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Large Signal Displacement Measurement with an MTI Photonic Sensor

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Introduction:

I used an MTI 2100 Photonic Sensor (http://www.mtiinstruments.com/products/MTI 2100fotonic.aspx) to measure the displacement of a piezoelectric device constructed with Radiant's integrated ferroelectric film capacitor process. The report below describes the characteristics of the MTI sensor and presents the results of the measurements.

Test Setup:

The MTI 2100 sensor consists of a mainframe with a backplane for inserting measurement units. The mainframe will hold one or two measurement units. In this case, I used the 2032RX measurement probe which has a stated resolution close to 0.5nm (5Å). The sensor is a fiber optic bundle that projects a cone of white incoherent light onto the sample surface with a known conic angle. Light reflected from the sample surface is captured by the fiber optic bundle and returns to the measurement unit. Because of the increasing diameter of the light beam with distance, the further the sample surface from the exit port of the fiber optic bundle, the lower the amplitude of the captured light in relation to the emitted light. The measurement unit uses the ratio of the emitted and captured light to calculate the distance from the tip of the fiber optic bundle to the sample surface. The tip diameter of the photonic probe of the 2032RX measurement unit is 300μ, making it suitable to study the displacements of MEMs type devices.

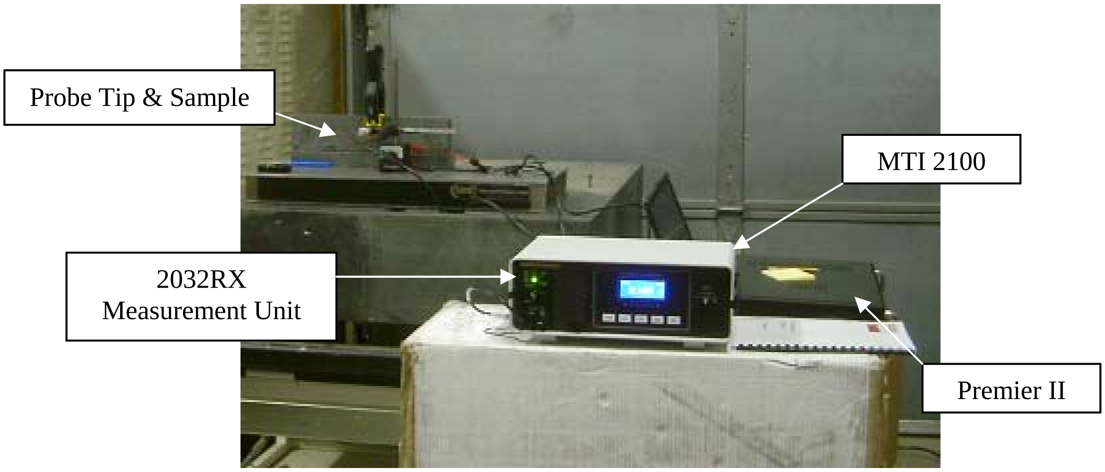
Since the sensing medium is photonic, the sensor response can be very fast. The frequency specification for the 2032RX is 100 kHz. Selectable high and low past filters are available on the front panel of the 2032RX. Due to the geometry of the sensing light beam, the tip of the fiber optic bundle must be within 1 millimeter of the sample surface. The sample surface must be at least partially reflective. If the sample surface is not sufficiently reflective, adhesive reflectors are available from MTI. The MTI 2100 generates absolute distance information, not differential information. Consequently, there is no need to connect the SYNC signal from the Precision tester to the MTI unit. Only the output of the measurement unit needs to be connected to the SENSOR input of the Precision tester using a coax cable. For my tests, I used a Precision Premier II Non-linear Materials Tester.

The 2032RX measurement probe had a displacement sensitivity of -550nm/V or -5500Å/V. This is roughly half the resolution of the SIOS laser vibrometer profiled in the report "Butterfly on SIOS Sensor …". Although it has a lower resolution than the SIOS laser vibrometer and a significantly lower resolution than the Polytec laser vibrometer, the MTI 2100/2032RX system is much less expensive than either of those units, making it a viable alternative for university material research programs. 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 single pass, the Premier II SENSOR input combined with the 2032RX unit generated a noise limited displacement resolution of approximately 5.5Å.

The resolution limit calculated in the previous paragraph assumed no noise contribution by the 2032RX unit. The sensor added its own noise to the measurement. I set the Low Pass Filter of the 2032RX to 100 Hz and set the High Pass Filter of the 2032RX to DC while running 1 Hz loops for the measurements. With this arrangement, the noise level for a single pass was approximately 8Å, or 0.8nm, a relatively clean signal.

> NOTE: It is extremely important to set the High Pass Filter control of the 2032RX to DC. Otherwise, the filter will block the hysteresis loop itself!

The MTI 2100 is shown in Figure 1 below. The sample and test fixture can be seen in the background.

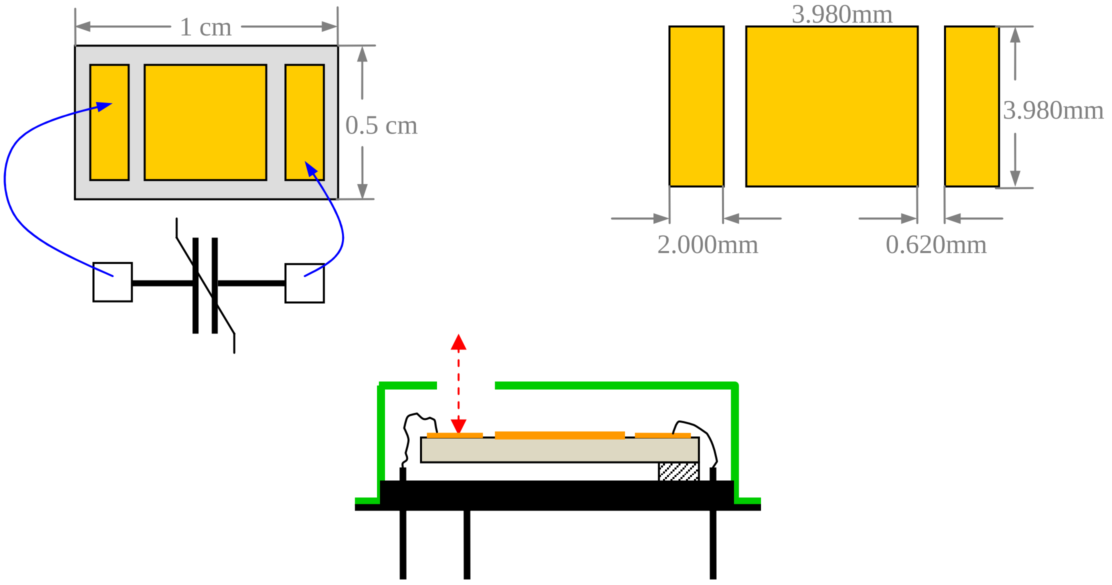


MTI 2100 Test Fixture
Figure 1

For the measurements, I covered the test fixture with a cloth box to minimize disturbances from air currents.

Test Fixture with a Somewhat Beat Up Air Current Shield
Figure 2

Sample Description:
I measured the Cantilever-in-a-Can device, one that is also mentioned in the document about the SISO laser vibrometer, “Butterfly on SIOS Sensor …”. It consists 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 3.



Cross-section of the Cantilever-in-a-Can
Figure 3

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 4. The probe tip of the 2032RX, which must be within 1mm of the sample surface, extends into the access hole of the unit. Note the Bakelite board on which the sample is mounted and how tip of the photonic probe extends into the interior volume of the device package.

Cantilever-in-a-Can on the Test Fixture
Figure 4

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 an MTI Photonic Sensor:
Due to the fact that the MTI Photonic Sensor generates absolute distance data as opposed to differential displacement data, it is less sensitive to parasitic noise than may be a laser vibrometer or an AFM. Nevertheless, there are some parasitics that the user must account for when making measurements with the MTI.

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

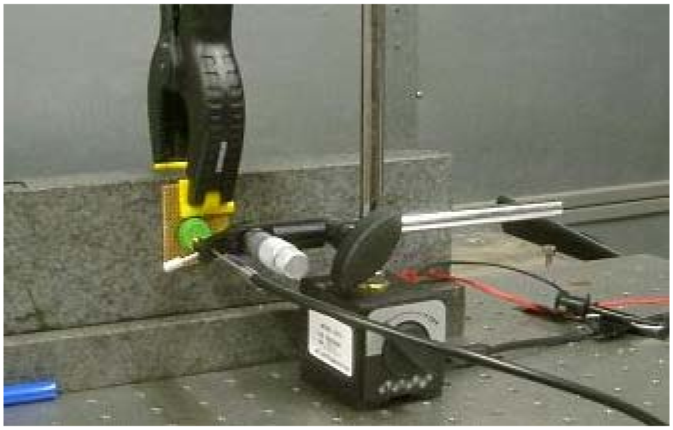
Radiant's testers and displacement sensors have a base-line 60Hz (50Hz) oscillation in their electrical ground which they cannot see or control since their only reference to a solid ground, the earth ground, comes to them over a power cable, otherwise known as an antenna. In fact, many of you no doubt 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.

Mechanical Amplification

The MTI 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.

One source of mechanical amplification unique to the MTI comes from the test fixture supplied by MTI. Examine Figure 5.



MTI Test Fixture
Figure 5

The magnetic stand that holds the photonic probe has metal arms wherein the user can adjust the length and height of the sensor probe from the base of the stand. These arms will act as resonators that collect and amplify any vibration in the foundation of the test fixture. Always make these arms a short as possible to minimize such amplification. Notice in Figure 5 that I have set the horizontal arm and the vertical arm to zero length with good result.

Mechanical Creep

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.

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.

Sensor Acquisition Speed:

The 2032RX measurement module used in this experiment has a frequency response of 100kHz. 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 since the Radiant testers do not filter the analog signals they measure. The MTI can generate a significant amount of high frequency electrical noise that lowers the resolution achievable on a single-pass measurement. Use the Low Pass Filter function available on the front panel of the 2032RX unit. It is preferable to have the LPF filter setting at least 1000 times faster than the period of the measurement. Sometimes, this may not be possible if the displacement being studied is small. For this test, I set the LPF to 100 Hz and executed a 1 Hz test.

Because of the large displacement the sample generated, I probably could have used a higher setting on the LPF without a significant loss of fidelity.

SYNC Control Speed:
The SYNC control is not needed for the MTI sensor products.

Mechanical Vibration:
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 MTI photonic sensor is more than sensitive enough to see this parasitic signal in the measured data. Making very fast measurements in the 2 kHz 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!

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.

Note that the cables connecting the MTI2100 controller and the tester to the test fixture can transmit mechanical noise onto an otherwise perfectly isolated sample holder. The MTI 2100 control unit has a small cooling fan that can generate vibrational noise in the kHz range. In particular, do not place the MTI 2100 control unit on the test fixture platform. Also, make sure to isolate the fiber optic probe cable from the sample in a manner so as to prevent the transfer of this vibration to the sample during measurement.

Environmental Noise:
The MTI 2100 will not have significant sensitivity to air currents in the room because the photonic tip is so close to the sample surface. Nevertheless, this is a parasitic noise source that should be examined to ensure that it can be ignored or shielding should be used to prevent any possibility of air currents from distorting the measurements.

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 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 MTI Photonic Sensor:

The calibration procedures for the MTI 2032RX are described in the documentation provided by MTI. It consists of two stages: 1) calibrate Range 1 of the 2032RX using the standard procedures and 2) switch to Range 2 to adjust the DC bias.

To calibrate Range 1,

1) Position the sensor probe very close to the sample surface and align it as close as possible to be perpendicular to the sample surface.

2) Set the MTI 2100 to the calibration mode on the front panel.

3) Adjust the micrometer that positions the probe tip above the sample surface to maximize the signal strength displayed on the front panel of the MTI 2100.

4) Once the maximum signal is reached, press the “Cal Start” button on the front panel. The unit will then self-calibrate, determining a reference ratio of the transmitted signal to the reflected signal for the maximum distance. When calibrated, the display will show 10 Volts, the saturation level.

5) Once the self-calibration is completed, adjust the micrometer to move the probe tip closer to the surface and reduce the value displayed on the front panel of the MTI. I generally set the display to output the sensor voltage and move the probe tip to reduce the sensor voltage to about 3V.

To calibrate Range 2:

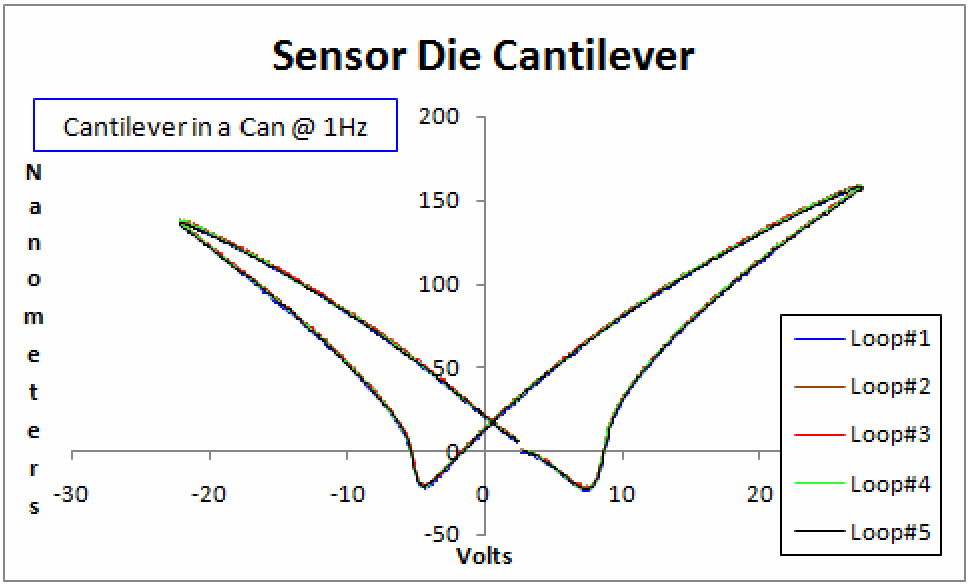
1) Press the selection button on the front panel of the 2032RX to change from Range 1, which you just calibrated, to Range 2.

2) Adjust the DC Bias knob on the front panel of the 2032RX to set the sensor output to 0 volts. It is not necessary to move the probe.

Results:

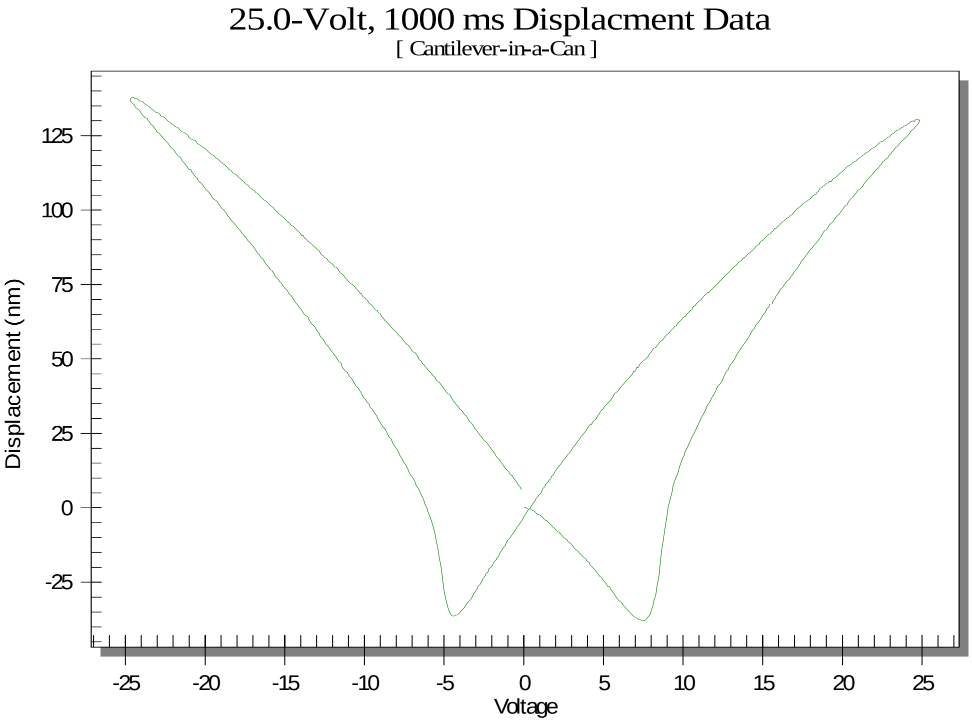
I tested the sample by looping the PIEZO task five times. Inside the loop I used the SENSOR task to pull out the displacement data from the PIEZO task and then used the Loop Averaging Filter to average the five loops. After the looping, I included two PIEZO Filters set to the Accumulate mode to plot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

Figure 6 plots the five zero’d raw data loops measured of the Cantilever-in-a-Can sample. The data was zero’d vertically in the program. You can see that, for the magnitude of the displacement, the measurement is clean and the five loops align closely.



Five Butterfly Loops from the Cantilever-in-a-Can
Figure 6

Below is the averaged value of the five loops in Figure 6. This plot was *not* smoothed since the signal-to-noise ratio is quite high.



Averaged of the Loops in Figure 6 *without* Smoothing
Figure 7

Conclusion

The MTI 2100 Photonic Sensor is an excellent sensor for measuring piezoelectric MEMs displacements. The system balances performance and price. 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 MTI photonic sensor is capable of achieving a noise level of better than 10Å with averaging. Application of a smoothing filter will further reduce the noise level. The 300µ aperture of the MTI will limit its application to larger devices but its high acquisition speed will aid in measuring the dynamic performance of MEMs actuators.