Comparing Capacitive and Inductive Sensors

Last update: 2021-04-22

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1 Introduction

Non-contact sensors using capacitive and inductive technologies each represent a unique blend of advantages and disadvantages for a variety of applications. This comparison of the two technologies' strengths will help you select the best technology for your application.

2 Comparison table

A quick reference with details below.

•• Best Choice, • Functional Choice, – Not an option

Factor	Capacitive	Inductive
Dirty Environments	–	••
Small Targets	••	•
Large Range	•	••
Thin Materials	••	•
Material Versatility	••	•
Multiple Probes	••	•
Probe Mounting Ease	••	•
Resolution	••	•
Bandwidth	•	••
Cost	•	••

3 Sensor construction

Understanding the difference between capacitive and inductive sensors begins by looking at how they are constructed. At the centre of a capacitive probe is the sensing element. This piece of stainless steel generates the electric field which is used to sense the distance to the target. Separated from the sensing element by an insulating layer is the guard ring, also made of stainless steel. The guard ring surrounds the sensing element and focuses the electric field toward the target. A few electronic components are connected to the sensing element and guard ring. All of these internal assemblies are surrounded by an insulating layer and encased in a stainless-steel housing. The housing is connected to the grounded shield of the cable (Figure 1).

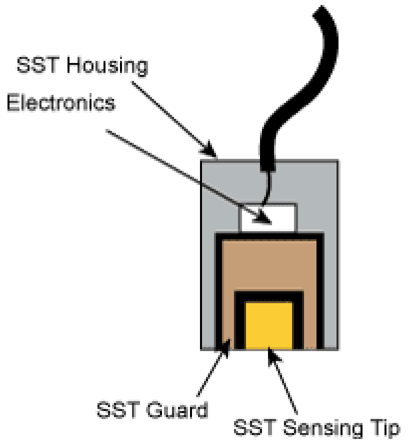

Figure 1 Capacitive Probe Construction

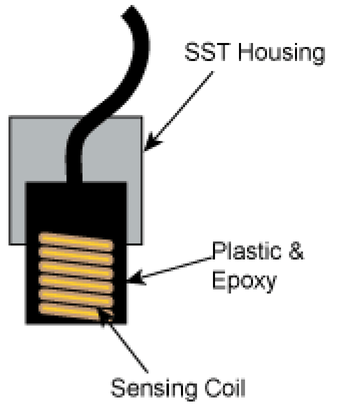

Figure 2 Inductive Probe Construction

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The primary functional piece of an inductive probe is the sensing coil. This is a coil of wire near the end of the probe. Alternating current is passed through the coil which creates an alternating magnetic field; this field is used to sense the distance to the target. The coil is encapsulated in plastic and epoxy and installed in a stainless-steel housing. Because the magnetic field of an inductive sensor is not as easily focused as the electric field of a capacitive sensor, the epoxy covered coil extends from the steel housing to allow the full sensing field to engage the target (Figure 2)

4 Spot Size, Target Size, and Range

The sensing field of a non-contact sensor's probe engages the target over a certain area. The size of this area is called the spot size. The target must be larger than the spot size or special calibration will be required. Spot size is always proportional to the diameter of the probe. The ratio between probe diameter and spot size is significantly different for capacitive and inductive sensors. These different spot sizes result in different minimum target sizes.

Capacitive sensors use an electric field for sensing. This field is focused by a guard ring on the probe resulting in a spot size about 30% larger than the sensing element diameter (Figure 3). A typical ratio of sensing range to the sensing element diameter is 1:8. This means that for every unit of range, the sensing element diameter must be eight times larger. For example, a sensing range of 500µm requires a sensing element diameter of 4000µm (4mm). This ratio is for typical calibrations. High resolution and extended range calibrations will alter this ratio.

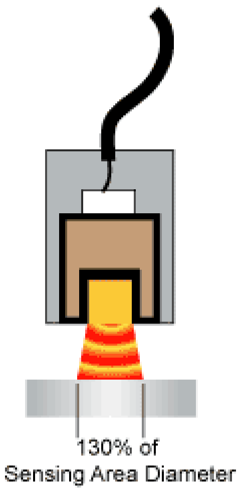

Figure 3 Capacitive probe spot size

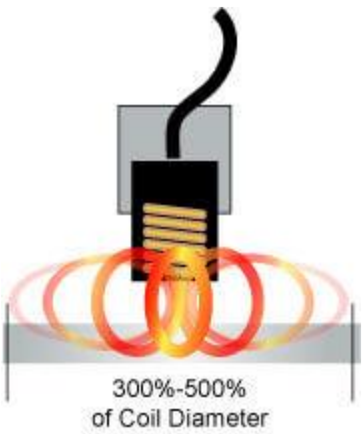

Figure 4 Inductive probe spot size

Inductive sensors use magnetic fields that completely surround the end of the probe. This creates a comparatively large sensing field resulting in a spot size approximately three times the probe's sensing coil diameter (Figure 4). For inductive sensors, the ratio of the sensing range to the sensing coil diameter is 1:3. This means that for every unit of range, the coil diameter must be three times larger. In this case, the same 500µm sensing range only requires a 1500µm (1.5mm) diameter inductive sensor.

When selecting a sensing technology, consider target size. Smaller targets may require capacitive sensing. If your target must be smaller than the sensor's spot size, special calibration may be able to compensate for the inherent measurement errors.

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5 Sensing Technique

Capacitive and inductive sensors use different techniques to determine the position of the target. Capacitive sensors used for precision displacement measurement use a high-frequency electric field, usually between 500 kHz and 1 MHz. The electric field is emitted from the surfaces of the sensing element. To focus the sensing field on the target, a guard ring creates a separate but identical electric field which isolates the sensing element's field from everything but the target (Figure 5).

The amount of current flow in the electric field is determined in part by the capacitance between the sensing element and the target surface. Because the target and sensing element sizes are constant, the capacitance is determined by the distance between the probe and the target, assuming the material in the gap does not change. Changes in the distance between the probe and the target change the capacitance which in turn changes the current flow in the sensing element. The sensor electronics produce a calibrated output voltage which is proportional to the magnitude of this current flow, resulting in an indication of the target position.

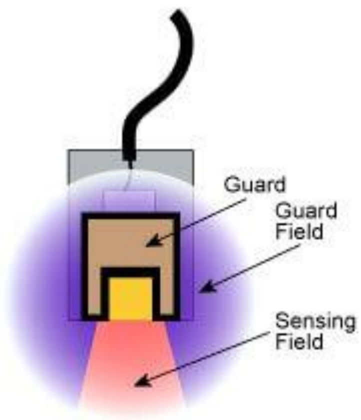

Figure 5 Capacitive probe guarding

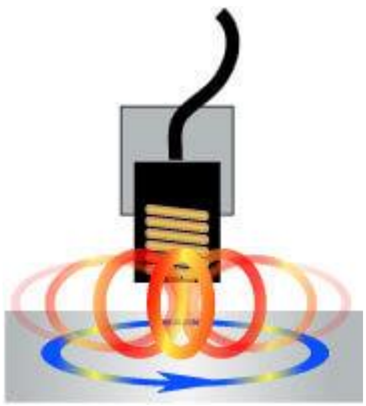

Figure 6 Magnetic field induces eddy current in conductive target

Rather than electric fields, inductive sensors use magnetic fields to sense the distance to the target. Sensing begins by passing alternating current through the sensing coil. This creates an alternating magnetic field around the coil. When this alternating magnetic field interacts with the conductive target, it induces a current in the target material called an eddy current. This eddy current produces its own magnetic field which oppose the sensing coil's field (Figure 6).

As the eddy currents in the target oppose the sensing field, the impedance of the sensing coil will change. The amount of impedance change is dependent on the distance between the target and the sensing coil in the probe. Current flow in the sensing coil, which is impedance dependent, is processed to create the output voltage which is an indication of the position of the target relative to the probe.

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6 Error Sources

Inductive sensors use changes in a magnetic field to determine the distance to the target; capacitive sensors use changes in capacitance. There are factors other than the distance to the target that can also change a magnetic field or capacitance. These factors represent potential error sources in your application. Fortunately, in most cases these error sources are different for the two technologies. Understanding the presence and magnitude of these error sources in your application will help you choose the best sensing technology.

The remainder of this article will explain these error sources so that you can make the best choice for your application and get the best possible results.

7 Gap Contamination

In some applications, the gap between the sensor and target can become contaminated by dust, liquids such as coolant, and other materials which are not part of the intended measurement. How the sensor reacts to the presence of these contaminants is a critical factor in choosing capacitive or inductive sensors.

Capacitive sensors assume that changes in capacitance between the sensor and the target are a result of a change in distance between them. Another factor that affects capacitance is the dielectric constant (ε) of the material in the gap between the target and sensor. The dielectric constant of air is slightly greater than one; if another material, with a different dielectric constant, enters the sensor/target gap, the capacitance will increase, and the sensor will erroneously indicate that the target has moved closer to the sensor (Figure 7). The higher the dielectric constant of the contaminant, the greater the effect on the sensor. Oil has a dielectric constant between 8 and 12. Water has a very high dielectric constant of 80.

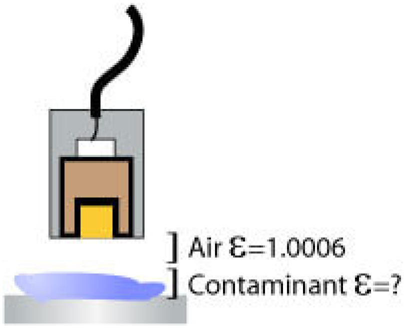

Figure 7 Gap contamination

Because of the sensitivity to the dielectric constant of the material between the sensor and the target, capacitive displacement sensors must be used in a clean environment when measuring target position.

The dielectric sensitivity of capacitive sensors can be exploited for use in sensing the thickness or density of non-conductive materials.

Unlike capacitive sensors, inductive sensors use magnetic fields for sensing. Magnetic fields are not affected by non-conductive contaminants such as dust, water, and oil. As these contaminants enter the sensing area between an inductive sensor and the target, the sensor's output is not affected.

For this reason, an inductive sensor is the best choice when the application involves a dirty or hostile environment. Lion Precision inductive probes are rated at IP67 and can even be used completely immersed in non-corrosive liquid.

8 Target Materials and Rotating Targets

Capacitive and inductive sensors respond differently to differences in target material. The magnetic field of an inductive sensor penetrates the target and induces an eddy current in the material which creates a magnetic field that opposes the field from the probe. The strength of the eddy current and the resulting magnetic field depend on the permeability and resistivity of the material. These properties vary between different materials. They can also be changed by different processing techniques such as heat treating or annealing. For example, two otherwise identical pieces of aluminium that were processed differently may have different magnetic properties. Between different non-magnetic materials such as aluminium and titanium the variance of permeability and resistivity can be small, but a high-performance inductive sensor calibrated for one non-magnetic material will still produce errors when used with a different non-magnetic material.

The differences between non-magnetic materials like aluminium and titanium and magnetic materials such as iron or steel are enormous. While the relative permeability of aluminium and titanium are approximately one, the relative permeability of iron can be as high as 10,000.

Inductive sensors calibrated for non-magnetic materials are not likely to function at all when used with magnetic materials. When using inductive sensors for precise measurements, it is critical that the sensor be calibrated for the specific material used in the application.

The high permeability of magnetic materials such as iron and steel can also cause small inductive sensor errors within the same piece of material. Within any imperfect material, there are microscopic cracks and material variations. The material's permeability changes slightly around these areas. While the changes are relatively small, the extremely high permeability of magnetic materials enables high-resolution inductive sensors to detect these changes. This problem is most evident in rotating targets of magnetic materials.

An inductive sensor can be mounted to measure the runout of a rotating shaft. But even if the shaft is ideal, with absolutely no runout, a high-resolution inductive sensor will detect a repeatable pattern of changes as the shaft rotates (Figure 8). These changes are a result of small variations in the material. This phenomenon is well known and is called electrical runout. These errors can be small, often in the micron range. Many shaft runout applications, especially those in hostile environments where inductive sensors are the norm, are looking for much larger errors and can therefore tolerate these errors. Other more precise applications will need to use techniques to address these errors or use a different sensing technology such as capacitive sensors.

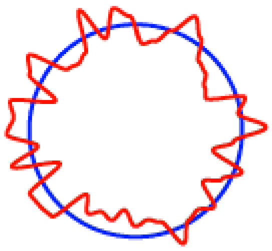

Figure 8 Runout plot showing actual runout in blue, and electrical runout from inductive sensor in red.

The electric field of a capacitive sensor uses the target as a conductive path to ground. All conductive materials offer this equally well, so capacitive sensors measure all conductive materials the same. Once a capacitive sensor is calibrated, it can be used with any conductive target with no degradation in performance.

Because the electric field of a capacitive sensor does not penetrate the material, variations within the material do not affect the measurement. Capacitive sensors do not exhibit the electrical runout phenomenon of inductive sensors and can be used with rotating targets of any conductive material without additional error.

Inductive sensors should be calibrated to the same material as the target in the application and should not be used with rotating magnetic material targets unless the electrical runout errors are acceptable in the application.

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Capacitive sensors, once calibrated, can be used with any conductive material with no material related errors, and they work well with rotating targets.

9 Environmental Parameters: Temperature and Vacuum

Because of differences in the sensing physics and the associated differences in driver electronics, capacitive and inductive sensors have different probe operating temperature ranges and vacuum compatibility.

Lion Precision capacitive and inductive probes have different operating temperature ranges. Inductive probes, because of their tolerance of hostile environments have a greater temperature range. Standard inductive probes, which use polyurethane cables, have an operating range from -25 to +125°C. High temperature probes, which use Teflon FEP cables, have an operating range of -25 to +200°C. Capacitive probes, which are affected by condensation, only have an operating range of +4 to +50 °C. The driver electronics for both sensing technologies have an operating range of +4 to +50°C.

Capacitive and inductive probes can both be used in vacuum applications. Materials in the probes are selected for structural stability and minimized outgassing under vacuum. Vacuum compatible probes are subjected to an extra cleaning process and special packaging to remove foreign materials that may threaten a delicate vacuum environment.

Many vacuum applications require precise temperature control. The probe's power consumption, with its associated contribution to temperature change, is where capacitive and inductive technologies differ. A capacitive probe has extremely small current flow and power consumption. A typical capacitive probe consumes less than 40µW of power, contributing little heat to the vacuum chamber.

The power consumption in an inductive probe can vary from 40µW to as high as 1mW. At these higher powers, the inductive probe will contribute more heat to the vacuum chamber and could disturb high-precision vacuum environments. The power consumption in an inductive probe is dependent on many factors; probe size alone is not a good predictor of power consumption. Each inductive sensor's power consumption must be assessed individually.

Either capacitive or inductive sensors can work well in vacuum environments. In temperature sensitive vacuums, inductive sensors may contribute too much heat for the application. In these applications, capacitive sensors will be a better choice.

10 Probe Mounting

Because of differences in the shape and reactive nature of the sensing fields of capacitive and inductive sensors, the technologies have different probe mounting requirements. Inductive probes produce comparatively large magnetic fields. The field diameter is at least three times larger than the probe diameter and greater than three diameters for large probes. If multiple probes are mounted close together, the magnetic fields will interact (Figure 9). This interaction will create errors in the sensor outputs. If this type of mounting is unavoidable, sensors based on digital technology such as the ECL202 can be specially calibrated to reduce or eliminate the interference from adjacent probes.

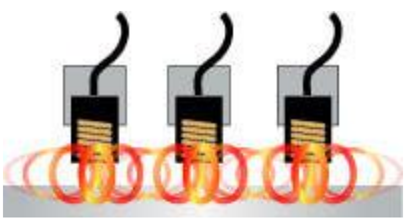

Figure 9 Interference occurs when inductive probes are mounted near each other.

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The magnetic field from an inductive probe also extends about one and a half diameters behind the probe. Any metallic objects in this area, usually mounting hardware, will interact with the field and affect the sensor output (Figure 10). If nearby mounting hardware is unavoidable, sensors can be calibrated with the mounting hardware in place which will compensate for the effect of the hardware.

The electric fields of capacitive probes are only emitted from the front surface of the probe. The field has a slightly conical shape resulting in a spot size about 30% larger than the sensing area diameter. Nearby mounting hardware or other objects are rarely in the field area and therefore do not affect the sensor's calibration. When multiple, independent capacitive sensors are used with the same target, the electric field from one probe may be trying to add charge to the target, while another sensor is trying to remove charge (Figure 11).

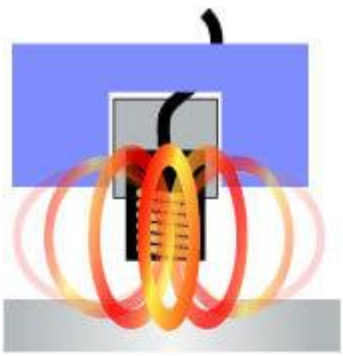

Figure 10 Mounting hardware can interfere with inductive probe magnetic field.

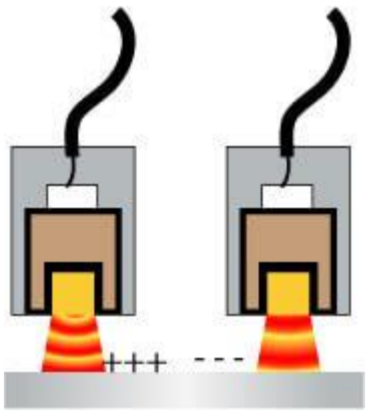

Figure 11 Non-synchronized capacitive sensors will interfere when used on the same target.

This conflicting interaction with the target will create errors in the sensors' outputs. This problem is easily solved by synchronizing the sensors. Synchronization sets the drive signal of all sensors to the same phase so that all probes are adding or removing charge simultaneously and the interference is eliminated. All Lion Precision multiple channel systems are synchronized, eliminating any concern about this error source.

When an application requires the use of multiple probes with a common target, synchronized capacitive sensors are easy to use. If the application requires inductive technology, special care must be taken in the mounting plan and special calibration may be required.

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11 Summary

There are many factors to consider when choosing between capacitive and inductive displacement sensors. Any application that involves measurement area contaminants such as liquids or waste material requires inductive sensing. Capacitive sensors require a clean environment.

Small targets will be more easily measured with capacitive sensors because of the comparatively small size of the capacitive sensing field. When inductive sensing is required, special calibration can be used with small targets.

For the same size capacitive or inductive probe, the inductive probe will have a larger measurement range.

Because capacitive probes interact with the surface of the target, the material thickness is not a factor in capacitive measurements. Inductive sensors have minimum target thickness requirements.

Capacitive sensors have no sensitivity to the target material provided it is conductive. Inductive sensors are sensitive to material differences and must be calibrated to the application's target material.

When using multiple probes, capacitive sensors must be synchronized, but can be mounted close together without interference. Even when synchronized, inductive probes will interact if mounted close together. When this is unavoidable, special calibration can be used but is only available with digital sensors like the Lion Precision ECL202.

A capacitive probe's small sensing field, which is directed only at the target, prevents it from sensing mounting hardware or nearby objects. Inductive's large, surrounding sensing field can detect mounting hardware or other objects if they are too near the sensing area.

Two other specifications differ between the two technologies: resolution and bandwidth. Capacitive sensors have higher resolutions than inductive sensors making them a better choice for high resolution, precise applications.

Most capacitive and inductive sensors have bandwidths of 10-15kHz, but some inductive sensors (ECL101) have bandwidths as high as 80 kHz.

Another difference between the technologies is cost. Generally speaking, inductive sensors are lower cost.

This review of the differences between capacitive and inductive sensing technologies will help you determine which technology is the best choice for your application. Please contact us for more help in selecting the best sensor.