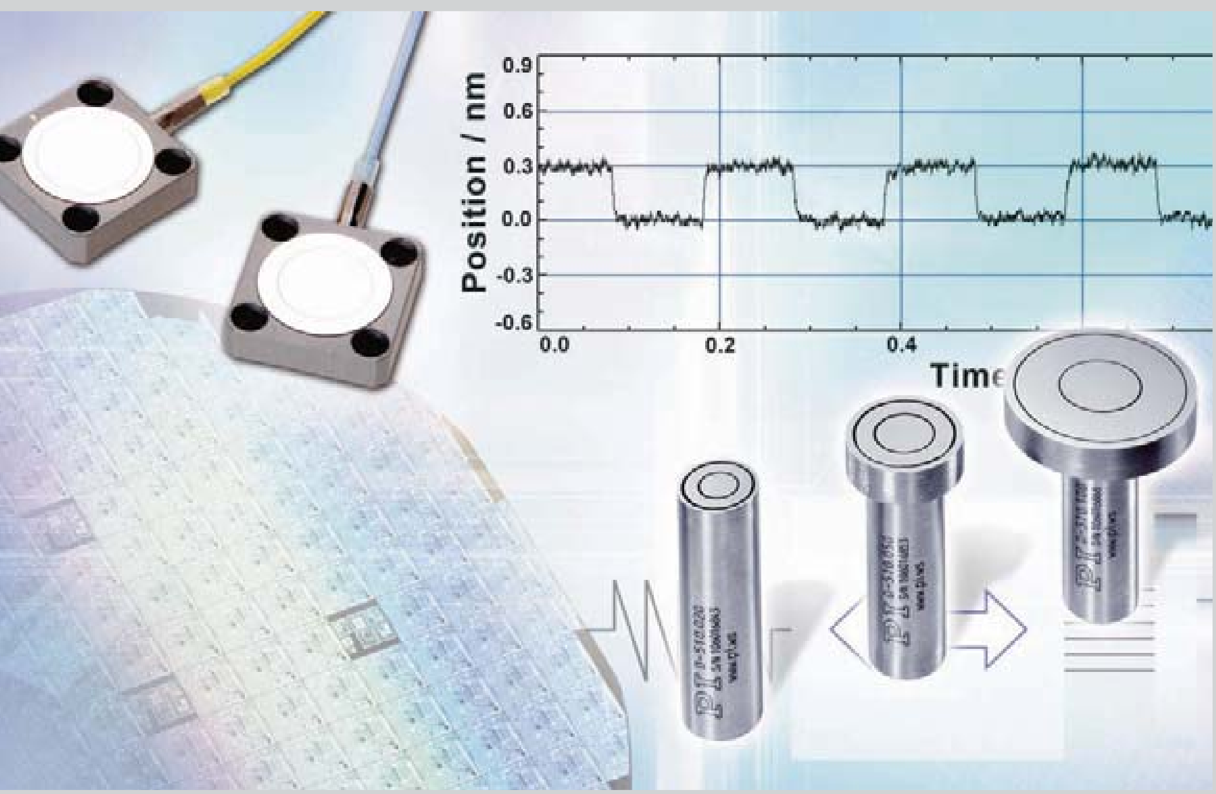
Piezo • Nano • Positioning

Nanometrology

Capacitive Sensors with Sub-Nanometer Resolution



Selection Guide: Nanometrology Sensors & Electronics

Single and Dual Probe Capacitive Nanometrology Position Sensors

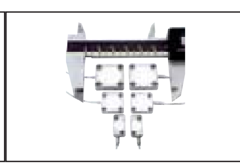
Capacitive Sensor Overview

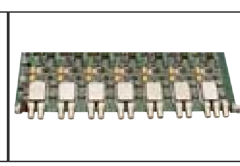
PI provides dual-plate and single-plate capacitive sensors for ultra-high precision position-sensing applications. The sensors and special control electronics with PI's proprietary ILS circuitry were developed to provide the highest linearity and resolution and have also been employed in PI's reference class nanopositioning stages for many years.

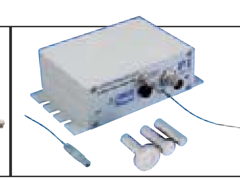
Models	Description	Measurement Range [µm]*	Sensor Type	Page
D-510	PISeca™ Single-Electrode Capacitive Sensors for Sub-Nanometer Precision Measurements	20-500	Single-electrode, capacitive	3-8
D-015, D-050, D-100	Sub-Nanometer-Resolution Capacitive Position Sensors	to 1000	Integrated Linearization System (ILS)	3-14

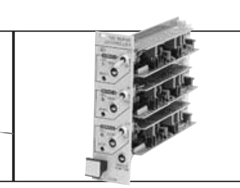
Models	Description	Channels	Sensor Type	Page
E-852	PISeca™ Signal Conditioner Electronics for Single-Electrode Capacitive Sensors	1	Single-electrode, capacitive	3-10
E-509	Servo Controller card for PISeca™ 1-Plate and Dual-Plate Capacitive Sensors	1,3	Dual and single-electrode, capacitive	3-12 3-16

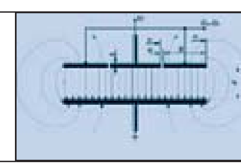

D-510 PIseca™ single-plate nanometrology sensors


D-015, D-050, D-100 dual-plate capacitive position sensors


Customized capacitive sensor electronics


E-852 Signal conditioner electronics for single plate sensors


E-509 Servo controller card for single & dual plate sensors


Background Information on capacitive sensors, p. 3-17 *ff* Nanometrology Fundamentals

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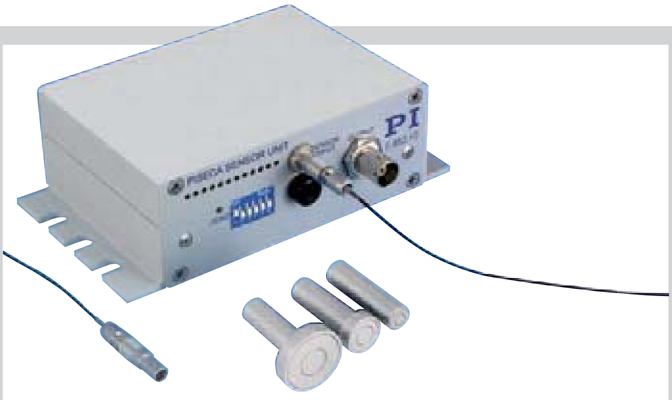
Capacitive Sensors / Signal Conditioners

Capacitive Position Metrology

Overview



E-852 signal conditioner electronics with PISeca™ D-510.020 1-plate capacitive sensor

Properties of PI Sensors

- **Measurement Ranges from 10 up to 500 µm and More**
- **Sub-Nanometer Position Resolution**
- **Non-Contact Absolute Measurement of Displacement / Motion / Vibration**
- **Immune to Wear and Tear**
- **Ideal for Multi-Axis Applications**
- **Improved Linearity with ILS Signal Electronics**
- **High Bandwidth up to 10 kHz**
- **Measures Position of the Moved Interface (Direct Metrology)**
- **High Temperature and Long-Term Stability (<0.1 nm/3 h)**
- **Vacuum Compatible**
- **Compact 1- and 2-Electrode Sensors, Custom Designs**
- **Guard-Ring Electrode Eliminates Boundary Effects**
- **Invar Versions for Highest Temperature Stability (5 x 10^{-6}/K)**

Standard D-015, D-050, D-100 2-plate sensors (front from left) and a selection of custom sensors

One- and Two-plate Sensors

Capacitive sensors perform non-contact measurements of geometric quantities representing distance, displacement, separation, position, length or other linear dimensions with sub-nanometer accuracy. PI offers capacitive sensors for the integration in user applications in two-plate-capacitor versions for highest performance and as PISeca™ single-electrode sensors, for more flexibility and easier integration.

Measurement Principle

The measurement principle in both cases is the same: two conductive surfaces set up a homogenous electric field; the change in displacement of the two plates is proportional to the signal conditioner output. Dual-plate sensors measure the distance between two well-defined sensor plates with carefully aligned surfaces which generate the most accurate electric field and hence provide optimal results. Single-plate capacitive sensors measure the capacitance against electrically conductive references, such as metallic plates, and are very convenient to install and connect.

Nanopositioning and Nanometrology

PI offers the widest range of high-dynamics and high-resolution nanopositioning systems worldwide. The precision and repeatability achieved would not be possible without highest-resolution measuring devices. Capacitive sensors are the metrology system of choice for the most demanding nanopositioning applications. The sensors and the equally important excitation and read-out electronics are developed and manufactured at PI by expert teams with longstanding experience.

Test and Calibration

PI's nanometrology calibration laboratories are seismically, electromagnetically and thermally isolated, and conform to modern international standards.

PI calibrates every capacitive measurement system individually, optimizing the performance for the customer's application. Such precision is the basis of all PI products, standard and customized, and assures optimum results in the most varied of applications.

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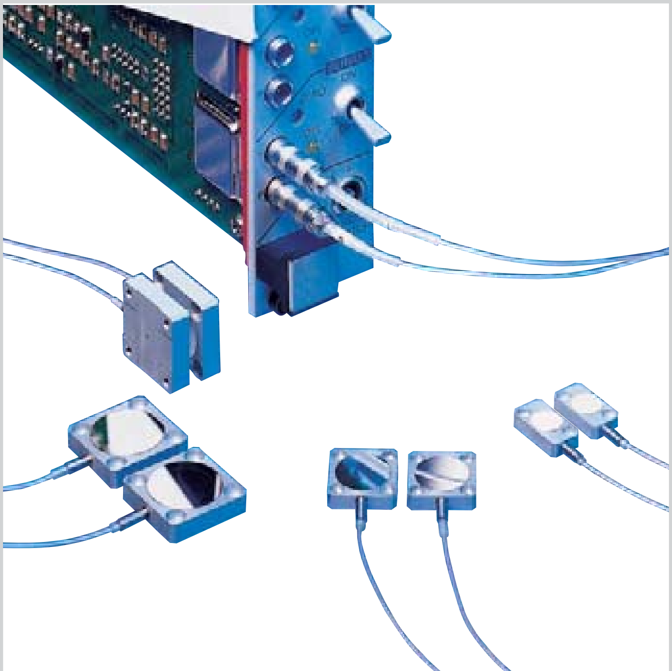
Function, Properties, Advantages



Two-plate capacitive sensors D-100 (2 pairs), D-050 and D-015

D-510.050 with LEMO connector for easy handling

Accuracy

Accuracy, linearity, resolution, stability and bandwidth are far better than with conventional nanometrology sensors like LVDT or strain gauge sensors.

Non-contact operation means no parasitic forces influencing the application and results in measurement free of friction and hysteresis.

Guard-Ring Design for Improved Linearity

Sensor design has a strong influence on linearity. The superior PI design uses a guard-ring electrode that eliminates sensor electrode boundary effects. This ensures a homogenous field in the measurement zone and results in higher measuring linearity.

Single- and Multi-Channel Electronics

PI's signal conditioner electronics are specially designed for high bandwidth, linearity and ultra-low noise and are perfectly matched to the various PI sensor probes. PI offers signal conditioner electronics and controllers for one to three channels. The E-509 multichannel modules plug into the modular E-500 / E-501 controller chassis. Bandwidth and measurement range can be factory-set to meet the specific needs of each application. The E-852 one-channel signal conditioner electronics for PISeca™ single-plate sensors are designed as stand-alone systems with user-selectable bandwidth and range setting and can be synchronized to operate in multi-channel applications.

Higher Linearity through ILS Electronics

All of PI's signal conditioning electronics are equipped with the PI proprietary ILS linearization circuit that minimizes nonparallelism errors.

Easy Handling and Integration

PISeca™ single-electrode sensors are particularly easy to install in a measurement system. On the single-channel electronics, an LED-bar indicates the optimum probe-to-target gap for the different measurement range settings. The multi-channel electronics come optionally with displays and/or a PC interface on a module in the same housing.

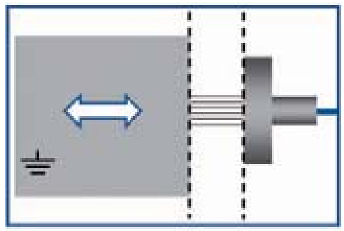
Ideal for Closed-Loop Piezo Nanopositioning

Closed-loop nanopositioning systems may be controlled by sensor / servo-controller modules of PI's E-500 series. Such modules are available for connecting up to three position sensors, either stand-alone or integrated into the motion system. Closed-loop operation eliminates the drift and hysteresis that otherwise affect piezo actuators.

For nanopositioning tasks with the most stringent accuracy requirements PI offers high-end digital controllers.

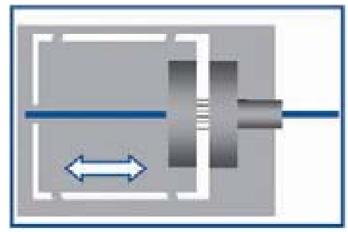
The P-752.11C piezo nanopositioning system with integrated capacitive sensors provides position resolution down to 0.1 nm

Applications for Capacitive Position Sensors



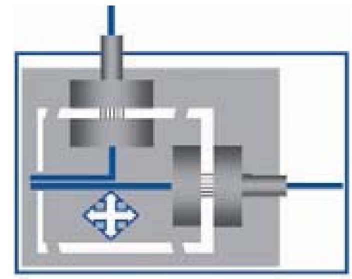
Measuring Displacement with Nanometer Precision

Capacitive displacement sensors measure the shortest of distances with highest reliability. The quantity measured is the change of capacitance between sensor plate and the target surface using a homogenous electric field. Accuracies in the sub-nanometer range are regularly achieved. Absolute measurement is possible with a well-adjusted, calibrated system.



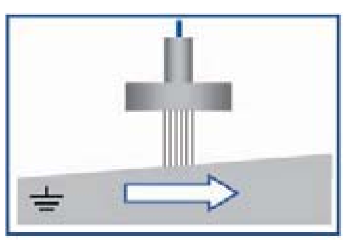
Nanopositioning / Closed-Loop Systems

One application of high-resolution displacement measurement is for nanopositioning. Two-plate capacitive sensors can measure distance, and hence position, of a moving object with excellent precision. The high sensor bandwidth allows closed-loop control in high-dynamics applications.



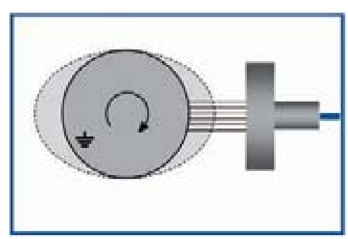
Parallel Metrology / High-Precision Multi-Axis Measurements

Closed-loop, multi-axis nanopositioning tasks are realized with high-performance positioners that make use of direct metrology and parallel kinematics. This allows measuring all degrees of freedom at the same time, which compensates guiding errors (Active Trajectory Control concept). Here, capacitance gauges are the most precise measuring systems available, and give the best position resolution results.



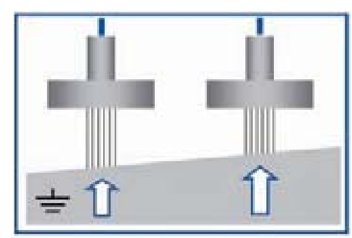
Measuring Straightness and Flatness / Active Cross-Talk Compensation

Excellent resolution in straightness and flatness measurements over long travel ranges is achieved with capacitive single electrode sensors. One application is measuring cross-talk in nanopositioning. Crosstalk, off-axis motion from one actuator in the motion direction of another, is detected immediately and actively compensated out by the servo-loops. The high sensor bandwidth provides excellent dynamic performance.



Out-of-Plane Measurement / Constant-Height Scans / Out-of-Round Measurement

Compensation of undulating and oscillating motion, e.g. in constant height scans or in white-light interferometry, are applications for which capacitive sensors are especially well suited.



Tip / Tilt Measurement and Compensation

Integrating capacitive sensors in a system is a good way to measure tip/tilt motion precisely. The moved object's tip angle is measured differentially, and, if required, compensated out.

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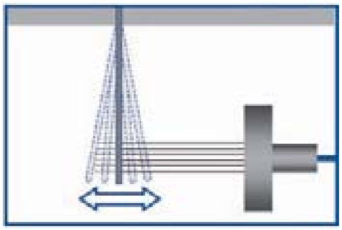
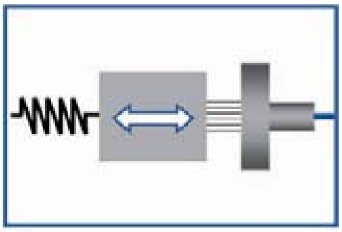


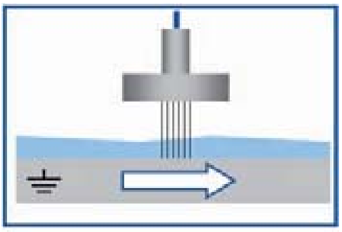
Vibration, Flatness, Thickness

The high dynamics of the PISeca™ capacitive gauge system even allows measurements of vibrations and oscillations with excellent resolution. Flatness of a rotating workpiece or differences in thickness in the nanometer range can be detected. One field of application is in the production of disk drives or in active compensation of vibration.



Force Sensors with Micronewton Sensitivity

Single-electrode capacitive sensors, which measure subnanometer displacement from a distance with no contact, are frequently used as high-resolution force sensors. In a system having suitably well-defined stiffness, the measured displacements translate to forces with resolutions in the micronewton range, all without influencing the process being measured.

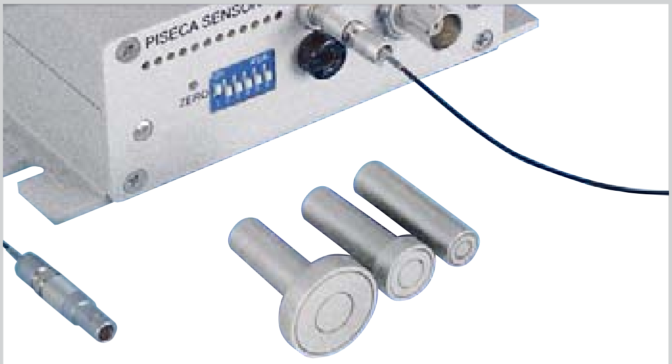


Layer Thickness with Sub-Micron Accuracy

Measuring the thickness of a film or layer of non-conducting material on a moving, conductive, surface (e.g. a rotating drum) is an ideal job for capacitive sensors due to their non-contact operation and their high dynamic performance.

D-510 PISeca™ Capacitive Sensors

Single-Plate Sensors with Excellent Position Resolution



PISeca™ high-precision capacitive 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 Position 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 p. 3-14 *ff*).

D-510.050 with LEMO-connector for easy handling

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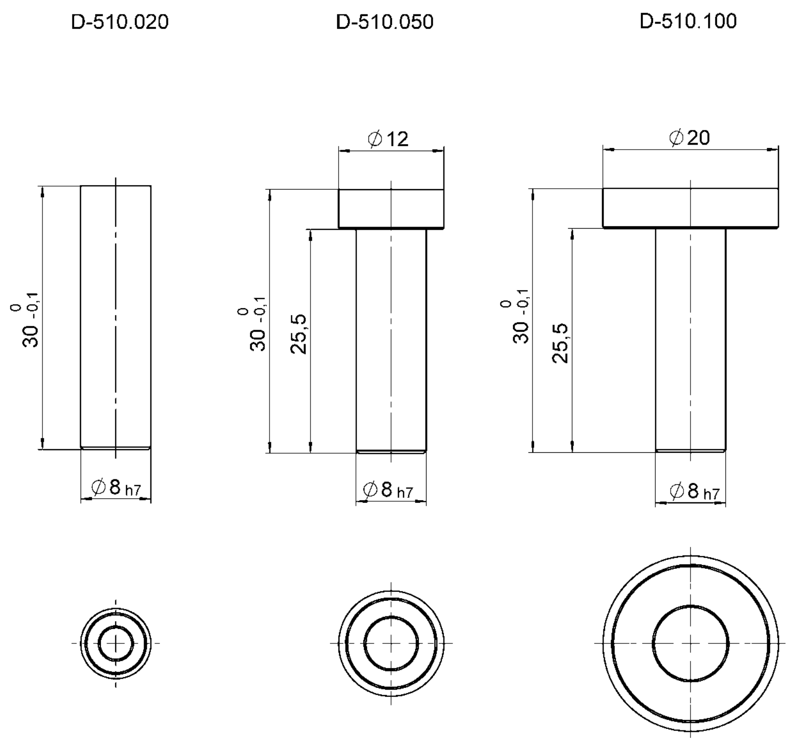


D-510.020, D-510.050 and D-510.100 capacitive sensor probes, dimensions in mm.
Sensor connection LEMO FFC00.650.CLA.543, triaxial, cable length 1 m

Technical Data

Model	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 measure-ment range	typical
Dynamic resolution**	<0.002	<0.002	<0.002	% of measure-ment 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-509.E	E-852.10 E-509.E	E-852.10 (p. 3-10) E-509.E (p. 3-12)		

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

E-852 PISeca™ Signal Conditioner

For Capacitive Single-Plate Sensors

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

- **Cost-Effective System Solution for PISeca™ Capacitive Position Sensor Probes**
- **Special Linearization System (ILS) for Maximum Linearity**
- **Bandwidth Adjustable from 10 Hz to 10 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 position 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 10 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

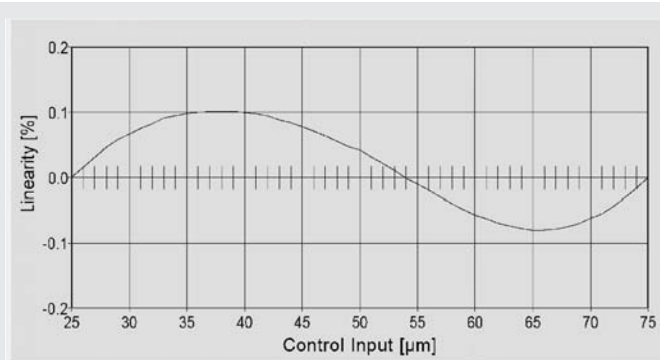
The simple installation of the single-electrode PISeca™ probes is facilitated by the E-852´s LED-bar indicating the optimum gap between probe and target.

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%).



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

Ordering Information

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

Ask about custom designs!

Multi-Channel Measurements

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

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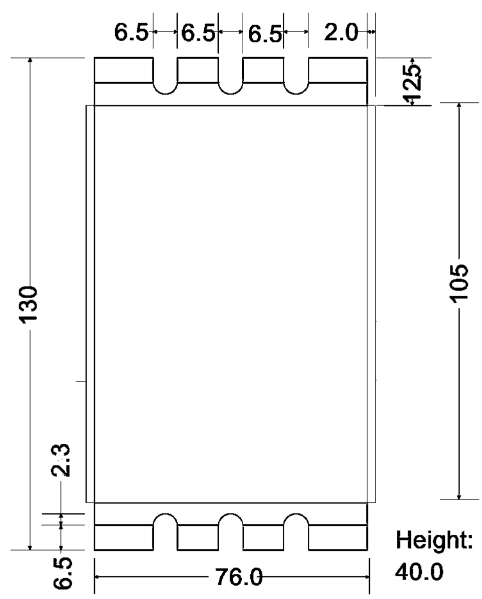

E-852.10, dimensions in mm

Technical Data

Model	E-852
Function	Signal conditioner for PISeca™ capacitive sensor probes
Channels	1
Sensor	
Sensor type	Single-electrode, capacitive
Sensor bandwidth	10 / 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	0.71 ±0.25 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)
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
Mass	0.355 kg, E-852.PS1 power supply: 1.2 kg
Dimensions	80 x 130 x 40 mm, E-852.PS1 power supply: 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 10 kHz, cable length 1 m

E-509 PISeca™ Signal Conditioner / Piezo Servo Module

3-Channel Sensor Module with/without Servo-Controller, for E-500 System

The E-509.E3 module offers sensor signal read-out and servo control for three channels

- **E-509.E03: 3-Channel Signal Conditioner Module**
- **E-509.E3: 3-Channel Sensor Module with Additional Servo Controllers for Piezo Positioning Systems**
- **Integrated Linearization System (ILS) for Maximum Linearity**
- **Optional: Measurement Range**
- **Variable Bandwidth**
- **Plug-In Modules for E-500 / E-501 Chassis**

The analog E-509.Ex sensor electronics is specially designed for the PISeca™ D-510 series of single-electrode, capacitive position sensor probes. Based on the E-500 modular controller system, it provides three channels of analog output featuring very high linearity, exceptional long-term stability, sub-nanometer position resolution and bandwidths up to 10 kHz.

Application Examples

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

Two models are available: E-509.E03 is a signal conditioner module. In addition, the E-509.E3 version includes a full servo-controller. With it, the position values from external single-plate capacitive sensors can thus be used for servo-control of piezo nanopositioning systems.

The combination of sensor and electronics provides a system for capacitive displacement measurement with flexible high-end solutions for best linearity and highest resolution.

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 300 Hz. For high-dynamics applications, a bandwidth up to 10 kHz is possible, with a resolution still better than 4 nm.

Factory-set measurement ranges from 20 to 500 µm are possible, depending on the nominal measurement range of the selected sensor head.

Factory Calibration for Improved Linearity

Highest possible linearity and accuracy are achieved with factory calibration of the sensor electronics for the particular measurement range. Factory calibration also optimizes parameters like ILS (linearization), gain and offset and eliminates cable capacitance influences.

Position Servo Control with PISeca™

The position servo-control portion of the E-509 is identical for all versions, consisting of an analog P-I (proportional, integral) controller. Proportional and integral gain can be set internally. Control bandwidth can also be set. A notch filter allows operation of the piezo positioning system closer to its mechanical resonant frequency.

Multi-Channel Measurements

The three channels of the PISeca™ E-509.Ex sensor electronics are automatically synchronized for the use in connected sensor systems.

Ordering Information

E-509.E3
PISeca™ Sensor / Piezo Servo-Control Module for Single-Electrode Capacitive Sensor Probes, 3 Channels

E-509.E03
PISeca™ Modular Signal Conditioner Electronics for Single Electrode Capacitive Sensors, 3 Channels

Accessories:

E-500.00
19"-Chassis for Modular Piezo Controller System, 1 to 3 Channels

E-501.00
9.5" Chassis for Modular Piezo Controller System, 1 to 3 Channels

E-515.03
Display Module for Piezo Voltage and Displacement, 3 Channels

E-517.i3
Interface / Display Module, 24 Bit D/A, TCP/IP, USB, RS-232, 3 Channels

E-503.00
Piezo Amplifier Module, -20 to +120 V, 3 Channels

E-515.E3
Analog Output for Controller Signal, Plug-In Module, 3 Channels

Ask about custom designs

The E-509.E3 servo-controller module in an E-501 9.5" chassis with E-503 piezo amplifier module and E-516 PC-interface/display module provides servo-control of piezo nanopositioning systems with external PISeca™ D-510 capacitive 1-plate sensors

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Linear Actuators & Motors
Nanopositioning / Piezoelectrics
Nanometrology
Capacitive Sensors / Signal Conditioners
Nanometrology Fundamentals
Micropositioning
Index

Technical Data

Model	E-509.E03	E-509.E3
Function	Signal conditioner electronics for PISeca™	Sensor / Servo-Controller Module for PISeca™
Channels	3	3
Sensor		
Servo characteristics	–	Analog proportional-integral (P-I) algorithm with notch filter
Sensor type	PISeca™ single-electrode, capacitive	PISeca™ single-electrode, capacitive
Sensor bandwidth	3 kHz 0.3 / 10 kHz (selectable)	3 kHz 0.3 / 10 kHz (selectable)
Measurement range extension factors*	2 / 2.5 / 5 (option)	2 / 2.5 / 5 (option)
Synchronization	3 synchronized channels	3 synchronized channels
Electrical properties		
Output voltage	0 to 10 V	0 to 10 V
	-5 to +5 V, -10 to 0 V (selectable)	
Thermal drift	<1 mV / °C	<1 mV / °C
Resolution @ 300 Hz (RMS)	<0.001 % of measurement range	<0.001 % of measurement range
Resolution @ 3 kHz (RMS)	<0.0025 % of measurement range	<0.0025 % of measurement range
Linearity @ nominal range	<0.1 % (<0.2 % for D-510.020)	<0.1 % (<0.2 % for D-510.020)
Interfaces and operation		
Sensor connection	3 x LEMO ECP.00.650.NLL.543 socket, triaxial	3 x LEMO ECP.00.650.NLL.543 socket, triaxial
Signal output	LEMO 6-pin FGG.0B.306.CLAD56	LEMO 6-pin FGG.0B.306.CLAD56
Display	–	3 x Overflow LED
Supported functionality	ILS	ILS
Miscellaneous		
Operating temperature range	+5 to +40 °C	+5 to +40 °C
Dimensions	7T/3H	7T/3H
Target ground connector	3 x banana jack	3 x banana jack
Operating voltage	E-500 system	E-500 system

*Extension factors to multiply by the nominal measurement range of the selected sensor head D-510, to be specified with order

D-015 · D-050 · D-100 Capacitive Sensors

Sub-Nanometer-Resolution Position Sensors

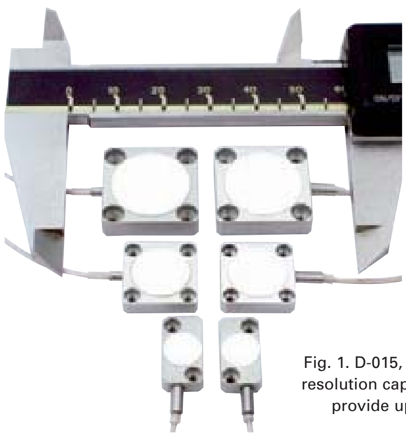

Fig. 1. D-015, D-050, D-100 ultra-high-resolution capacitive position sensors provide up to 10,000 times higher resolution than calipers

- **For Applications Requiring Highest Precision**
- **Measuring Range to 1000 microns**
- **Resolution to 0.01 nm**
- **Linearization to 0.01 % with Digital Controller**
- **Bandwidth up to 10 kHz**
- **Servo Controller E-509.CxA, Compatible with E-500 Controller System**
- **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. 3-19, Fig. 5). 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. 2-8 *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. 2-212 *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.

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!

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.

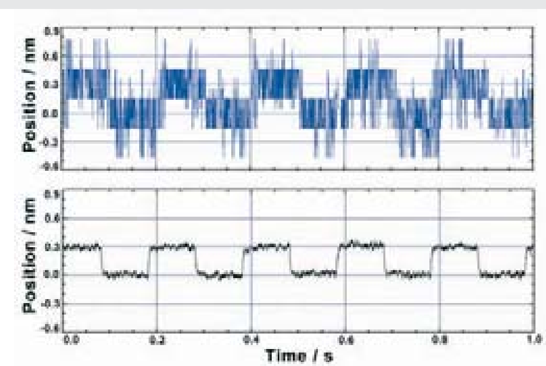

Fig. 2. Piezo nanopositioning system making 0.3 nm steps, measured with PI capacitive sensor (lower curve) and with a highly precise laser interferometer. The capacitive sensor provides significantly higher resolution than the interferometer.

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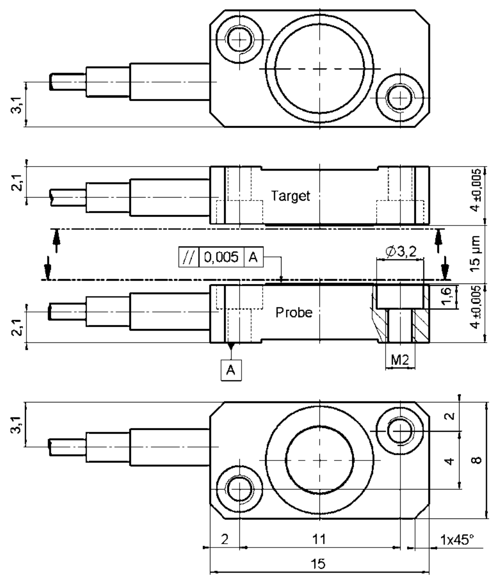
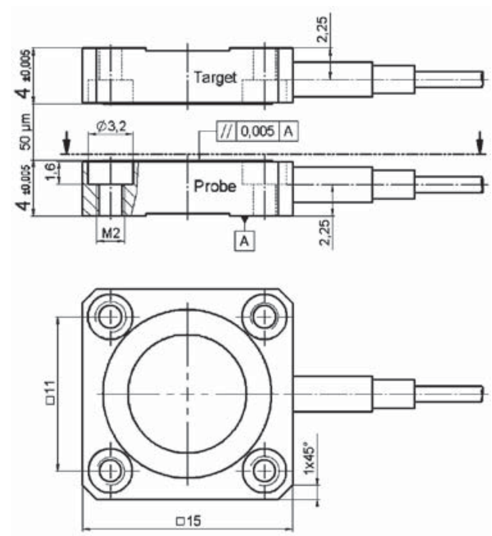
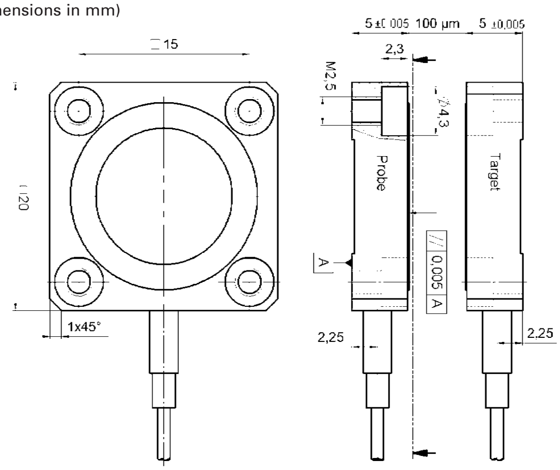


D-015.00 (dimensions in mm)



D-050.00 (dimensions in mm)



D-100.00 (dimensions in mm)

Technical Data

Model	D-015.00	D-050.00	D-100.00	Units
Sensor				
Sensor typ	Capacitive	Capacitive	Capacitive	
Nominal measurement range	15	50	100	µm
Extended measurement range	45	150	300	µm
Resolution*	0.0005	0.0005	0.0005	% of measurement range
Linearity**	0.01	0.01	0.01	%
Sensor active area	16.6	67.7	113.1	mm²
Thermal drift***	50	50	50	ppm/K
Miscellaneous				
Operating temperature range	-20 bis 80	-20 bis 80	-20 bis 80	°C
Material	Aluminum	Aluminum	Aluminum	
Recommended sensor electronics	E-509.CxA	E-509.CxA	E-509.CxA (p. 3-16)	

Ask for custom materials
*3 kHz, with E-509.C3A servo controller
**With digital controller. Up to 0,05 % typ. with E-509 analog controller
***Change of active surface size in ppm (parts per million), refers to measurement range

E-509 Signal Conditioner / Piezo Servo Module

3-Channel Servo-Controller Module for E-500 Piezo Controller System

E-509 3-channel servo-controller module for nanopositioning systems with strain gauge sensors

Ordering Information

E-509.C1A
Sensor / Piezo Servo-Control Module, Capacitive Sensor, 1 Channel

E-509.C2A
Sensor / Piezo Servo-Control Module, Capacitive Sensors, 2 Channels

E-509.C3A
Sensor / Piezo Servo-Control Module, Capacitive Sensors, 3 Channels

Ask about custom designs!

- **1-, 2- and 3-Channel Versions**
- **Improves Linearity**
- **Eliminates Drift and Hysteresis**
- **Notch Filter for Higher Bandwidth**
- **Increases Piezo Stiffness**
- **ILS Circuitry Maximizes Capacitive Sensor Linearity**
- **Plug-In Module for E-500 System**
- **Prepared for Interfaces / Display Modules (optional)**

The E-509 module is both a signal conditioner for high-resolution capacitive and SGS displacement sensors and a servo-controller for closed-loop piezo nanopositioning mechanics. For more information (see page 2-152).

Technical Data

Model	E-509.C1A/E-509.C2A/E-509.C3A	E-509.S1/E-509.S3
Function	Signal conditioner & servo-controller for piezo mechanics	Signal conditioner & servo-controller for piezo mechanics
Channels	1/2/3	1/3
Sensor		
Servo characteristics	P-I (analog), notch filter	P-I (analog), notch filter
Sensor type	Capacitive	SGS
Sensor channels	1 / 2 /3	1 / 3
Sensor bandwidth	0.3 to 3 kHz (selectable with jumper); up to 10 kHz on request	0.3; 1; 3 kHz
Noise factor	0.115 ppm/Hz½	
Thermal drift	<0.3 mV / °C	<3 mV / °C
Linearity	<0.05%	<0.2%
Interfaces and operation		
Sensor connection	LEMO EPL.00.250.NTD	LEMO ERA.0S.304.CLL
Sensor monitor output	0–10 V	0–10 V
Sensor monitor socket	LEMO 6-pin FGG.0B.306.CLAD56	BNC (1-ch.) / 3-pin. LEMO (3-ch.)
Supported functionality	ILS (Integrated Linearization System)	ILS (Integrated Linearization System)
Display	Overflow LED	Overflow LED
Miscellaneous		
Operating temperature range	+5 to +50 °C	+5 to +50 °C
Dimensions	7HP/3U	7HP/3U
Mass	0.35 kg	0.35 kg
Operating Voltage	E-500 System	E-500 System
Max. power consumption	4 to 8 W	4 to 8 W

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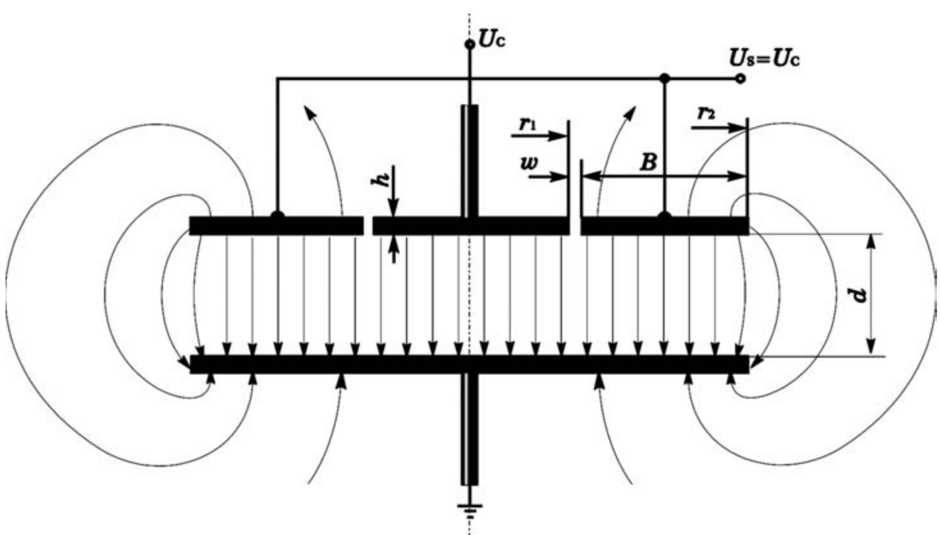
Nanometrology Fundamentals



Resolution / Bandwidth

Resolution in nanopositioning relates to the smallest change in displacement that can still be detected by the measuring devices.

For capacitive sensors, resolution is in principle unlimited, and is in practice limited by electronic noise. PI signal conditioner electronics are optimized for high linearity, bandwidth and minimum noise, enabling sensor resolution down to the picometer range.

Electronic noise and sensor signal bandwidth are interdependent. Limiting the bandwidth reduces noise and thereby improves resolution. The working distance also influences the resolution: the smaller the working distance of the system, the lower the absolute value of the electronic noise.

Figure 1 shows measurements of nanometer-range actuator cycles taken with a D-015, 15 µm capacitive position sensor and a laser interferometer. The graphs clearly show the superior performance of the capacitive position sensing technique.

Figure 2 illustrates the influence of bandwidth upon resolution: the PISeca™ single-electrode sensors show excellent resolution down to the sub-nanometer range, even at high bandwidths.

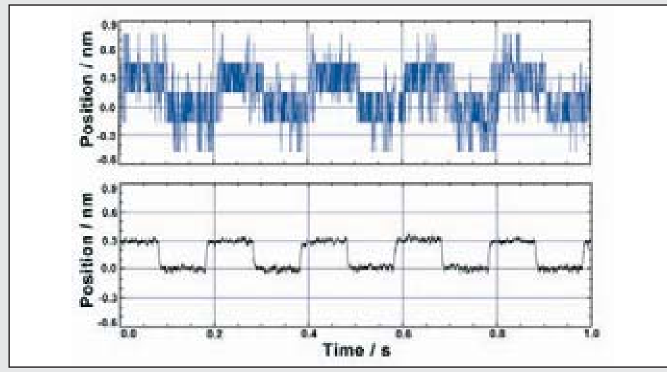


Fig. 1: Piezo nanopositioning system making 0.3 nm steps, measured with PI capacitive sensor (lower curve) and with a highly precise laser interferometer. The capacitive sensor provides significantly higher resolution than the interferometer

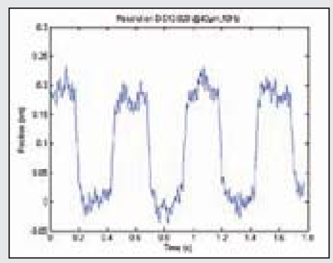


Fig. 2: Resolution significantly below 1 nm is achieved with a 20 µm PISeca™ single-electrode sensor (D-510.020) and the E-852 signal conditioner electronics. Left: 0.2 nm-steps under quasi-static conditions (bandwidth 10 Hz), right: 1 nm-steps with maximum bandwidth (6.6 kHz)

Linearity and Stability of PI sensors

The linearity of a measurement denotes the degree of constancy in the proportional relation between change in probe-target distance and the output signal. Usually linearity is given as linearity error in percent of the full measurement range. A linearity error of 0.1 % with range of 100 µm gives a maximum error of 0.1 µm. Linearity error has no influence whatsoever upon resolution and repeatability of a measurement.

Linearity is influenced to a high degree by homogeneity of the electric field and thus by any non-parallelism of the probe and target in the application. 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 non-parallelism influences.

A comparison between a conventional capacitive position sensor system and a PI ILS system is shown in Figure 3. When used with PI digital controllers (which add polynomial linearization) a positioning linearity of up to 0.003 % is achievable.

Figure 4 shows the linearity of a P-752.11C piezo flexure nanopositioning stage with integrated capacitive position sensor operated in closed-loop

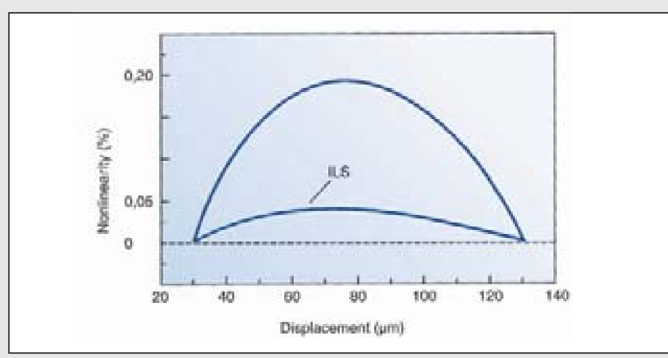


Fig. 3: Linearity of conventional capacitive position sensor system vs. PI ILS (integrated linearization system), shown before digital linearization

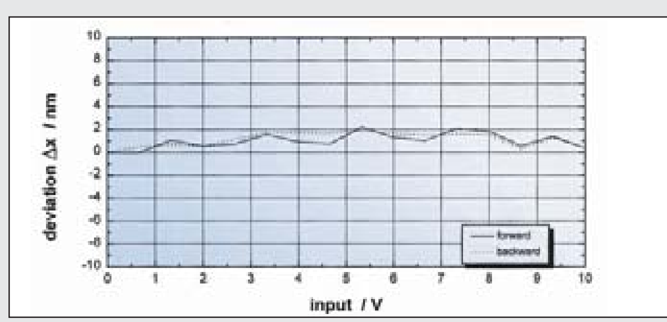


Fig. 4: Linearity of a P-752.11C, 15 µm piezo nanopositioning stage operated with E-500/E-509.C1A control electronics. The travel range is 15 µm, the gain 1.5 µm/V. Linearity is better than 0.02 %; even higher linearity is achievable with PI digital controllers

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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 like the E-710.

Stability of the measurement is limited mainly by thermal and electronic drift. For accuracy and repeatability reasons, it is thus necessary to maintain constant environmental conditions. The exceptional long-term stability of the PI capacitive position sensor and electronics design is shown in Figure 5.

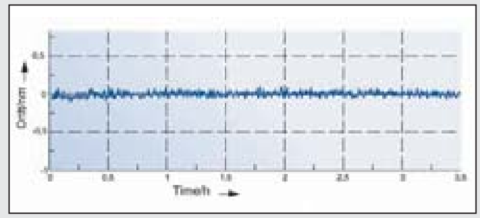

Fig. 5: Measurement stability of an E-509.C1A capacitive position sensor control module with 10 pF reference capacitor over 3.5 hours (after controller warm-up)

Principle of the Measurement

Signal/Displacement Proportionality

When a voltage is applied to the two plates of an ideal capacitor, it creates a homogenous electric field. Apart from constant factors, the electrical capacitance of the setup is determined by sensor area and plate distance. Thus, a change in displacement leads directly to a change in capacitance. This value is matched to a reference capacitance in a bridge circuit.

The Design of the signal conditioner electronics is such that the output signal is proportional to the gap change. The planes of the sensor surface ("probe") and the target form the two capacitor plates. The target should not be below a certain size because of boundary effects. This is important for applications with, say, a rotating drum as target. For metallic materials, the thickness of the target has no influence on the measurement.

Guard Ring Geometry/Design

The proportionality referred to is based on the homogeneity of the electric field. To eliminate boundary effects, the superior PI design uses a guard-ring electrode that surrounds the active sensor area and is actively kept at the same potential (see Fig. 7). This design shields the active sensor area and provides for excellent containment of the measurement zone. Thus optimum measuring linearity over the full range is achieved within the specified accuracy.

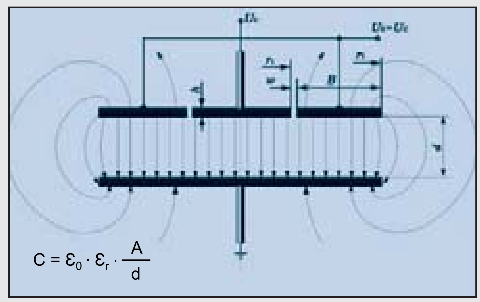

Fig. 6: Capacitive sensor working principle. The capacitance C is proportional to the active sensor area A, ϵ_0 is constant, ϵ_r is the dielectric constant of the material between the plates, generally air

Fig. 7: Capacitive sensors with guard ring design provide superior linearity

Calibration for Best Accuracy

PI's nanometrology calibration laboratories offer optimum conditions for factory calibration. As references, ultra-high-accuracy incremental sensors like laser interferometers are used.

PISeca™ systems are calibrated at PI with a NEXLINE® positioning system having a closed-loop resolution better than 0.01 nm in a test stand with friction-free flexure guidance and an incremental reference sensor featuring a resolution better than 0.1 nm (Fig. 8 and 9).

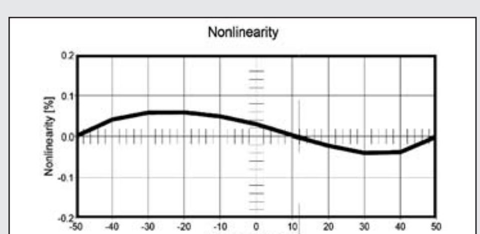

Fig. 8: Output linearity error of a PISeca™ single-electrode system is typically less than 0.1% over the full measurement range

Direct Metrology, Parallel Metrology

Direct Metrology / Parallel Metrology with Two-Plate Capacitive Sensors

Capacitive sensors are the ideal choice for nanometrology applications in positioning, scanning and metrology requiring the highest possible accuracy. Two-plate capacitive sensors achieve the highest linearity and long-term stability. The measurement probe can be attached directly to the moved surface (direct metrology) and provide absolute, non-contact displacement values against a reference surface, with no influence whatsoever on the motion performed. These sensors are particularly well-suited for parallel-kinematics nanopositioning systems. There, in a multi-axis system, motion in all degrees of freedom is measured against a common reference, and the runout of the various actuators can be compensated out in real time (active trajectory control). In this way, motion accuracies in the subnanometer and submicroradian ranges can be achieved.

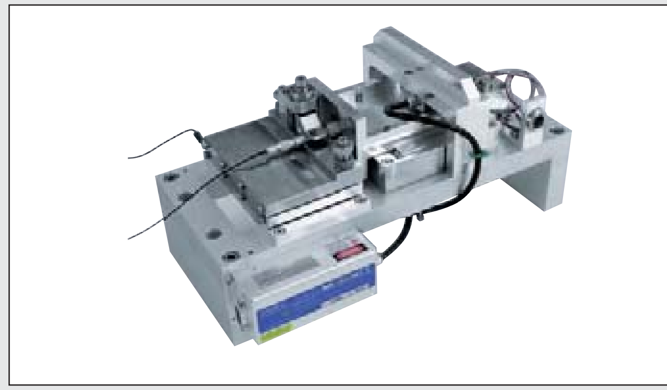

Fig. 9: Ultra-high-precision NEXLINE® positioning system with incremental sensor in a calibration and test stand for PISeca™ sensors. The resolution is significantly better than that of a laser interferometer

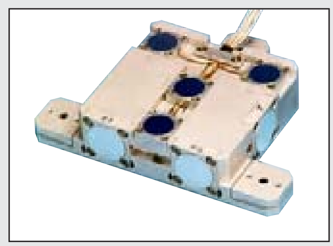

Fig. 10: Capacitive position sensors in an ultra-high-accuracy, six-axis nanopositioning system designed by PI for the German National Metrology Institute (PTB). Application: scanning microscopy

Fig. 11: Digital sensor-signal transmission (DST) allows a distance up to 15 m between positioning unit and controller, here an E-710 multi-axis digital piezo controller

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.

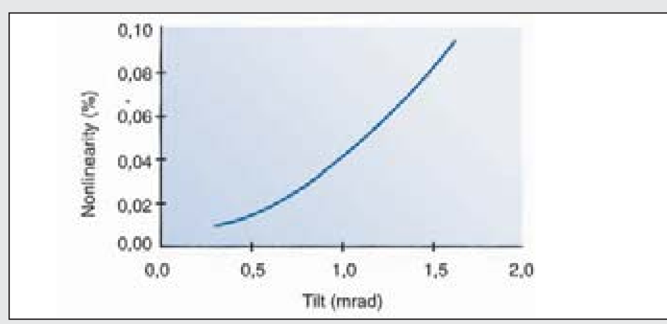

Fig. 12: Nonlinearity vs. tilt. Resolution and repeatability are not affected by tilt

Electrode Geometry, Sensor Surface Flatness and Finish

During sensor production, great care is taken to maintain critical mechanical tolerances. Measuring surfaces are diamond machined using sophisticated process control techniques. The result is the smooth, ultra-flat, mirrored surfaces required to obtain the highest resolution commercially available.

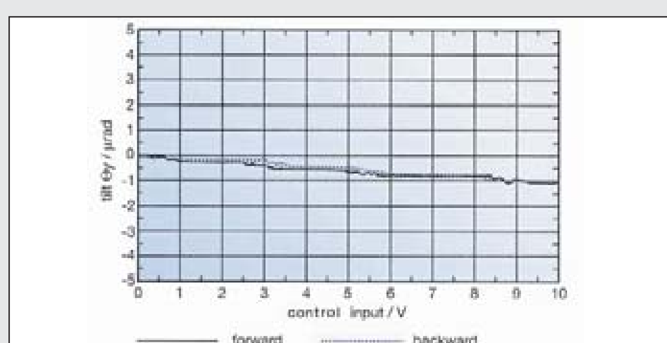

Fig. 13. Flexure-guided nanopositioning systems like the P-752 offer submicroradian guiding accuracy and are optimally suited for capacitive sensors

Parallelism of Measuring Surfaces

For optimum results, target and probe plates must remain parallel to each other during measurement. For small measurement distances and small active areas, any divergence has a strong influence on the measurement results. Tilt adversely affects linearity and gain, although not resolution or repeatability (see fig. 12).

Positioning systems with multi-link flexure guidance reduce tip and tilt to negligable levels (see Fig. 13) and achieve outstanding accuracy.

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Glossary

Measurement Range

The measurement range depends on the size of the active sensor area as well as on the electronics used.
Due to PI's proprietary signal conditioner electronics design, the mid-range distance is always identical to the selected measurement range. The probe-to-target gap may vary from 50 % to 150 % of the measurement range (see Fig. 14).
The sensor capacitance is the same as that of the reference capacitance in the electronics. Different reference capacitances can be used to extend the nominal (standard) measurement range (see Fig. 15).

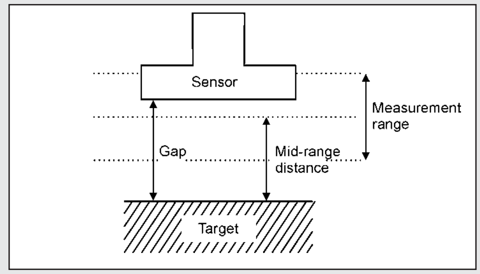

Fig. 14: Definitions: measurement range and mid-range distance have identical values

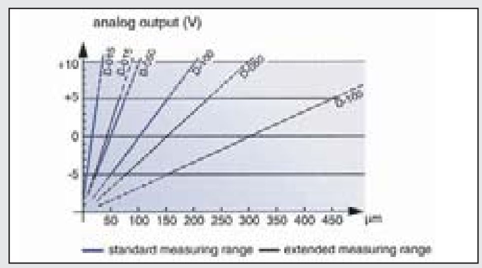

Fig. 15: Measuring ranges of different PI capacitive position sensors (standard ranges in blue, extended ranges in black)

Target

Two-electrode capacitive sensors consist of two electrodes, named probe and target.
Single-electrode sensors measure against a surface that is called the target. The target surface is, in principle, a conductive material electrically connected to ground. Measurement against semi-conductors is possible as well.

While two-plate capacitive sensors consist of two well-defined high-quality planes, with single-plate sensors, target surface characteristics can influence the results. A curved or rough surface will deteriorate the resolution because the results refer to an average gap (see Fig. 16 and 17). Surface shape also influences the homogeneity of the electric field and thereby the measurement linearity. For factory calibration, a target plane that is considerably larger than the sensor area is used.

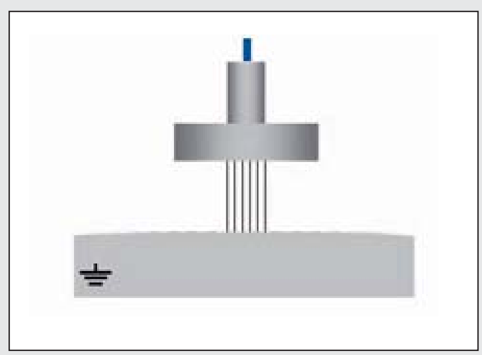

Fig. 16: Roughness of the target surface downgrades resolution and linearity

Environment

Precision measurement with nanometer accuracy requires minimizing environmental influences. Constancy of temperature and humidity during the measurement are as essential as cleanliness.
Electronics from PI are basically very temperature stable. Temperature drift is under 0.2% of full measurement range with a change of temperature of 10 C°.
Temperature changes also cause all material in the system to expand or contract, thus changing the actual measured gap.
The influence of a change in relative humidity of 30 percentage points is less than 0.5% of the measurement range. Condensation must always be avoided.
Dusty or damaged sensor surfaces will also worsen the measurement quality.
Environmental conditions at the time of calibration are noted on the calibration sheet PI provides with each individual system.

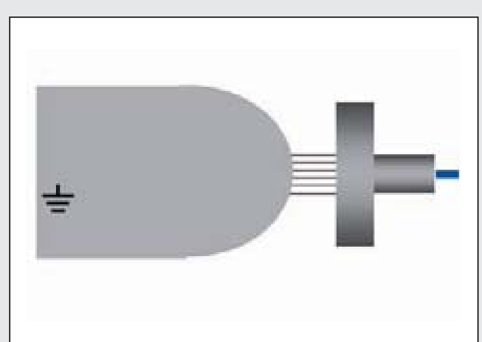

Fig. 17: Curved surfaces lead to an averaged distance measurement