LION
PRECISION

TechNote

LT03-0020 • July, 2006

Capacitive Sensor Operation and Optimization

Contents

Applicable Equipment:

Capacitive displacement measurement systems.

Applications:

All capacitive measurements.

Summary:

This TechNote reviews concepts and theory of capacitive sensing to help in optimizing capacitive sensor performance. It also defines capacitive sensing terms as used throughout Lion Precision literature and manuals.

A Capacitive Measurement System

Capacitive dimensional measurement requires three basic components:

- a probe that uses changes in capacitance to sense changes in distance to the target,
- driver electronics to convert these changes in capacitance into voltage changes,
- a device to indicate and/or record the resulting voltage change.

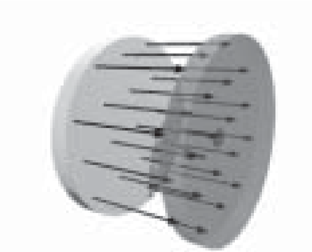
Each of these components is a critical part in providing reliable, accurate measurements. The probe geometry, sensing area size, and mechanical construction effect range, accuracy, and stability. A probe requires a driver to provide the changing electric field that is used to sense the capacitance. The driver electronics are a primary factor in determining the resolution of the system and must be well designed. The voltage measuring device is the final link in the system. Oscilloscopes, voltmeters and data acquisition systems must be properly selected for the application.

The Farad

Capacitance is measured in Farads, named after Michael Faraday who did pioneering experiments in electricity and magnetism in the middle 1800s.

A Farad is a rather large unit. Most capacitors in electronic circuitry are measured in microfarads (μF, 10-6). The capacitance changes sensed by a capacitance gage are around 1 femtofarad (fF, 10-15).

What is Capacitance?



Capacitance effects the electric field between conductors

Capacitance describes how the space between two conductors effects an electric field between them. If two steel plates are placed with a gap between them and a voltage is applied to one of the plates, an electric field will exist between the plates. This electric field is the result of the difference between electric charges that are stored on the surfaces of the plates. Capacitance refers to the “capacity” of the two plates to hold this charge. A large capacitance has the capacity to hold more charge than a small capacitance. The amount of existing charge determines how much current must be used to change the voltage on the plate. It’s like trying to change the water level by one inch in a fifty-five gallon drum compared to a coffee cup. It takes a lot of water to move the level one inch in the drum, but in a coffee cup it takes very little water. The difference is their capacity.

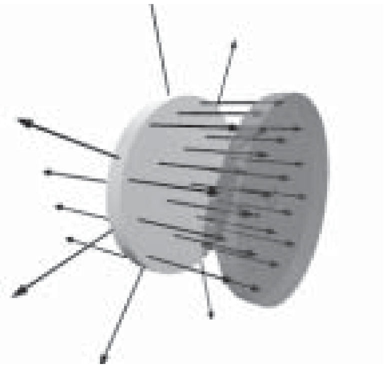
When using a capacitance sensor, the sensor surface is the electrified plate and what you’re measuring (the target) is the other plate (we’ll talk about measuring non-conductive targets later). The sensor electronics continually change the voltage on the sensor surface. This is called the excitation voltage. The amount of current required to make the change is measured by the circuit and indicates the amount of capacitance between the probe and the target.

$$C = \frac{\text{Area x Dielectric}}{\text{Gap}}$$

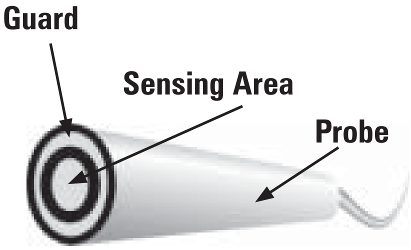
Capacitance is determined by Area, Gap, and Dielectric (the material in the gap). Capacitance increases when Area or Dielectric increase, and capacitance decreases when the Gap increases.

$$C \approx \frac{1}{\text{Gap}}$$

Area and Dielectric are held constant for ordinary capacitive sensing so only the Gap can change the capacitance.



The electric field is not only between the plates but generated from all surfaces of the charged plate.



Probes use a guard to focus the electric field.

How Capacitance Relates to Distance

The capacitance between two plates is determined by three things:

- Size of the plates: capacitance increases as the plate size increases
- Gap Size: capacitance decreases as the gap increases
- Material between the plates (the dielectric): dielectric material will cause the capacitance to increase or decrease depending on the material

In ordinary capacitance sensing the size of the sensor, the size of the target, and the dielectric material (air) remain constant. The only variable is the gap size. Based on this assumption, driver electronics assume that all changes in capacitance are a result of a change in gap size. The electronics are calibrated to output specific voltage changes for corresponding changes in capacitance. These voltages are scaled to represent specific changes in gap size. The amount of voltage change for a given amount of gap change is called the sensitivity. A common sensitivity setting is 1.0V/100µm. That means that for every 100µm change in the gap, the output voltage changes exactly 1.0V. With this calibration, a +2V change in the output means that the target has moved 200µm closer to the probe.

Focusing the Electric Field

When a voltage is applied to a conductor, there is an electric field coming from every surface. For accurate gaging, the electric field from a probe needs to be contained within the space between the probe's sensing area and the target. If the electric field is allowed to spread to other items or other areas on the target then a change in the position of the other item will be measured as a change in the position of the target. To prevent this from happening a technique called guarding is used. To create a guarded probe, the back and sides of the sensing area are surrounded by another conductor that is kept at the same voltage as the sensing area itself. When the excitation voltage is applied to the sensing area, a separate circuit applies the exact same voltage to the guard. Because there is no difference in voltage between the sensing area and the guard, there is no electric field between them. Any other conductors beside or behind the probe form an electric field with the guard instead of the sensing area. Only the unguarded front of the sensing area is allowed to form an electric field to the target.

Effects of Target Size

The target size is a primary consideration when selecting a probe for a specific application. When the sensor's electric field is focused by guarding, it creates a field that is a projection of the sensor size and shape. The minimum target diameter for standard calibration is 30% of the diameter of the sensing area. The further the probe is from the target, the larger the minimum target size.

The sensor's electric field covers an area about 30% larger than the sensing area of the probe.

Range of Measurement

The range in which a probe is useful is a function of the area of the sensor. The greater the area, the larger the range. The driver electronics are designed for a certain amount of capacitance at the sensor. Therefore, a smaller sensor must be considerably closer to the target to achieve the desired amount of capacitance. The electronics are adjustable during calibration but there is a limit to the range of adjustment.

In general, the maximum gap at which a probe is useful is approximately 40% of the sensor diameter. Standard calibrations usually keep the gap considerably less than that.

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Multiple Channel Sensing

Frequently, a target is measured simultaneously by multiple probes. Because the system measures a changing electric field, the excitation voltage for each probe must be synchronized or the probes would interfere with each other. If they were not synchronized, one probe would be trying to increase the electric field while another was trying to decrease it thereby giving a false reading.

Using multiple probes on the same target requires that the excitation voltages be synchronized. This is accomplished by configuring one driver as a master and others as slaves.

Driver electronics can be configured as masters or slaves. The master sets the synchronization for the slaves in multiple channel systems.

Effects of Target Material

The electric field from the probe sensor is seeking a conductive surface. For this reason, capacitance sensors are not effected by the target material provided that it is a conductor. Because the electric field from the sensor stops at the surface of the conductor, target thickness does not effect the measurement.

Capacitive sensors measure all conductors: brass, steel, aluminum, or even salt-water, with equal accuracy.

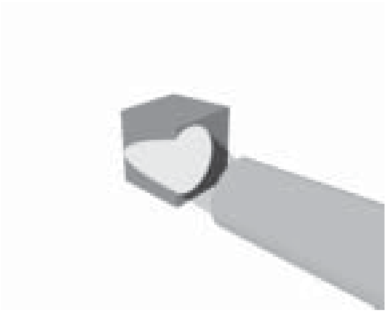
Surface finish can effect the measurement. Capacitance probes will measure the average position of the target surface within the spot size of the sensor.

Non-conductors can be measured by passing the electric field through them to a stationary conductive target behind.

Fringing can be used to measure non-conductive targets without a conductive background target.

Material	Dielectric Constant Relative (ξ_r)
Vacuum	1.0
Air	1.0006
Epoxy	2.5-6.0
PVC	2.8-3.1
Glass	3.7-10.0
Water	80.0

Dielectric constants of common materials



Small targets make measurement accuracy sensitive to small probe post ion errors.

Measuring Non-Conductors

Capacitance probes are most often used to measure the change in position of a conductive target. But capacitance probes can be very effective in measuring presence, density, thickness, and location of non-conductors as well. Non-conductive materials like plastic have a different dielectric constant than air. The dielectric constant determines how a non-conductive material effects capacitance between two conductors. By inserting a non-conductive material in the gap between the probe and a stationary reference target, the capacitance will change in relationship to the thickness, density, or location of the material.

Sometimes it's not feasible to have a reference target in front of the probe. Often, measurements can still be made by a technique called fringing. If there is no conductive surface directly in front of the probe, the sensor's electric field will wrap back to the shell of the probe itself. This is called a fringe field. If a non-conductive material is brought in proximity to the probe, its dielectric will change the fringe field and this can be used to measure the non-conductive material.

Maximizing Accuracy

Now that we've discussed the basics of how capacitance gaging works, we can form some strategies for maximizing effectiveness and minimizing error when capacitance gaging systems are used. Accuracy requires that the measurements be made under the same conditions in which the system was calibrated. Whether it's a system calibrated at the factory, or one that's calibrated during use, repeatable results come from repeatable conditions. If we only want the gap size to change the reading, then all the other variables must be constant. The following sections discuss sources of these errors and how to minimize them.

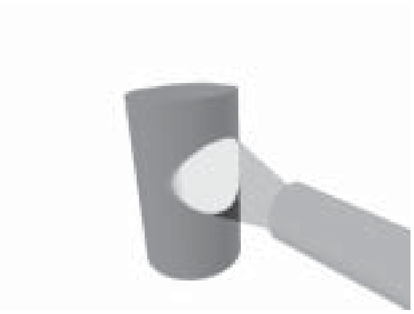
Target Size

Unless otherwise specified, factory calibrations are done with a flat conductive target that is considerably larger than the sensor area. A system calibrated in this way will give accurate results when measuring a flat target more than 30% larger than the sensing area. If the target area is too small, the electric field will begin to wrap around the sides of the target. In this case, the electric field extends farther than it did in calibration and will measure the target as farther away. This means that the probe must be closer to the target for the same zero point. Because this distance differs from the original calibration, error will be introduced. Error is also created because the probe is no longer measuring a flat surface.

An additional problem of an undersized target is that the system becomes sensitive to X and Y location of the probe relative to the target. Without changing the gap, the output will change significantly if the probe is moved up, down, left, or right because less of the electric field is going to the center of the target and more is going around to the sides.

Target Shape

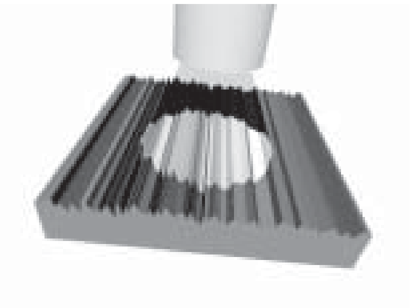
Shape is also a consideration. Since the probes are calibrated to a flat target, measuring a target with a curved surface will cause errors. Because the probe will measure the average distance to the target, the gap at zero volts will be different than when the system was calibrated. Errors will also be introduced because of the different behavior of the electric field with the curved surface. In cases where a non-flat target must be measured, the system can be factory calibrated to the final target shape. Alternatively, when flat calibrations are used with curved surfaces, multipliers can be provided to correct the measurement value.



Curved targets change the shape of the electric field, affecting accuracy.

Surface Finish

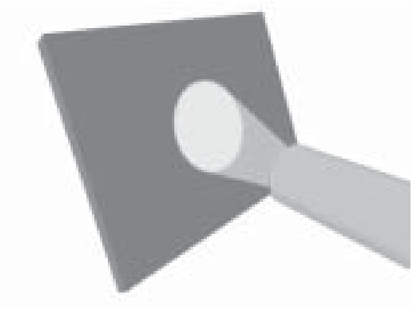
When the target surface is not perfectly smooth, the system will average over the area covered by the spot size of the sensor. The measurement value can change as the probe is moved across the surface due to a change in the average location of the surface. The magnitude of this error depends on the nature and symmetry of the surface irregularities.



Irregular surface finish can cause different measurements as the target moves parallel to the probe.

Parallelism

During calibration the surface of the sensor is parallel to the target surface. If the probe or target is tilted any significant amount, the shape of the spot where the field hits the target elongates and changes the interaction of the field between the probe and target. Because of the different behavior of the electric field, measurement errors will be introduced. Parallelism must be considered when designing a fixture for the measurement.



If the surface of the target is not parallel to the surface of the probe, the elongation of the electric field will introduce errors.

Environment

Lion Precision capacitance systems are compensated to minimize drift due to temperature from 22°C - 35°C (72°F - 95°F). In this temperature range errors are less than 0.5% of full scale.

A more troublesome problem is that virtually all target and fixture materials exhibit a significant expansion and contraction over this temperature range. When this happens, the changes in the measurement are not gage error. They are real changes in the gap between the target and the probe. Careful fixture design goes a long way toward maximizing accuracy.

The dielectric constant of air is affected by humidity. As humidity increases the dielectric increases. Humidity can also interact with probe construction materials. Experimental data shows that changes from 50%RH to 80%RH can cause errors up to 0.5% of full scale.

While Lion Precision probe materials are selected to minimize these errors, in applications requiring utmost precision, control of temperature and humidity is standard practice. International standards specify that measurements shall be done at 20°C or corrected to “true length” at 20°C.

More temperature related errors are due to expansion and contraction of the measurement fixture than probe or electronics drift.

Factory Calibration

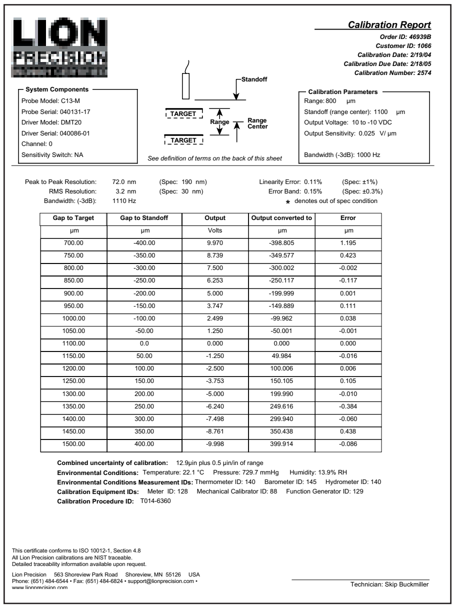
Lion Precision's calibration system was designed in cooperation with Professional Instruments, a world leader in air bearing spindle and slide design. It's state of the art design is driven by precision motion control electronics with positional accuracies of less than 0.012µm uncertainty.

The calibration system is certified on a regular basis with a NIST traceable laser interferometer. The measurement equipment used during calibration (digital meters and signal generators) are also calibrated to NIST traceable standards. The calibration information for each of these pieces of equipment is kept on file for verification of traceability.

Technicians use the calibration system to precisely position a calibration target at known gaps to the probe. The measurements at these points are collected and the sensitivity and linearity are analyzed by the calibration system. The analysis of the data is used to adjust the system being calibrated to meet order specifications.

After sensitivity and linearity are calibrated, the systems are placed in an environmental chamber where the temperature compensation circuitry is calibrated to minimize drift over the temperature range of 22°C to 35°C. Measurements are also taken of bandwidth and output noise which effect resolution.

When calibration is complete, a calibration certificate is generated. This certificate is shipped with the ordered system and archived. Calibration certificates conform to section 4.8 of ISO 10012-1.



Calibration Report

Order ID: 46939B
Customer ID: 1066
Calibration Date: 2/19/04
Calibration Due Date: 2/18/05
Calibration Number: 2574

System Components

Probe Model: C13-M
Probe Serial: 040131-17
Driver Model: DMT20
Driver Serial: 040086-01
Channel: 0
Sensitivity Switch: NA

See definition of terms on the back of this sheet

Calibration Parameters

Range: 800 µm
Standoff (range center): 1100 µm
Output Voltage: 10 to -10 VDC
Output Sensitivity: 0.025 V/ µm

Bandwidth (-3dB): 1000 Hz

Peak to Peak Resolution: 72.0 nm (Spec: 190 nm)
RMS Resolution: 3.2 nm (Spec: 30 nm)
Bandwidth: (-3dB): 1110 Hz

Linearity Error: 0.11% (Spec: ±1%)
Error Band: 0.15% (Spec: ±0.3%)
* denotes out of spec condition

Gap to Target	Gap to Standoff	Output	Output converted to	Error
µm	µm	Volts	µm	µm
700.00	-400.00	9.970	-398.805	1.195
750.00	-350.00	8.739	-349.577	0.423
800.00	-300.00	7.500	-300.002	-0.002
850.00	-250.00	6.253	-250.117	-0.117
900.00	-200.00	5.000	-199.999	0.001
950.00	-150.00	3.747	-149.889	0.111
1000.00	-100.00	2.499	-99.962	0.038
1050.00	-50.00	1.250	-50.001	-0.001
1100.00	0.0	0.000	0.000	0.000
1150.00	50.00	-1.250	49.984	-0.016
1200.00	100.00	-2.500	100.006	0.006
1250.00	150.00	-3.753	150.105	0.105
1300.00	200.00	-5.000	199.990	-0.010
1350.00	250.00	-6.240	249.616	-0.384
1400.00	300.00	-7.498	299.940	-0.060
1450.00	350.00	-8.761	350.438	0.438
1500.00	400.00	-9.998	399.914	-0.086

Combined uncertainty of calibration: 12.9µin plus 0.5 µin/in of range
Environmental Conditions: Temperature: 22.1 °C Pressure: 729.7 mmHg Humidity: 13.9% RH
Environmental Conditions Measurement IDs: Thermometer ID: 140 Barometer ID: 145 Hydrometer ID: 140
Calibration Equipment IDs: Meter ID: 128 Mechanical Calibrator ID: 88 Function Generator ID: 129
Calibration Procedure ID: T014-6360

This certificate conforms to ISO 10012-1, Section 4.8
All Lion Precision calibrations are NIST traceable.
Detailed traceability information available upon request.

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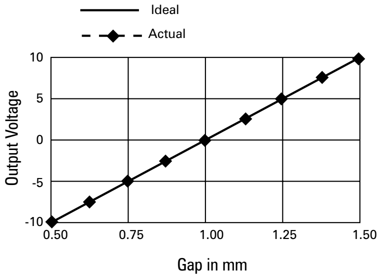
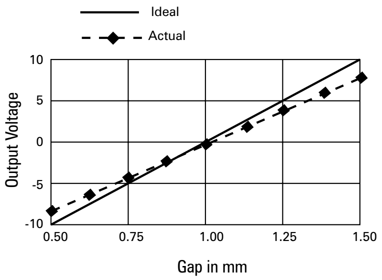
Technician: Skip Buckmiller

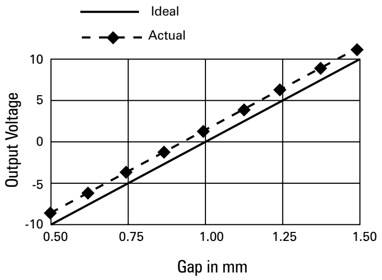
NIST traceable calibration certificate



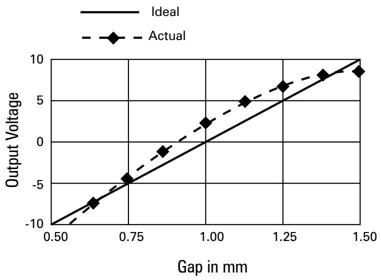
Sensitivity - The slope of the line is the sensitivity; in this case 1V/0.05mm.



Sensitivity Error - The slope of the actual measurements deviates from the ideal slope.



Offset Error - A constant value is added to all measurements.



Linearity Error - Measurement data is not on a straight line.

Definitions

Sensitivity

Sensitivity indicates how much the output voltage changes as a result of a change in the gap between the target and the probe. A common sensitivity is 1V/0.1mm. This means that for every 0.1mm of change in the gap, the output voltage will change 1V. When the output voltage is plotted against the gap size, the slope of the line is the sensitivity.

Sensitivity Error

A system's sensitivity is set during calibration. When sensitivity deviates from the ideal value this is called sensitivity error, gain error, or scaling error. Since sensitivity is the slope of a line, sensitivity error is usually presented as a percentage of slope; comparing the ideal slope with the actual slope.

Offset Error

Offset error occurs when a constant value is added to the output voltage of the system. Capacitance gaging systems are usually "zeroed" during setup, eliminating any offset deviations from the original calibration. However, should the offset error change after the system is zeroed, error will be introduced into the measurement. Temperature change is the primary factor in offset error. Lion Precision systems are compensated for temperature related offset errors to keep them less than 0.04%F.S./°C.

Linearity Error

Sensitivity can vary slightly between any two points of data. This variation is called linearity error. The linearity specification is the measurement of how far the output varies from a straight line.

To calculate the linearity error, calibration data is compared to the straight line that would best fit the points. This straight reference line is calculated from the calibration data using a technique called least squares fitting. The amount of error at the point on the calibration line that is furthest away from this ideal line is the linearity error. Linearity error is usually expressed in terms of percent of full scale. If the error at the worst point was 0.001mm and the full scale range of the calibration was 1mm, the linearity error would be 0.1%.

Note that linearity error does not account for errors in sensitivity. It is only a measure of the straightness of the line and not the slope of the line. A system with gross sensitivity errors can be very linear.

Error Band

Error band accounts for the combination of linearity and sensitivity errors. It is the measurement of the worst case absolute error in the calibrated range. The total error is calculated by comparing the output voltages at specific gaps to their expected value. The worst case error from this comparison is listed as the system's total error.

Gap (mm)	Expected Value (VDC)	Actual Value (VDC)	Error Band (mm)
0.50	-10.000	-9.800	**-0.010**
0.75	-5.000	-4.900	-0.005
1.00	0.000	0.000	0.000
1.25	5.000	5.000	0.000
1.50	10.000	10.100	0.005

Error Band - the worst case deviation of the measured values from the expected values in a calibration chart. In this case, the total error is -0.010mm.

Bandwidth

Bandwidth is defined as the frequency at which the output falls to -3dB. This frequency is also called the cutoff frequency. A -3dB drop in the signal level equates to approximately 70% drop in actual output voltage. With a 15kHz bandwidth, a change of ±1V at low frequency will only produce a ±0.7V change at 15kHz.

Excitation frequency of the driver electronics is a major factor in determining bandwidth. A meaningful change in output voltage requires several cycles of the changing electric field in the gap. Lion Precision uses an excitation frequency of 1MHz compared to a more typical 10kHz-15kHz. This higher excitation frequency gives Lion Precision a standard bandwidth of 15kHz compared to an industry average of less than 5kHz. Bandwidth is also affected by the geometry of the probe. Bandwidth tends to drop as the probe size decreases.

Fast responding outputs maximize phase margin when used in servo-control feedback systems. Some drivers provide selectable bandwidth for maximizing resolution or response time.

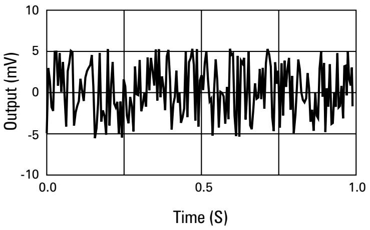
> Fast responding outputs maximize phase margin when used in servo-control feedback systems.

Resolution

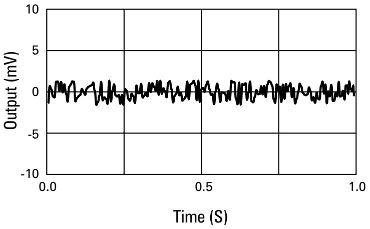
Resolution is defined as the smallest reliable measurement that a system can make. The resolution of a measurement system must be better than the final accuracy the measurement requires. If you need to know a measurement to within 0.02μm, then the resolution of the measurement system must be better than 0.02μm.

The primary determining factor of resolution is electrical noise. Electrical noise appears in the output voltage causing small instantaneous errors in the output. Even when the probe/target gap is perfectly constant, the output voltage of the driver has some small but measurable amount of noise that would seem to indicate that the gap is changing. This noise is inherent in electronic components and can only be minimized, but never eliminated.

If a driver has an output noise of 0.002V with a sensitivity of 10V/1mm, then it has an output noise of 0.000,2mm (0.2μm). This means that at any instant in time, the output could have an error of 0.2μm.



Full Bandwidth Output Noise - typical output noise from a system with 15kHz bandwidth. The peak to peak noise during the one second sample period is 0.010V. With sensitivity of 10V/1mm the peak to peak resolution is 1.0μm.



100Hz Filtered Output Noise - typical output noise from a system with 100Hz bandwidth. The peak to peak noise during the one second sample period is 0.002V. With sensitivity of 10V/1mm the peak to peak resolution is 0.2μm; a 500% improvement over the 15kHz resolution.

The amount of noise in the output is directly related to bandwidth. Generally speaking, noise is distributed uniformly over a wide range of frequencies. If the higher frequencies are filtered before the output, the result is less noise and better resolution. When examining resolution specifications it's critical to know at what bandwidth the measurements were taken.

Resolution Calculation

Resolution as indicated in this catalog is calculated by measuring and recording the output noise over a period of one second with a digital oscilloscope sampling at 100kHz. The maximum peak to peak value during this time is defined as the peak to peak resolution. This same sampling of measurements is used to calculate the RMS value for the RMS resolution.

Test methods to determine resolution vary. This makes resolution and noise difficult to compare with numbers only. In applications where these values are critical, we recommend that systems be evaluated in the application. This is the best way to accurately determine whether or not system performance is sufficient.