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Application Note for Advanced Piezo

Rev B

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Introduction:

True excitement surrounds the discipline of piezoelectric MEMs. Even as capacitors, actuators, and sensors grow smaller, displacement sensors are becoming more sensitive to the point that mechanical movements less than the diameter of one atom may be detected in the laboratory. All instruments built by Radiant, including the EDU, are capable of capturing the output of a displacement sensor while measuring the polarization hysteresis of a non-linear capacitor. The displacement measurement will be synchronous with the voltage stimulus as well as the polarization state of the sample during the test. While the test circuits and Vision Tasks necessary to capture piezoelectric movement have always been available from Radiant, unique problems begin to emerge as the measurement scale approaches the Ångstrom level. At this scale, changes in the sample's absolute position due to environmental noise become larger than the intended measured displacement. Also, for those displacement sensors that depend upon optical path measurement, air turbulence and temperature changes on the order of ten's of milliKelvins will modulate the measured path length on the order of the piezoelectric piston motion. The problem may be likened to attempting to photograph a finch from a distance through the shimmer of a hot summer's day while the bird perches on the end of a weed stalk waving in the wind! The Advanced Piezo Task for Vision provides tools for the researcher to assemble acceptable butterfly loops under such conditions.

Ambient Noise Sources and Parasitics:

Noise in displacement measurements arise from a variety of sources, including the test instrument itself. The noise may be classified as periodic, random, or unpredictably excursive. It may arise from electrical, mechanical, pneumatic, or temperature sources or from cross-talk between integrated circuits inside the tester. Even the building utility services or noise from a nearby highway may overwhelm the targeted signal. For each source of noise there are multiple solutions that, together, reduce its effect on the measurement to acceptable levels.

Advanced Piezo uses mathematical averaging combined with mathematical smoothing to improve the quality of Ångstrom scale displacements. These two mathematical tools *will not eliminate periodic noise*! Mechanical methods and is necessary to shield the sample from periodic noise. That is the subject of another application note: "Application Note for the Precision Displacement Test Stand" available at www.ferrodevices.com/displacement.html.

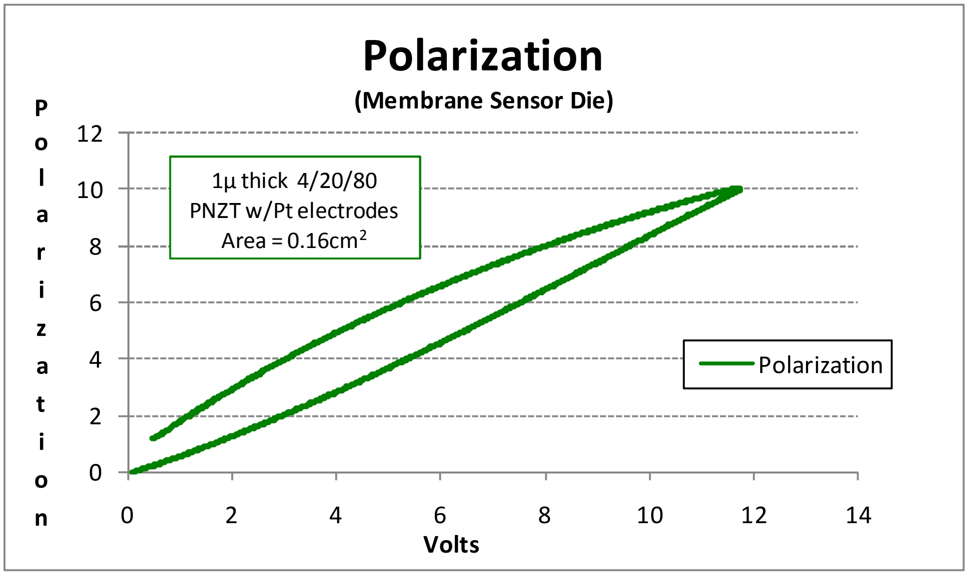
Random Noise:

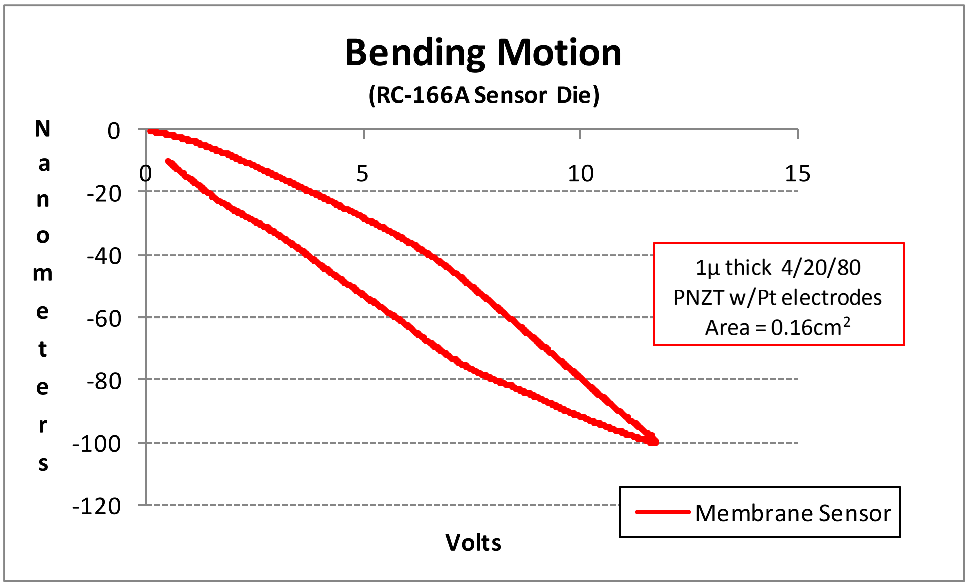
High frequency random noise arises primarily from the electrical circuits involved in the measurement: the tester, the sensor device, and any amplifier/filter that operates the sensor device. Lower frequency random noise may arise from the environment; for instance sudden excursions in optical path length due to air turbulence that are a significant fraction of the sample displacement. Environmental sources usually are of such low frequency that they appear to be one-time distortions of the measurements. This *excursive* noise is the subject of the next section.

High frequency random noise has a significant effect on the Ångstrom level displacement measurements because the displacement signal to be measured may only be a few times larger than the noise amplitude (see Figure 9 below). This low Signal-to-Noise Ratio (SNR) is a typical problem in communications theory and is handled using filters to isolate the desired signal from the random noise. Classical filters work very well in the communications field *because the shape of the target signal is already known beforehand*! The distortion added to the signal by the filters may be later removed mathematically. That luxury is not available in the world of non-linear materials because the shape of the measured signal is never known beforehand.

Averaging is the only acceptable method by which random noise may be reduced without adding distortion to the measured signal. Therefore, it is the technique used by the Advanced Piezo task. Averaging has its practical limits. The resolution of the averaged signal decreases with the *square root* of the number of averages. Therefore, to double the resolution of a measurement that has already been averaged ten times requires thirty more measurements for a total of forty. Averaging is subject to time limits as well. The time limit for averaging is dependent upon the sample test fixture that is holding the sample: How much will the sample move during the data acquisition period leading to non-random inaccuracies between the measurements?

Another limit to the number of measurements entered into the averaging routine of Advanced Piezo arises from the unique nature of non-linear capacitors. Most non-linear capacitors do not return to their original starting point, leaving a gap between start and end points of the measurement. An example of simultaneous single-sided polarization and displacement measurement highlighting the gap is displayed in Figure 1.





Simultaneous Actuator Polarization and Displacement Highlighting the Gap
Figure 1

The gaps for the device in Figure 1 will decay over a period of milliseconds or seconds back to the original starting position. If this same device is subjected to a high-speed continuous repetitive stimulus signal, it will change its response until it has a closed loop, that is the start and end points will join up. In order to prevent this effect, Advanced Piezo can execute a delay between each test to allow the gap to decay and each measurement to overlay with the same shape. These delays take time. Such delays can become a problem for long test periods if the sample's intrinsic hysteresis response changes over the time frame of the test. This is especially true for capacitors with the active region exposed to visible light or temperature changes, either of which will accelerate ageing effects over short time frames.

The Smoothing Filter

The second tool used by Advanced Piezo to clean up the small signals generated by Ångstrom-scale displacement measurements is the smoothing filter. The smoothing filter is unlike a low-pass, high-pass, or band-pass filter in that the smoothing filter only works on a few points at a time, a small subset of the total points in the measurement. It will change the shape of the measured response of the sample, as do all filters, but only on a small scale relative to the entire measured signal. The smoothing filter in Advanced Piezo applies at most nine points. For a thousand point measurement the smoothing filter will reduce apparent high frequency noise but will not significantly affect the shape of the measured loop. Exceptions are at the "points" or "tips" of the loop. These will become slightly rounded by the smoothing filter. For measurements less than 200 points, which occur in Vision for very fast measurements, the nine-point smoothing filter will have a larger distortion effect on the shape of the results. The user has the option in Advanced Piezo to use or not use the smoothing filter according to his or her judgment.

The smoothing filter will not take out noise with a wavelength longer than nine points. If, for example, the sample is resonating due to the stimulus signal, it will still be visible in the smoothed signal as long as the wavelength of the measured signal in points is longer than the nine points of the smoothing filter. If the resonance frequency wavelength is shorter than the nine points of the smoothing filter, the smoothing filter should be turned off or the test frequency increased so the resonance wavelength is longer than nine points.

Tester Noise
Radiant Technologies designed its USB-based Precision tester family with the express objective of reducing as low as possible the noise floor of each measurement. In order to accomplish this, Radiant separated the tester from the personal computer host. An 8051-architecture microprocessor in each tester sets the hardware configuration for each test and executes the measurements. The microprocessor communicates with the host computer via USB, physically separating the tester from the ground and power noise generated by the fast and powerful processor in the host computer. The power supplies for the Precision testers are those normally used in medical equipment so they provide significant isolation from the 60 Hz or 50 Hz ripple of the wall power. These combinations of characteristics significantly lower the noise floor.

> NOTE: The architecture described above does not apply to the original Precision Premier I or the Precision Workstation, each of which has a built-in PC.

The application note "Displacement Sensor Operation", available at www.ferrodevices.com/displacement.html, has an extensive discussion about the noise floor in Radiant USB testers. The table below, taken from that application note, discloses the noise floors we have measured for the Precision Premier II, the Precision LC, and the Precision SC.

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

Noise-Limited Resolution per Tester
Table 1

Given the information in Table 1, the application note then calculates the minimum resolution that may be achieved from a variety of displacement sensors.

Parameter: Instrument	**Scale Factor**	**Absolute Resolution on Premier II**	**Noise Limited Resolution Premier II**	**Absolute Resolution on LC**	**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	7.00Å	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

Noise-Limited Resolution per Tester
Table 2

The single pass noise floor for each tester in Table 1 is lower than the noise floor for all displacement sensors that may be used with these systems. Consequently, the internal tester noise floor for the Radiant

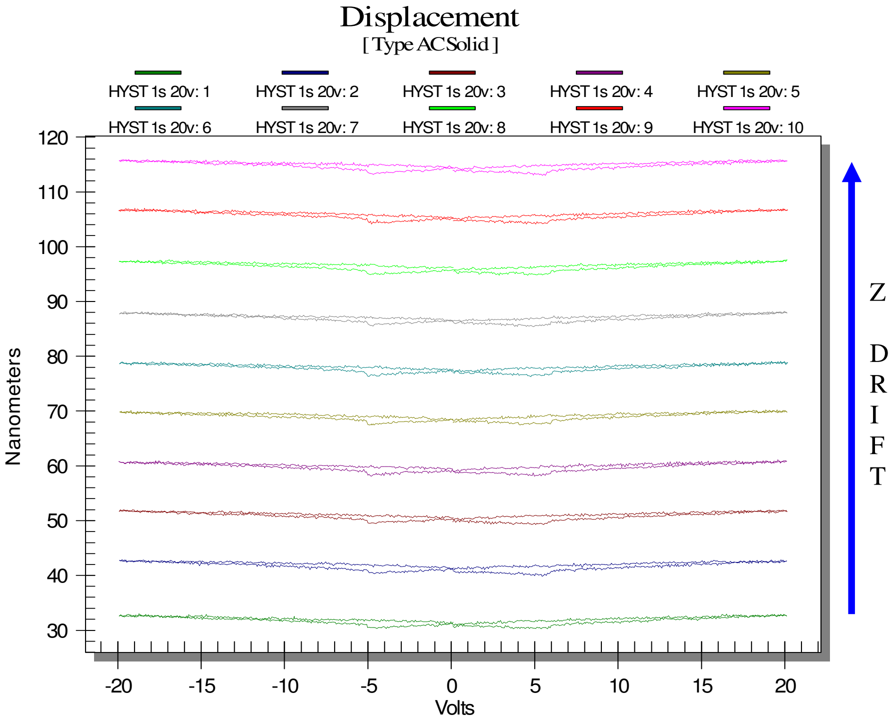
Technologies Precision tester family will not be a major factor in the noise limits for displacement measurements.

Summary of Random Noise

Random noise in Ångstrom-scale displacement measurements usually arises from the electronic circuits in the measurement path. The averaging and smoothing filter tools provided in Advanced Piezo, combined with the naturally quiet architecture for the Precision testers, allow sub-Ångstrom resolution in displacement measurements when coupled to a quiet test fixture.

Z-drift Error

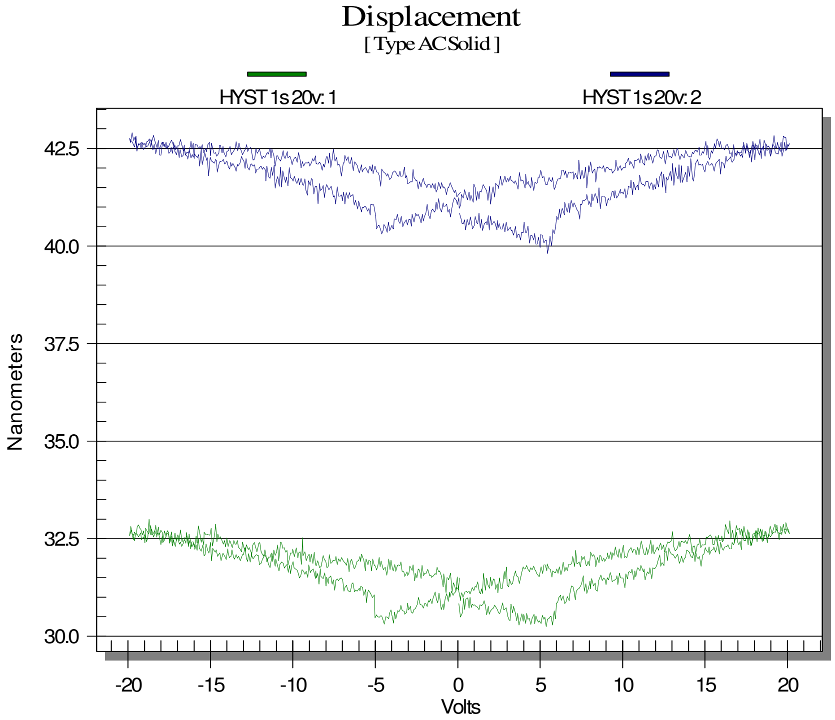
A fundamental issue with Ångstrom level measurements is the mechanical or thermal drift of the test fixture. In other words, the sample does not remain at a constant distance from the displacement sensor during a test. This drift is particularly strong in AFMs. The amount of drift differs from machine to machine and from day to day. The sensor cannot distinguish between the sample moving due to electrical stimulation and the test fixture moving the sample due to mechanical or thermal drift. These effects will not only cause the starting point of each measurement to be different, as noted earlier, but will also cause a "slope" in the resulting measurement so the starting point and ending point of each butterfly loop do not line up. B*ecause the scale of the measurement is so small, these drifts can overwhelm the measurement.* Figure 2 is a particularly vivid demonstration of the Z-drift. It is a plot of 10 successive butterfly loops measured on an AFM by Vision in a program loop. The amplitude of each loop is about 10 to 20 Ångstroms. In the period required to measure all ten loops, the AFM stage drifted 900Ångstroms.



Sequential Measurements of the Same Sample on an AFM

Figure 2

The result of the drift is that each loop has a different starting point in Z. An additional distortion is that the drift rate is high enough in Figure 2 to introduce a slope to each butterfly loop. Figure 3 shows two raw data loops adjacent in time. The slope added to each butterfly loop by the Z-drift, indicated by the difference between the first and last points for each loop, is readily apparent.



Two of the Loops from Figure 2 Showing Drift Effects
Figure 3

Correcting Z-drift

The two distortions introduced by Z-drift are corrected separately by Advanced Piezo. First, the task eliminates the vertical separation between each measurement by zeroing each loop. The value of the first point of each measurement is subtracted from every point in the loop. Second, the built-in slope added to each measurement by the Z-drift is determined as the distance between the first and last points. A linear fit to that distance is then subtracted from each point in the measurement. The correction calculated for three points in a measurement is sufficient to demonstrate the correction.

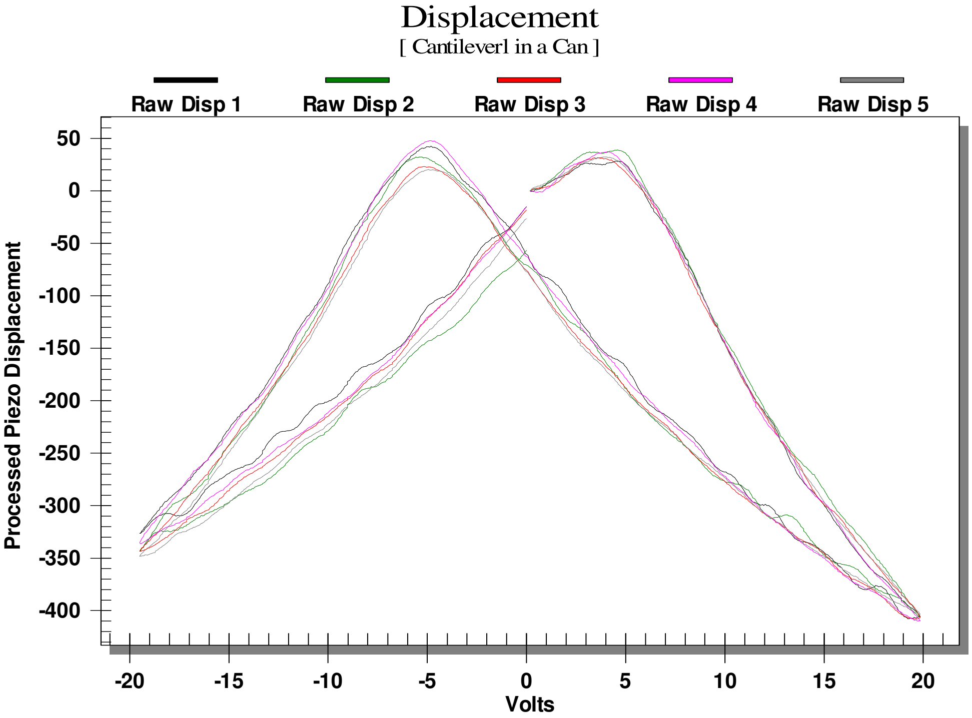
First Point:	The first point needs no correction.
Last Point:	The difference between the first and last point is subtracted from the last point.
Middle Point:	Half of the difference between the first and last point is subtracted from the middle point.

There are a variety of situations where the Z-drift corrections may induce more error in the measurement than they correct. First, for very noisy measurements, each point will have the RMS noise probability of being displaced from its true noiseless value. Therefore, the zeroing algorithm in Advanced Piezo, which uses only the first point of the measurement, will still result in an RMS noise probability of vertical displacement of the entire loop from the origin after the zeroing. Second, the same RMS noise issue will affect the drift-correction algorithm applied within each measurement, affecting the apparent shape of the corrected measurement. As with all stochastic processes, increasing the number of measurements to be averaged will decrease any distortion from the RMS noise effect on the correction algorithms. Nevertheless, under certain circumstances that the user may recognize but Advanced Piezo cannot, these effects may result in a reduced accuracy of reproduction. In those situations, the user has the option in Advanced Piezo of turning off one or both of the Z-drift correction algorithms.

Excursive Errors

Environmental effects on Ångstrom-scale displacement measurements usually have very low frequency content with amplitudes that might be larger than the signal to be measured. These low frequency events may appear only once or only a few times during the measurement. They will appear to be single-event excursions in the data. Over several measurements these events might occur at different points with different amplitudes in the measured signal. The only solution for this problem is to average the signals. If the events are so large or numerous that they affect the final averaged value, the user should examine the test fixture and/or air turbulence shielding.

An example of excursions is shown in the plot below. This data was taken with a Polytec laser vibrometer on a Radiant Cantilever-in-a-Can actuator sample. The data being displayed is the raw data that has been zeroed only. Raw data has not been averaged or smoothed. Low frequency or non-repetitive deviations from the average value are apparent in the data.



Example of Variations in Displacement from Measurement to Measurement
Figure 4

Mechanical Amplification – A Non-correctable Error

The IEEE standard for piezoelectric coefficient determination uses an electroded disk as the primary geometric test structure. Theoretically, such a structure should show a constant extension of the distance between its flat surfaces across its entire face during electrical activation. In reality, non-equal stresses in the electrodes and defects in the piezoelectric material can make the disk wrinkle, bow, or warp in any number of ways. For thin films, a single micron of PZT film is capable of bending a 550 µ thick silicon wafer, overwhelming the piston displacement of the capacitor itself. To make an accurate determination of the converse d_{33} constant of either sample mentioned above means selecting the proper spot on the sample surface at which to place the displacement sensor. In summary, displacement measurements may generate unintended behaviors based on characteristics of the samples beyond the researcher's knowledge or control. Advanced Piezo cannot correct for these issues. Only the proper selection of sample geometry and careful sample preparation will minimize this effect.

As a recommendation for measuring the converse piezoelectric constant for thin films, it is best to target a capacitor with lateral dimensions much smaller than the thickness of the substrate. The length of the substrate "lever arm" available to capacitor is much smaller than the thickness of the substrate, i.e. the sample is a column not a disk. Even in this situation, the measurement point must be placed as close as possible to the geometric center of the capacitor top electrode to further reduce mechanical amplification effects. On an AFM, the AFM can scan the capacitor surface to find the geometric center.

Here is one final note about mechanical amplification. There has been some speculation that thin film capacitors, being constrained strongly by single-crystal substrates like silicon, will expand into the substrate surface as well as expanding away from the substrate surface. The displacement sensor will see only the external expansion, thus underestimating the converse piezoelectric coefficient. This issue requires further study by the piezoelectric community.

Advanced Piezo Procedures

Advanced Piezo performs the following functions in order:

Step 1: Execute the requested number of repeat hysteresis measurements as specified by the user.

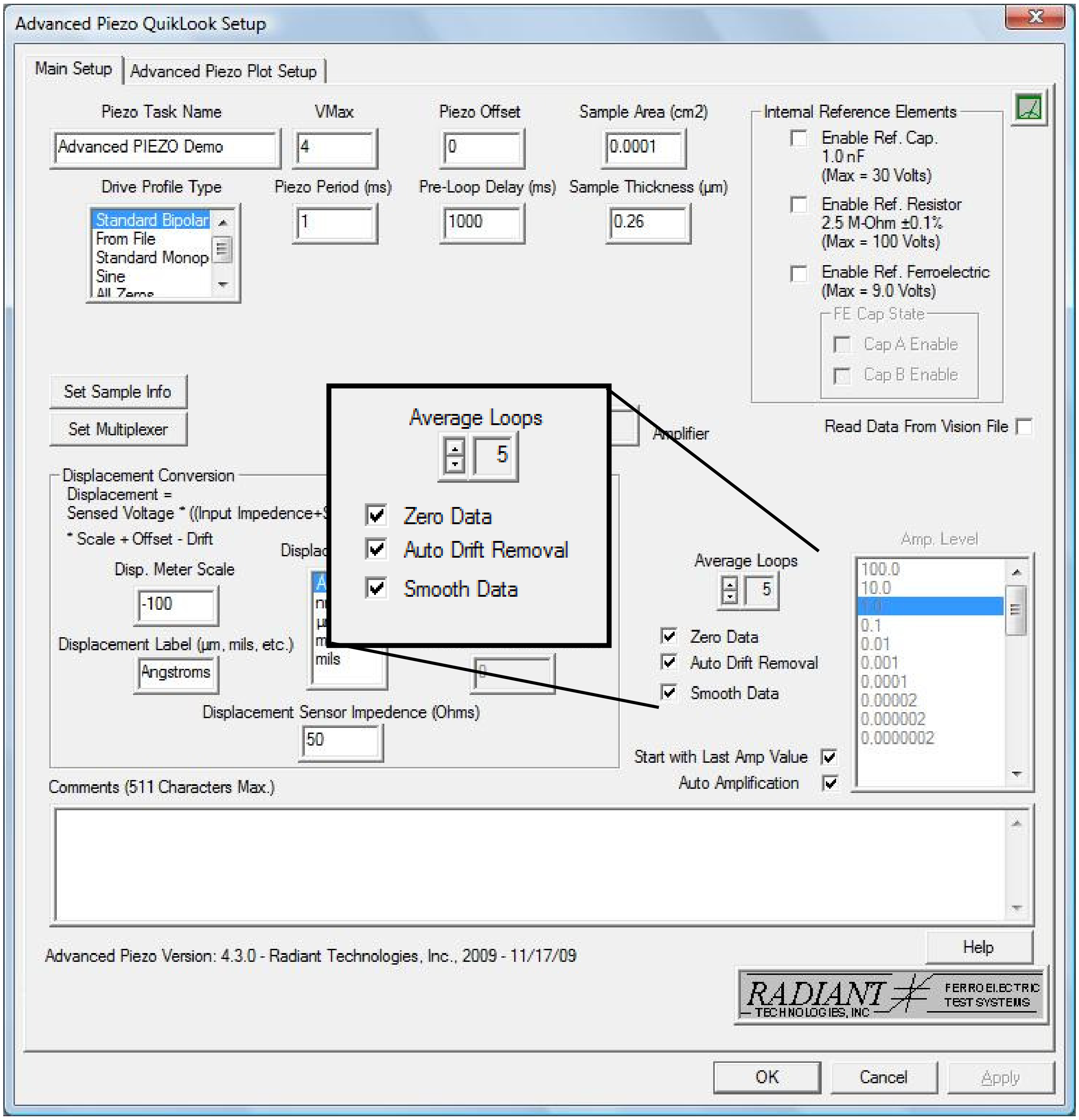
Step 2: ZERO all measurements so the first point of each measurement is on the X-axis.

Step 3: Average the zeroed measurements to produce a single measurement.

Step 4: Apply the smoothing filter to the averaged signal.

Step 5: Store and display the results.

The user may turn off any of the steps listed above. More details about each of these steps may be found in the HELP pages of Advanced Piezo.


Advanced Piezo QuikLook Setup

Main Setup | Advanced Piezo Plot Setup

Piezo Task Name: Advanced PIEZO Demo
VMax: 4
Piezo Offset: 0
Sample Area (cm2): 0.0001
Drive Profile Type: Standard Bipolar, From File, Standard Monop, Sine, All Zeros
Piezo Period (ms): 1
Pre-Loop Delay (ms): 1000
Sample Thickness (µm): 0.26

Internal Reference Elements
☐ Enable Ref. Cap. 1.0 nF (Max = 30 Volts)
☐ Enable Ref. Resistor 2.5 M-Ohm ±0.1% (Max = 100 Volts)
☐ Enable Ref. Ferroelectric (Max = 9.0 Volts)
FE Cap State
☐ Cap A Enable
☐ Cap B Enable

Read Data From Vision File ☐

Displacement Conversion
Displacement =
Sensed Voltage * ((Input Impedence+S
* Scale + Offset - Drift
Disp. Meter Scale: -100
Displacement Label (µm, mils, etc.): Angstroms
Displacement Sensor Impedence (Ohms): 50

Average Loops: 5
☑ Zero Data
☑ Auto Drift Removal
☑ Smooth Data

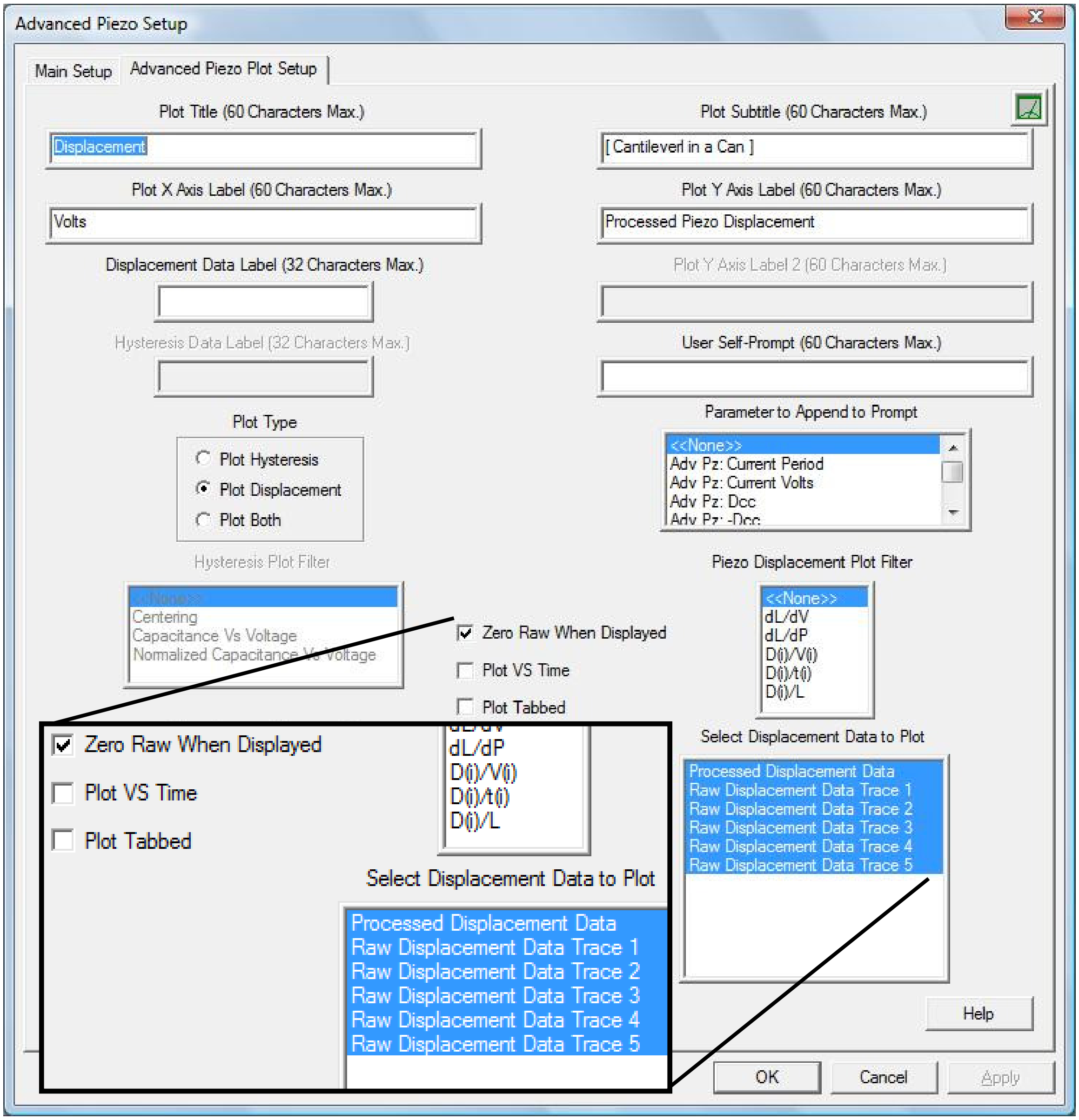
Amp. Level: 100.0, 10.0, 1.0, 0.1, 0.01, 0.001, 0.0001, 0.00002, 0.000002, 0.0000002
Start with Last Amp Value ☑
Auto Amplification ☑

Comments (511 Characters Max.)

Advanced Piezo Version: 4.3.0 - Radiant Technologies, Inc., 2009 - 11/17/09

Front Page of the Advanced Piezo Menu
Figure 5

After the data is acquired, the user may select any or all of the raw loops and/or the corrected loop for display. Note that the raw data may be displayed with or without the zeroing function enabled.



Plot Title (60 Characters Max.): Displacement

Plot Subtitle (60 Characters Max.): [Cantileverl in a Can]

Plot X Axis Label (60 Characters Max.): Volts

Plot Y Axis Label (60 Characters Max.): Processed Piezo Displacement

Displacement Data Label (32 Characters Max.):

Plot Y Axis Label 2 (60 Characters Max.):

Hysteresis Data Label (32 Characters Max.):

User Self-Prompt (60 Characters Max.):

Plot Type
○ Plot Hysteresis
● Plot Displacement
○ Plot Both

Parameter to Append to Prompt
<<None>>
Adv Pz: Current Period
Adv Pz: Current Volts
Adv Pz: Dcc
Adv Pz: -Dcc

Hysteresis Plot Filter
<<None>>
Centering
Capacitance Vs Voltage
Normalized Capacitance Vs Voltage

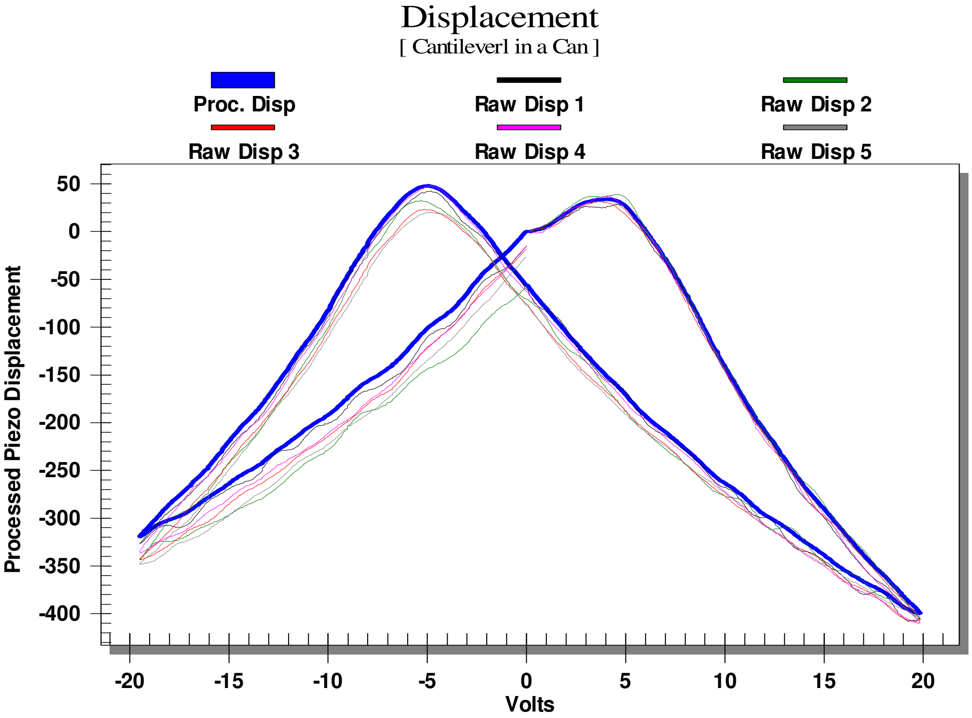
☑ Zero Raw When Displayed
☐ Plot VS Time
☐ Plot Tabbed

Piezo Displacement Plot Filter
<<None>>
dL/dV
dL/dP
D(i)/V(i)
D(i)/t(i)
D(i)/L

Select Displacement Data to Plot
Processed Displacement Data
Raw Displacement Data Trace 1
Raw Displacement Data Trace 2
Raw Displacement Data Trace 3
Raw Displacement Data Trace 4
Raw Displacement Data Trace 5

Second Page of the Advanced Piezo Menu
Figure 6

As a demonstration of this feature in Advanced Piezo, the raw data displayed in Figure 4 above is re-plotted with its Processed Displacement Data in Figure 7. The processed signal is thick **BLUE**.

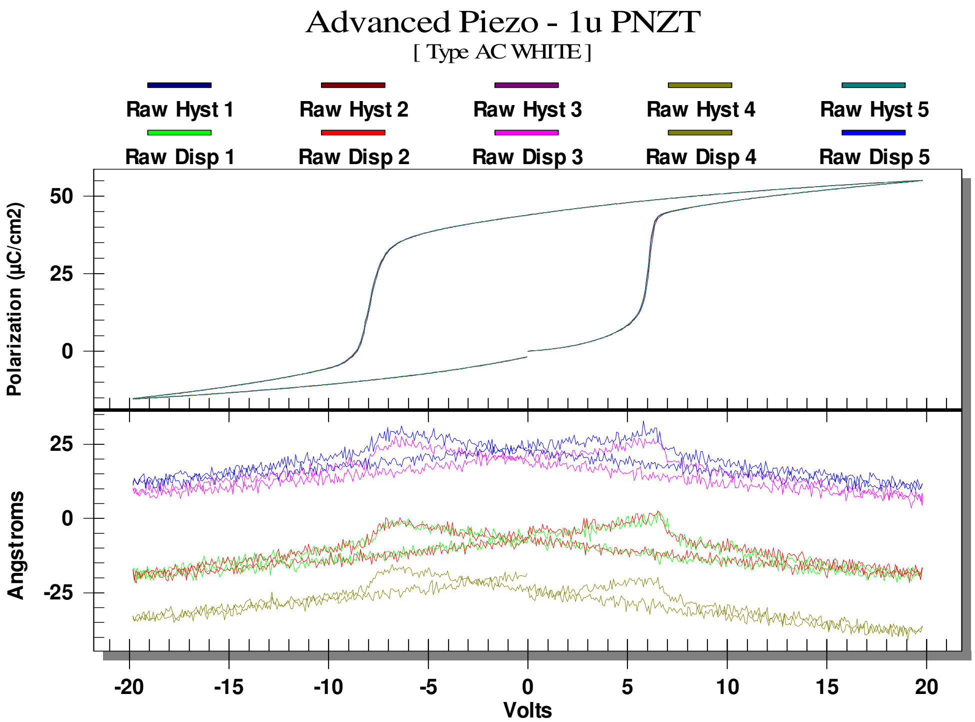


The Raw Displacement Data of Figure 4 with the Averaged and Smoothed Result
Figure 7

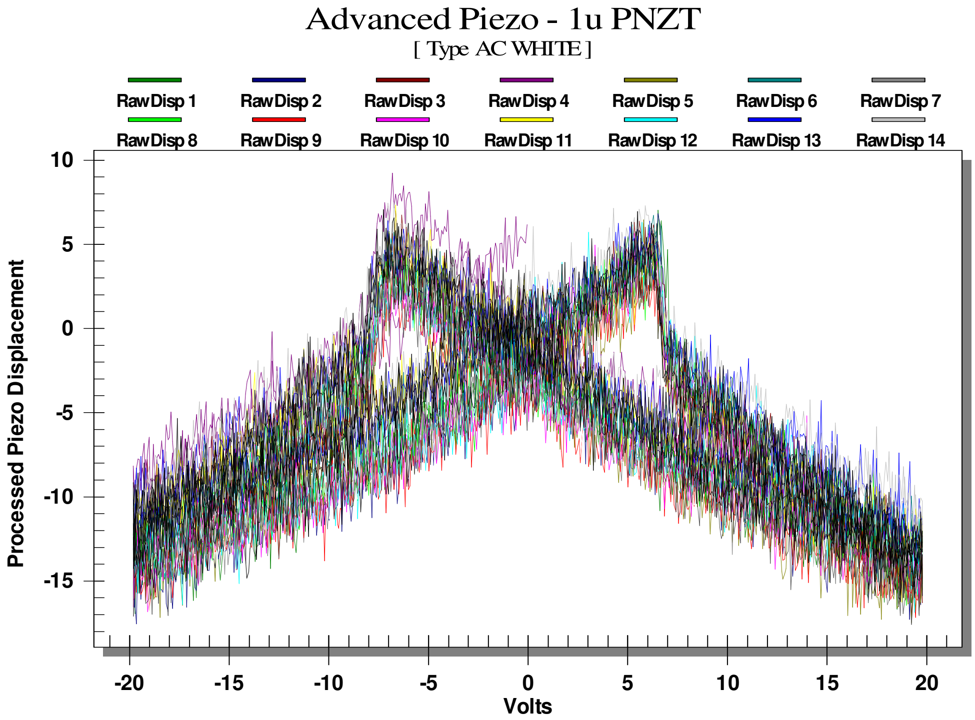
Note that unsetting all of the math processes in Figure 5 and electing to take only one measurement with no averaging will result in the same operation as the original Piezo Task.

Sample Data with Step-by-Step Correction:

Below is the sequence of corrections made to a set of displacement data taken from the surface of a 1μ-thick PNZT capacitor made by Radiant. The total displacement by the sample surface is 17 Ångstroms. The displacements were captured by a Polytec laser vibrometer mounted on Radiant's Precision Displacement Test Stand. The hysteresis period was 1 millisecond. In this measurement, twenty loops were averaged to get the processed measurement. Only five of the raw loops are displayed in Figure 8 for purposes of clarity.

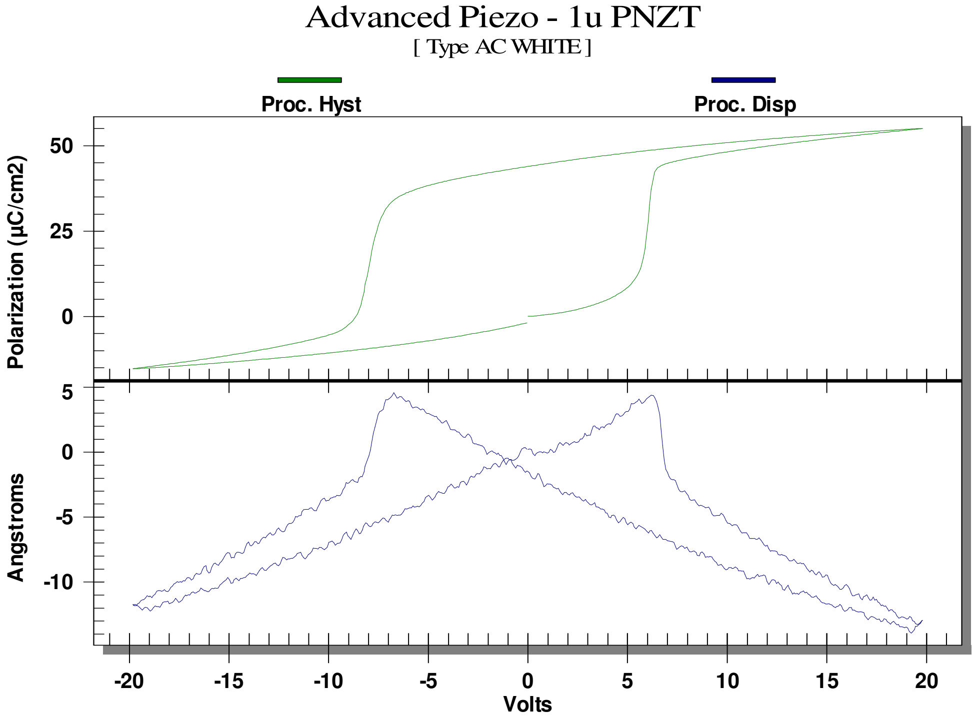


The Raw Polarization and Displacement Hysteresis Loops
Figure 8



The Twenty Raw Displacement Loops after Zeroing
Figure 9

Figure 10 displays the polarization loop and the butterfly loop after corrections by Advanced Piezo. The polarization loop in the figure is the average of the twenty polarization measurements in Figure 8. In this case, the actually need no averaging to remove noise. The butterfly loop is the average of the twenty zeroed loops shown in Figure 9 after they have been de-sloped for Z-drift and then smoothed by Advanced Piezo.



The Averaged and Smoothed Displacement Loop
Figure 10

Note: the polarity of the scale factor entered into the Displacement Conversion section of the first page of the Advanced Piezo menu (see Figure 5) for all of the displacement measurements plotted in this report is such that the direction towards the sensor and away from the substrate surface is in the negative Y direction on the plots. The butterfly loop in Figure 10 thus appears upside down compared to the traditional presentation in the literature. *The vertical orientation of any displacement measurement is arbitrary and may be selected by the user by changing the sign of the scale factor.*

Conclusion

The Advanced Piezo Task is a powerful tool for acquiring clean butterfly loops for Ångstrom level displacements by thin piezoelectric films or piezoelectric MEMs. It will correct multiple measurements for test stand drift and then average/smooth the measurements to correct high and low frequency noise. Advanced Piezo functions with any displacement sensor that will attach to a Precision tester.