Application Report

Sensor Design for Inductive Sensing Applications Using LDC

TEXAS INSTRUMENTS

ABSTRACT

Getting the best performance out of an LDC requires a sensor suitable for the measurement. This app note covers the parameters to consider when designing a sensor for a specific application. Specific areas of focus include the physical routing characteristics of PCB based sensors, considerations for the sensor capacitor, and techniques to minimize or compensate for parasitic effects.

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1 The Sensor

LDC sensing applications use a sensor composed of an inductor in parallel with a capacitor to form an L-C tank oscillator.

1.1 Sensor Frequency

The inductance and capacitance determine the sensor frequency, from the equation:

$$f_{SENSOR}(Hz) = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

Figure 1-1 graphs several sensor frequency settings across capacitor and inductor values. For example, a 5-MHz sensor could use a 1-nF capacitor with an approximately 25-µH inductor. Refer to the Analog Wire blog post *Inductive Sensing: Sensor frequency constraints* for more information on how this graph is constructed.

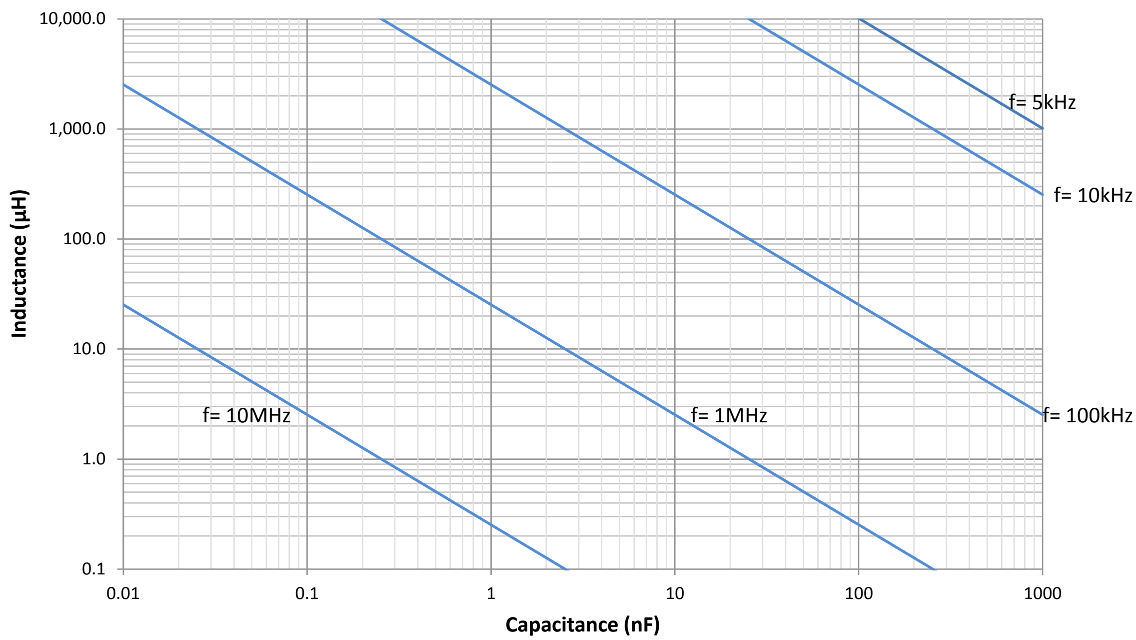

Figure 1-1. Sensor Frequency Versus Inductance and Capacitance

TI's LDC devices work over a wide frequency range, from 1 kHz to 10 MHz for the LDC1312 family and LDC1612 family of devices. The LDC0851 can operate up to 19 MHz, and the LDC211x and LDC3114 can support a sensor frequency up to 30 MHz.

It is important to remember that the frequency of operation changes based on the position of the target. Typically, when the target is closest to the sensor, the sensor frequency is highest. The highest frequency cannot exceed the specified operation range for the LDC.

1.2 R_S and R_P

An inductive sensor is intrinsically lossy due to series losses in the conductor used to construct the inductor. These resistive losses mainly come from two sources – the energy dissipated in the target or other nearby conductors, and the distributed losses from the conductive windings of the inductor. When measuring R_P, the intention is to measure only the eddy current losses on the target. The distributed losses in the sensor reduce the measurement dynamic range of the LDC. Even when measuring inductance (L only) with an LDC131x or LDC161x device, higher losses reduce the measurement accuracy.

Users can represent this loss electrically in one of two ways – as a series model or a parallel model, as shown in Figure 1-2. In the series representation, the higher R_S, the more parasitic losses and the more energy the LDC needs to drive into the sensor to maintain oscillation. This model matches the physics of the system more closely than does the parallel model.

The parallel model is easier to determine what sensor current is needed to for a given sensor peak voltage. With the parallel model, it is clear that if R_P is too low it attenuates the sensor oscillation. If the R_S becomes too high (which is the same as the R_P becoming too low), the LDC may not be able to effectively drive the sensor, resulting in increased noise or even a collapse of the sensor oscillation.

The R_P can be calculated from the R_S with:

$R_P = L / (R_S C) = (2\pi f_{SENSOR} L)^2 / R_S$

From previous equation, it is clear that the R_P is a function of the sensor frequency and the sensor inductance. The lowest sensor R_P that occurs in the system must be within the LDC drive capabilities.

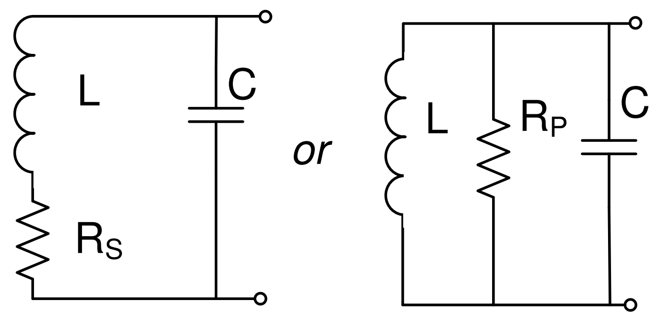

Figure 1-2. R_S and R_P

1.2.1 AC Resistance

As the sensor is oscillating a specific frequency range, it is critical to always use the AC resistance in the frequency of interest. Unless specifically mentioned otherwise, the resistances in this app note are always the AC resistance.

In general, trying to minimize R_S is recommended to improve the sensor performance.

1.2.2 Skin Effect

A DC current can take advantage of the entire cross section of a conductor. However, at higher frequencies electrical current prefers to simply travel along the surface of the conductor. This tendency is called Skin Effect, and is primarily a function of the conductivity and the frequency. With a copper conductor, more than 95% of a 1 MHz current flows in at the surface in a shell only 0.2 mm thick. At 10 MHz, the 95% of the current flows in a shell only 0.06 mm from the surface of the conductor.

The skin effect is the primary source of the increase in the AC R_S at higher frequencies. This effect also affects the eddy currents on the target surface - the generated eddy currents flow on the surface of the conductive target closest to the inductor.

2 Inductor Characteristics

To better understand how to obtain the optimum capabilities of a sensor, the sensor must be deconstructed into the inductor and the capacitor components. There are several inductor characteristics to consider, and while it may seem that there is an infinite range of possibilities for a given sensor, with use of the guidelines provided here, users can quickly converge on a suitable sensor design.

A parallel R-L-C electrical model of the sensor is shown in Figure 2-1.

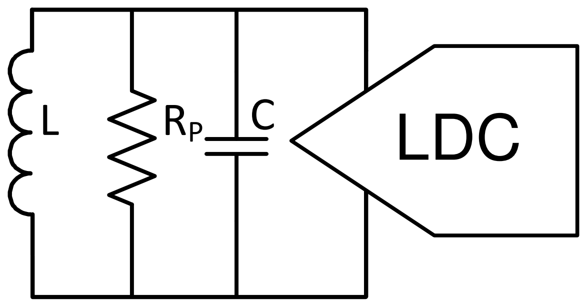

Figure 2-1. RLC Model

First, this app note needs to review the basic characteristics which determine the sensor capabilities.

2.1 Inductor Shape

The inductor shape is an important characteristic of the inductor because it determines the shape of the generated magnetic field. A circular spiral generates a more symmetrical magnetic field than other shapes, and is the optimum shape from an inductance verus R_S consideration. In general, it is recommended to use a circular inductor for the highest possible sensing capabilities, unless specific system requirements warrant the tradeoffs of an alternative shape.

For nearly all proximity applications, in which a target is moved orthogonally to the sensor plane, the appropriate shape is a circular sensor that has the best Q (and lowest R_S) for a given area, as shown in Figure 2-2.

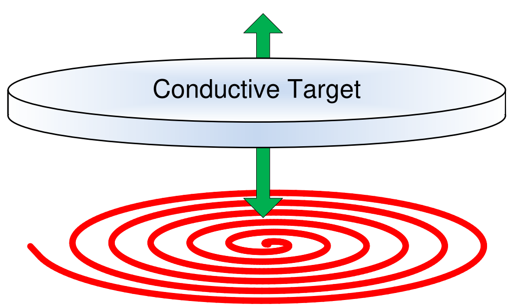

Figure 2-2. Axial Sensing with Circular Spiral Inductor

For other applications, different shapes may be more suitable. For PCB based sensors, designing alternative shapes is much easier than wire-wound inductors. For example, rectangular coils can be used to sense accurate movement along the X-axis while having reduced sensitivity to a shift in the Y-axis.

2.1.1 Example Uses of Different Inductor Shapes

Figure 2-3 is an example of a trapezoidal inductor. For a physically small rotational measurement application, using a set of trapezoidal inductors increases the inductor area compared to circular coil; this increase in area increases the sensor inductance. This is especially useful for very small sensor sizes, which may be lower than the minimum inductance that the LDC can effectively drive. In such a case, it may be necessary to include an additional series SMT inductor if the inductance is not high enough. Refer to the Analog Wire blog post *Inductive sensing: How to use a tiny 2mm PCB inductor as a sensor* for more details.

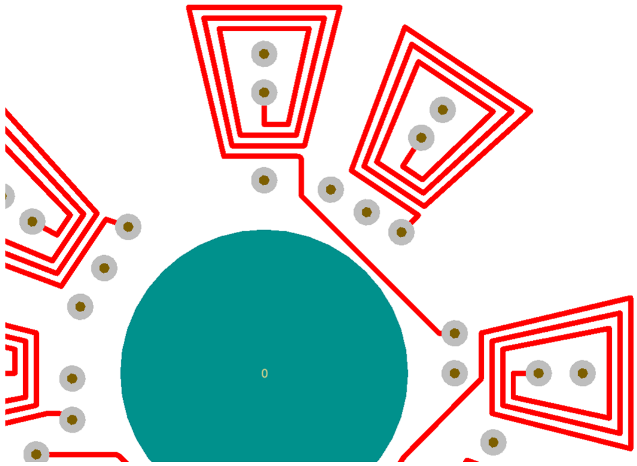

Figure 2-3. Trapezoidal Inductor for Rotational Encoding

2.2 Number of Turns

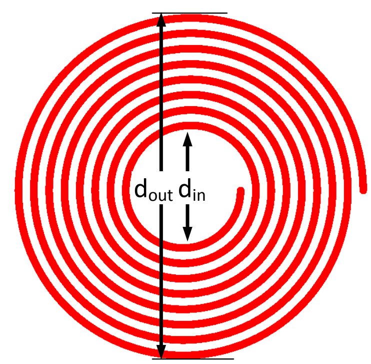

Figure 2-4. Flat Circular Spiral Inductor

For a single-layer PCB spiral inductor, Mohan's Equation, as discussed in Reference [1], is useful for understanding how inductance is related to coil geometry. This equation can be used to calculate the overall inductance of a coil for various geometries:

$$L = K_1 \mu_o \frac{n^2 d_{avg} c_1}{1 + K_2 \rho} \left(\ln\left(\frac{c_2}{\rho}\right) + c_3 \rho + c_4 \rho^2 \right) \quad (2)$$

where

- K_1 and K_2 are geometry dependent, based on the shape of the inductor
- μ_o is the permeability of free space, $4\pi \times 10^{-7}$
- n is the number of turns of the inductor
- d_{avg} is the average diameter of the turns = $(d_{OUT} + d_{IN})/2$
- $\rho = (d_{OUT} - d_{IN})/(d_{OUT} + d_{IN})$, and represents the fill ratio of the inductor – small values of ρ are a hollow inductor ($d_{OUT} \approx d_{IN}$), while large values correspond to ($d_{OUT} \gg d_{IN}$)

- c_i are layout dependent factors based on the geometry (for a circle, use c_1 = 1.0, c_2 = 2.46, c_3 = 0, c_4 = 0.20), refer to [1] for additional shapes

As the total inductance is proportional to the number of turns, adjusting the number of turns is an effective control on the total inductance. However, when adding inner turns (which reduces the inner diameter), the d_{avg} value begins to decrease, which reduces the additional inductance from the extra turns. For most applications, the ratio of d_{IN}/d_{OUT} must be greater than 0.3 for a higher inductor Q. The reason for this guideline is that the inner turns, which do not have a significant area, do not contribute significantly to the overall inductance while they still increase R_S. However, for applications where the target is very close to the sensor, such as touch-on-metal, a ratio as low as 0.05 is often acceptable, as the inner turns provide increased sensitivity. Refer to Reference [2] for more information.

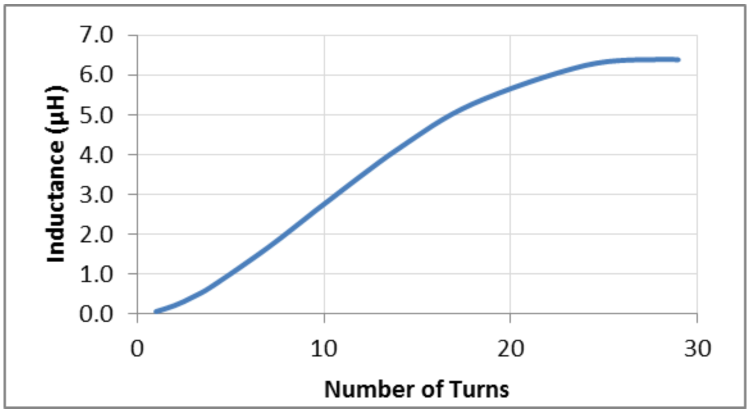

Figure 2-5. Inductance Versus Number of Turns for 18-mm Circular Inductor

A key limitation on the number of turns that can be added is the practical minimum PCB trace width – a common value is 0.1 mm (or 0.004 in.). Under this constraint, with each increase of 2 mm in sensor diameter up to 5 additional turns can be added to a PCB inductor.

In Figure 2-5, it can be seen that the first few turns contribute the most inductance, while the last few turns contribute less inductance. This example with an 18-mm outer diameter coil with 0.15-mm trace width and trace spacing shows that the total inductance levels off at approximately 20 turns.

2.3 Multiple Layers

For PCB inductors, there is a maximum number of turns that can be placed in a given diameter. If the overall inductance of the sensor is still too low, adding an additional inductor on another layer increases the total inductance. Note that these additional inductors need to be physically aligned, as shown in Figure 2-6, so that the magnetic fields positively add. Electrically, the inductors are connected in series. In general, with a PCB spiral inductor, a second layer is generally available because most PCBs are at least two layers.

When routing multiple layers, it is important to alternate the rotation of the coils – if the top layer is routed with a clockwise rotation, the next layer down must have a counter-clockwise rotation. While this may seem counter-intuitive, this physical arrangement is needed in order to keep the current rotating in a constant direction.

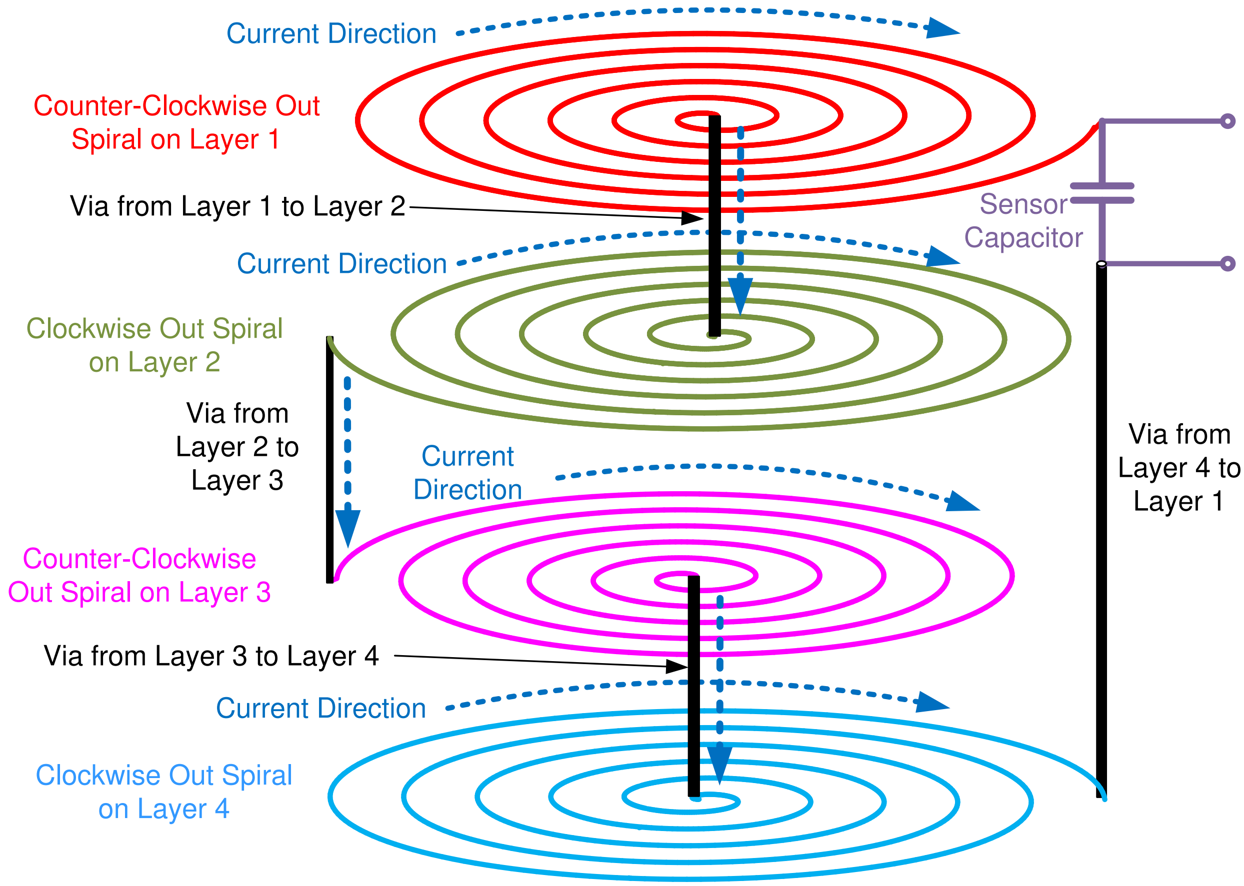

Figure 2-6. Multiple Layer Inductor Construction (Series)

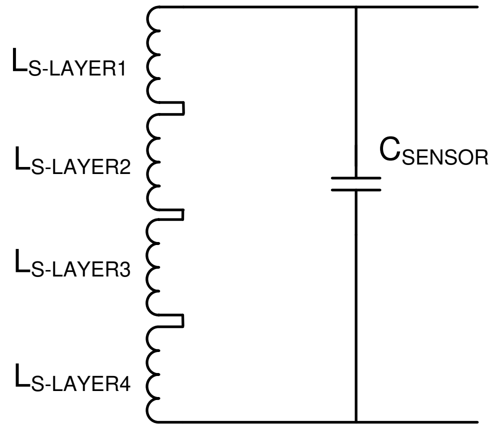

Figure 2-7. Simplified Electrical Model of Four-Layer Series Sensor (Ignoring R_P)

2.3.1 Mutual Inductance of Coils in Series

With multi-layer coils aligned as in Figure 2-6, the magnetic fields between each of the layers couple, resulting in an increase in the overall inductance. The equivalent circuit model for a two coil arrangement is shown in Figure 2-8.

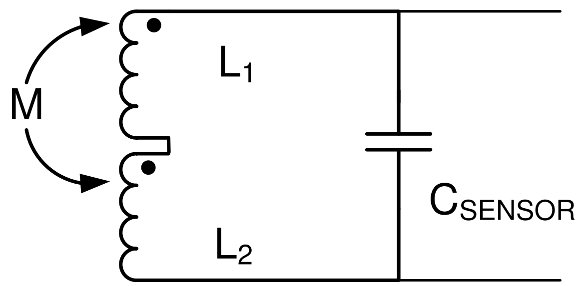

Figure 2-8. Mutual Inductance for Two-Layer Sensor (Ignoring R_P)

Because the linkage between the coil fields is positive, the total inductance of the coils in series is:

$$L_{TOTAL} = L_1 + L_2 + 2M \quad (3)$$

where

- L_1 = inductance of coil 1,
- L_2 = inductance of coil 2, which is typical the same as L_1 as the geometries are the same, and
- M = mutual inductance between the coils = $k \times \sqrt{(L_1 \times L_2)}$

The parameter k is a measure of the flux linkage between the coils and varies between 0 and 1, and depends only on the distance between the coils. The mutual inductance is stable and, as shown by Equation 3, increases the total inductance beyond the simple sum of the individual inductances.

In general, for N coils connected in series with positively linked fluxes, the total inductance is given by:

$$L_{TOTAL} = \sum_{i=1}^{N} L_i + 2 \cdot \left(\sum_{j=1}^{N-1} \sum_{m=j+1}^{N} M_{j,m} \right) \tag{4}$$

Equation 4 takes into account that there is flux linkage between coils in adjacent layers, plus between coils in alternating layers. Because the degree of mutual inductance between coils is dependent on the separation between layers, the individual mutual inductances vary.

For example, an 18-mm outer diameter, 0.15-mm trace width and trace spacing coil with 12 turns has an inductance of 3.5 µH. If a multi-layer inductor is constructed using of 4 of these single-layer inductors in a 1.0 mm thick PCB, the total inductance is not 4×3.5 µH (14 µH), but is actually 39 µH. The additional 25 µH mutual inductance is actually greater than the 14 µH from the four coils. This mutual inductance has the additional beneficial property of not increasing the sensor R_S.

Texas Instruments online WEBENCH® tool supports multi-layer coil design and eliminates the need to employ complex calculations. This can be accessed at http://webench.ti.com/wb5/LDC/#/spirals.

2.3.2 Multi-Layer Parallel Inductor

Minimizing the R_S is necessary to obtain the highest resolution R_P measurements. This also improves the L measurements for the LDC161x and LDC131x devices. With four or more layers users can start using the parallel coil structure shown in Figure 2-9 and Figure 2-10 to lower R_S. This design may be useful for some applications which need to optimize R_P measurements.

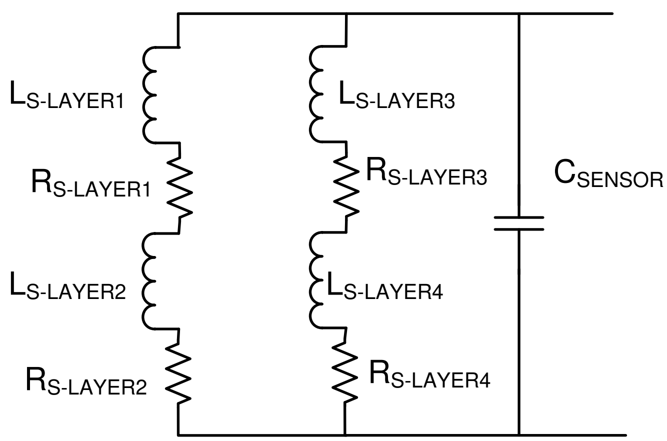

Figure 2-9. Multi-layer Parallel Coil Schematic

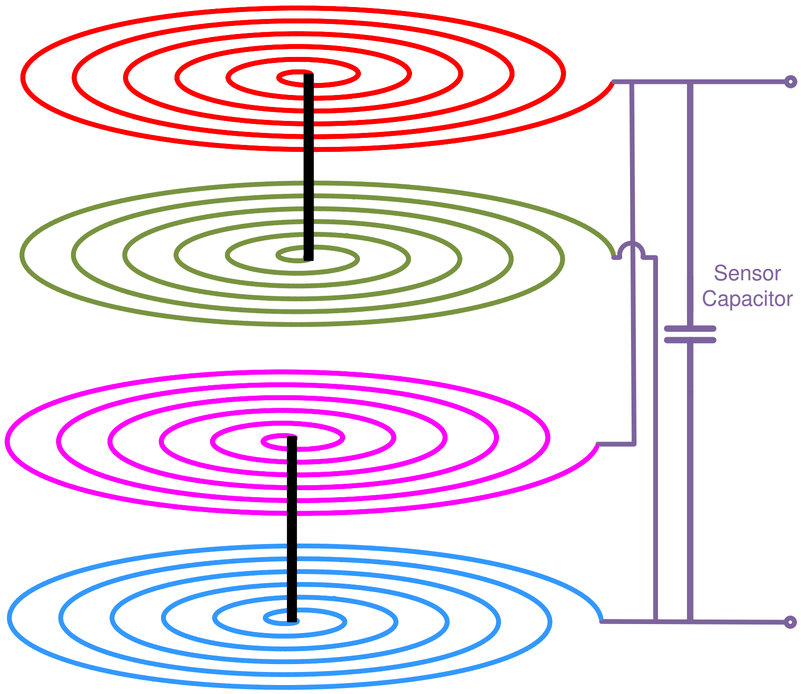

Figure 2-10. Multi-layer Parallel Inductor

2.3.3 Temperature Compensation

When the inductor is composed of a pair of coils on multiple layers, the multiple layers result in an inductor with improved temperature stability. The application note *LDC100x Temperature Compensation* discusses this effect in more detail.

2.4 Inductor Size

The primary inductor characteristic that determines sensing range is the physical size of the inductor. More specifically, the outer diameter (d_{OUT}) determines the sensing range. In order to sense the movement of a target, the magnetic field of the sensor needs to extend to the target. The physical size of the inductor controls the physical size of the generated magnetic field. The change in sensor inductance as a function of the target distance has a consistent shape, as seen in Figure 2-11 and Figure 2-12. The change in inductance versus the change in target distance has such a consistent shape that users can effectively scale the response to the sensor diameter (d_{OUT}) to simplify system design.

It may be surprising to learn that the overall inductance of the sensor, which corresponds to the intensity of the magnetic field, does not significantly affect the sensing range.

Figure 2-11 and Figure 2-12 show the transfer functions of an example 14-mm diameter sensor. While a different inductor geometry has a different scale on the Y-axis on the graphs, the overall shape is similar as the target is proportionally moved. As the distance between the sensor and target decreases, both L and R_P decrease. The amount of the decrease is based on the target size and composition, although for some target materials the L and R_P can actually increase as the target gets closer. It must be noted that in the sensor/target scenario, the flux linkage between the sensor and target does not add, but instead, the fields oppose one another, so that the mutual inductance between the two has on a negative sign.

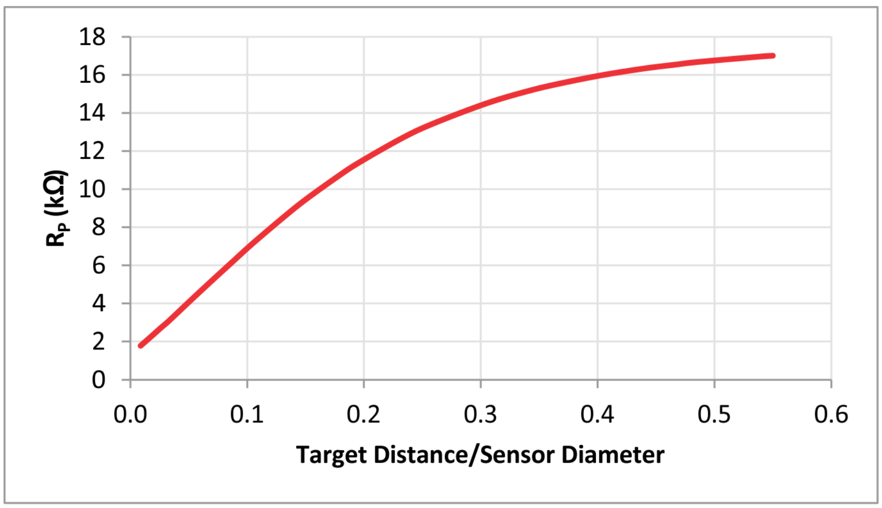

Figure 2-11. R_P Versus Normalized Target Distance

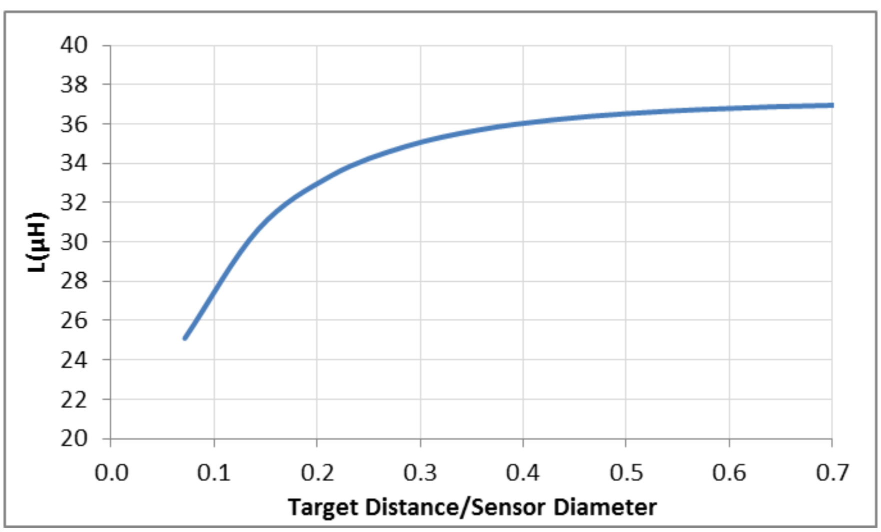

Figure 2-12. Inductance Versus Normalized Target Distance

For LDC131x and LDC100x devices, the effective sensing range is approximately one-half the sensor diameter. While the L versus distance response is the same for LDC161x devices, the higher resolution of the LDC161x enables it to effectively sense target shifts at much larger distances – up to twice the sensor diameter, but with reduced effective measurement resolution. The LDC211x and LDC3114 devices have an equivalent sensing range to the LDC161x. For the LDC0851, the maximum switching distance is 40% of the coil diameter.

If a system requires a sensing range of 4 mm, then the minimum sensor size must be 8 mm; and an even larger sensor provides improved measurement resolution. This leads to the first rule of thumb for inductive sensor design: use the biggest coil that can physically fit in the application. The second rule of thumb for inductive sensor design is that the target must be similar in size to the sensor.

When using rectangular inductors or other non-circular shapes, the sensing range is based on the smaller axis rather than the longer axis, as shown in Figure 2-13.

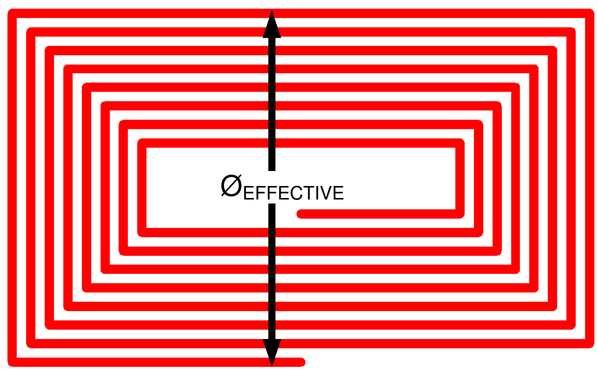

Figure 2-13. Sensor “Diameter” for a Non-circular Coil

2.5 Self-Resonance Frequency

Figure 2-14 shows how the individual turns of an inductor have a certain physical area and are separated by a dielectric; this produces a small parasitic capacitor across each turn. At a sufficiently high frequency, signals find it easier to simply jump across the distributed parasitic capacitance rather than traverse along the spiral winding of the trace. The frequency where these two paths are matched is self-resonance frequency, which is represented as f_{SR} or SRF. Because the parasitic capacitance is not very stable, it is recommended to keep the sensor frequency below 75% of the SRF.

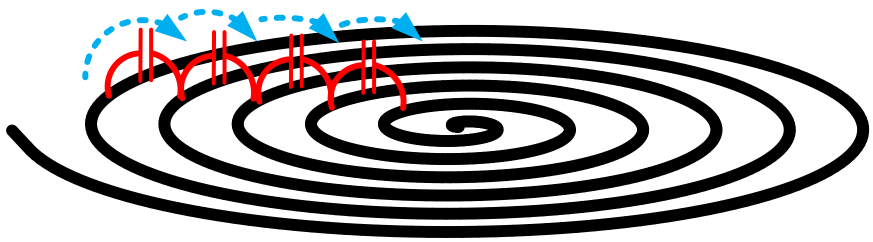

Figure 2-14. Parasitic Capacitive Components in an Inductor

2.5.1 Measurement of SRF

The SRF of an inductor can be easily measured with an impedance analyzer. With an impedance analyzer, the SRF is measured by simply connecting the inductor and plotting the magnitude of the impedance and phase versus frequency. The frequency at which θ=0° corresponds to the SRF. In the example shown in Figure 2-15, the SRF occurs at 4.6 MHz. Note that the SRF is a function of the target interaction — when the target is interaction is stronger, the SRF almost always increases.

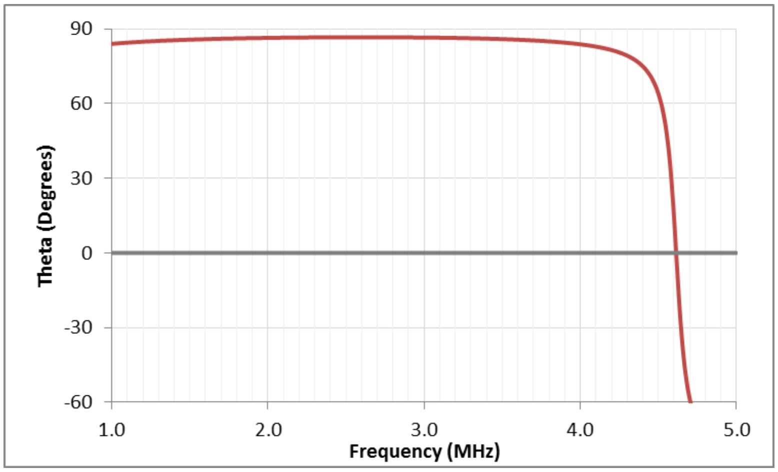

Figure 2-15. Inductance T Versus Frequency

A Vector Network Analyzer (VNA) is also able to perform this measurement. As always with VNAs, it is important to properly calibrate the VNA. The calibration plane must be at the connections to the inductor, otherwise the offset introduces a transmission line into the measurement that results in a measurement error. Once calibrated, simply measure S11 over an appropriate frequency span. The SRF is the frequency where the S_{11} graph crosses the real axis close to the open, as indicated in Figure 2-16.

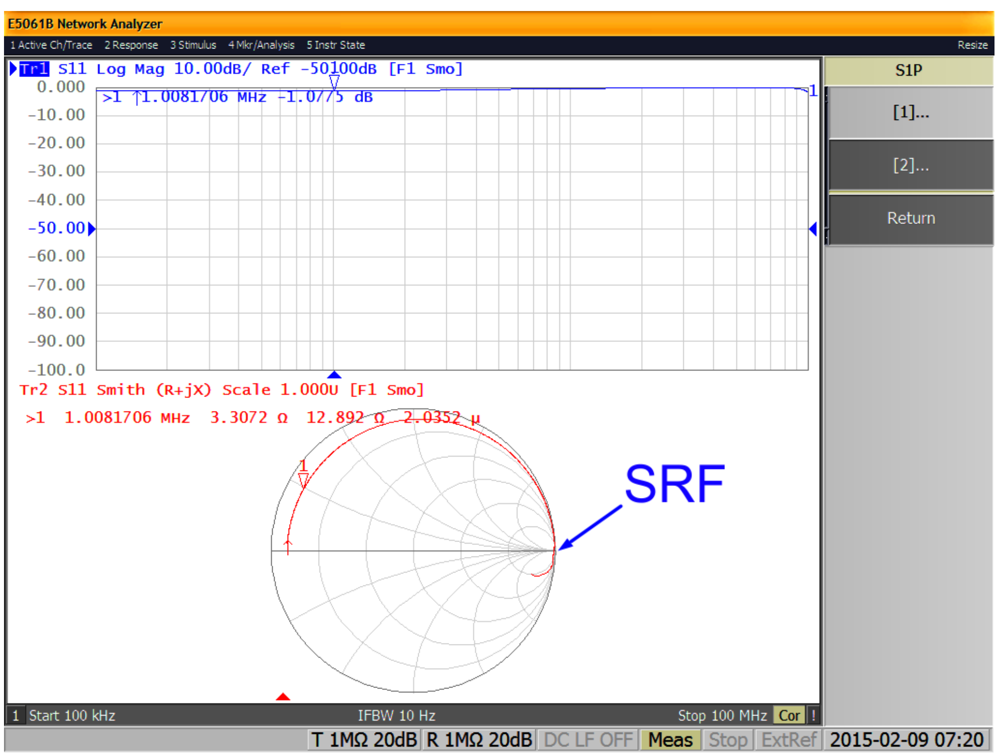

Figure 2-16. Measurement of SRF with a VNA

2.5.2 Techniques to Improve SRF for Wire-wound Inductors

Wire-wound inductors can typically have a very large numbers of turns (or windings) and, as a result, while they can have very high inductances and relatively high R_P values, they often have a low SRF.

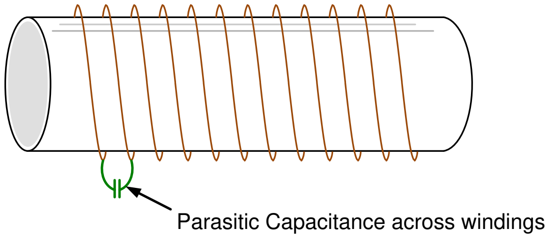

Figure 2-17. Wire-Wound Inductor Parasitic Capacitance

The SRF is a highly dependent on the geometry of the windings. With wire-wound inductors composed of large numbers of turns, there are specific winding patterns that can reduce the parasitic capacitance and therefore increase the SRF. One of the first methods is to wind the coil out, then wind across, as shown in Figure 2-18. This method reduces area between turns with a large voltage differential.

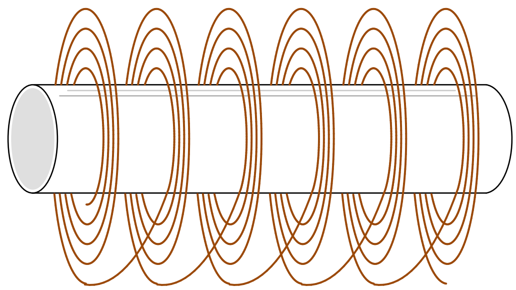

Figure 2-18. Winding-Out Method

A second winding method, shown in Figure 2-19, is to configure windings so that they cross at an angle, which reduces the cross-sectional area between windings. Crossing angles must be as close to 90° as possible. A coil designed in this manner is often called a Honeycomb coil.

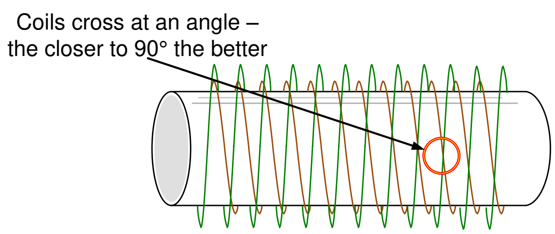

Figure 2-19. Winding Crossing for Honeycomb Coil

It is an acceptable to combine the techniques to produce groups of windings, as shown in Figure 2-20.

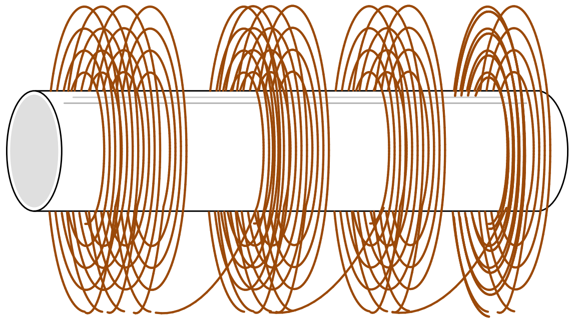

Figure 2-20. Combination of Both Winding-out and Crossing

3 Capacitor Characteristics

The capacitor used in the sensor is a critical, yet often overlooked component. In LDC applications, we recommend using C0G-grade ceramic capacitors (they are also referred to as NP0 capacitors). These capacitors use the highest quality ceramic dielectric, and as a result they are very stable and avoid many of the non-idealities capacitors using other dielectrics:

- They are not polarized.
- They exhibit minimal aging shifts.
- Excellent temperature stability at only ±30 ppm/°C.
- Very low ESR (equivalent series resistance) – typically less than a few mili-Ω.
- No piezoelectric effects – some dielectrics convert physical stresses into electrical shifts; which is undesirable.
- Can operate at very high frequencies.
- Exhibit almost no dC/dV effects, in which the voltage across the capacitance affects the capacitance.
- Generate minimal distortion.
- Available in voltage ratings suitable for LDC operation.

However, compared to other dielectrics, they do not have a large amount of capacitance per unit volume, so it becomes difficult to find C0G capacitors of more than 0.47 µF. For capacitance values of 47 pF to 3300 pF typically used for LDC sensors, C0G capacitors are available in small footprints and are reasonably priced.

3.1 Capacitor R_S, Q, and SRF

The R_S of the sensor capacitor is added to the sensor, but this contribution is typically very low compared to the inductor – for a 1000-pF 0603 C0G capacitor, the R_S is typically around 20 mΩ (compared to 2 Ω or more for the inductor). Due to its very low R_S, the capacitor Q is typically very high – well over 100, and reaching 1000 in some cases. However, the lower Q of the inductor is what dominates the response.

Capacitors also have a SRF, but it is typically much higher than the SRF of the inductor due to the smaller physical size and the construction. For example, 1000-pF capacitors with SRF above 200 MHz are readily available. Since the SRF is so much higher than that of the sensor inductor, it typically does not affect the performance of the sensor.

3.2 Effect of Parasitic Capacitance

While the sensor capacitance seems simple, it is quite easy to get a few pF of parasitic capacitance in many physical systems. Generally, parasitic capacitances are not very stable. Because users expect only the inductance of the sensor to vary, variable capacitance causes measurement inaccuracy. For example, with a sensor of 100 µH in parallel with 10.1 pF, an additional 0.5 pF of parasitic capacitance causes the free-air sensor frequency to shift from 5 MHz to 4.88 MHz. This is equivalent to a shift in this inductance of this sensor of 5 µH. If the absolute value of the inductance is the critical measurement, then a 5% error has been introduced by this shift in the parasitic capacitance. If the sensor capacitor is increased to 704 pF, the sensor frequency is nominally 600 kHz, but the same parasitic shift of 0.5 pF causes only produce a shift from 600 Hz to 599.8 kHz; which only appears as an inductance shift of 0.07 µH, which is an error of less than 0.07%.

Some of the sources of parasitic capacitances include the wiring connecting the LDC pins to the inductor, the ESD structures of the LDC input pins, and the actual turns of the inductor. Standard PCB design techniques such as minimizing ground floods near the inductive sensors can reduce the parasitic capacitance.

3.2.1 Recommended Capacitor Values

For most application, a sensor capacitance of 300 pF to 2 nF is generally recommended unless a specific sensor frequency is needed. For some touch-on-metal applications in which the sensor is placed very close to the conductive target, smaller sensor capacitances down to 47 pF may be optimum.

3.3 Capacitor Placement

For the LDC1101, LDC131x, and LDC161x devices, it is recommended to place the capacitor physically as close as possible to the inductor to minimize the parasitic R_S due to the traces between the inductor and capacitor. For the LDC0851, LDC211x and LDC3114 devices, the sensor capacitor must be placed as close as possible to the appropriate device pin.

4 Physical Coil Design

4.1 Example Design Procedure Using WEBENCH

WEBENCH provides two methods for PCB coil design. The first method finds a coil design that fits a specific application, in which the desired measurement capabilities are used to recommend a sensor.

The second method is an interactive design tool in which the coil size, shape, number of turns, and other parameters can be adjusted to optimize the sensor design to fit a specific need. This tool can be accessed at *WEBENCH Inductor Design Tool*.

Figure 4-1. WEBENCH Coil Designer Tool

The top-middle pull-down menu selects the desired coil shape – choices include:

- Circular
- Square
- Hexagonal
- Octagonal

As discussed earlier, for most applications a circular sensor is the optimum shape, although square coils may be useful for smaller geometry sensors.

The lower-left section of the screen is where various sensor parameters can be entered and adjusted. Parameters to enter include the size, number of turns, and PCB fabrication characteristics.

The middle section reports the sensor characteristics based on the current settings.

Finally, the sensor design can be exported to the following output formats:

- Altium Designer
- Cadence Allegro 16.0-16.6
- CadSoft EAGLE PCB (v6.4 or newer)
- DesignSpark PCB
- Mentor Graphics PADS PCB

The output can then be imported into CAD tools to complete a system design.

4.1.1 General Design Sequence

The recommended sensor design process is:

1. Determine the maximum size inductor that can physically be used in the application, and set the d_{OUT} value to that size. If the sensor is near the edge of a PCB, be sure to include any edge clearance rules from the PCB manufacturing rules.
2. Based on the PCB manufacturing rules, set:
   a. Trace Width and Trace Space to the minimum permitted. This value is commonly between 4 mils (0.1 mm) and 6 mils (0.15 mm).
   b. Copper thickness; this is commonly 1 oz-cu (approximately 35 μm). Thicker is better.
3. Set the Number of Layers to match the number of board layers in the design.
4. Set the Capacitance — the range of 300 pF to 2 nF is typically near the optimum unless a specific sensor frequency is needed. Adjust the capacitance as needed if the sensor frequency is not with the device limits.
5. Set the number of turns so that the ratio of D_{in} / D_{out} is > 0.3.
6. Export the design into the desired format.

4.2 PCB Layout Recommendations

4.2.1 Minimize Conductors Near Sensor

To keep the R_P as high as possible, keep ground planes and any thick traces away from the sensor — minimize any conductors within at least 30% of the diameter of sensor. This includes ground planes and power planes. Do not place a ground pour around the sensor or use thieving on the board. In Figure 4-2, the ground pour on the inner tan layer has been recessed away from the coil to reduce coupling to the inner grounds.

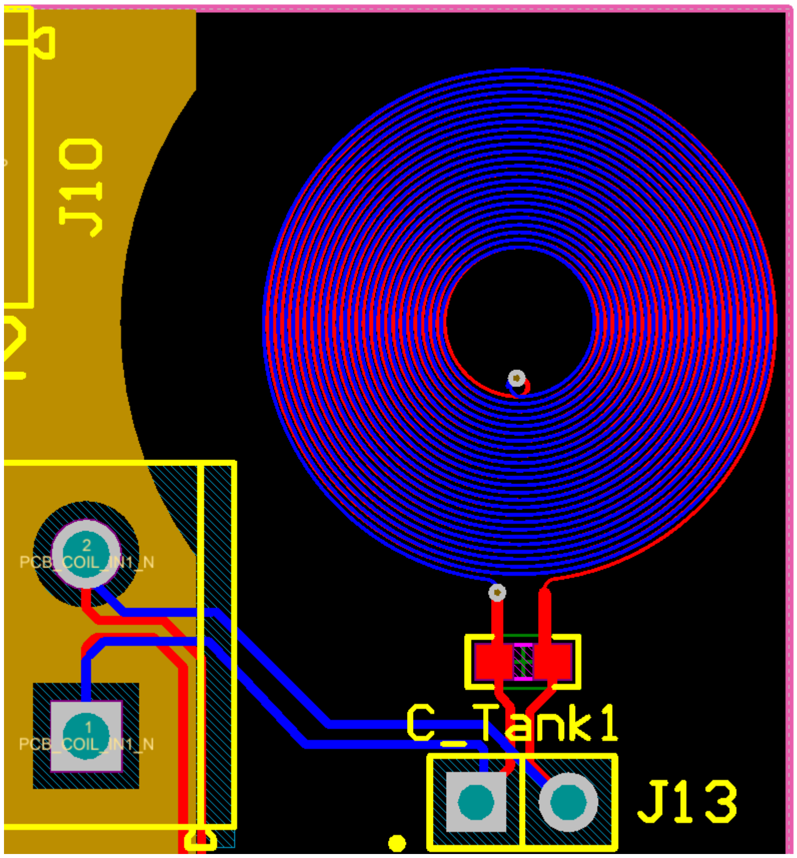

Figure 4-2. Minimize Copper Around the Sensor

4.2.2 Sensor Vias and Other Techniques for PCBs

- Inner vias must be placed close to the traces and not in the absolute center of the inductor — this reduces the parasitic resistance.
- Keep the inner 30% of the sensor area unwound for most applications, but for inductive metal button replacement, place as many turns as possible.
- The sensor capacitor must be placed as close as possible to the sensor to minimize the R_S of the traces. Note that this rule does not apply to LDC0851, LDC2112, LDC2114, and LDC3114 devices. For these devices, place the sensor capacitor close to the corresponding device pin.
- Use thicker traces between the inductor and capacitor when possible. Typically 10 mil (0.25 mm) is sufficient.
- Do not use a ferrite bead as a sensor inductor — it does not generate a magnetic field effective for LDC applications.

5 Summary

This application report has reviewed the main characteristics of sensors, various geometries, the uses of them, and how to construct wire-wound and PCB inductors. The core principles for sensor design — use the biggest sensor that can fit in the application, use a circular coil if possible for optimum R_S, and leave the center 30% of a PCB sensor open are effective guidelines.

Remember that coil diameter must be larger than twice the maximum expected sensing distance to maintain adequate resolution.

Use NP0/C0G grade capacitors for the sensor capacitor, which are placed as close to the inductor as possible. Also use larger sensor capacitor values to minimize the effects of parasitic capacitances.

6 References

[1] S. S. Mohan, M.del Mar Hershenson, S. P. Boyd, and T. H. Lee, “Simple Accurate Expressions for Planar Spiral Inductances,” *IEEE Journal OF Solid-state Circuits*, vol. 34, no. 10, pp 1419-1424, Oct. 1999.

[2] Y.Su, X. Liu, C.K. Lee, and S.Y. Hui, “On the Relationship of Quality Factor and Hollow Winding Structure of Coreless Printed Spiral Winding (CPSW) Inductor,” *IEEE Transactions on Power Electronics*, vol. 27, no. 6, pp. 3050–3056, Jun. 2012.

- Texas Instruments, Inductive Sensing FAQ
- Texas Instruments, Inductive Sensing Design Calculator Tool

7 Revision History

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

Changes from Revision B (September 2019) to Revision C (May 2021) **Page**

- Updated title....1
- Updated the numbering format for tables, figures, and cross-references throughout the document....1
- Added references to the LDC3114 device....1
- Updated application references for clarity....1

Changes from Revision A (April 2018) to Revision B (September 2019) **Page**

- Updated language for clarity throughout....1
- Added references to the LDC1001 device....1

Changes from Revision * (March 2015) to Revision A (April 2018) **Page**

- Added information on LDC0851 and LDC211x device performance....2
- Changed phrasing of various sections for better clarity....3
- Added details on calculation of R_P....3
- Added sensing range information on LDC0851 and LDC211x devices....11
- Added sensor capacitor placement guidelines for the LDC0851 and LDC211x devices....17