Radiant Technologies, Inc.
2835D Pan American Freeway NE
Albuquerque, NM 87107
Tel: 505-842-8007
Fax: 505-842-0366
e-mail: radiant@ferrodevices.com
www.ferrodevices.com

Large Signal Displacement Measurement with a Piezo Jena Vibrometer
Rev A

Date: January 26, 2009

Author: Joe Evans

Introduction:
Peter Viglas of Piezosystem Jena, Inc. of Hopedale, MA (www.piezojena.com) graciously loaned Radiant Technologies an SIOS laser vibrometer to measure the displacement of piezoelectric devices built by Radiant. By combining the SIOS vibrometer (www.sios.de) with a Precision Premier II, I was able to quickly measure the butterfly loops of piezoelectric cantilevers constructed with Radiant's integrated ferroelectric film capacitor process.

Test Setup:
The vibrometer included of the laser head (SP-S-120) with a mount suitable for attaching the laser head to an optical table. The laser head connected to a control unit. The control unit consisted of specialized modules plugged into a backplane. The modules for this controller were the

LA-02	Laser generator
EM-02	Signal Analysis module
RG-01	Calibration controls
SM-05	Displacement calculation module
SW-03	Jitter module
UW-11	Environmental sensing unit to correct atmospheric effects

The SM-05 module of the controller has a single voltage output for the displacement sensed by the laser sensor. The EM-02 module of the controller receives interferometric information from the laser head and converts that information into quadrature format. The SM-05 module receives the quadrature signal and integrates it into displacement. The SM-05 module provides a digital input via a BNC on the front panel to zero the integrator when it is not in use. I connected the displacement output of the SM-05 module to the SENSOR input of the Premier II. I then connected the SYNC output of the Premier II to the zero control BNC of the SM-05 module. Between tests, the SYNC output voltage was zero and it held the displacement output of the controller at zero. When a test started, the SYNC signal went high and freed the displacement module to output the change in the position of the sample surface. SYNC goes high microseconds before the Premier II begins its measurements and goes low again when the measurements are completed. Consequently, the control of the displacement output of the SIOS laser vibrometer was automated for the Precision Premier II.

The SIOS vibrometer had a displacement sensitivity of -240nm/V or -2400Å/V. The Premier II SENSOR input has a resolution of 76µV/bit and a single pass noise floor of 1mV. Having a 1mV noise floor on a

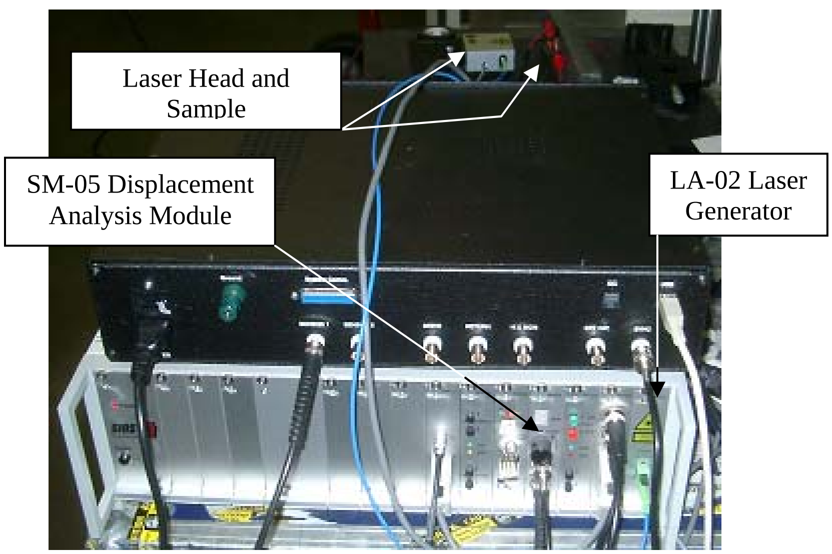
SOME RIGHTS RESERVED

single pass, the Premier II SENSOR input combined with the SIOS vibrometer sensitivity generated a noise limited displacement resolution of approximately 2.4Å.

The resolution limit calculated in the previous paragraph assumed no noise contribution by the SIOS unit. The sensor, in this case a laser vibrometer, added its own noise to the measurement. The noise generated by the SIOS laser vibrometer on the highest amplification setting of the SM-05 displacement module was approximately 20Å. With averaging, the noise reduced to less than 10Å. One of the samples moved about 70nm so the noise level after averaging was still apparent in the results. The other sample moved several hundred nanometers so that the displacement signal from the vibrometer was well above its noise floor.

See the document "Displacement Sensor Operations" from Radiant Technologies, Inc. for more information on measurement resolution and the SYNC function.

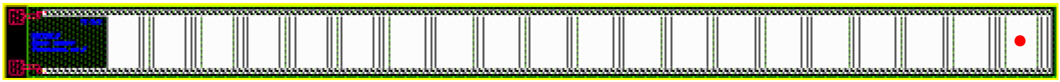
The SIOS control unit and Premier II are shown in Figure 1 below. The laser head and sample can be seen in the background.



SIOS Controller and the rear panel of the Premier II
Figure 1

Sample Description:
I measured two different samples for this experiment. The first sample was a cantilever especially packaged in a ceramic DIP for displacement measurements. The cantilever was fabricated by Radiant on the same mask set as our commercial sensor dice. The cantilever was 0.2cm wide by 1cm long. It was fabricated on standard P-type silicon wafers 550μ thick. The capacitor formed by the interdigitated capacitors had 5μ wide interdigitated electrodes with 10μ gaps between the fingers. It had 1μ-thick 4/20/80 PNZT as the piezoelectric film. Since the electric field was parallel to the surface of the substrate during actuation, the capacitor shrunk laterally when it switched, causing the tip to bend up towards the sensor. The capacitor expanded when the voltage was oriented in the same direction as the remanent polarization, causing the cantilever to bend *away* from the sensor. The red "dot" shows the displacement measurement point.

SOME RIGHTS RESERVED



Layout of the Cantilever to Show Length to Width Ratio
Figure 2

The device itself will not fit within the field of view of the Radiant's cleanroom microscope. Shown below is the left hand side of a cantilever with the bond pads for the electrical connection.

Photomicrograph of the Bond Pad End of the Cantilever
Figure 3

Carl Montross of Radiant mounted the cantilever in a 28-pin ceramic DIP such that the cantilever extended out over the die well of the package. He wire-bonded the two connections to pads on opposite sides of the package and then epoxied a small piece of silicon wafer over the bond pad end of the cantilever to protect the bond wires from handling. The final device is shown below.

Notice in Figure 4 that the pins of the package were not separated from their stabilizing rail. This is how empty ceramic DIP packages are shipped to prevent the pins from bending in transit. We left the pins on both sides of the package shorted in this manner so we only had to connect mini-grabbers to the end pins to connect to the cantilever electrically.

SOME RIGHTS RESERVED

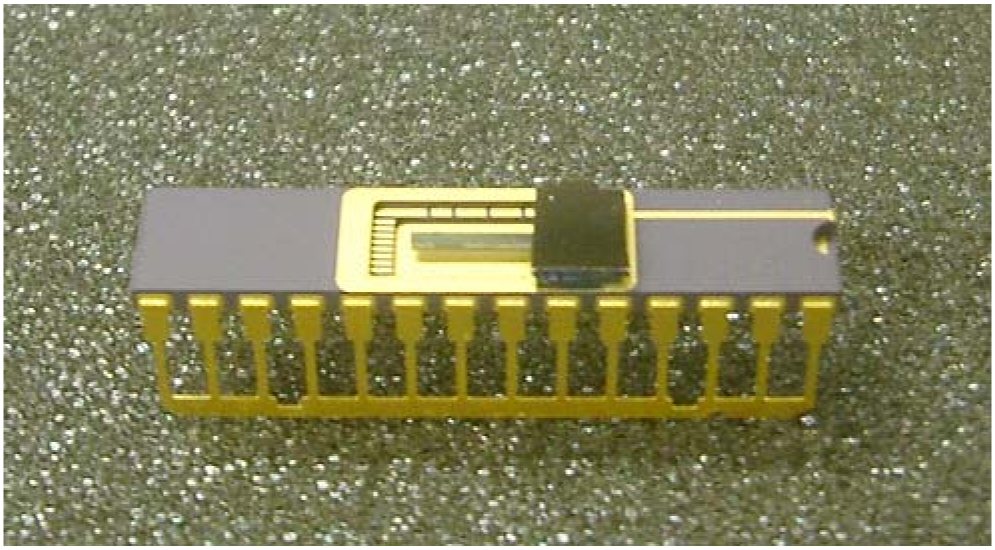
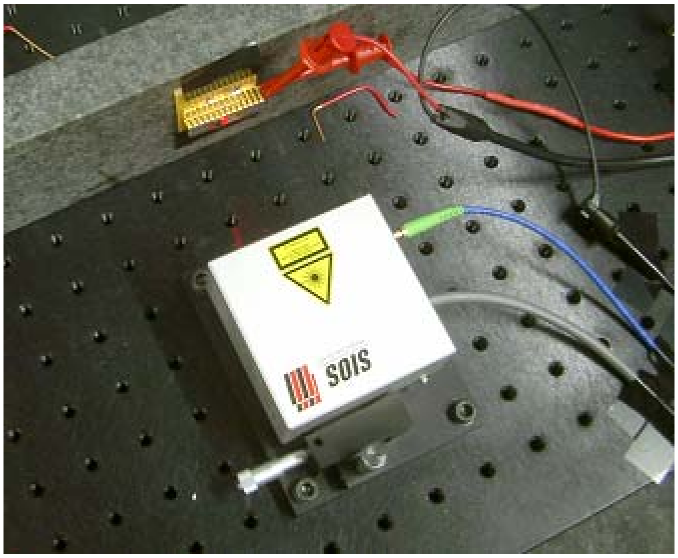


Figure 4
Cantilever in Package as Tested

The sample package was soldered to a Bakelite experiment board and then clamped to a granite block for stability. Coax cables were run from the tester to the granite block where they were clamped to the block to prevent the transmission of vibrations from the cables to the sample. Mini-grabbers terminated the coax cable and connected the two sides of the cantilever to the DRIVE and RETURN BNCs of the Premier II. The sample rested on an optical table plate which itself rested on a granite block Radiant has left over from a salvaged Ultratech stepper. A vibration isolation table would work in place of the granite foundation. The laser vibrometer head was bolted to the optical table using an adjustable tilt stage available from SIOS. The sample was then positioned in the laser beam at the proper distance from the laser head for optimal performance. Tilts were put into the sample mount and the laser head stage to force the reflection of the laser beam from the sample back into the laser head. This arrangement, according to Peter Viglas, provides the strongest signal for measurement. The test setup is shown in Figure 5 below.

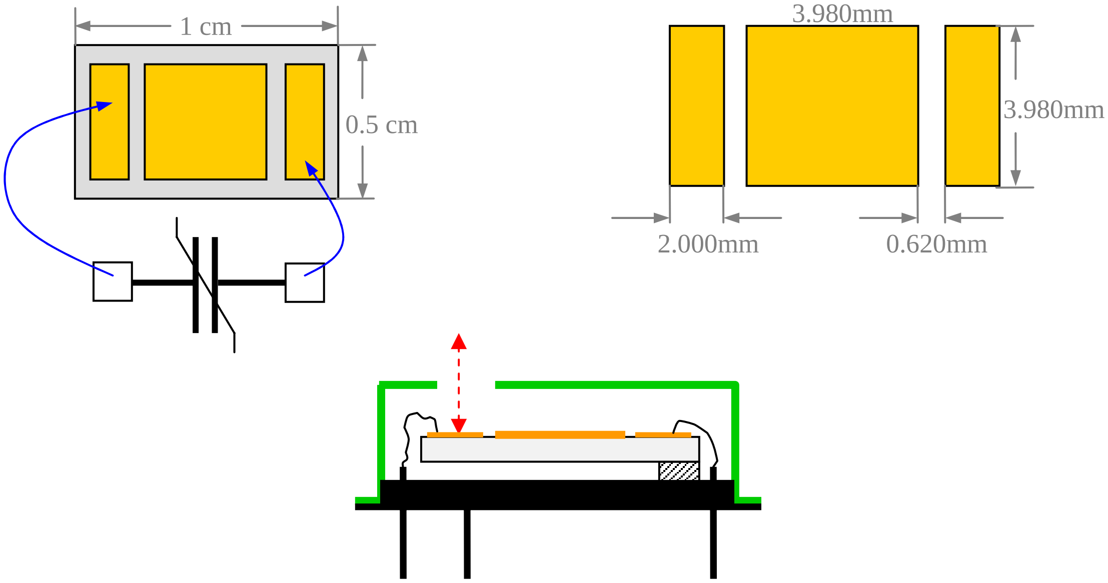
SOME RIGHTS RESERVED



The SIOS Laser Head and Sample
Figure 5

Notice the use of electrical tape to hold the sample board to the granite block. On later experiments, we switched to a carpenter's clamp. Nevertheless, even with the electrical tape, the sample was quite stable for the measurements. We just could not count on it being in the same place the next day.

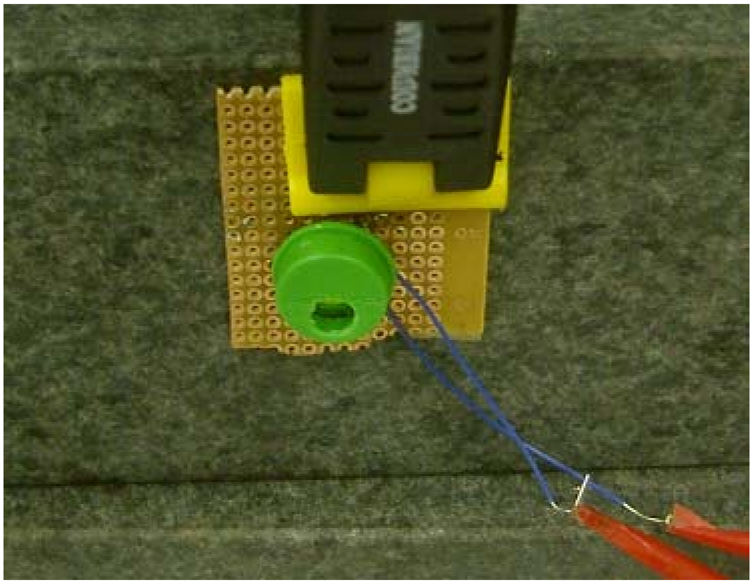
The second sample was a "Cantilever-in-a-Can". It consisted of a Radiant RC1-166A Sensor Die mounted on one end to a TO-3 power transistor type header with the other end free. A diagram is shown in Figure 6.



Cross-section of the Cantilever-in-a-Can
Figure 6

SOME RIGHTS RESERVED

The electrodes of the Sensor Die are on either end of the chip. Carl ran bond wires from each end to one of the transistor header pins. Carl then glued a plastic cap over the TO-3 transistor header to protect the bond wires. He had previously drilled a hole in the plastic cap to allow access by the displacement sensor to the free end of the Sensor Die. A picture of the sample mounted to the granite block with a carpenter's clamp is shown in Figure 7. Note the Bakelite board on which the sample is mounted.



Cantilever-in-a-Can on the Test Fixture
Figure 7

It is possible that the bond wire attached to the free end of the die may have impeded the movement of the cantilever during stimulation. Were the purpose of this experiment the calculation of the converse piezoelectric effect, I would have used a different sample configuration.

Note that the RC1-166A Sensor Die (www.ferrodevices.com/components2.html), with its large 4mm x 4mm PNZT capacitor, is designed to be used as a passive force or temperature sensor. However, it also makes a nifty cantilever. For more data on the piezoelectric performance of the Sensor Die, see the Radiant document "Evaluate Polytec Sensors Rev B.pdf".

Parasitics Affecting a Laser Vibrometer:
Laser vibrometers can measure extremely small displacements. Nevertheless, they are subject to several unique parasitic effects which can distort the results.

Electrical Noise:
The 60Hz (50Hz in Asia) EMF generated by all devices connected to the commercial power grid permeates our working environments and even finds ways to penetrate Faraday cages. Any isolated metal object will change the local EMF field by absorbing and re-radiating the energy at the same frequency. This constitutes an amplification and phase change in the area surrounding the floating metal object. Grounded metal objects distort the geometry of the field lines of the local EMF field. All instruments, including Radiant's testers as well as displacement sensors such as laser vibrometers, have a base-line 60Hz (50Hz)

SOME RIGHTS RESERVED

oscillation in their electrical ground which they cannot see or control since their only reference to a solid ground, the earth ground, comes to them over a power cable, otherwise known as an antenna. In fact, many of you no doubt envision the EMF noise as a smaller parasitic signal riding on the measured signal when in fact the truth is that the measured signal is sometimes a much smaller signal riding on a much larger parasitic EMF signal! What saves the day is that the EMF signal will be on both the center conductor of a coax cable as well as on the shield while the measured signal will be only on the center conductor. Radiant's testers are designed to take advantage of this situation by eliminating *common-mode* signals from their measurements. A problem occurs when the ubiquitous 60Hz (50Hz) EMF surrounding the sample or the sensor *differs in phase* from that surrounding the tester. Consequently, the key to minimizing or eliminating 60Hz (50Hz) noise from measurements is to make common-mode the EMF picked up by the tester, the sensor, and the sample. This is accomplished by proper grounding of all instruments and test fixtures.

Power sockets in laboratories can be at different phases of the 60Hz (50Hz) if they are wired physically to different branches of the power system for the building. Therefore, plug the test system, the sensor, and the test fixture into the same power receptacle to make their EMF common-mode. Ground all metal chucks locally and also to the green banana plugs on the rear panels of Radiant testers. Electrically isolate the sample from the grounded chuck with glass, sapphire, electrical tape, or paper. Connect the enclosure ground of the sensor to the tester. Sometimes this is accomplished automatically through the shields of coax cables but it is something that should be checked. You must even ground to the tester the tables or benches that the tester, sensor, and sample rest upon.

<u>Mechanical Amplification</u>

The SIOS sensor used for this experiment does not have the sensitivity to measure the piston motion of the surface of a piezoelectric capacitor. Nevertheless, its range of sensitivity is excellent for MEMs actuators, ones that use mechanical amplification to translate the movement of the piezoelectric capacitor to the larger movement of the actuator. The researcher must remain aware of the possibility that more than the actuator itself may be moving during the test, modifying the motion being measured by the sensor. Parts of the die holding the actuator that are supposed to anchor the actuator may themselves bend under the stress. Even the fixture holding the actuator might bend under the right circumstances.

<u>Mechanical Creep</u>

The mechanical structure of the fixture holding the sample may drift over time. This could be due to mechanical creep or to changes in temperature. There are two categories of creep. The first occurs over long time periods, requiring realignment of the sensor with the sample to make measurements. The second occurs at a rate equivalent to the data capture rate of the sensor or the repetition rate of measurements that are averaged. The drift appears in the data in four ways:

1) The test fixture drift moves the sample in depth, appearing directly as part of the sample displacement.

2) The sample moves laterally so that the any slope in the sample surface appears to be a change in Z.

3) If multiple measurements are being taken for averaging, the drift will cause the sequential measurements to differ by constants, causing errors in the average of the multiple measurements.

4) If the drift is fast enough, it might cause a "tilt" in each measurement so the end point is not where it should be.

SOME RIGHTS RESERVED

Vision provides a mechanism for zeroing each measurement by subtracting the first point of each measurement from all points in that measurement. Once mathematically zero'd, every measurement in a sequential list will start at the Z=0. Vision also provides corrective mathematics that can be applied to acquired displacement data to remove the tilt induced by fast mechanical creep. The tilt can be corrected by mathematically introducing a drift of equal magnitude in the opposite direction. This correction is only valid *if the drift has a constant rate*. To use this tool requires careful characterization of the sensor and test fixture over a time period equivalent to or longer than that required to capture all of the measurements to be averaged. It is extremely important to note that every test fixture and every sample are different so the corrective actions to take on the measured data, if any are possible, will be different for each case. It is imperative that the researcher examine his or her test environment thoroughly to determine if the corrective tools provided by Radiant in Vision can be used or not. The tools cannot anticipate or correct for correlated parasitics that appear randomly. Of course, continuous high-frequency random noise can be reduced using averaging tools in the Vision Library.

<u>Sensor Acquisition Speed:</u>
The SIOS laser vibrometer used in this experiment has a frequency response of 150kHz. This is much faster than the expected response frequencies of the samples I tested. As a general rule, the test frequency (i.e. loop period) should be at least 1000 times slower than the frequency response of the sensor in order to eliminate any possibility of phase distortion in the measurements. Sometimes this is not possible if the acquisition frequency of the sensor and the maximum test period of the tester do not allow that much margin. Radiant testers do not filter the analog signals they measure in order to prevent phase distortion. Some sensors generate a significant amount of high frequency electrical noise that might lower the resolution achievable on a single-pass measurement. While it is possible to use filters between the displacement sensor and the tester SENSOR input to reduce this electrical noise, the user must be careful to prevent phase distortion by this arrangement. The same rule applies: go at least 1000 times slower than the filter setting if possible.

<u>SYNC Control Speed:</u>
The SYNC control from the Precision Premier may give only a few microseconds of buffer from its leading edge to the start of the voltage stimulus. On the Precision LC, this grace period may be as long as 70μs. Nevertheless, the sensor might respond slowly to the SYNC signal such that the sensor output does not start *until after the tester begins the voltage stimulus*. You will see this effect as flat SENSOR data in the first few points of the measurement when plotted against time. Should this occur, you must lengthen the measurement period to slow down the tester's measurement clock and allow time for the sensor to respond to the SYNC signal.

<u>Mechanical Vibration:</u>
The test fixture upon which the sample is fastened may vibrate. The table or bench upon which the test fixture sits may vibrate. The building in which the experiment is conducted may vibrate, all due to stimulation by the building services like water, heat, and air conditioning. The SIOS laser vibrometer is more than sensitive enough to see this parasitic signal in the measured data. Making very fast measurements in the 2kHz range will help but even that speed is not fast enough to prevent phase effects from the 120Hz, 240Hz, and 360Hz vibrations typically present in a building structure.

The solutions to this problem are:

1) Move the entire test setup to the slab of the building. Typically, this will be the basement of the building.

2) Do not use a table or bench. Put the test fixture on the floor!

SOME RIGHTS RESERVED

3) Use a vibration isolation table.

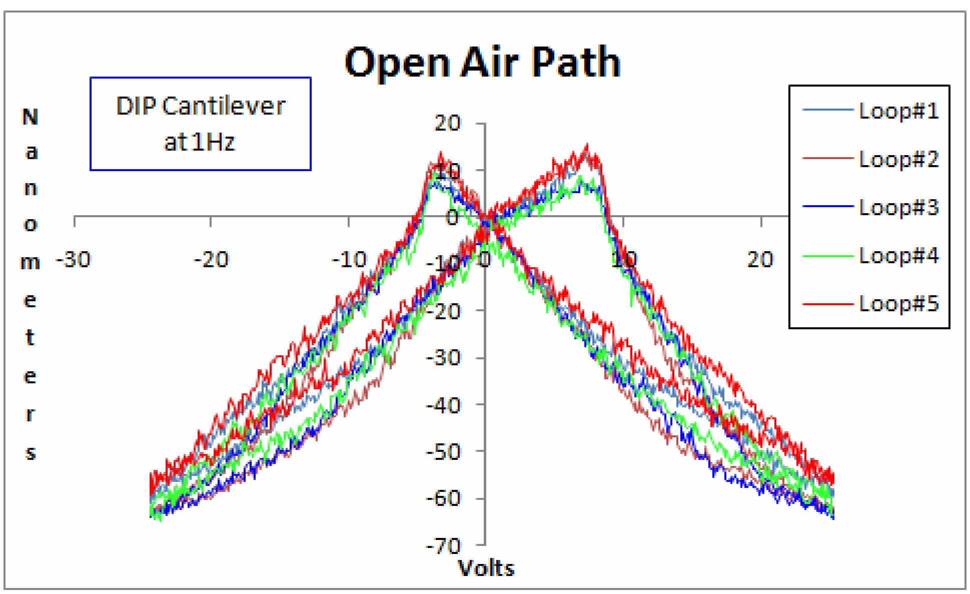
4) Use very stable sample holders. As you have already seen, I mounted the sample for this experiment directly to a granite block.

5) Use a heavy, stable platform such as a large granite block. Salvage an old photolithographic stepper if you can find one.

A final warning, the cables connecting the laser head controller and the tester to the test fixture can transmit mechanical noise onto an otherwise perfectly isolated sample holder.

<u>Environmental Noise:</u>
Laser vibrometers are subject to a unique environmental noise source: air currents. The laser beam in such a test system usually traverses 10cm or more through the air between the laser head and the sample. The laser beam itself will heat the air slightly, creating a "desert mirage" type effect on the optical path. (This effect is what makes shooting down missiles through the atmosphere with a high-powered laser so difficult!) There is nothing the researcher can do for this situation except to use the lowest power laser source available.

A larger problem comes from air currents moving through the test room. Your brain has been conditioned to ignore their effect on your skin so you do not realize that these currents are almost always there. They can add a significant amount of random distortion to your measurements. Below is a plot of five sequential measurements executed using the test fixture configuration shown in Figure 5.



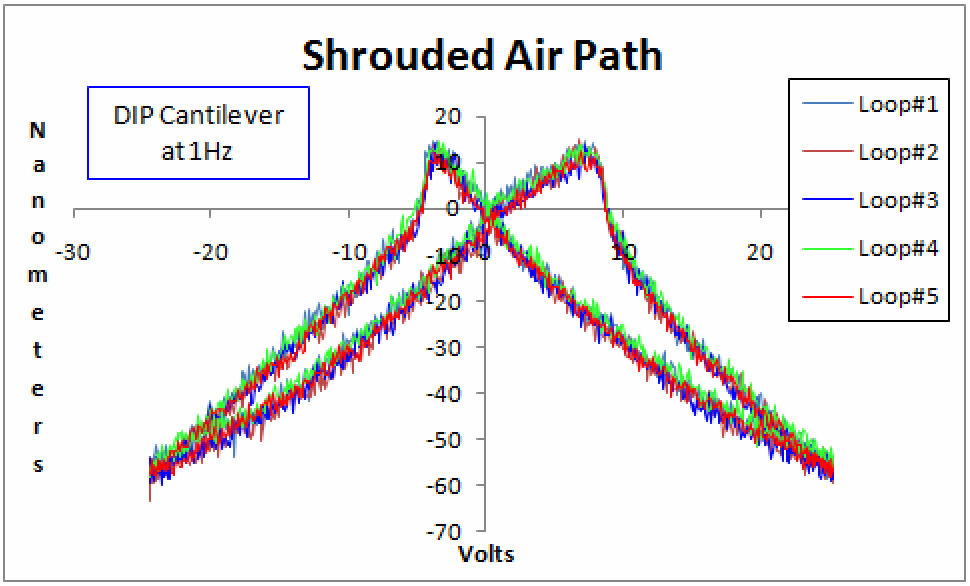
Sequential Measurements of the Sample on the Test Fixture in Figure 5
Figure 8

I placed a shroud over the test path of Figure 5 as shown in Figure 9.

SOME RIGHTS RESERVED

Shrouded Optical Test Path
Figure 9

It is amazing the effect that the shrouding of the optical test path had on the resulting measurements. Compare Figure 10 below with Figure 8 above. In both cases, the measurements were zero'd vertically to the origin before being plotted.



Sequential Measurements of the Same Sample in Figure 8 with Shroud
Figure 10

Summary:
Great care must be taken in the selection of the displacement sensor, in designing the test fixture, and in designing the test path for the optical beam. The goal must be to minimize distortion and noise injection

SOME RIGHTS RESERVED

from external sources. Every sample and every test fixture will be different. Fortunately, these parasitics can be controlled.

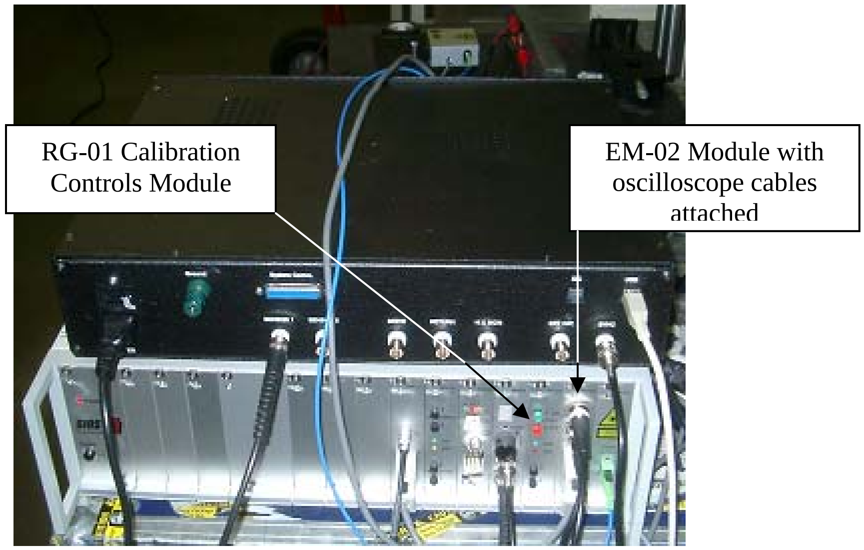
Radiant is developing a new filter for the Vision Library with which to do the corrections listed above should they be needed. The PIEZO Filter will read the SENSOR data from the PIEZO task and provide the mathematical tools to adjust for parasitics. I used the prototype of this filter in the measurements below.

Calibrating the Piezosystem Jean Laser Vibrometer:

The SIOS laser vibrometer has an unusual calibration procedure. In order to understand the calibration procedure, it helps to understand how the interferometer works. The laser head generates a laser beam, more than likely at 6328Å, the frequency for the He-Ne laser. Optics in the laser head breaks the beam into two parts, one of which remains in the head while the other travels to the sample surface to reflect back into the laser head aperture. The laser head then combines the two beams so they interfere at the photonic detector. The intensity of the He-Ne laser light impinging on the detector is the square of the sum of the amplitudes of both beams. The phase difference between the two beams times the product of the two amplitudes determines the absolute intensity seen by the detector. However, it is a messy business extracting the phase value from the intensity measured by the detector because the amplitudes of the two beams, especially that of the beam reflecting back from the sample, are not known precisely due to in-transit losses. To solve this problem, SIOS employs heterodyne modulation to convert the measurement from a static Amplitude Modulation (AM) to a dynamic Frequency Modulation (FM) with the subsequent reduction in noise and the elimination of ambiguous amplitudes. The only value that counts in the detected signal is the phase delay between the two beams. Analog amplitudes do not affect the results. As a result, the sample surface does not have to be perfectly reflective and the laser beam does not have to reflect precisely back into the laser head for the phase measurement to be accurate. For more information on this powerful technique, research the term “heterodyne interferometry”. In fact, this technique is used in your cell phone to allow your phone to easily jump frequencies as it moves from the range of one cell tower into the range of another.

In heterodyne interferometry, one or both beams are phase modulated with a sinusoid in the radio frequency range. The intensity of the interference pattern of the two beams oscillates with the same sinusoid as the modulating signal. Its phase relative to the original modulation signal is determined by the path length to the sample in wavelength residuals. The heterodyned interference signal is resolved into its quadrature amplitudes, i.e. the A and B of $[A \sin(\omega) + B \cos(\omega)]$, in the EM-02 module and is then sent to the SM-05 module for integration into the displacement signal. The A and B amplitudes are also output from BNCs on the face of the EM-02 module to be used to calibrate the output signal with an oscilloscope.

SOME RIGHTS RESERVED



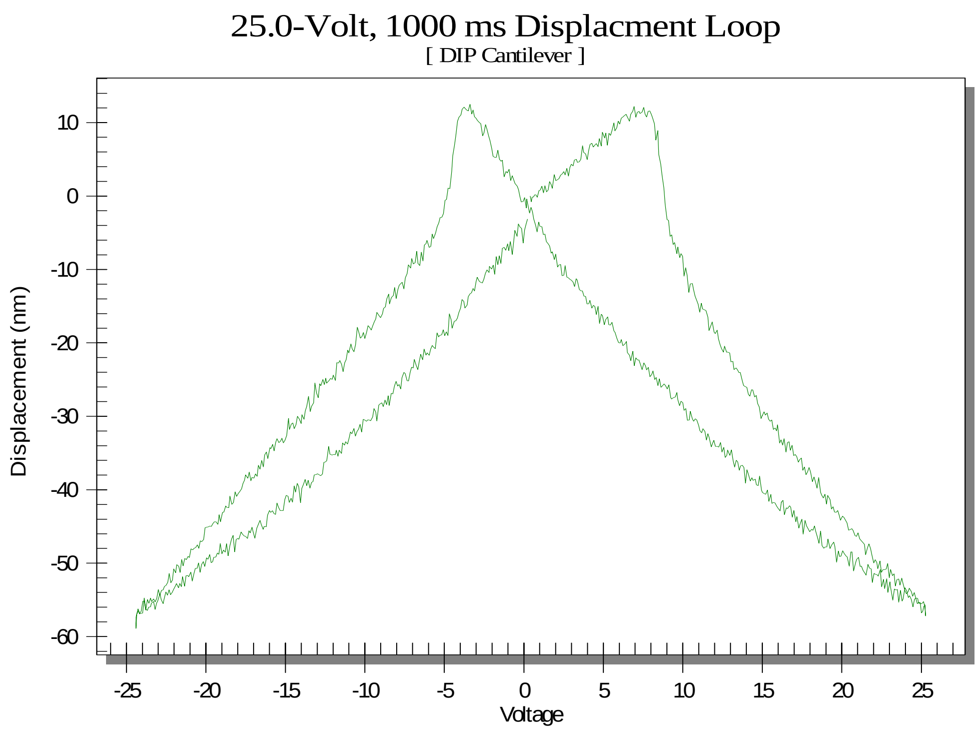
SIOS Controller and the rear panel of the Premier II
Figure 11

The oscilloscope should be set to X:Y mode. The amplification level selected in the SM-05 module should normally be set to "0" for MEMs displacement, the highest level of the SIOS system. The quadrature signals should trace out a circle on the oscilloscope when the sample surface moves. Using the controls of the RG-01 module, the circle should be set to 1.5V in both X and Y and should be centered on the origin. In my case, the granite test fixture I used to mount the sample was so stable that the quadrature signals stayed at a single point on the circle. I did not have a circle. The SIOS controller I used did have an SW-03 module which can force the quadrature signals to rotate and create a circle on the oscilloscope. I did not use the SW-03 module; I simply knocked on the test fixture with my knuckles while adjusting the RG-01 module controls. I found that the SIOS laser and controller should be allowed to stabilize at their operating temperatures before executing the calibration.

Results:
I tested both samples by looping the PIEZO task five times. Inside the loop I used the SENSOR task to pull out the displacement data from the PIEZO task and then used the Loop Averaging Filter to average the five loops. After the looping, I included two PIEZO Filters set to the Accumulate mode to plot all five loops as raw data as well as zero'd data.

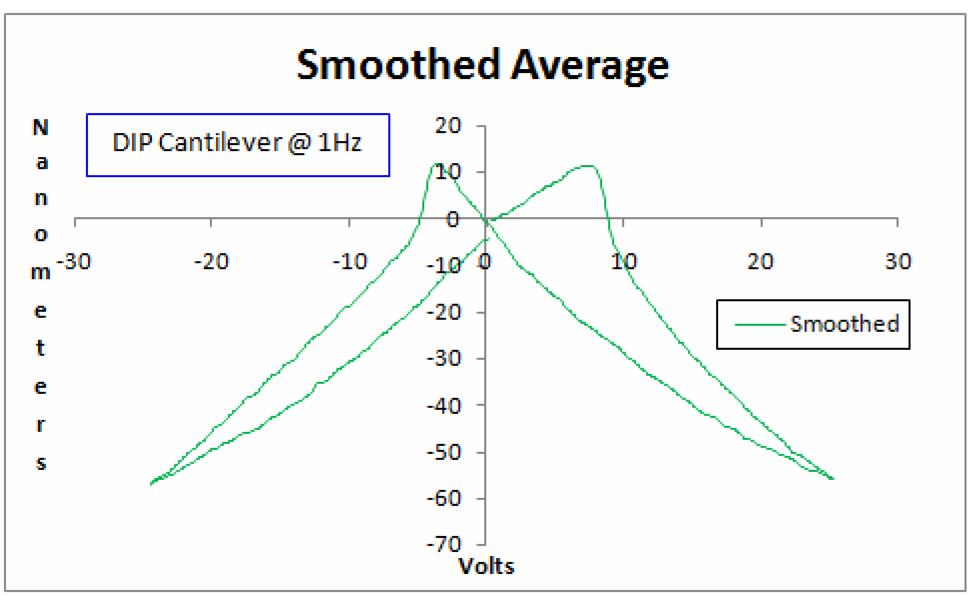
The five raw displacement loops for the DIP Cantilever, zero'd vertically, can be seen in the plot of Figure 10 above. Figure 12 below plots the average of the five loops. The range of the butterfly loop is a little more than 70nm and you can clearly see the residual noise amplitude on the average. Also, the end point and start point of the loop do not align. It is not clear if this was due to fixture drift or the sample itself so I did not apply and tilt correction to the results.

SOME RIGHTS RESERVED



Displacement of the DIP Cantilever Tip at 1Hz Averaged Five Times
Figure 12

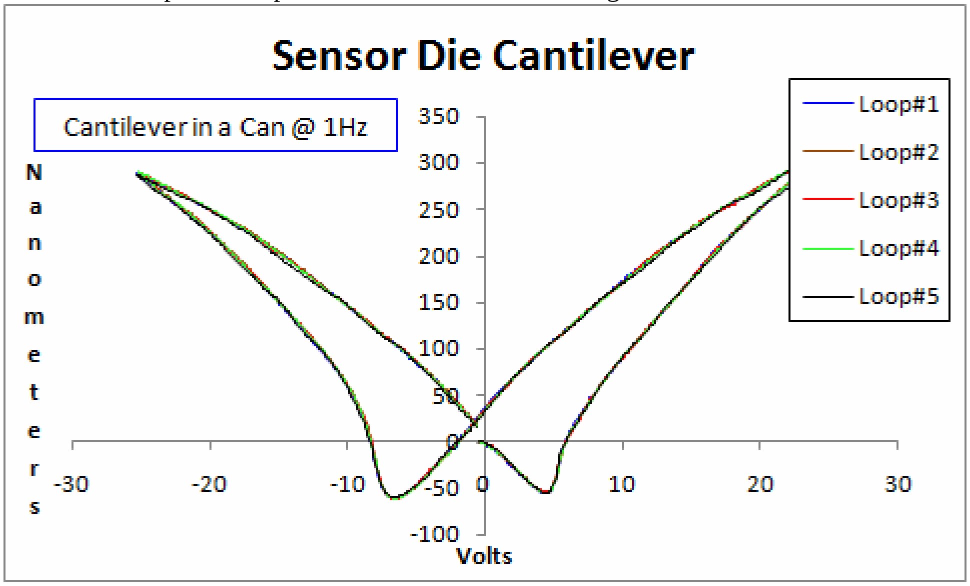
I applied a 9-point smoothing filter to the averaged data in Figure 12 to give a very nice result for the DIP cantilever performance.



The Averaged Data in Figure 12 Smoothed
Figure 13

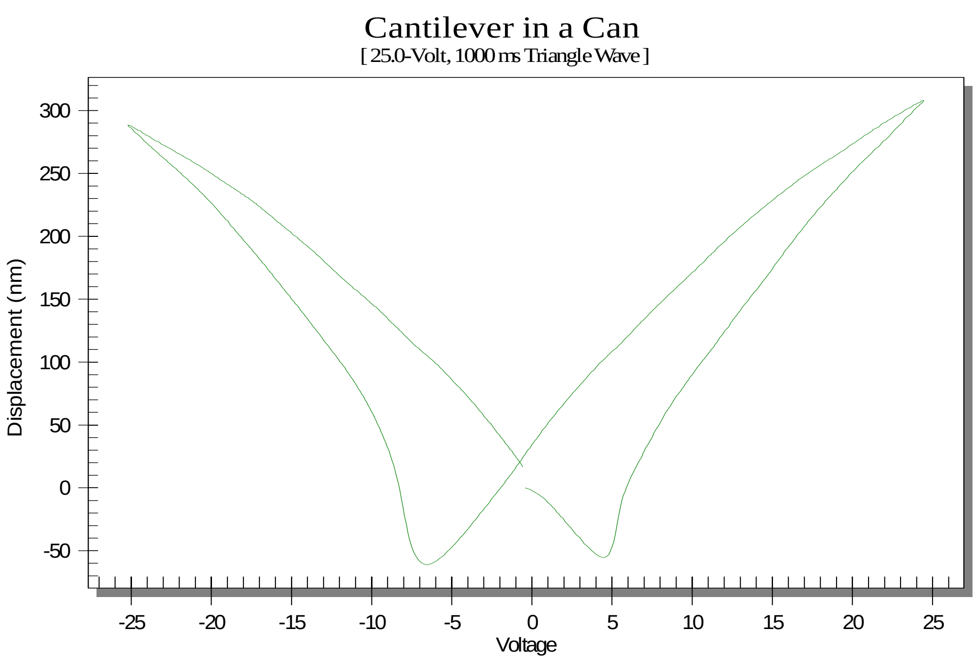
SOME RIGHTS RESERVED

Figure 14 plots the five zero'd raw data loops measured of the Cantilever-in-a-Can sample. This data was taken with a shrouded optical test path. The data was zero'd using the PIEZO Filter in Vision.



Five Butterfly Loops from the Cantilever-in-a-Can
Figure 14

Below is the averaged value of the five loops in Figure 14. This plot is *not* smoothed since its total displacement is almost six times that of the DIP cantilever and the signal-to-noise ratio is quite high.



Averaged of the Loops in Figure 13 *without* Smoothing
Figure 15

SOME RIGHTS RESERVED

Note the difference in displacement amplitude between the two different samples and the effect this had on the relative noise levels of the two measurements. Also note that the two cantilevers moved in opposite directions. This occurred because of the difference in electrode arrangement. The DIP cantilever had interdigitated electrodes, making the applied field parallel with the substrate surface, while the Sensor Die Cantilever had vertical parallel plate electrodes, making its field applications perpendicular to the substrate surface.

Conclusion

The SIOS laser vibrometer available from Piezosystems Jena, Inc. is an excellent sensor for measuring piezoelectric MEMs performance. Great care must be taken by the researcher when configuring the test fixture, the sensor, and the tester to minimize the effects of parasitic noise sources. The SIOS vibrometer is capable of achieving a noise level better than 10Å with averaging and smoothing will further reduce the noise level to almost the Ångstrom level. The fast acquisition frequency of the SIOS sensor will allow characterization of the high frequency response of the device under study.

SOME RIGHTS RESERVED