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Application Note:
Displacement Sensor Operation with Radiant Testers
Rev B

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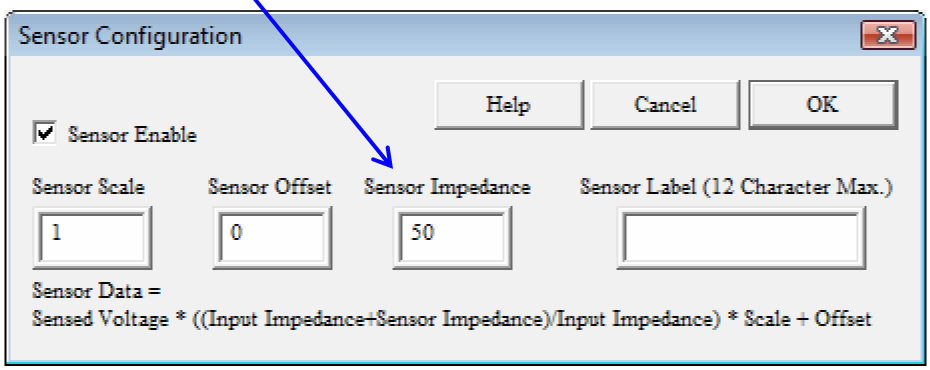
Discussion:
The growing efforts worldwide to build and understand piezoelectric MEMs devices is encouraging Radiant's customers to examine the capabilities of our test equipment with commercial high-resolution displacement sensors to see their samples move. There are four types of displacement sensors that will work easily with Radiant's equipment: 1) non-contact optical sensors like the MTI2100; 2) laser vibrometers; 3) atomic force microscopes, and 4) LVDTs. The ability to use external sensors has been integral to the Radiant Technologies tester architecture since the introduction of the RT6000 in 1993. Every member of Radiant's Precision family of testers, including the inexpensive Radiant EDU, retains this important capability. As well, every measurement task in the Vision Library (Hysteresis, Pulse, Leakage, IV, Small Signal Capacitance, PIEZO, and Chamber) will capture external sensor data during execution. Filter tasks in the Vision Library can separate external sensor data from the polarization data to allow independent mathematics and plotting of the sensor measurements.

The discussion below is a tutorial on the use of external displacement sensors with a Radiant tester. First will be a discussion of how external displacement sensors connect to the tester and are protected from overvoltage. Next will be a description of the architecture of the data acquisition system including how measured sensor data relates to the polarization data and the maximum resolution of a sensor when used during hysteresis measurement. A discussion of the effect of noise on the SENSOR measurements follows. The final section provides a comparison of the various sensors presently used with Radiant's testers.

The SENSOR Input:
To collect data from external sensors during measurements, the Precision testers all include one or two high input-impedance voltage measurement ports labeled SENSOR: SENSOR1 or SENSOR2.

Each input is connected directly to the "+" input of an operational amplifier where the op amp is arranged as a voltage follower. In the voltage follower configuration, the input impedance is that of the op amp itself can reach 10^{12} ohms. The exceptions are the original Precision Premier, the origina Precision Pro, and the Precision Workstation, all of which have 4kΩ input impedance on their SENSOR inputs.

Note: The SENSOR menu for each task has an entry for the output impedance of the sensor device.



The output impedance of the sensor and the input impedance of the tester SENSOR port form a resistor-divider. If the SENSOR input impedance is 10^{12} ohms, this divider does not matter. It does matter if the SENSOR input impedance is 4kΩ. Therefore, if you are using the Premier, Pro, or Workstation, determine the output impedance for your sensor device and enter it in the "Sensor Impedance" window on the SENSOR CONFIGURATION menu. Vision will then correct the SENSOR data for the resistor-divider effect. If you are using a USB-controlled tester, the sensor impedance will not matter.

The SENSOR inputs are diode protected on all testers. A diagram of the SENSOR input is shown in Figure 1 below.

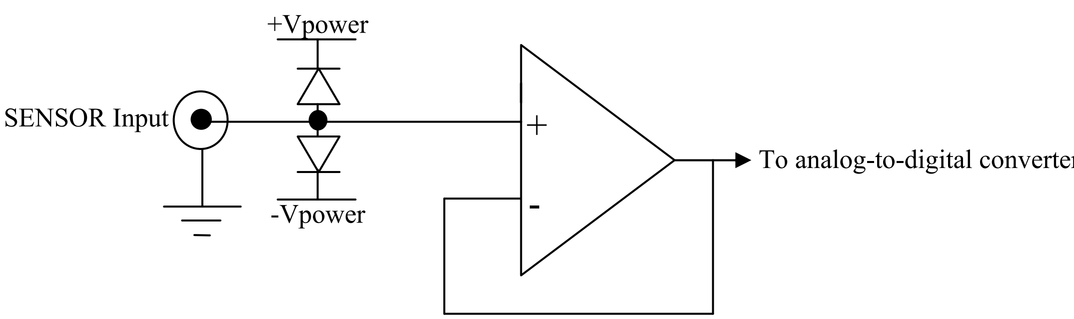


Figure 1
SENSOR Input Circuit

The reverse-biased diodes are connected to the internal power rails of the tester. These rails are at ±15V for all testers except the Precision LC, the Precision SC, and Precision Workstation. Some Precision LCs and Precision Workstations have ±12V busses while others have ±15V busses.

NOTE: Contact Radiant with your tester serial number if you need to know the clipping voltage for your particular tester.

If the voltage at the SENSOR input exceeds either power voltage plus one diode drop, the appropriate diode will turn on and clamp the SENSOR input to that power voltage. Clipping will not damage the tester but it might damage the external instrument connected to the SENSOR input if that instrument is not protected appropriately. Normally, this issue only applies to atomic force microscopes (AFMs) if you are monitoring the actual control voltage applied to the AFM piezo stack. The AFM piezo stack control voltage can reach several hundred volts.

> **NOTE**: The piston effect of a 1µ thick ferroelectric film normally is less than 40Å. An AFM set to maximum sensitivity will have a resolution of approximately 100Å per volt. A 40Å excursion at a100Å/volt sensitivity corresponds to 400mV total signal. Many AFMs have less resolution so a 40Å displacement might only generate 30mV. If you are monitoring the piezo stack control voltage of an AFM to see such small displacements, adjust the AFM chuck position so the piezo stack control voltage is nominally at zero volts before connecting the AFM output to the SENSOR input. *Then, disconnect the AFM output from the SENSOR input before moving the stage.*

The Precision Premier II has two SENSOR inputs labeled SENSOR1 and SENSOR2. In normal operation, only SENSOR1 is enabled. Radiant has reserved SENSOR2 for special measurement applications to be developed for the Premier II.

> **NOTE**: Unless specified by the task being executed, always use SENSOR1.

Data Acquisition Architecture:
The fundamental design criterion for the Radiant tester is the simultaneous capture of all signals related to a measurement. Without the simultaneity, the results might be slightly distorted as plotted because ferroelectric capacitors keep changing between individual measurement points. The RT66A and the RT6000 both used sequential clocks to capture the different measurement channels in the following order: Polarization, SENSOR, and the DRIVE output voltage. The Precision testers capture the different data channels *simultaneously* triggered by a single high-speed clock. Because of the skew effect of sequential capture, you will find a very slight difference in the hysteresis curves of the RT66A/RT6000 versus a Precision tester with its simultaneous capture. The data measured by the Precision testers are more correct. The circuit architecture is shown in Figure 2.

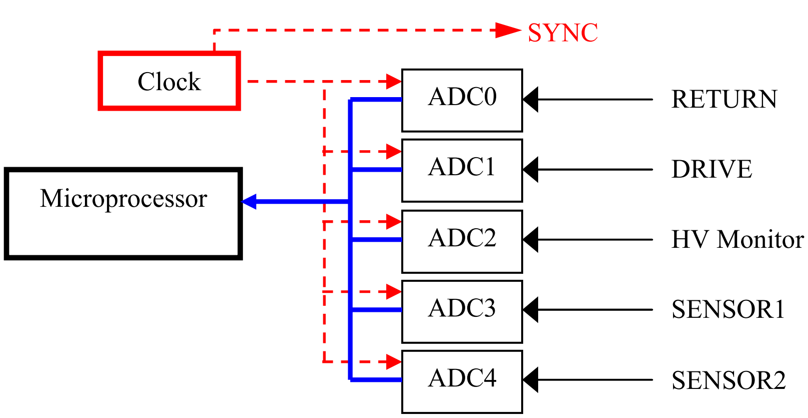


Figure 2
A Single Clock fires *All* ADCs on every Precision Tester
(The channels for the Premier II are shown above.)

As a result of Radiant's data acquisition architecture, the SENSOR input data is *synchronous* with the polarization and drive voltage data. As long as the displacement sensor being used with the Precision tester *is much faster than the measurement period*, there will be 1) no distortion of the displacement data as captured by the tester and 2) no time skew between the electrical measurements and the displacement measurements of the sample.

The SYNC signal shown in Figure 2 exists on the Precision LC, the Precision SC, and the Precision Premier II. It is a TTL 5V logic output that the Clock in Figure 2 that is low during self-calibration and preset loops but asserts to HIGH while a measurement is being mde. The SYNC signal is very handy for coordinating external sensors with the measurement. As an example, the Polytec OFV-5000 controller, the SIOS SM-05 unit, and the Asylum AFMs all use integrators to calculate absolute displacement of the surface being measured. Integrators are naturally unstable and will drift to their maximum value over time. To combat this problem, all three of the displacement measurement instruments above have integrator control inputs that permit an external digital signal to force the integrator back to zero or let it run free again. The SYNC signal from the Precision tester can be connected to any of these three units to zero the displacement output of the unit just prior to the beginning of a test.

> **NOTE:** On the Premier II, the delay between the rise of the SYNC signal and the first voltage out the DRIVE may be as little as a 3.5 microseconds. On the LC or the SC, the minimum delay is at least 70 microseconds. When using the SYNC, the user must check how fast the integrator of user's external sensor unit zeros and returns to open mode. If the SYNC delay period is shorter than the minimum time required for the integrator to zero and then open again, the first measured points of the test may occur while the integrator is still closed. Should this happen, those initial measurement points will be zero. To eliminate this problem, slow the Premier II measurement period to a value beyond 1 millisecond or the LC/SC measurement period beyond 5 milliseconds.

Absolute Resolution:
All SENSOR inputs have a maximum measurement range of ±10V. Any input voltages above this level, even those that do not activate the clipping diodes, will show a saturated measurement of +10V or -10V. The difference between the testers consists of the number of bits used by the analog-to-digital converters and the data acquisition clock speed.

Parameter: Tester	ADC Bits	Minimum Data Acquisition Period	Minimum Measurable SENSOR Voltage
Premier II	18	0.5µs	76µV
Precision LC	16	10µs	305µV
Precision SC	16	10µs	305µV
RT66B	14	50µs	1.22mV

Table 1
SENSOR Resolution per Tester

Noise-Limited Resolution:
The analog circuitry of the SENSOR input generates noise. Noise also originates from the ground plane of the tester which connects the analog and digital circuitry. The noise sources generate an average background noise floor for each tester type which sums with the signal to be measured by the analog-to-digital converter. For a *single pass* measurement, the noise floor represents the fundamental measurement

resolution if it is larger than the absolute resolution of the tester. Radiant does not *filter* any measured signal as filters add phase-delay that distort the *shape* of the results. Averaging can be used to reduce noise levels in measurements without distorting the results. Below is a table of the single-pass and averaged noise floor for the Precision Premier II, Precision LC, and Precision SC testers. The noise values in the table are an estimate of the peak-to-peak noise amplitude, not the RMS value.

Parameter: Tester	Measurement Period	Single Pass Noise Floor	x16 Averaged Noise Floor	Absolute Resolution from Table 1
Premier II	1ms	1mV	0.3mV	76µV
Precision LC	-	~1.2mV	-	305µV
Precision SC	5ms	0.9mV	0.4mV	305µV

Table 2
Noise-Limited Resolution per Tester

Displacement Sensors:
Any displacement sensor that outputs its measurements as a voltage may be connected to a Precision tester to capture the movements of a sample during a measurement. Radiant has experience with the following sensor units:

Parameter: Instrument	Scale Factor	Absolute Resolution on Premier II	Single Pass Noise Limited Resolution Premier II	Absolute Resolution on LC	Single Pass Noise Limited Resolution LC
DI Dimension 3100 AFM	100Å/V	0.008Å	0.10Å	0.031Å	0.12Å
Seiko Epson SPA 400 AFM	50Å/V	0.004Å	0.05Å	0.015Å	0.06Å
Asylum SA AFM	700Å/V	0.053Å	0.70Å	0.214Å	0.84Å
MTI2100 2032RX Photonic Sensor	5000Å/V	0.380Å	5.00Å	1.525Å	6.00Å
MTI2100 2032R Photonic Sensor	19µ/V	14.44Å	190Å	57.95Å	228Å
Polytec OFV534 Laser Vibrometer	500Å/V	0.038Å	0.50Å	0.153Å	0.60Å
SIOS SP-S 120 Laser Vibrometer	2400Å/V	0.182Å	2.40Å	0.732Å	2.88Å

Table 3
Noise-Limited Resolution per Tester

The **Scale Factor** is the ratio of the measured displacement to the voltage output of the sensor. The Noise Limited Resolution is calculated for a single pass measurement.

> **NOTE**: The Noise Limited Resolution values in the Table 3 are for the tester only and *do not include* electronic noise from the sensor or environmental noise from the test fixture, noise such as vibration or air turbulence effects. Typically, sensor and environmental noise have amplitudes far above that of the tester resolution.

Figure 3 is a plot of the butterfly loop of 1µ-thick 4/20/80 Niobium-doped PNZT capacitor with platinum electrodes. The capacitor had platinum electrodes with a 80µx125µ area. The displacement loop was measured with a Precision Multiferroic tester using a Polytec OFV-534 laser vibrometer mounted in a Radiant Precision Displacement Test Stand.

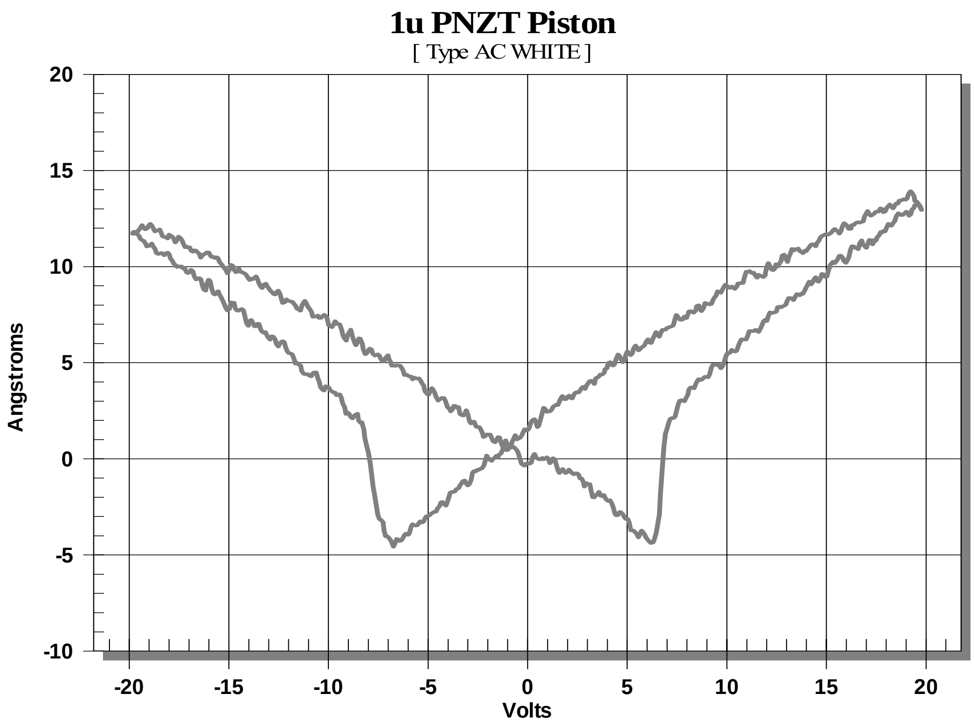


Figure 3
Piston Butterfly Loop of 1µ-Thick PNZT

The measurement in Figure 3 is the average of twenty loops. Note that the vertical axis is in units of Ångstroms. The upper arms of the plot in Figure 3 are moving *away* from the substrate surface. They indicate a converse piezoelectric coefficient of 60pm/V.

The SENSOR input can be measured with no load to determine the intrinsic noise level of the tester. Figure 4 is such a No Load measurement on the sample in Figure 3 activated with zero volts. The noise level in Figure 4 includes both that of the laser vibrometer and the tester.

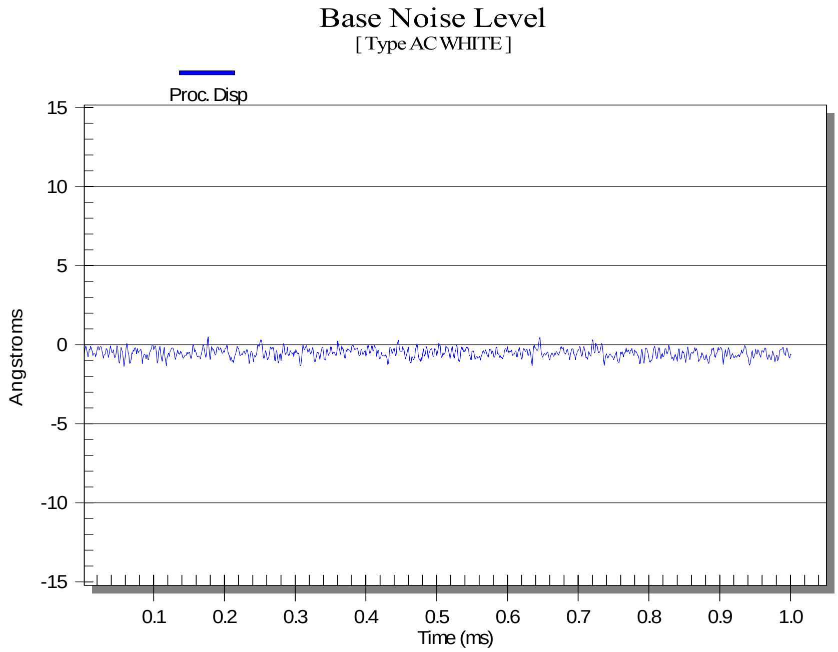
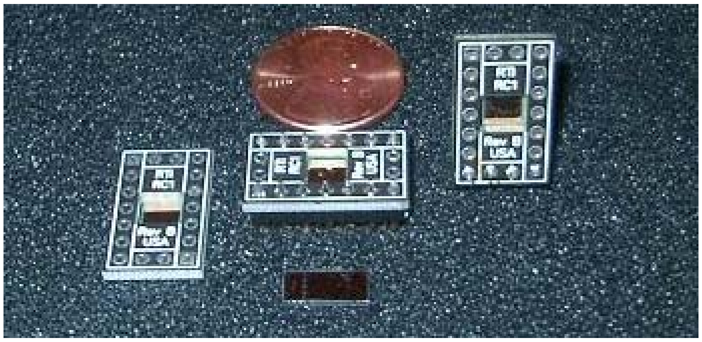
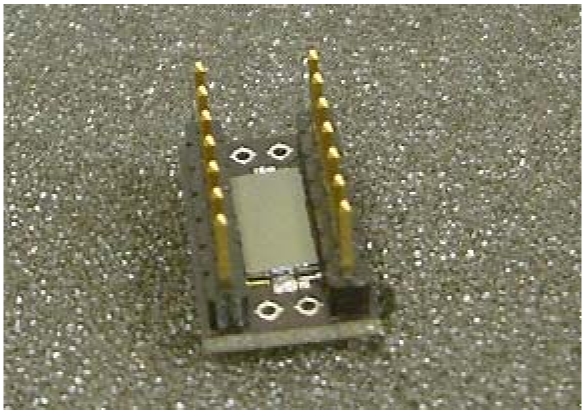


Figure 4
Single Pass Noise on the Sample in Figure 3

Figure 7 is the measurement of a Radiant RC1-166A Sensor Die soldered to its PC Board carrier. The measurement was made with the Polytec OFV-534 laser vibrometer. Figures 5 and 6 are pictures of the device. The die is 0.5cm x 1.0cm long and the capacitor has an area of 4mm x 4mm. The capacitor also consists of 1µ PNZT with platinum electrodes.

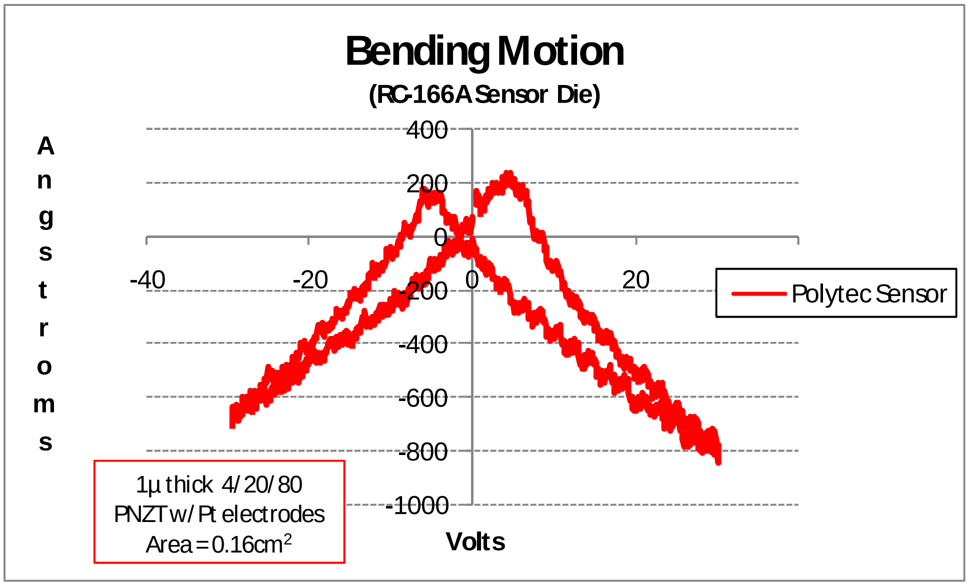


4mm Sensor Die and PC Board Carrier
Figure 5



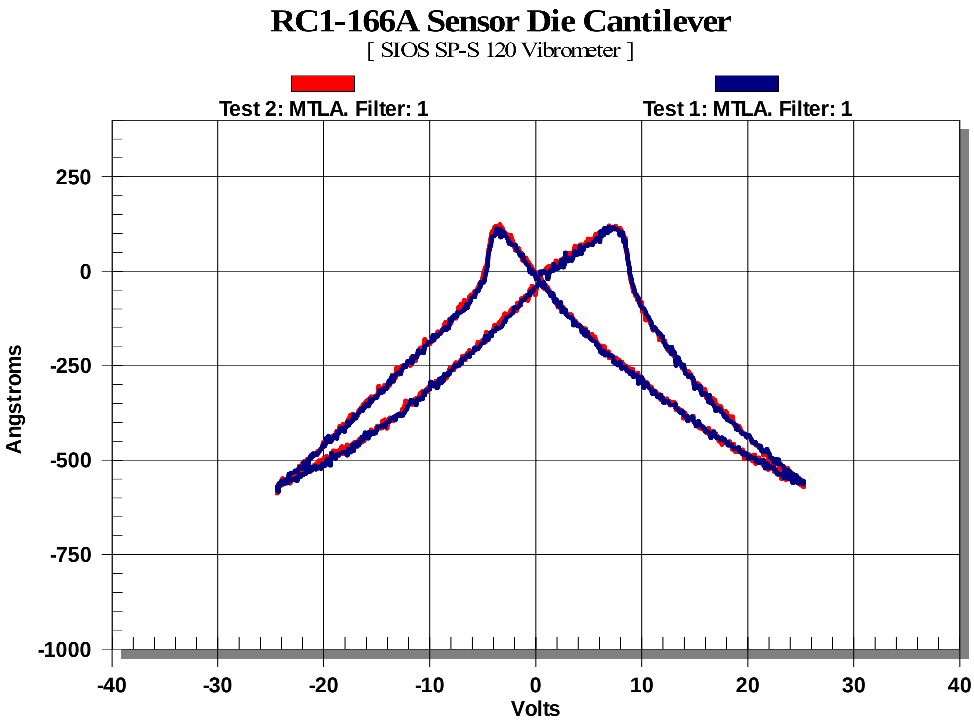
4mm Sensor Die on its PC Board Carrier
Figure 6

The die has two points at which it is soldered to the PCB so the die will flex piezoelectrically when the capacitor is cycled around its hysteresis loop. The device is intended to be used as a sensor but its cantilever effect is useful for evaluating displacement sensors.



4mm Sensor Die Bending Moment Measured with Polytec Laser Vibrometer
Figure 7

The same type of device is shown in Figure 8 as measured by the SIOS SP-S 120 laser vibrometer. Two sequential measurements are plotted in Figure 8. Each measurement was averaged five times.



4mm Sensor Die Bending Moment Measured with SIOS Laser Vibrometer
Figure 8

The difference in scale is significant between the cantilever measurements in Figures 7 and 8 and the piston measurement in Figure 4 even though all three were acquired with laser vibrometers. The piston motion in Figure 4 has only ~1% of the amplitudes of the loops in Figures 7 and 8. The "wiggle" in the cantilever motion in Figure 7 originates from vibration at resonance for the silicon substrate on which the capacitor is fabricated. That wiggle is larger in magnitude than the peak-to-peak piston motion in Figure 4. The measurement in Figure 8 was first attempted on the sample with the sample and laser vibrometer sitting on a standard lab table. The amplitude of the table vibrations on the lab table was so great that the displacement loop could not be seen in the measurement! *Achieving the minimum resolutions listed in Table 3 will only be possible if significant effort is made to quiet the test fixture.*

Recommended Ranges for Specific Sensors:
The scale factor and geometry of the different sensors determines the best application for each one. There are three categories of piezoelectric samples that may be tested with the different sensors: bulk ceramic devices, piezoelectric MEMs, and thin ferroelectric or piezoelectric film capacitors. LVDTs are not discussed below but their implementation with Radiant testers is the same.

MTI2100:
The MTI2100 with the 2032RX sensor module is simple to set up and is the least expensive of the sensors in Table 3. The sensor tip of the 2032RX module for the MTI2100 has a diameter of 300 microns and must be within 1 millimeter of the sample surface. The tip size of the MTI2100 makes it best suited for

measuring bulk ceramics and physically larger piezoMEMs although it has a noise-limited resolution of 5Å to 6Å.

The 2032R sensor module for the MTI2100 operates the same as the 2032RX but with 40 times less resolution. It is suitable for measuring bulk ceramics that move 0.5 microns or more during actuation. It has a minimum single-pass resolution of 0.019μ on the Premier II and 0.0228μ on the LC. This resolution gives a signal-to-noise ratio of 50:1 for a 1μ displacement. For smaller displacements of 0.5μ or less, clean signals can be achieved using averaging. Vision provides averaging tools in its Task Library.

<u>SIOS SP-S 120</u>:
The SIOS laser vibrometer is about three times more expensive than the MTI2100. It has a much smaller spot size than the MTI2100 and a working distance of centimeters, making it easier to align with the sample. It also has a very high frequency response so it can be used at the 1 kHz to 100 Hz frequency range. With its scale factor and small spot size, the SIOS vibrometer is suitable for measuring the displacements of piezoMEMs. However, it does not have the resolution to measure piston motion of thin ferroelectric film capacitors.

<u>Polytec OFV-534</u>:
The OFV-534 is about five times more expensive than the MTI2100. For that increase in cost, the OFV-534 provides a spot size as small as 1.5μ and a video camera with a microscope lens aligned with the laser interferometer beam. Consequently, the OFV-534 can be easily aligned on integrated scale piezoMEMs components having micron dimensions. The OFV-534 also has the scale factor to capture piston displacement of the capacitor surface. The Polytec sensor is suitable for direct study of the piezoelectric displacement of thin ferroelectric film capacitors while also being able to capture the much larger displacements of piezoMEMs actuators. An issue with measuring Ångstrom-level displacements with the Polytec sensor is the Z-drift produced by its displacement integrator. Radiant's Advanced Piezo Task has the ability to correct for this drift once it has been characterized by the researcher.

<u>AFMs</u>:
AFMs are the most sensitive displacement sensors of all with submicron "spot" sizes. They can theoretically measure displacements down to small fractions of an Ångstroms confined to areas with nanometer dimensions. Three weaknesses of AFMs as displacement sensors are:

1) Cost: they are the most expensive type of displacement sensor.
2) Sample mounting under the AFM cantilever tip.
3) Z-drift in the AFM output. (NOTE: Advanced Piezo can compensate for Z-drift.)

On the other hand, an AFM is capable of producing extremely accurate Ångstrom-level measurements over submicron areas. The AFM is best suited, then, for thin film capacitor piezoelectric displacements as well as those movements by integrated scale piezoMEMs. The AFM is not well suited for measuring bulk ceramics because of the high test voltages confined to the tight area near the cantilever. Asylum Research is building a special sample holder to placing high-voltage ceramic samples in its AFMs.

Conclusion:
All testers in Radiant's Precision tester family are capable of capturing displacement data using the SENSOR input built into every system. When coupled with a sensitive displacement meter, the testers are capable of capturing piezoelectric displacements with high resolution. There are three categories of piezoelectric samples: bulk ceramics, piezoelectric MEMs, and thin film capacitors. The MTI2100 photonic sensor and the SIOS SP-S 120 laser vibrometer are bested suited for measuring bulk ceramics and large scale piezoelectric MEMs. The SIOS SP-S 120 can also measure small scale piezoelectric MEMs due to its small spot size. The Polytec laser vibrometer and AFMs are best used to measure integrated- scale piezoelectric MEMs and the thin piezoelectric film capacitors themselves. Finally, only AFMs may measure piezoelectric effects in areas on the order of 1000 square nanometers.