in mm

Technical Data

Models	**E-852**
Function	Signal conditioner for PISeca™ capacitive sensor probes
Channels	1
Sensor	
Sensor type	Single-electrode, capacitive
Sensor bandwidth	6.6 / 3 / 0.3 kHz 1.1 / 0.1 / 0.01 kHz (option)
Measurement range extension factors*	1 & 2.5 (calibrated), 2 & 5 (option)
Ext. synchronization	Auto master-slave
Temperature stability	1.56 mV / °C
Electrical properties	
Output voltage	-10 to +10 V / -5 to +5 V / 0 to +10 V
Output signal	1 kΩ / 1 nF
Supply voltage	±15 V (125 mA), +5 V (20 mA) supplied by E-852.PS / ±15 V
Static resolution**	<0.001 % of measurement range (RMS)
Dynamic resolution**	<0.002 % of measurement range (RMS)
Linearity @ nominal range	<0.1 % (<0.2 % for D-510.020)
Interface and operation	
Sensor connection	LEMO ECP.00.650.NLL.543 socket, triaxial
Analog output	BNC
Supported functionality	LED bar (gap indicator)
Linearization	ILS
Miscellaneous	
Operating temperature range	+5 to +40 °C
Weight	0.355 kg, E-852.PS: 1.2 kg
Dimensions	80 x 130 x 40 mm, E-852.PS: 100 x 170 x 62 mm
Target ground connector	Banana jack

* Extension factors to multiply by the nominal measurement range
** Static: bandwidth 10 Hz, dynamic: bandwidth 6.6 kHz, cable length 1 m

D-015 · D-050 · D-100

Dual-Electrode, Sub-Nanometer-Resolution Capacitive Position Sensors

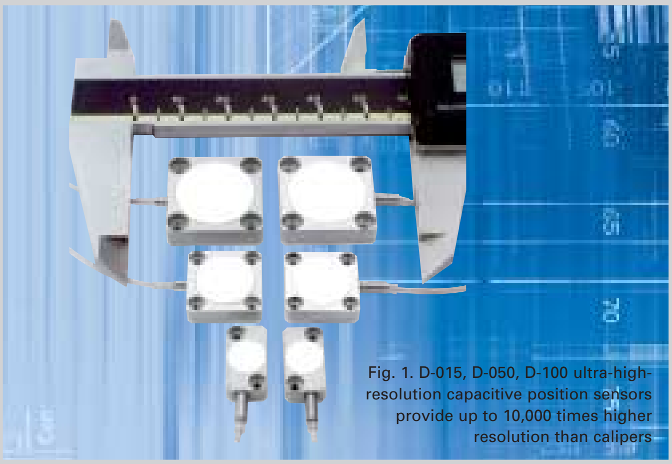


Fig. 1. D-015, D-050, D-100 ultra-high-resolution capacitive position sensors provide up to 10,000 times higher resolution than calipers

- **Measuring Range to 1000 µm**
- **Resolution <0.01 nm**
- **Linearity to 0.003 %**
- **Bandwidth to 10 kHz**
- **Integrated Linearization System (ILS)**
- **Custom Designs**

Measurement Method

Capacitive position sensors are analog non-contact devices. A two-electrode capacitive position sensor consists of two RF-driven plates that are part of a capacitive bridge. The high-frequency AC excitation provides better long term stability than DC excited sensors (see p. 5-6, Fig. 4). One plate (probe) is fixed, the other plate (target) is connected to the object to be positioned. Since the plate size and the dielectric medium (air) remains unchanged, capacitance is directly related to the distance between the plates. Ultra-precise electronics convert the capacitance information into a signal proportional to distance.

Direct Metrology, Parallel Metrology

The sensors offered by PI are the most accurate measuring systems for nanopositioning applications currently on the market. In contrast to high-resolution sensors measuring deformation in the drive train (see p. 2-5 *ff.*), like strain gauge or piezoresistive sensors, capacitive sensors are non-contact, direct-metrology devices—a fact which gives them many advantages:

- Better Phase Fidelity
- Higher Bandwidth
- No Periodic Error
- Non-Contacting
- Ideal for Parallel Metrology
- Higher Linearity
- Better Reproducibility
- Higher Long-Term Stability

Capacitive sensors are especially well-suited for parallel metrology configurations. In multi-axis nanopositioning systems, parallel metrology means that the controller monitors all controlled degrees of freedom relative to "ground" (the fixed frame) and uses each actuator to compensate the undesired off-axis motion of the others automatically (active trajectory control). As a result, it is possible to keep deviations in the sub-nanometer and sub-microradian range (see p. 4-44 *ff.* in the "Tutorial" section).

Resolution

Resolution on the order of picometers is achievable with short-range, two-electrode capacitive position sensors (single-electrode capacitive position sensors provide less resolution, linearity and accuracy than two-electrode sensors). Theoretical measurement resolution is limited only by quantum noise. In practical applications, stray radiation, electronics-induced noise and geometric effects are the limiting factors. For example, with the 100 µm range, a D-100.00 sensor and E-509.C1A electronics, the effective noise factor is 0.02 nm/$\sqrt{\text{Hz}}$. This translates to 0.2 nm at 100 Hz bandwidth. The maximum standard bandwidth (jumper selectable) is 3 kHz.

Figure 2 shows a D-015, 15 µm capacitive position sensor and an interferometer, both measuring nanometer-range actuator cycles. The graphs clearly show the superior resolution of the capacitive position sensing technique.

Notes

In addition to the standard sensors listed here, PI offers a variety of custom versions along with custom electronics for different measuring ranges, material match etc. If you don't find what you are looking for, please call your local PI Sales Engineer.

Ordering Information

D-015.00
Capacitive Position Sensor, 15 µm, Aluminum

D-050.00
Capacitive Position Sensor, 50 µm, Aluminum

D-100.00
Capacitive Position Sensor, 100 µm, Aluminum

Ask about custom designs!

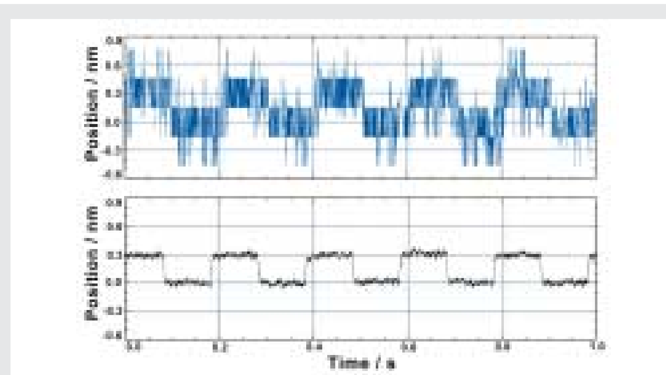
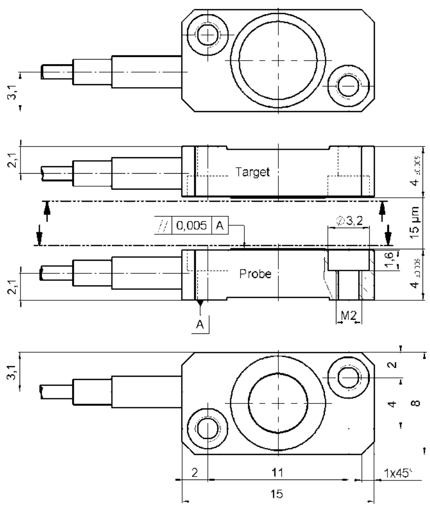
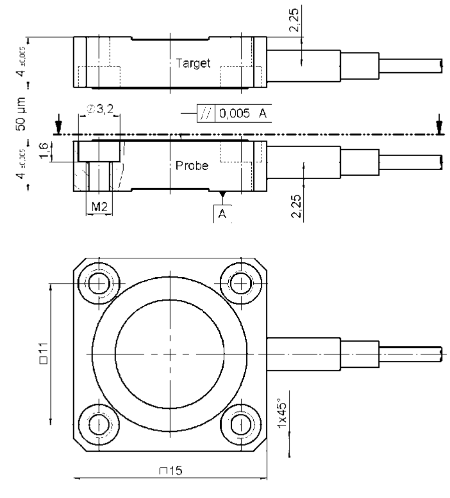


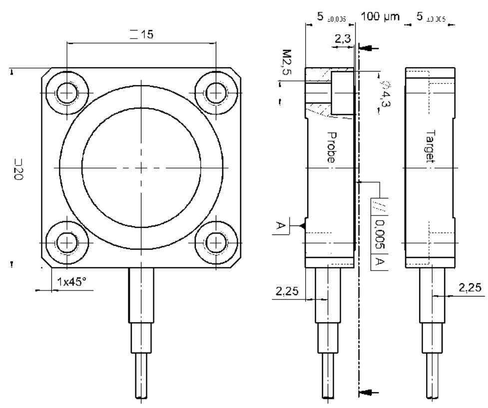
Fig. 2. Piezo nanopositioning system making 0.3 nm steps, measured with PI capacitive sensor (lower curve) and with a highly precise laser interferometer. The capacitive sensor provides significantly higher resolution than the interferometer.



D-015.00 (dimensions in mm)



D-050.00 (dimensions in mm)



D-100.00 (dimensions in mm)

Technical Data: Capacitive Sensor Electronics

Models	E-509.CxA
Power supply	±15 V
Analog output	±5 V (0V - 10V)
Noise factor*	0.115 ppm/√Hz
Bandwidth	0.3 to 3 kHz, selectable; up to 10 kHz on request
Temperature drift*	typ. -30 ppm/K
Linearity error (before digital polynomial linearization)	<0.05 %
Operating temperature range	-20 to 80 °C

* Specifications in ppm (parts per million) refer to measuring range

Technical Data: Capacitive Sensors

Sensor Models	D-015.00	D-050.00	D-100.00	Units
Material	Aluminum*	Aluminum*	Aluminum*	
Active Surface	16.6	67.7	113.1	mm²
Nominal Measuring Distance	15	50	100	µm
Extended Measuring Distance	45	150	300	µm
Therm. Drift **	50	50	50	ppm/K
Operating temperature range	-20 to +80	-20 to +80	-20 to +80	°C

* Other materials, measuring ranges and form factors or request.
** Change of the active measuring surface in parts per million as referred to the selected measuring range

Characteristics of Capacitive Position Sensors

Stability and Linearity of Dual-Electrode PI Capacitive Position Sensors

Fig 1. P-752.11C, 15 µm piezo nanopositioning stage with integrated capacitive position sensor.

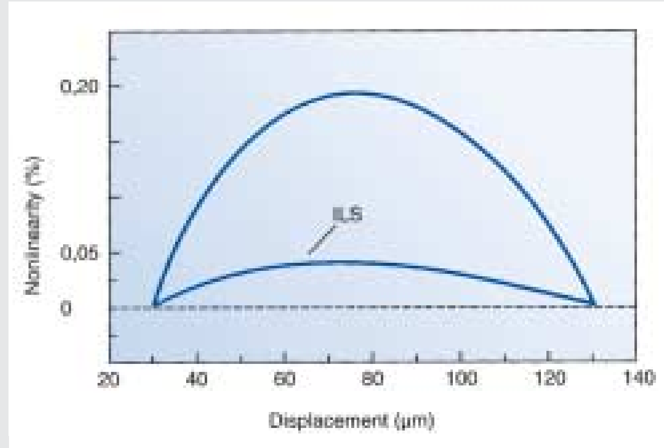


Fig 2. Linearity of conventional capacitive position sensor system vs. PI ILS (integrated linearization system), shown before digital linearization.

PI capacitive position sensor electronics incorporate a proprietary design providing superior linearity, low sensitivity to cable capacitance, low background noise and low drift.

The Integrated Linearization System (ILS) compensates for influences caused by errors, such as non-parallelism of the plates. A comparison between a conventional capacitive position sensor system and the results obtained with the PI ILS is shown in Figure 2 on this page. When used with PI digital controllers (which add polynomial linearization techniques) a positioning linearity of up to 0.003 % is achievable.

Figure 3 shows the linearity of a P-752.11C piezo flexure nanopositioning stage with integrated capacitive position sensor operated in closed-loop mode with an analog controller. All errors contributed by the mechanics, PZT drive, sensors and electronics are included in the resulting linearity of better than 0.02 %. Even higher linearity is achievable with PI digital controllers, see the E-710 on pp. 6-14 *ff*.

The exceptional long-term stability of the PI capacitive position sensor and electronics design is shown in Figure 4.

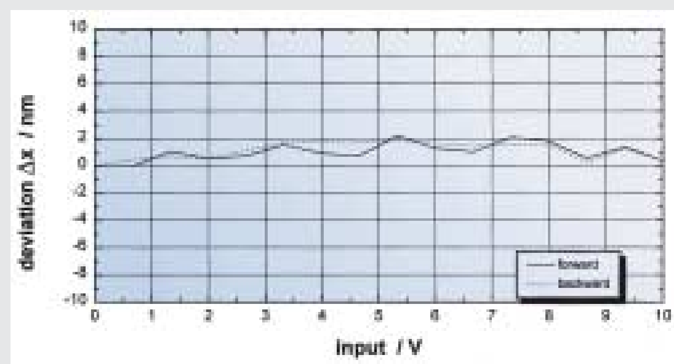


Fig 3. Linearity of a P-752.11C, 15 µm piezo nanopositioning stage operated with E-500/ E-509.C1 control electronics. The travel range is 15 µm, the gain 1.5 µm/V. Linearity is better than 0.02 %; even higher linearity is achievable with PI digital controllers.

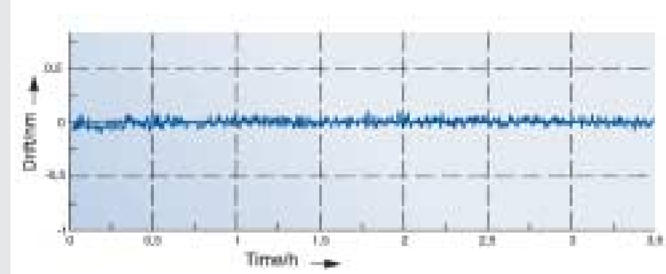


Fig 4. Measurement stability of an E-509.C1 capacitive position sensor control board with 10 pF reference capacitor over 3.5 hours (after controller warm-up).

Electrode Geometry, Sensor Surface Flatness and Finish

During sensor production great care is taken to maintain critical mechanical tolerances. Measuring surfaces are diamond-tool machined using sophisticated process control techniques. The result is the smooth, ultra-flat, mirrored surfaces required to obtain the highest resolution commercially available. The target and probe plates are configured in such a way that the sensor capacitance in air is 10 pF for all models at the nominal measuring distance. This means that one sensor electronics module can operate all sensor range models without modification.

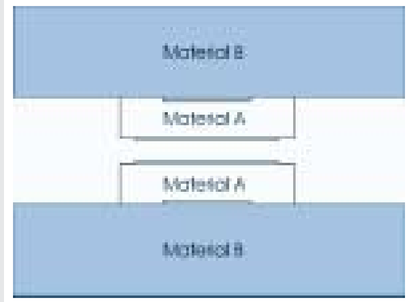


Fig. 5a. Optimum match between sensor material and environment

Special Design Eliminates Cable Influences

When measuring distance by detection of capacitance changes, fluctuations in the cable capacitance can have an adverse effect on accuracy. This is why most capacitive measurement systems only provide satisfactory results with short, well-defined cable lengths. PI Systems use a special design which eliminates cable influences, permitting use of cable lengths of up to 3 m without difficulty. For optimum results, we recommend calibration of the sensor-actuator system in the PI Metrology Lab. Longer distances between sensor and electronics can be spanned with special, loss-free, digital transmission protocols, see the E-710, pp. 6-15 *ff.*

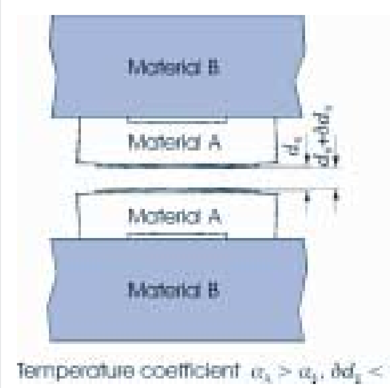


Fig. 5b. CTE of sensor material and enviroment are different. Buckling can reduce sensor flatness and accuracy.

Materials Match for Greater Accuracy

The best measurements are obtained when the coefficient of thermal expansion of the sensor and the substrate to which it is affixed are as nearly equal as possible (Fig. 5a). If they differ, temperature changes lead to mechanical stress and deformation which can compromise accuracy (Fig. 5b). It is the match that counts, not the absolute value of the temperature coefficient. A low-temperature-coefficient Invar sensor mounted on a stainless steel stage will thus give poorer results than a steel sensor.

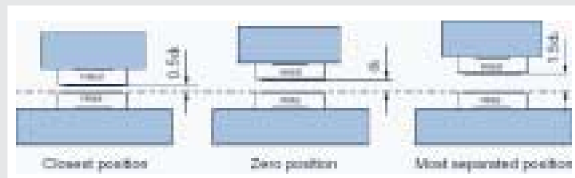


Fig. 6. Distance between probe and target at center position, closest spacing and maximum separation.

Mounting, Calibration and Measuring Ranges

The sensors should be mounted with a mid-range distance between the plates equal to the nominal measuring range (see Fig. 6). The measuring range then comprises 50 % to 150 % of this distance. The corresponding range at the output of the sensor electronics is 10 volts in width. The probe/target capacitance at a distance equal to the nominal measuring range equals that of the 10 pF reference capacitor in the electronics. The nominal range itself can be increased or decreased by selecting a different reference capacitor in the electronics (see Fig. 7).

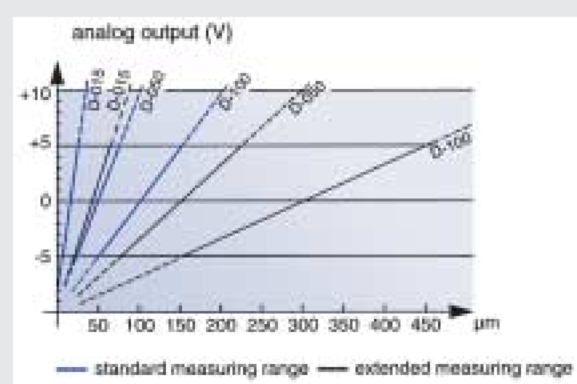


Fig. 7. Measuring ranges of different PI capacitive position sensors (standard ranges in blue, extended ranges in black).

Characteristics of Dual-Electrode Capacitive Displacement Sensors (cont.)

Parallelism of Measuring Surfaces

For optimum results, target and probe plates must remain parallel to each other during measurement (see Fig. 8a, 8b). Positioning systems with multi-link flexure guidance reduce tip and tilt to negligable levels (see Fig. 9) and achieve outstanding accuracy.

Electronics Support

Standard PI capacitive position sensor electronics are supported by all PI digital controllers (e.g. models E-750, E-710, see the "Piezo Drivers & Nanopositioning Controllers" section, p. 6-12 and p. 6-14). Inputs are also available on E-509.Cx Euroboard cards (fitting the E-500 and E-501 series controllers) and on several OEM controllers (E-610.C0 Eurocard controller, E-612 high-speed parallel port PZT controllers, p. 6-38). In addition, custom designs providing up to 7 channels tailored to specific needs are available.

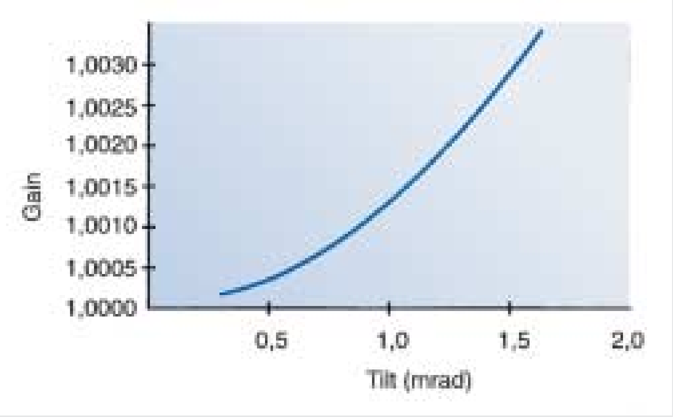


Fig. 8a. Relative sensor gain vs. tilt This effect is negligible in nanopositioning systems with microradian-range guiding accuracy (see Fig. 9).

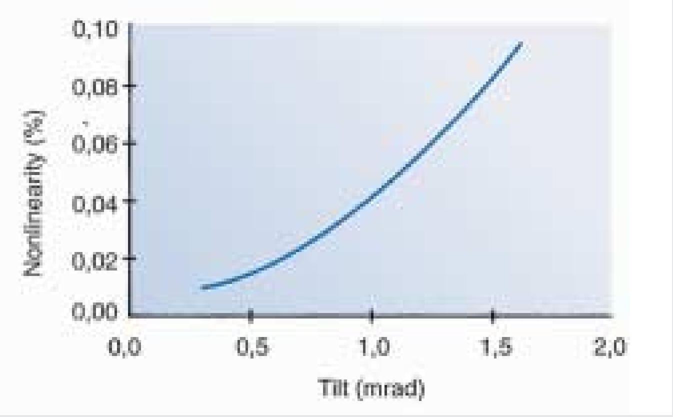


Fig. 8b. Nonlinearity vs. tilt
This effect is negligible in nanopositioning systems with microradian-range guiding accuracy (see Fig. 9).

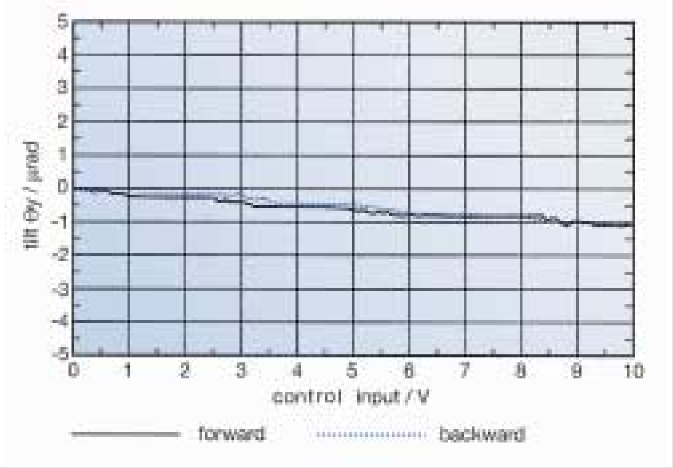


Fig. 9. Flexure-guided nanopositioning systems like the P-752 offer submicroradian guiding accuracy and are optimally suited for capacitive sensors.

Headquarters

Germany

Physik Instrumente (PI) GmbH & Co. KG
Auf der Römerstraße 1
76228 Karlsruhe
Tel. +49 721 4846-0
Fax +49 721 4846-100
info@pi.ws · http://www.pi.ws

PI Ceramic GmbH
Lindenstraße
07589 Lederhose
Tel. +49 36604 882-0
Fax +49 36604 882-25
info@piceramic.com
http://www.piceramic.com

Subsidiaries

USA (East) & Canada (East)

PI (Physik Instrumente) L.P.
16 Albert Street
Auburn, MA 01501
Tel. +1 508 8323456
Fax +1 508 8320506
info@pi-usa.us
http://www.pi-usa.us

PI (West), Canada (West), Mexico

PI (Physik Instrumente) L.P.
5420 Trabuco Road, Suite 100
Irvine, CA 92620-5743
Tel. +1 (949) 679-9191
Fax +1 (949) 679-9292
info@pi-usa.us
http://www.pi-usa.us

JAPAN

PI-Japan Co., Ltd.
2-38-5 Akebono-cho
Tachikawa-shi
J-Tokyo 190-0012
Tel. +81 42 5267300
Fax +81 42 5267301
info@pi-japan.jp
http://www.pi-japan.jp

PI-Japan Co., Ltd.
Hanahara Dai-ni-Building #703
4-11-27 Nishinakajima,
Yodogawa-ku, Osaka-shi
J-Osaka 532-0011
Tel. +81 6 63045605
Fax +81 6 63045606
info@pi-japan.jp
http://www.pi-japan.jp

CHINA

Physik Instrumente (PI Shanghai) Co., Ltd.
Building No. 7-306,
Longdong Avenue 3000
201203 Shanghai
Tel. +86 21 68790008
Fax +86 21 68790098
info@pi-china.cn
http://www.pi-china.cn

UK & Ireland

Lambda Photometrics Ltd.
Lambda House
Batford Mill
GB-Harpenden, Hertfordshire
AL5 5BZ
Tel. +44 1582 764334
Fax +44 1582 712084
info@lambdaphoto.co.uk
http://www.lambdaphoto.co.uk

France

Polytec PI S.A.
32 rue Delizy
F-93694 Pantin Cedex
Tel. +33 1 48103930
Fax +33 1 48100803
pi.phot@polytec-pi.fr
http://www.polytec-pi.fr

Italy

Physik Instrumente (PI) S.r.l.
Via G. Marconi, 28
I-20091 Bresso (MI)
Tel. +39 02 66501101
Fax +39 02 66501456
info@pionline.it
http://www.pionline.it

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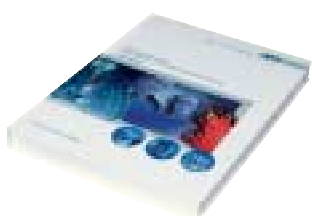

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