Application Report
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LDC Target Design

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ABSTRACT

Texas Instruments' Inductive-to-Digital Converter (LDC) technology can accurately measure with a wide variety of target sizes, shapes, and material composition. There are several target design guidelines to maximize the effectiveness of an LDC measurement system. This application note covers the relevant factors of target design that affect inductive sensing, and provides guidelines for optimizing sensing range and accuracy.

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1 The Sensor

An inductive-to-digital converter (LDC) senses the change in inductance caused by the movement of a conductive target through the senor's AC magnetic field. The target movement with respect to the sensor may be either axial or lateral with respect to the plane of the sensor. The characteristics of the sensor, as discussed in the TI application note LDC Sensor Design, determine the characteristics of the sensor's magnetic field and the overall system measurement resolution and accuracy.

2 Eddy Currents

Whenever a conductor interacts with an AC magnetic field, eddy currents are induced on the conductor's surface. Lenz's Law states that induced currents will flow in a manner to oppose the magnetic field, which weakens the original magnetic field in a measurable way. LDC devices use an inductor in a resonant circuit to generate an AC magnetic field, as shown in Figure 1. Any generated eddy currents will weaken the inductor's magnetic field, which effectively reduces the inductance of the resonant circuit, which is typically detectable by the LDC. Depending on the device, an LDC measures either the shift in resonance and/or the energy losses in the resonant circuit and in the target (due to the eddy currents).

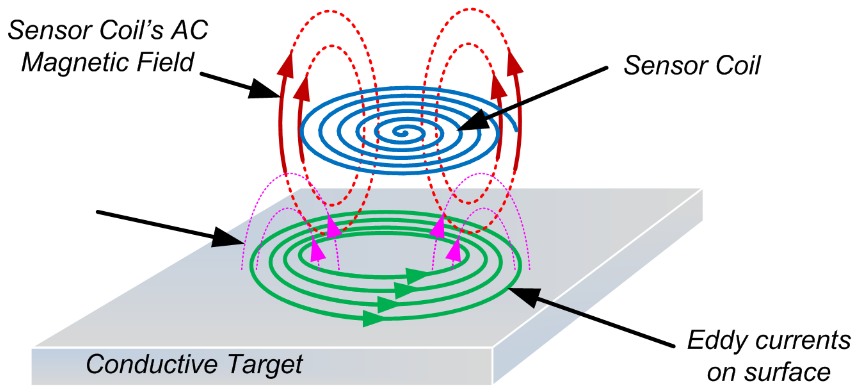

Figure 1. AC Magnetic Field Interaction With Conductor

2.1 Image Currents and Target Size

For many LDC applications, a flat spiral inductor printed on a PCB is an effective sensor design. An example is shown in Figure 2. Some of the primary considerations for the sensor include the total inductance, the resonant frequency, and the physical size of the inductor.

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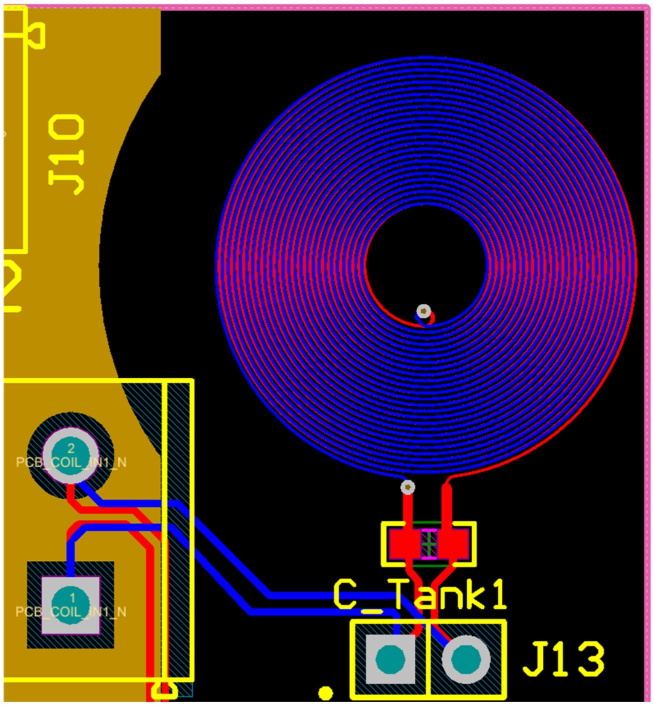

Figure 2. Spiral PCB Inductor

When a conductive target is brought into the magnetic field of the inductor coil, the eddy currents on the surface of the conductor will flow in the lowest possible impedance path. This path take is composed of concentric loops which match the shape of the sensor.

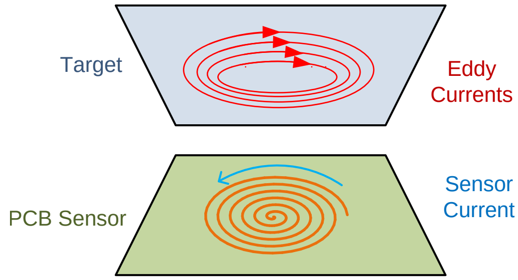

Figure 3. Image Current Flow on Target

Any differences in the image current path compared to the sensor current path will result in a weaker change in the sensor's magnetic field. For this reason, the strongest target response occurs when the target size larger than the sensor size, as the image current path can better mirror the flow of current in the sensor. If the target size is smaller than the sensor, the change in sensor frequency will be reduced, as shown in Figure 4.

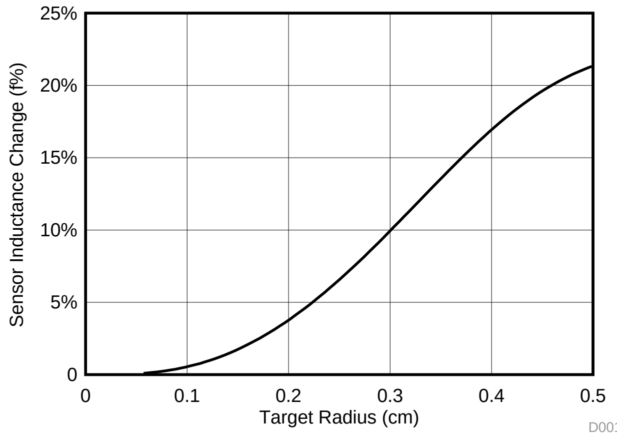

Figure 4. Sensor Inductance Shift vs Target Radius With Target 1 mm From Sensor

In Figure 4, the sensor is a spiral of 10 mm diameter, 25 turns per layer, with 4 layers having an inductance of 36 µH. The targets are stainless steel 304 disks, and held coaxially at a 1 mm distance from the sensor. As always, a larger change in the sensor inductance is desirable, since a larger change allows the target position to be measured with higher resolution. When the target radius is less than 0.1 cm, the sensor measurement changes by less than 1% of its nominal value. Position measurement of such a small target will have lower effective resolution due to the smaller inductance change. When the target size is increased to match the size of the sensor, the sensor measurement changes by >21%. This larger shift can be measured with much greater resolution.

2.2 Skin Depth

Like all AC currents, the eddy currents induced by the LDC's AC magnetic field flow near the surface of the conductor, and reduce in amplitude deeper into the conductor. The attenuation of current follows an exponential trend with distance from the surface. The skin depth, δ, is the distance at which the current is reduced to 1/e (~37%) of the density at the surface. Every additional increase of δ from surface will see an additional 1/e reduction in current.

For highly conductive materials, such as metals, the skin depth δ_s can be calculated by:

$$\delta_S = \sqrt{\frac{\rho}{\pi \mu f}} \tag{1}$$

where

- µ is the magnetic permeability of the material, which is µo (4π×10-7) multiplied by the conductor's relative permeability,
- ρ is the resistivity of the conductor, and
- f is the frequency of the AC magnetic field.

Skin depth varies with the material and sensor frequency. At higher frequencies, the skin depth becomes smaller and smaller, which results in the eddy currents concentrating at the surface of the conductor. Poorer conductors, such as carbon, have a larger value for their skin depth, as shown in Figure 5. Poorly conductive materials have a limit on skin depth; as an example, silicon never gets below 11 m.

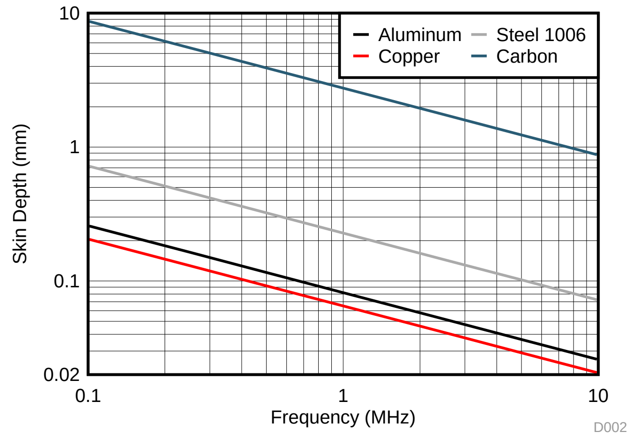

Figure 5. Skin Depth vs. Frequency for a Variety of Conductors

A conductor with a thickness equal to 1 skin depth for a given frequency will carry 63.2% of the current of an infinitely thick conductor. With a conductor of 3 skin depths thick, 95% of the total current will be induced, as shown in Figure 6.

To achieve best performance, a good rule of thumb is to that the target thickness should be at least 2 to 3 skin depths. To achieve this, either increase the target thickness or sensor frequency.

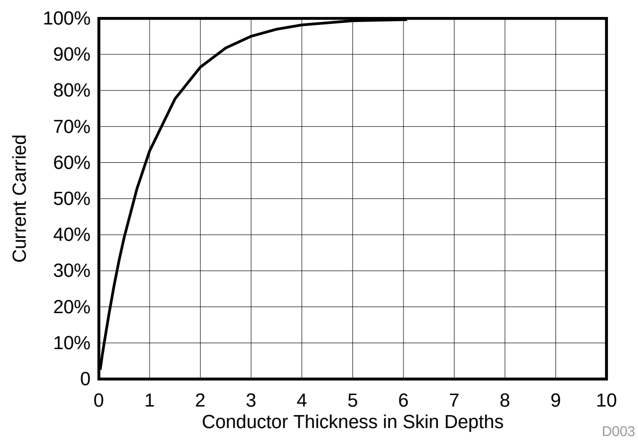

Figure 6. Current vs. Conductor Skin Depth

2.3 Sensors Have Two Sides

The magnetic field generated by the sensor, is symmetrical above and below the sensor, as shown in Figure 7.

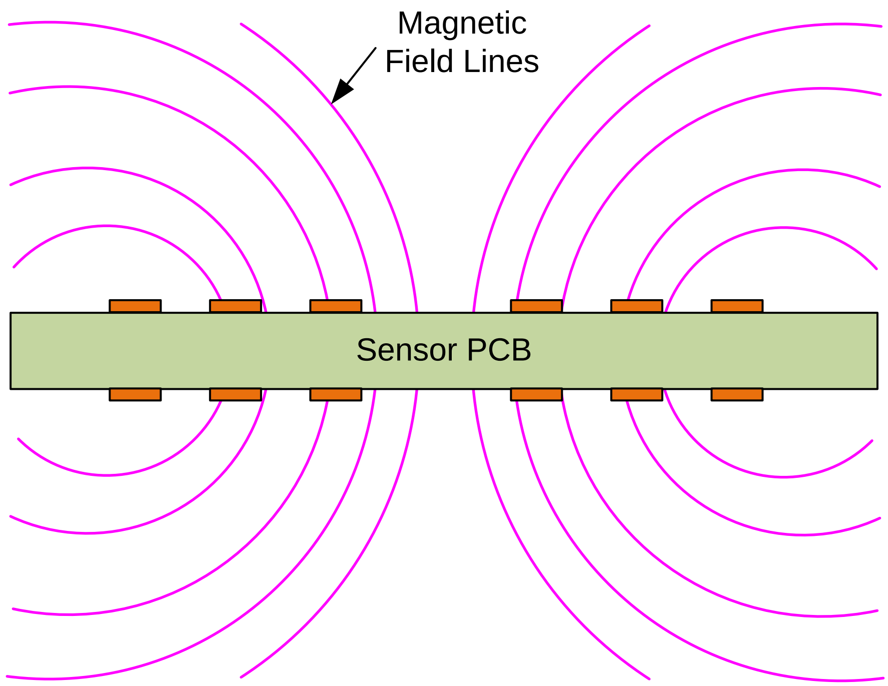

Figure 7. Symmetrical Field Lines

Movement of a conductive object on the opposite side of the sensor from the target can interfere with measurement of the target position. There are several methods that can be used to mitigate this effect:

- Move the interferer far enough away from the target that the interferer movement does not affect the target measurement (refer to the Texas Instruments Analog Wire blog post *How far can I sense* (https://e2e.ti.com/blogs_/b/analogwire/archive/2015/06/17/inductive-sensing-how-far-can-i-sense) for more information.
- Bring the target closer to the sensor.
- If the interfering conductor is farther away than the target, consider reducing the sensor size (although this can reduce the measurement resolution when the target-to-sensor distance exceeds sensor radius).
- Fix the position of the interferer so that it does not move with respect to the sensor. This approach is effective as long as the loading from the interferer does not exceed the sensor drive.
- Change the material composition of the interferer to larger resistivity such as plastic.
- Use a magnetic shielding material such as a ferrite. This does not reduce the sensitivity to the target, and in some cases can even extend the range slightly – refer to the TI Analog Wire blog post *How to shield from metal interference* (https://e2e.ti.com/blogs_/b/analogwire/archive/2014/10/08/inductive-sensing-how-to-shield-from-metal-interference) for additional details.
- Use a sheet of metal to shield. This will reduce the measurement accuracy of the target position. A minimum metal sheet thickness of 3 skin depths is recommended to shield from any other conductive objects on the reverse side of the sensor.

2.4 LDC Interaction Through Conductor

With lower sensor frequencies, skin depths increase, such that the sensor field can pass through the target and interact with conductive objects behind the target. Interference can occur with conductors located behind thin targets. Movement of a conductive object behind the target can affect the LDC measurement, as shown in Figure 8.

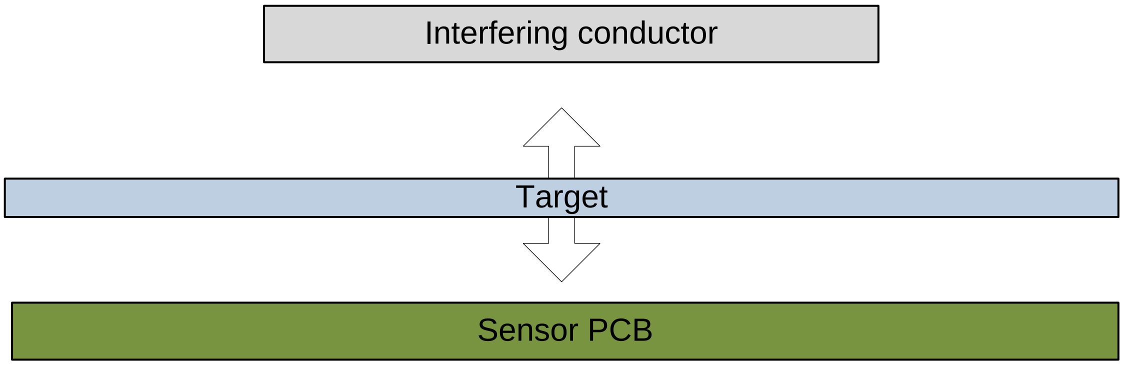

Figure 8. Interference from a Conductor Behind The Target

Depending on the system accuracy and resolution requirements, this can be a concern even with targets that are 3 skin depths thick. Simply increasing the sensor frequency will reduce the effect if it is not feasible to use a thicker target.

Some LDC devices, such as the LDC1612 and LDC1614, have specific sensor frequency ranges which provide higher measurement resolution (as discussed in section 2.4 of the TI application note *Optimizing L Measurement Resolution for the LDC161x and LDC1101* (SNOA944)). If the increased sensor frequency is outside of the optimum range for the LDC, the LDC's internal input dividers can be used to mitigate this degradation.

3 Target Shape

Because the eddy currents flow on the target in closed loops, any discontinuities in the current paths can result in higher measurement noise. If the target has any gaps or voids, the eddy currents on the target surface will need to flow around the void, as seen in Figure 9.

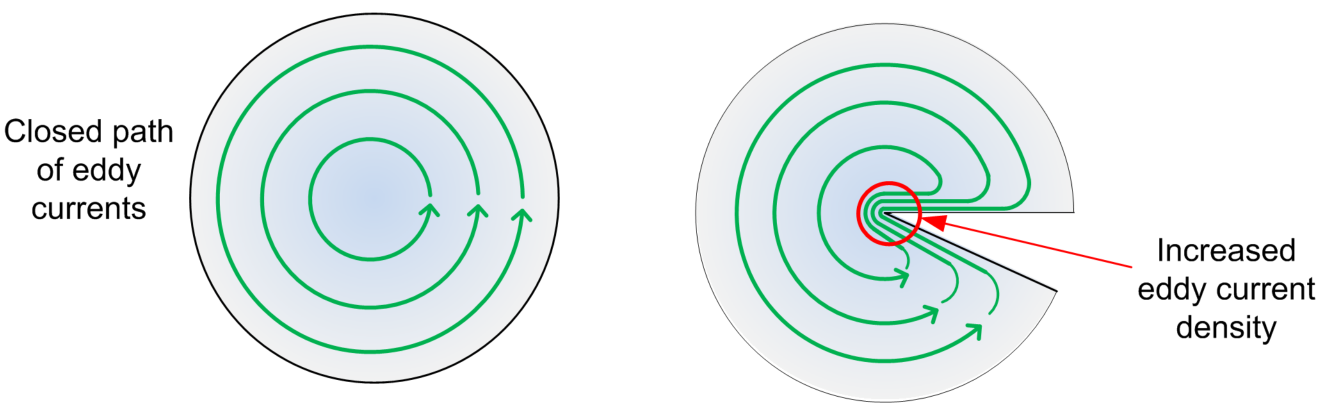

Figure 9. Current Flow for a Uniform Surface Target vs a Target With a Gap

This mismatch in image current path compared to sensor current path reduces the coupling between the target and the sensor, and results in a smaller shift in sensor inductance and reduced measurement resolution.

3.1 Lateral Sensing Target Shape

Some applications are designed to sense lateral target movement relative to the sensor, rather than axial with respect to the sensor. For these types of applications, the target is held at a fixed distance from the sensor and moved laterally above or below the sensor, as shown in Figure 10. The TI application note *LDC1612/LDC1614 Linear Position Sensing* (SNOA931) provides more information on this type of application.

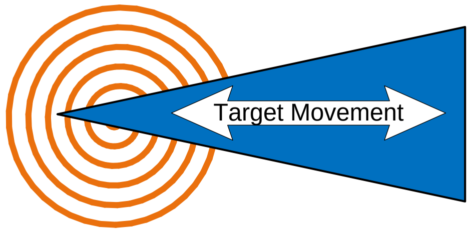

Figure 10. Lateral Sensing Target Over Sensor

The target shape can be modified to produce more resolution over a specific region if desired. Figure 11 shows an example of such a target configuration. In this example, the LDC will be able to measure the lateral position with higher resolution when the middle section of the target moves over the sensor, as this region has an increased rate of target exposure for a given lateral movement.

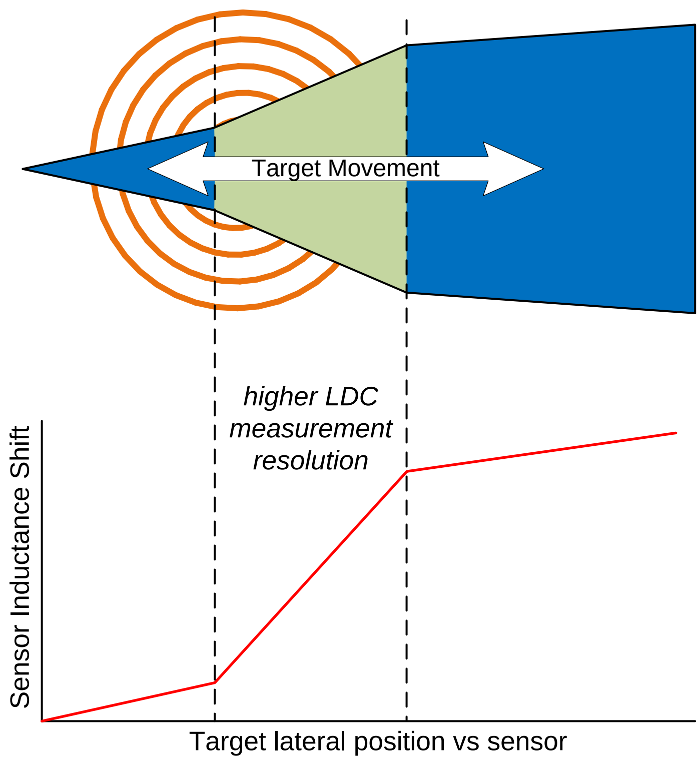

Figure 11. Lateral Target With Varying Profile

This lateral sensing technique can also be used to measure angular motion. Details on LDC applications implementing this sensing configuration can be found at *1° Dial Reference Design Using the LDC1314* (TIDU953) and a variation at *32 Position Encoder Using the LDC1312* (TIDUBG4).

4 Target Composition

4.1 Perfect Target Material Characteristics

From an electrical perspective, the perfect target material needs to have the highest possible conductivity for optimum inductive measurements. The highest possible conductivity results in the most generated eddy currents; the eddy currents create the strongest opposition magnetic field. The stronger magnetic field results in a larger shift in the sensor inductance, which can be measured with more resolution.

Silver, the highest conductivity metal, is the optimum target material based on this parameter. However, other characteristics such as cost limit the suitability of silver.

From a mechanical perspective, the target material should be physically stable and exhibit uniform movement without warping or tilting, which could be incorrectly measured as a position shift. The material's thermal expansion coefficient should be as low as possible so that any temperature change does not change the effective position of the target.

Figure 12 shows the change in sensor frequency vs target position for targets of different materials. A larger frequency shift is desirable; since the LDC can measure the larger shift can with more resolution. Unfortunately, a silver target was not available for comparison.

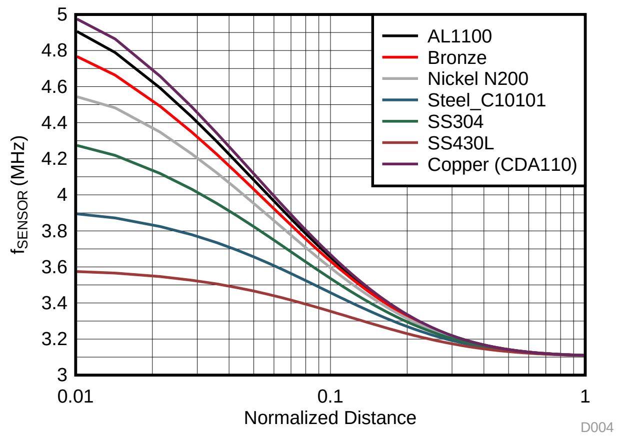

Figure 12. Comparison of Sensor Frequency Shift for Different Target Metals

The data used in Figure 12 was collected for a 14 mm diameter circular sensor with a free space resonant frequency of 3.11 MHz. The target distance is scaled by the sensor diameter, so the 0.1 value on the X-axis corresponds to a sensor to target distance of 1.4 mm.

4.2 Aluminum Targets

Aluminum is an excellent target material for many reasons – it is reasonably inexpensive, light weight, strong, easy to machine, and also resistant to corrosion. Its high conductivity results in a skin depth only 25% larger than copper. It has a slightly lower temperature-coefficient than copper – 4200 ppm/°C vs. copper's 4300 ppm/°C.

Anodized finishes, which are typically only a few microns thick, do not affect the performance of aluminum targets as long as the overall thickness of the aluminum is sufficient for the sensor frequency.

Aluminum alloys, such as AL6061, exhibit all of these benefits, but it is recommended to check the conductivity of any selected alloy.

4.3 Copper Targets

Copper is an excellent target material, with conductivity that is 95% of silver. But it is heavier and weaker than aluminum, so from a mechanical perspective it is often not an optimum target material. Note that some copper alloys may have lower conductivity than aluminum, leading to the unexpected result of a weaker response than an Al target.

Constructing a target as a copper region on a PCB is a technique that we have utilized for many applications. Commonly available PCB fabrication can reliably produce features finer than 5 mils (0.125 mm) with 1-oz. copper on FR4. The common plating thickness of 1-oz. copper is 37 µm thick, which is one skin depth for a sensor frequency of 3.1 MHz. While operation below one skin depth is still effective, to obtain a larger response, the sensor frequency should be above 6 MHz with 1-oz. copper. Thinner copper platings perform better with a correspondingly higher sensor frequency.

Duplicating the target design onto several layers will provide some improvement in response with lower frequency sensors.

FR4 is an excellent substrate for the PCB target – it is strong, dimensionally stable, light, and has a low loss tangent at the frequencies used by LDC sensors. In addition, the FR4 has a temperature coefficient of expansion which closely matches the copper traces on the board.

If the sensor is a spiral trace on a PCB, then the thermal expansion of the PCB target has the added benefit of matching the thermal expansion of the sensor.

4.4 Steel and Magnetic Material Targets

Steel and targets composed of magnetic materials can be used in LDC applications, but these materials can present special challenges for inductance measurements. In general, systems using these targets should have either f_{SENSOR} < 20 kHz or f_{SENSOR} > 1 MHz.

Steel has a lower conductivity than copper (typically <10% of copper). This reduces the amount of eddy currents generated on the surface of the target. As a result, the inductance shift due to target movement is reduced at lower sensor frequencies. The smaller inductance shift results in lower measurement resolution of the target movement.

Magnetic steels, such as Stainless Steel 416, produce a significantly different inductance response across sensor frequency, as shown in Figure 13. This behavior is caused by the magnetic field lines permeating the steel, which results in an increase in the sensor inductance, instead of a decrease in the inductance due to eddy currents. At higher frequencies, the skin depth becomes small enough that the eddy current generation on the surface of the steel blocks the magnetic field lines from entering the metal. At these higher sensor frequencies the inductance drops in a manner consistent with other conductive materials.

There is actually a frequency at which the magnetic permeability and eddy currents balance and there is no noticeable inductance shift. This frequency is not stable and can shift due to outside influences, such as temperature. This effect can actually result in a non-monotonic output for target movement. In addition, the sensor frequency changes due to target movement, and it is possible that the sensor frequency can shift to a poorer measurement accuracy range.

R_P measurements do not have this issue, as the eddy current losses are still present.

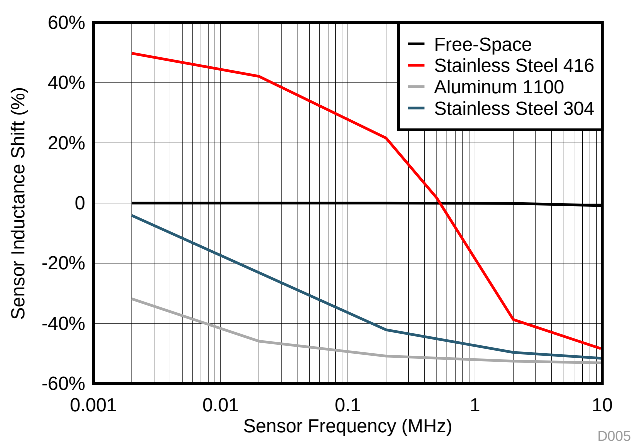

Figure 13. Shift in Sensor Inductance for Different Target Materials vs Frequency

4.5 Conductive Ink

Targets printed in conductive ink can be used to create a wide variety of target shapes. Many conductive inks are based on silver, which is an excellent conductor but due to the additional materials in the ink conductivity is typically just ~30% of pure silver. This reduction in conductivity unfortunately increases the skin depth of conductive inks, which are also quite thin - typically 15 µm or thinner. The measured LDC response is typically <10% compared to a silver conductor with a thickness of 4+ skin depths.

This reduced response limits the precision of applications using conductive ink targets, but for many cases it is acceptable.

4.6 Ineffective Target Materials

Use of low conductivity materials will result in a correspondingly small inductive sensor shift, which restricts the measurement resolution of the LDC. For example, water is not an effective target material. Even a saturated salt water solution has a conductivity that is 0.000001% of copper, which results in an extremely small inductive response.

The human body is another poor target; while in some conditions it may appear to provide a noticeable response, the actual source of the shift is a capacitive interaction with the sensor.

5 Summary

LDC systems provide the highest performance when the target is able to provide the largest shift in sensor inductance. To obtain the largest inductance shift requires maximizing the eddy currents on the target subject to the constraints of the system design. Using the techniques discussed here, matching the shape and size of the target to the sensor, using targets with the highest possible conductivity, and ensuring that the target thickness is sufficient to support at least 3 skin depths, will maximize the sensor response to provide the highest possible measurement resolution.

6 References

- TI Analog Wire blog post *How far can I sense* (https://e2e.ti.com/blogs_/b/analogwire/archive/2015/06/17/inductive-sensing-how-far-can-i-sense)
- TI Analog Wire blog post *How to shield from metal interference* (https://e2e.ti.com/blogs_/b/analogwire/archive/2014/10/08/inductive-sensing-how-to-shield-from-metal-interference)
- *LDC1612/LDC1614 Linear Position Sensing* (SNOA931)
- *Optimizing L Measurement Resolution for the LDC161x and LDC1101* (SNOA944)
- *1° Dial Reference Design Using the LDC1314* (TIDU953)
- *32 Position Encoder Using the LDC1312* (TIDUBG4)

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

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• Changed to correct link	11

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