LION PRECISION

TechNote

LT03-0020 • February, 2009

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.

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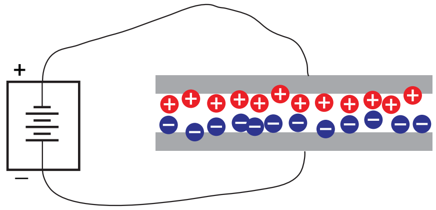


Figure 1

Applying a voltage to conductive objects causes positive and negative charges to collect on each object. This creates an electric field in the space between the objects.

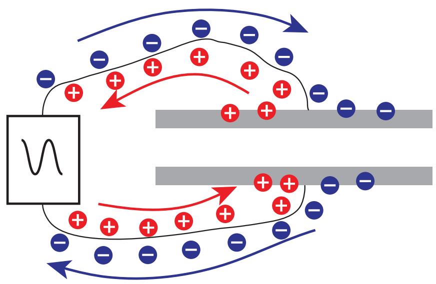


Figure 2

Applying an alternating voltage causes the charges to move back and forth between the objects, creating an alternating current which is detected by the sensor.

$$\frac{\text{Area x Dielectric}}{\text{Distance}}$$

Figure 3

Capacitance is determined by Area, Distance, and Dielectric (the material between the conductors). Capacitance increases when Area or Dielectric increase, and capacitance decreases when the Distance increases.

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 capacitive sensor are around 1 femtofarad (fF, 10^{-15}).

Capacitance and Distance

Noncontact capacitive sensors work by measuring changes in an electrical property called capacitance. Capacitance describes how two conductive objects with a space between them respond to a voltage difference applied to them. When a voltage is applied to the conductors, an electric field is created between them causing positive and negative charges to collect on each object (Fig. 1). If the polarity of the voltage is reversed, the charges will also reverse.

Capacitive sensors use an alternating voltage which causes the charges to continually reverse their positions. The moving of the charges creates an alternating electric current which is detected by the sensor (Fig. 2). The amount of current flow is determined by the capacitance, and the capacitance is determined by the area and proximity of the conductive objects. Larger and closer objects cause greater current than smaller and more distant objects. The capacitance is also affected by the type of nonconductive material in the gap between the objects.

Technically speaking, the capacitance is directly propotional to the surface area of the objects and the dielectric constant of the material between them, and inversely proportional to the distance between them (Fig. 3).

In typical capacitive sensing applications, the probe or sensor is one of the conductive objects; the target object is the other. (Using capacitive sensors to sense plastics and other insulators is discussed in the nonconductive targets section.) The sizes of the sensor and the target are assumed to be constant as is the material between them. Therefore, any change in capacitance is a result of a change in the distance between the probe and the target. The electronics are calibrated to generate specific voltage changes for corresponding changes in capacitance. These voltages are scaled to represent specific changes in distance. The amount of voltage change for a given amount of distance change is called the sensitivity. A common sensitivity setting is 1.0V/100µm. That means that for every 100µm change in distance, 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.

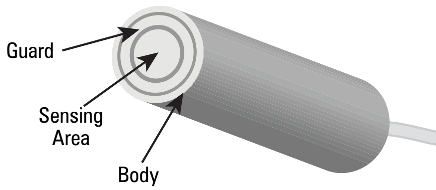


Figure 4

Capacitive sensor probe components

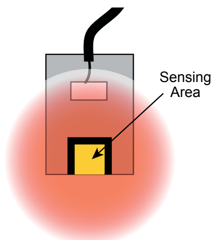


Figure 5

Cutaway view showing an unguarded sensing area electric field

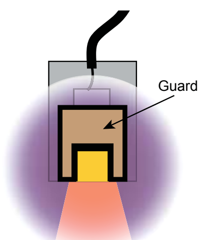


Figure 6

Cutaway showing the guard field shaping the sensing area electric field

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

> 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.

> 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.

Focusing the Electric Field

When a voltage is applied to a conductor, the electric field eminates from every surface. In a capacitive sensor, the sensing voltage is applied to the Sensing Area of the probe (Figs. 4, 5). For accurate measurements, the electric field from the sensing area needs to be contained within the space between the probe 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. A technique called "guarding is used to prevent this from happening. To create a guard, 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 (Fig. 4, 6). When the 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 with the target.

Effects of Target Size

The target size is a primary consideration when selecting a probe for a specific application. When the sensing electric field is focused by guarding, it creates a slightly conical field that is a projection of the sensing area. 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.

Range of Measurement

The range in which a probe is useful is a function of the size of the sensing area. The greater the area, the larger the range. The driver electronics are designed for a certain amount of capacitance at the probe. Therefore, a smaller probe 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 sensing area diameter. Standard calibrations usually keep the gap considerably less than that.

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.

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 sensing electric field is seeking a conductive surface. Provided that the target is a conductor, capacitive sensors are not aeffected by the specific target material. Because the sensing electric field stops at the surface of the conductor, target thickness does not affect the measurement.

Capacitive sensors measure all conductors: brass, steel, aluminum, or even salt-water, as the same.

Measuring Non-Conductors

Capacitive sensors are most often used to measure the change in position of a conductive target. But capacitive sensors 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 affects capacitance between two conductors. When a non-conductor is inserted between the probe and a stationary reference target, the sensing field passes through the material to the grounded target (Fig. 7). The preseence of the non-conductive material changes the dielectric and therefore changes the capacitance. The capacitance will change in relationship to the thickness or density of the material.

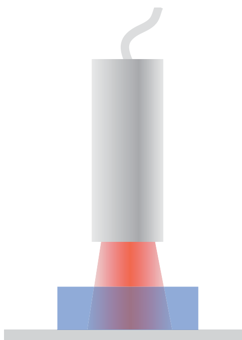


Figure 7

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

It is not always 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 reference directly in front of the probe, the sensing electric field will wrap back to the body 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; this can be used to sense the non-conductive material.

Figure 8

Without a conductive target behind, a fringe field can form through a nearby non-conductor allowing the non-conductor to be sensed

The sensitivity of the sensor to the non-conductive target is directly proportional to the dielectric constant of the material. The table below lists the dielectric constant of some common non-conductive materials.

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

Maximizing Accuracy

Now that we've discussed the basics of how capacitive sensing works, we can form strategies for maximizing effectiveness and minimizing error when capacitive sensors are used. Accuracy requires that the measurements be made under the same conditions in which the sensor was calibrated. Whether it's a sensor calibrated at the factory, or one that is calibrated during use, repeatable results come from repeatable conditions. If we only want distance to affect the measurment, then all the other variables must be constant. The following sections discuss common error sources and how to minimize them.

Figure 9

An undersized target causes the sensing field to extend to the sides of the target, introducing error

Target Size

Unless otherwise specified, factory calibrations are done with a flat conductive target that is considerably larger than the sensing area. A sensor 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 meaning the electric field extends farther than it did in calibration and will measure the target as farther away (Fig. 9). In this case, 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.

If the distance between the probe and the target is considered the Z axis, then an additional problem of an undersized target is that the sensor becomes sensitive to X and Y location of the probe. Without changing the gap, the output will change significantly if the probe is moved in either the X or Y axis because less of the electric field is going to the center of the target and more is going around to the sides.

Figure 10

A curved target will require that the probe be closer and the sensitivity will be affected

Target Shape

Shape is also a consideration. Because the probes are calibrated to a flat target, measuring a target with a curved surface will cause errors (Fig. 10). 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.

Figure 11

Rough surfaces will tend to average but can give different results at different locations on the target, especially with very small probes

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 (Fig. 11). 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.

Parallelism

Figure 12
Lack of parallelism will introduce errors

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 with the target (Fig. 12). Because of the different behavior of the electric field, measurement errors will be introduced. At very high resolutions, even a few degrees can introduce error. Parallelism must be considered when designing a fixture for the measurement.

Environment

Lion Precision capacitive sensors 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.

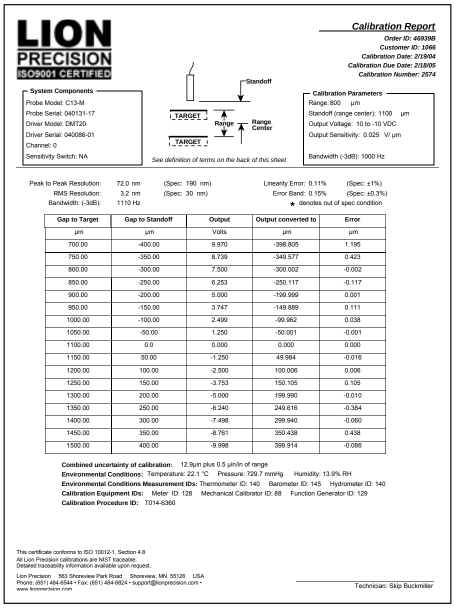
> More temperature related errors are due to expansion and contraction of the measurement fixture than probe or electronics drift.

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 gauge 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.

Factory Calibration



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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

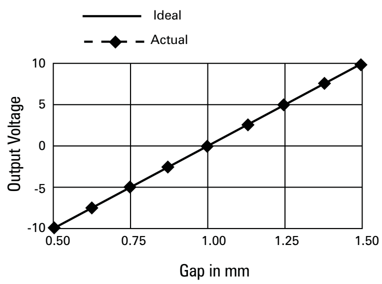
Lion Precision's calibration system was designed in cooperation with Professional Instruments, a world leader in air bearing spindle and slide design. Its state of the art design is driven by precision motion control electronics with positional accuracies of less than 0.012µm uncertainty.

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.

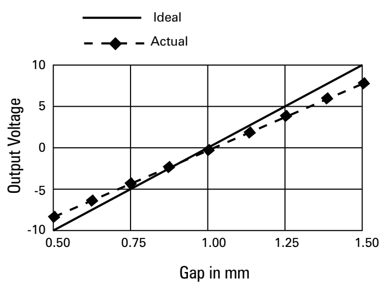
Technicians use the calibration system to precisely position a calibration target at known gaps to the probe. The measurements at these points are collected and the sensitivity and linearity are analyzed by the calibration system. The analysis of the data is used to adjust the system being calibrated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

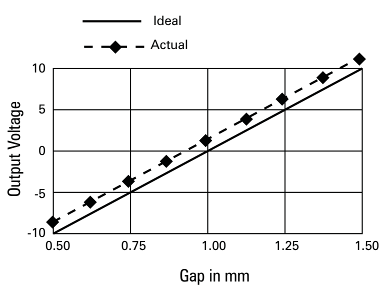
When calibration is complete, a calibration certificate is generated. This certificate is shipped with the ordered system and archived. Calibration certificates conform to section 4.8 of ISO 10012-1.



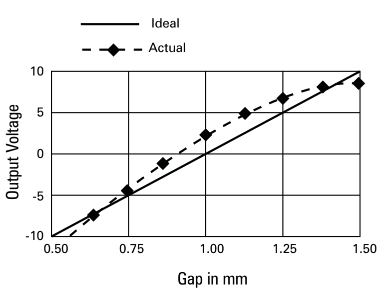
Sensitivity - The slope of the line is the sensitivity; in this case 1V/0.05mm.



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. Capacitive gauging 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. The accumulated effect of 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.

Gap (mm)	Expected Value (VDC)	Actual Value (VDC)	Error (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

Figure 13

Error band is the worst case error in the calibrated range. In this case, the Error Band is ±0.01.

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

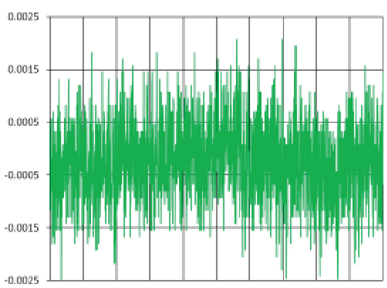


Figure 14

Noise from a 15kHz sensor

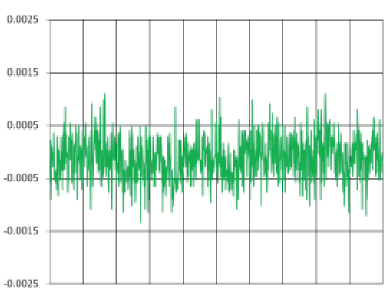


Figure 15

Noise from a 100Hz sensor

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 error band 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 error band (Fig. 13).

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.

In addition to sensing high-frequency motion, fast responding outputs maximize phase margin when used in servo-control feedback systems. Some drivers provide selectable bandwidth for maximizing either resolution or response time.

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 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.

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 (Figs. 14, 15). When examining resolution specifications, it is critical to know at what bandwidth the specifications apply.