LDC0851 Stacked Coil Design Considerations

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ABSTRACT

The LDC0851 inductive switch uses two inductor coils as the sensor inputs that are either arranged side by side or stacked. A stacked coil design refers to placing two coils on top of each other, which can be a useful coil arrangement for minimizing PCB area or creating a unidirectional sensor. This application report discusses the benefits and tradeoffs of a stacked coil design, including key factors to consider when trying to maximize sensing range.

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1 Introduction

The LDC0851 is an inductive switch that uses two channels for sensing and comparing inductance, LSENSE and LREF. The sensors are typically constructed on a PCB as spiral inductors that are sensitive to the proximity of nearby conductive objects. These inductor coils can either be arranged side by side or stacked on top of another as shown in Figure 1.

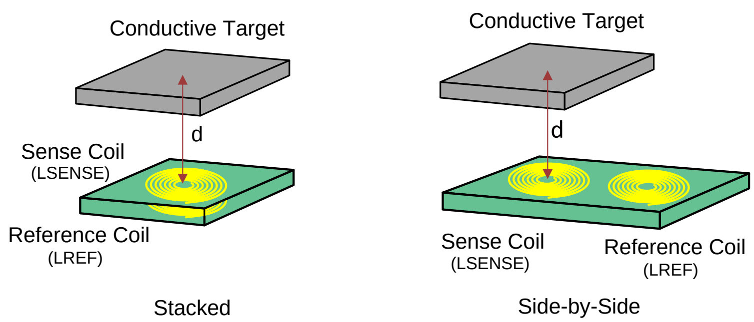

Figure 1. Stacked and Side-by-Side Coil Arrangements

A side-by-side coil arrangement is the most common, and it offers many advantages in terms of sensing range and ease of construction. If placing two coils side by side often requires more PCB space than is available, however, a stacked coil arrangement is preferred. A stacked coil configuration works with the LDC0851 more effectively than other LDC devices, because it internally disconnects the inactive channel instead of shorting it to ground. If the inactive channel was instead grounded or shorted, then a closed path would be created for eddy currents to form directly under the active sensing coil, which would dramatically reduce the sensing range.

2 Benefits and Tradeoffs of Stacked vs Side-by-Side Coils

2.1 Smaller PCB Area

The primary advantage that a stacked coil arrangement provides over a side-by-side arrangement is a smaller sensor footprint on the PCB. Components should not be routed or placed near the sensing coils to achieve the best sensitivity and channel-to-channel matching. The recommended keep-out distance is approximately ½ of the coil diameter length from the sensors. For a side-by-side arrangement, the minimum PCB area for routing the sensor is 2 coil diameters high and 3.5 coil diameters wide, whereas the stacked arrangement only needs 2 coil diameters high and wide as shown in Figure 2.

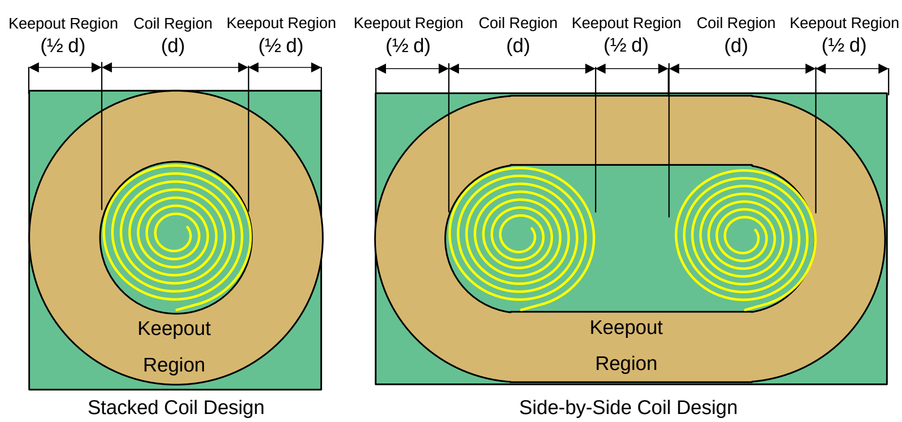

Figure 2. PCB Area Comparison for Stacked vs Side-by-Side Coils

2.2 Unidirectional Sensing

A unique advantage of placing the coils in a stacked arrangement is the possibility for a unidirectional sensor. This means that the LDC0851 will only switch states if a metal target approaches from the LSENSE side and will remain in the nominal state or OFF state if the metal approaches from the LREF side. A unidirectional sensor is created with the LDC0851 by using Threshold Adjust Mode to subtract a nominal offset from the LREF inductance and using a stacked coil configuration so that the LSENSE coil is always closer to the incoming metal than the LREF coil is as shown in Figure 3. This configuration ensures that the LSENSE inductance (LS) will only drop below the LREF inductance (LR) if the metal approaches from the LSENSE side, which creates the unidirectional switching behavior.

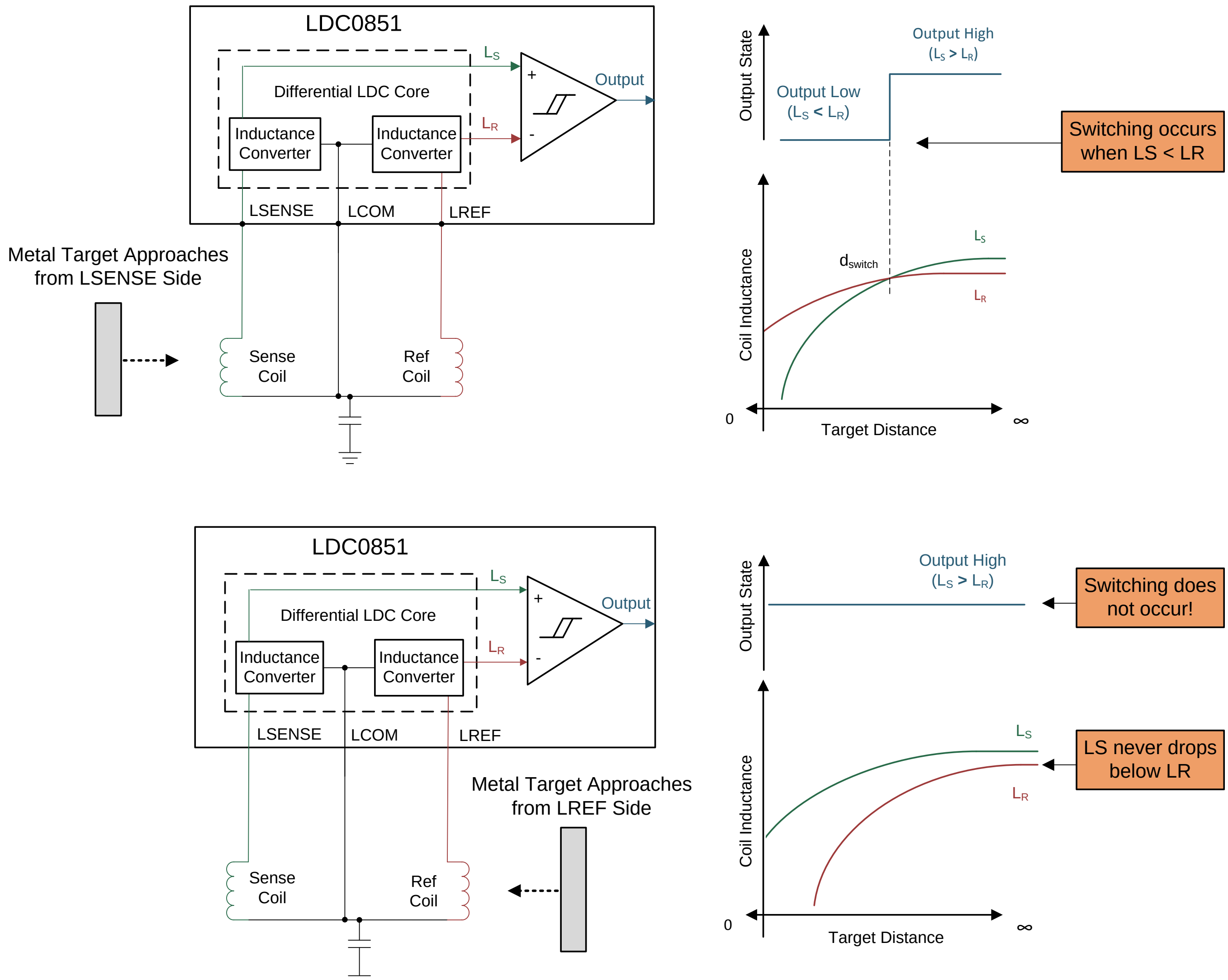

Figure 3. Unidirectional Sensing for Stacked Coils

A unidirectional sensor is especially useful for applications involving tamper avoidance or only detecting metal from a single side such as a door open / close. It is possible to use side-by-side coils with a metal shield under the coils to achieve the same effect, but the sensing range will be significantly reduced, however, compared to using a stacked coil approach.

2.3 Shorter Switching Distance

The longest switching distances for the LDC0851 are achieved by using side-by-side coils. A stacked coil configuration with good design can have a switching distance up to about 30% of the coil diameter whereas a side-by-side coil configuration supports up to 40%. This is because for a stacked coil design, both LSENSE and LREF coils sense the incoming metal target instead of only the LSENSE channel for the side-by-side case, as shown in Figure 1. This results in a smaller inductance difference at a given distance for stacked coils compared to a side-by-side design.

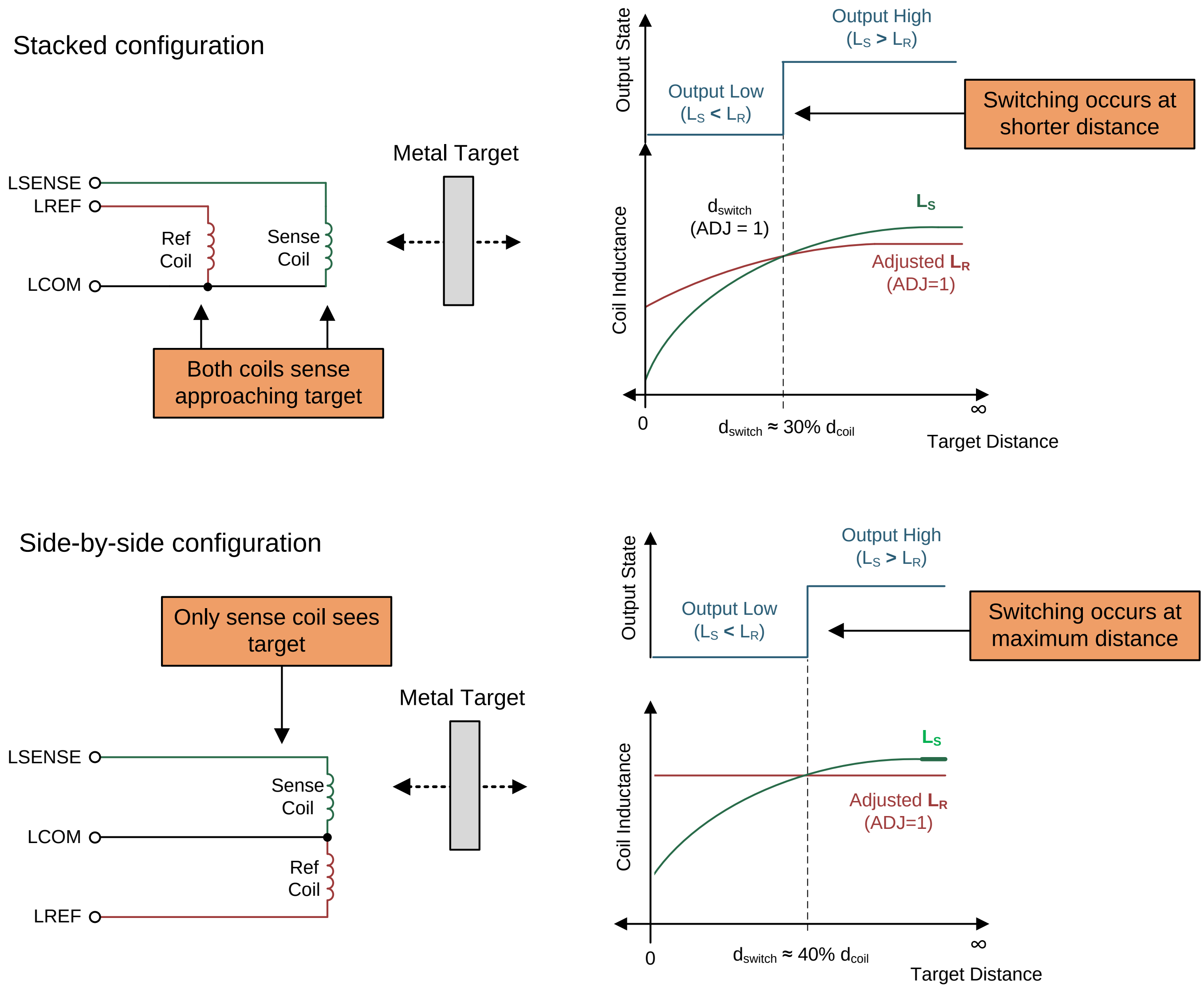

Figure 4. Stacked vs Side-by-Side Coil Switching Distance

It is important to note that the LDC0851 switches at a specific inductance ratio of LSENSE to LREF and not a specific distance which is the same regardless of the configuration. With an ADJ setting of 1, the output switches LOW when the value of LS / LR is less than 0.961 and returns HIGH when LS / LR is greater than 0.969. The Theshold Adjust Mode adjusts the nominal inductance value of LR (Adjusted LR) to be 3.6% lower than the true inductance value (LR) which effectively sets the switching distance to about 30-40% of the coil diameter depending on the configuration. For a stacked coil design, some of the coil parameters such as LSENSE-to-LREF coil spacing and PCB thickness can be tuned to get the maximum sensing range and this is discussed later in the application note, but the side-by-side arrangement will always achieve the maximum sensing range.

2.4 More PCB Layers Required

A PCB coil inductor requires at least two layers to construct the inductor as shown in Figure 5.

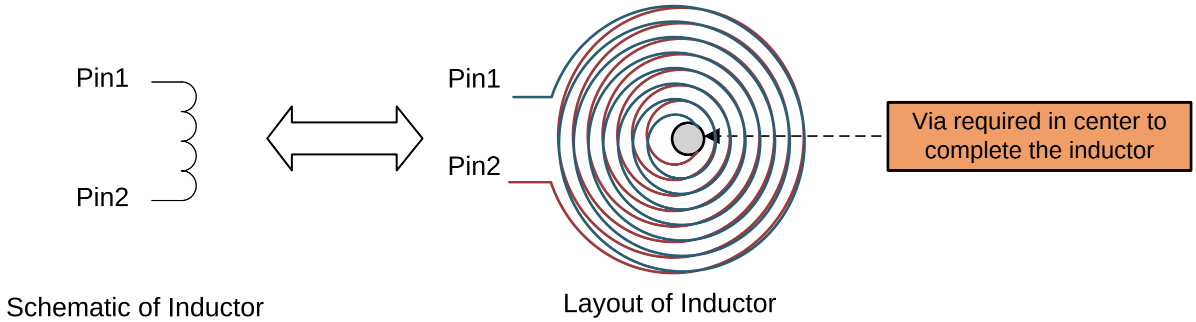

Figure 5. Schematic-Layout Equivalence of a PCB Inductor

For this reason, stacked coils typically require at least four PCB layers to build the coil arrangement, whereas a side-by-side arrangement can be constructed on as little as two layers as shown in Figure 6.

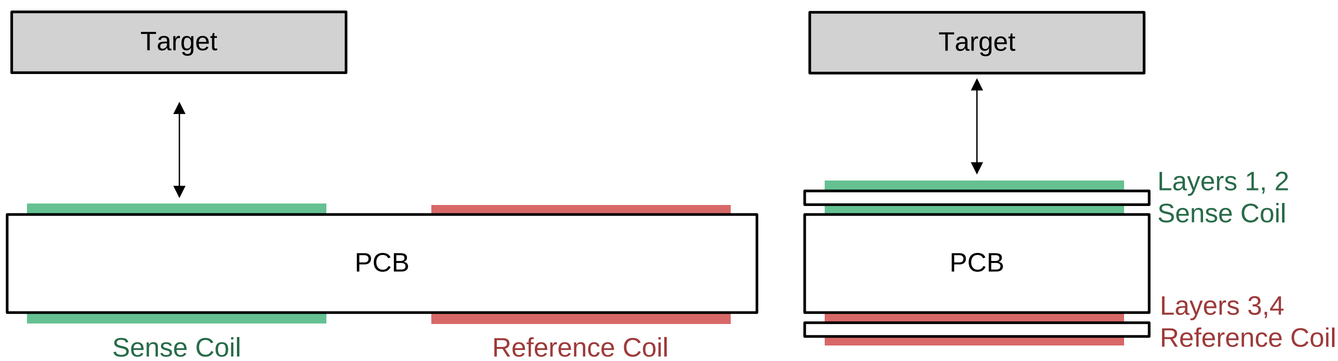

Figure 6. Number of Required PCB Layers for Side-by-Side and Stacked Coils

A 2-layer stacked coil design is possible, but it is an advanced technique that requires a larger PCB area than a 4-layer design, and it is much more difficult to ensure channel matching. For more information on the construction, see Section 3.5.

2.5 Decreased Temperature Robustness

The LDC0851 uses a single sensor capacitor for both channels and two well-matched PCB inductors, so the system inherently cancels out frequency shifts resulting from temperature shifts. However, it is important to note that the inductance is also a function of the separation or dielectric thickness of the layers, and the inductance value is affected by variations in thickness. Over temperature, the dielectric of the PCB can expand or contract, changing inductance of the coils slightly. This is not a concern for a side-by-side arrangement because both coils are constructed on the same layers with the same dielectric, so the expansion and contraction is seen evenly by both channels and this effect cancels out, providing a very stable switching point over temperature. In a stacked coil arrangement, the LSENSE and LREF coils are on different layers so there could be some variability in both the nominal layer thickness, as well as the behavior over temperature. In practice, it is more important to control the layer thickness tolerance during PCB fabrication because this will have a larger impact on the inductance matching and hence the switching distance repeatability board-to-board. The variation in inductance over temperature will be relatively small and should not produce a large mismatch because all layers will experience the temperature and expansion to some degree. The main caution is to ensure that there is not a large heat source on one side of the PCB or directly over one of the coils which would exaggerate the effect.

3 Stack Coil Design Considerations

3.1 Coil Orientation

Make sure to follow the data sheet's recommendations for stacked coil orientation. A 4-layer stacked coil orientation is shown in Figure 7. It is important that the orientation of the coils in the inner two layers where the LCOM connection meets is the same. This ensures that each channel only uses its designated two layers for the inductor instead of all four layers, which would otherwise result in electromagnetic coupling of active and inactive channels and could cause problems such as Inverted OUT pin behavior, decreased sensing range, or resonating at a frequency outside of the design space.

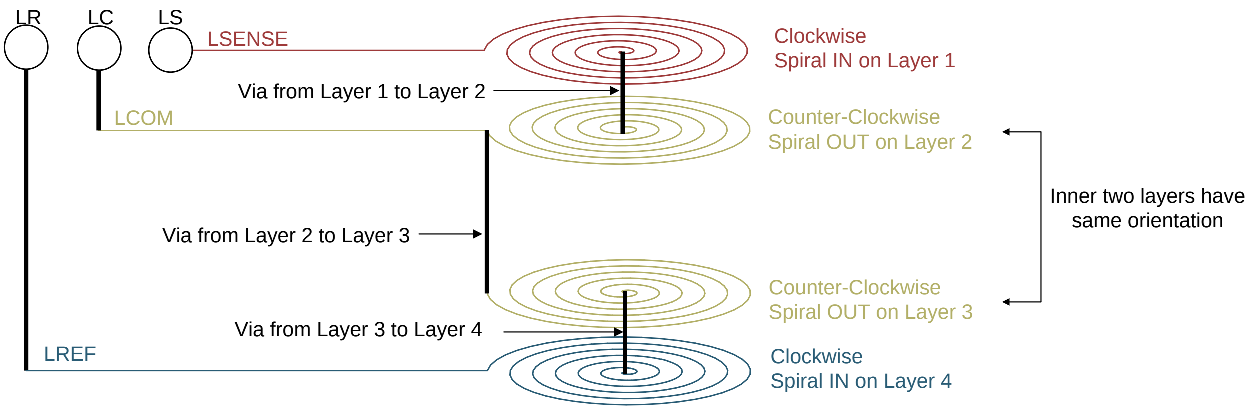

Figure 7. Stacked Coil Orientation for Four Layers

For some applications, an 8-layer coil design will be required to meet the minimum inductance of the LDC0851 sensor drive current. The same principle applies where the inner-most layers should have the same orientation. The 8-layer design is shown in Figure 8.

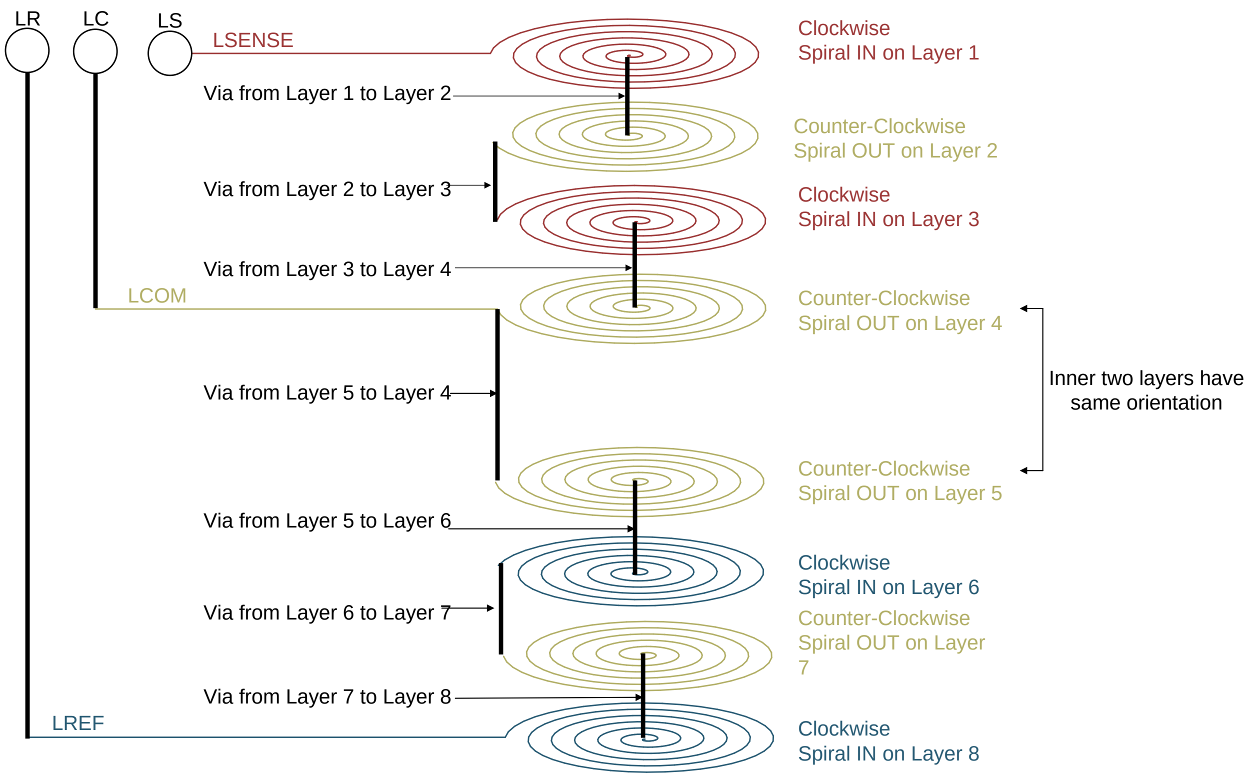

Figure 8. Stacked Coil Orientation for Eight Layers

3.2 Matching

Coil matching is critical to get the maximum sensing range for both a side-by-side and stacked coil arrangement. When using the ADJ setting of 1, the LDC0851 output switches low when the inductance ratio of LSENSE / LREF is less than 0.961 and switches high when LSENSE / LREF is greater than 0.969. This is roughly a 4% inductance shift for the output to switch low and then a 0.8% inductance hysteresis to switch off. For a good stacked coil design this translates to about 30% of the coil diameter for the switching distance. If the coils are mismatched by 1%, this could translate to the switching distance decreasing to 20%. Therefore it is important to follow the guidelines mentioned in this application note and to ensure good matching in the layout. The main source of mismatch is the routing between the sensors and the pins of the LDC0851. It is important to keep the trace routing symmetric in terms of length and not to induce additional parasitic capacitances by routing signals beneath the traces. Occasionally the sensor is located remotely from the main PCB and is connected by wires. In this case, use twisted pair and shielded cables if possible and keep the length to a minimum. This will ensure the greatest matching between the LSENSE and LREF channels and keep the switching distance consistent from board to board.

3.3 Sensor Separation

The PCB stackup and sensor separation has a large impact on the switching distance for a stacked coil design. It is important to minimize the amount of inductance shift that occurs on LREF when the metal is approaches the LSENSE coil because the LDC0851 switching point is determined by a fixed inductance ratio between LSENSE and LREF and not directly distance. Designs with a larger separation in distance between LREF and LSENSE will have a much larger separation in inductance for a given distance and hence longer switching distance than a design with thin separation as shown in Figure 9.

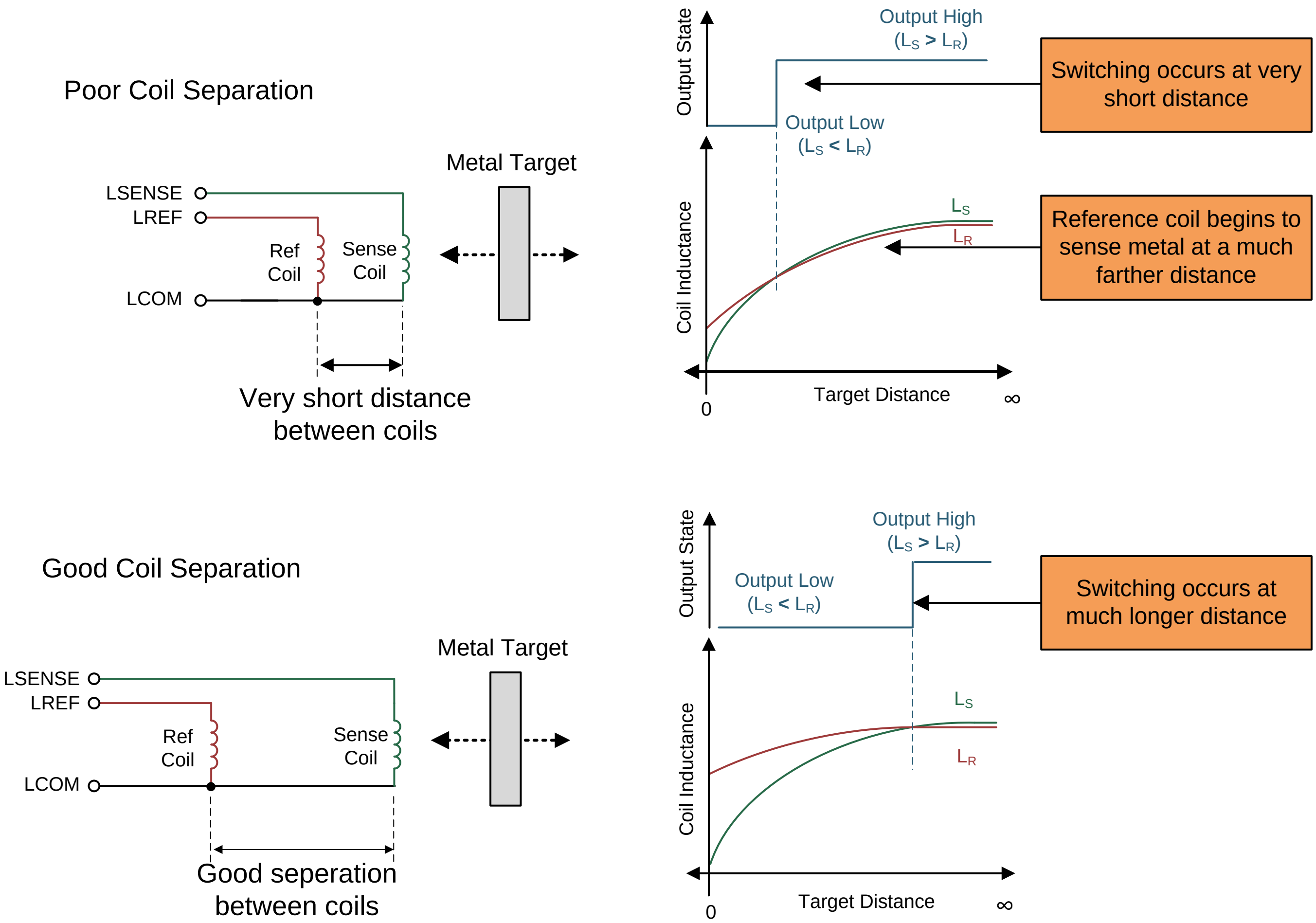

Figure 9. Effect of Poor vs Good Separation Between Coils

The critical parameter is the spacing between the closest layer of LREF to the metal target and the closest layer of the LSENSE layer to the metal target (d_{sep}) divided by the coil diameter (d_{coil}). Having a larger value of d_{sep} / d_{coil} translates to a farther switching distance. One simple way to increase this distance is to use a thicker dielectric in the PCB design denoted at "h" in Figure 10.

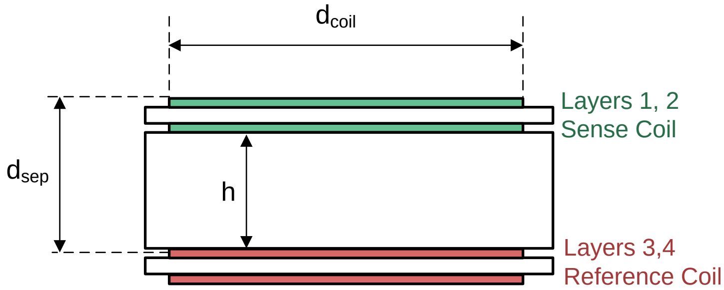

Figure 10. Key Dimensions for Stacked Sensor PCB Construction

Figure 11 shows how increasing the value of d_{sep} / d_{coil} can dramatically increase the switching distance. These results are shown for an ADJ setting of 1 where the target metal covers >200% of the coil diameter.

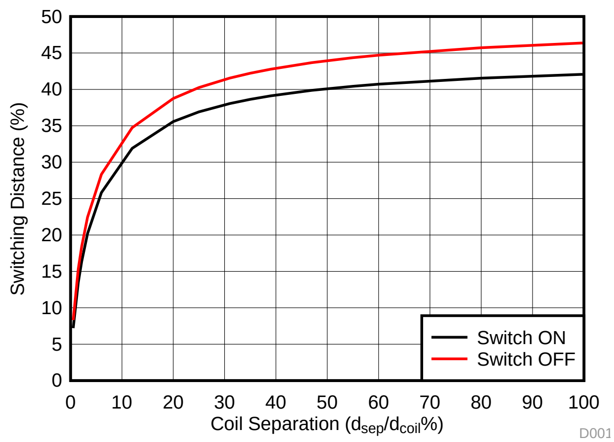

Figure 11. Switching Distance vs. Coil Separation

For example, the LDC0851EVM coil has a coil diameter of 20 mm and coil-to-coil separation of 1.2 mm which gives a value dsep / dcoil of 6%. Using Figure 11, the user can estimate about 25% switch on distance, or about 5 mm, which very closely approximates the actual behavior. For close switching distances less than 10 mm or so, a stacked coil design can work well, but it would require a very thick PCB to achieve comparable distances to a side-by-side coil approach as shown in Figure 12.

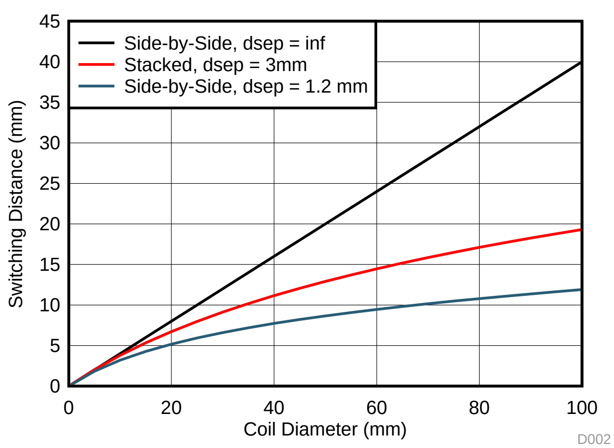

Figure 12. Switching Distance vs Coil Diameter

3.4 ADJ Code or Metal Reference

Typically the ADJ code is used to set the switching point. However, if ADJ = 0, then a metal target placed beneath the reference coil at a fixed distance can set the switching point as shown in Figure 13. The maximum sensing range could be upwards of 60-70% of the coil diameter away, but the metal reference target should be fixed in relation to the coils as to not cause the switching distance to move.

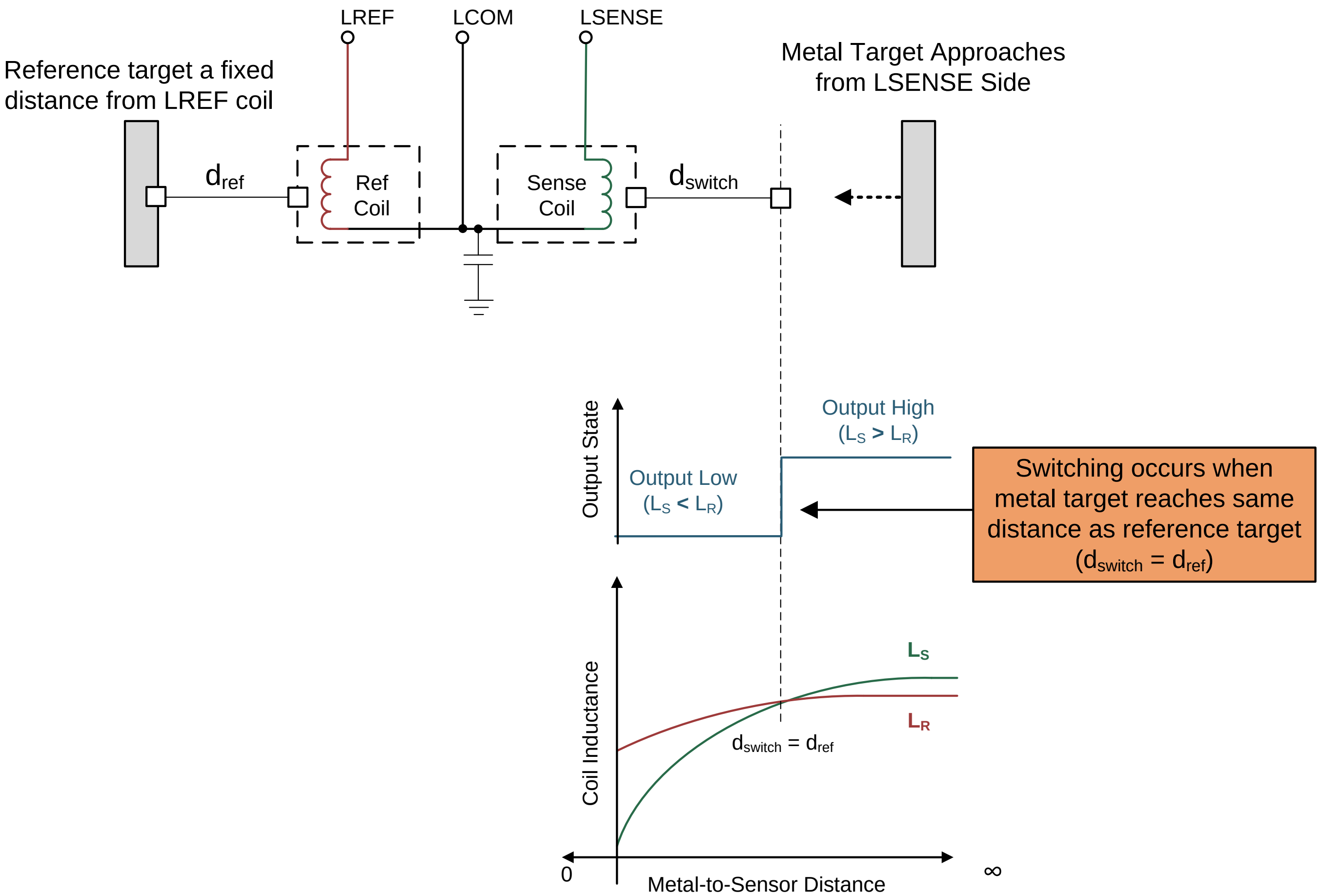

Figure 13. Fixed Distance Reference Target for Stacked Coils

3.5 2-Layer Stacked Coil Design

Many applications are limited to two layers due to cost restrictions. For these applications, a side-by-side coil arrangement is preferred because it is the easiest to design, but stacked coils can be used in 2-layer designs if there is enough PCB space available. The coils can be placed one inside the other as shown in Figure 14. The key point to note is that this technique is much more difficult to ensure good matching between the coils without simulation or iteration. Additionally the outer diameter needs to be much larger to accommodate the smaller inner coil to ensure that the minimum inductance is met for the LDC0851 design space. Many PCB vendors offer a low cost 2-layer PCB option with 5-mil trace width and 5-mil spacing. If using these geometries, the smallest 2-layer sensor that could be designed while maintaining the minimum inductance requirement for the LDC0851 is between 16 to 18 mm.

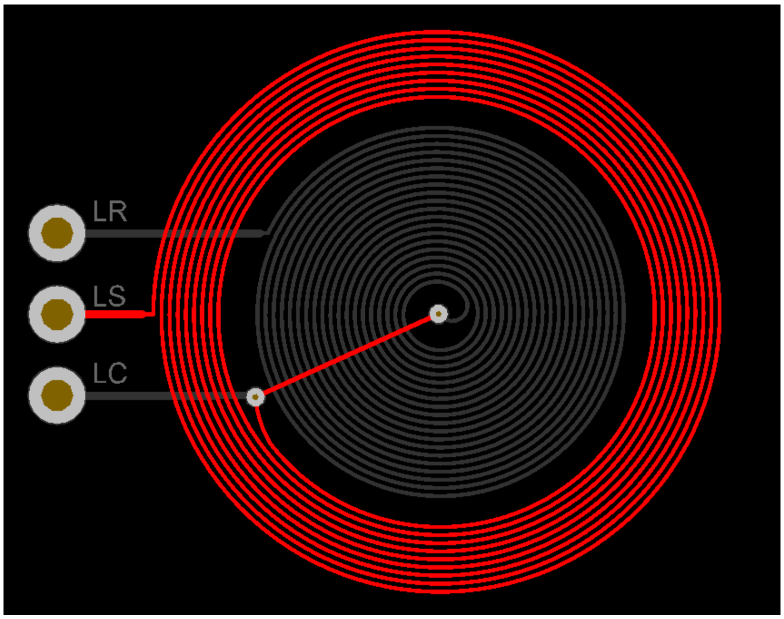

Figure 14. 2-Layer Stacked Coil, Top Layer (LSENSE)

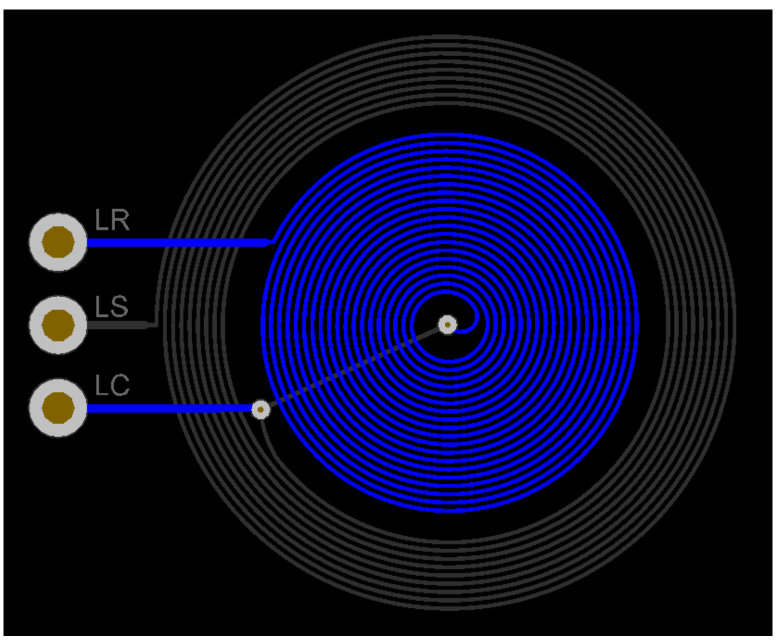

Figure 15. 2-Layer Stacked Coil, Bottom Layer (LREF)

3.6 WEBENCH® Tools

There is a WEBENCH® tool that has been optimized to design stacked coil designs for the LDC0851 and give an approximation of the switching distance. Refer to the following blog for a detailed design example using this tool: http://e2e.ti.com/blogs_/b/analogwire/archive/2016/12/13/inductive-sensing-make-your-proximity-switch-applications-are-as-easy-as-1-2-3-with-webench

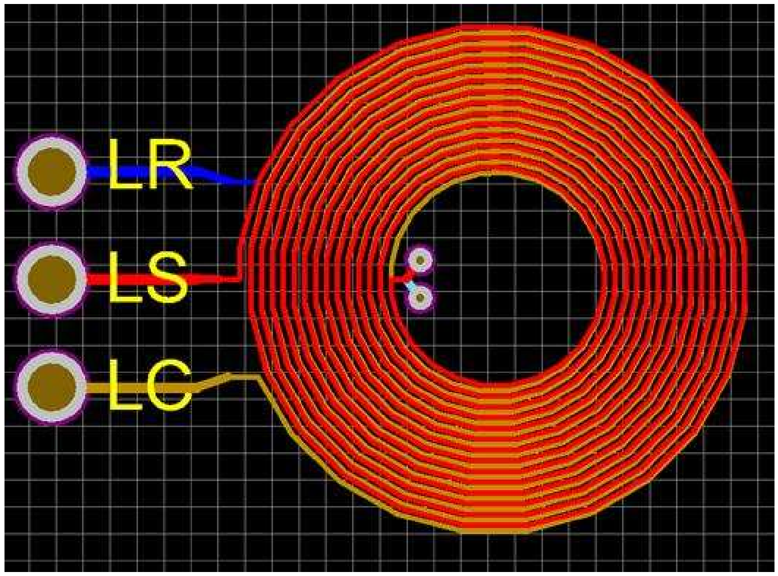

Figure 16. Example WEBENCH Coil Layout

4 Prototyping and Debugging

4.1 LDC0851EVM

The LDC0851EVM has been designed to include a 20-mm stacked coil by default which is useful for proximity sensing feasibility. The EVM also provides the option that the coil region can be disconnected and a custom coil can be attached for prototyping. Refer to the following blog for an example of using the LDC0851EVM and the LDCCOILEVM for this purpose:
http://e2e.ti.com/blogs_/b/analogwire/archive/2016/07/25/inductive-sensing-prototype-side-by-side-coils-in-four-easy-steps

The same technique can be used for testing stacked coils as shown in Figure 17.

Figure 17. Prototyping Stacked Coils With LDC0851EVM

4.2 Impedance Measurements

When measuring the impedance of the coils, it is important to leave the unused channel disconnected or floating. Figure 18 shows how to make the proper connections using the LSENSE inductance as the example.

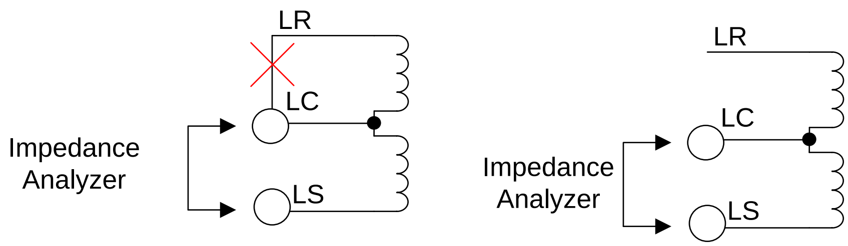

Figure 18. Coil Connections for Impedance Measurements

4.3 Impact of Nearby Metals

Nearby metal objects within approximately 100% of the coil diameter on either LSENSE or LREF side affect the matching and switching distance. In a side-by-side coil arrangement, metals that approach from the bottom or top will decrease both inductances equally which will leave the switching point relatively constant. For a stacked coil arrangement, the approaching metal unevenly affects the inductance of the two inputs. If the metal approaches from the bottom or LREF side it can reduce the switching point similar to principle shown in Figure 13. This is also the reason that ferrite materials cannot be used to shield the sensors in a stacked coil design because they skew the inductance matching. Additionally, ferrite materials tend to have a large variation in permeability across the surface of the material as well part-to-part matching which make them not well suited for use in stacked coil designs. In order to maximize the sensing range, interfering metals should be kept stationary or kept at least 100% of the coil diameter away.

5 Conclusion

Stacked coils have a number of benefits including small sensor PCB footprint and unidirectional sensing as highlighted in Table 1. However, if the user is not careful with the design, the switching distance can be much shorter than anticipated. By following the guidelines in this application note, the designer will be able to make a stacked coil layout with a maximized sensing range. If during the design analysis, it is determined that more distance is required then it may be beneficial to consider a side-by-side coil design especially when the coil diameter grows beyond 20 mm.

Table 1. Stacked Coil vs Side-by-Side Coil Summary

	STACKED COIL DESIGN	SIDE-BY-SIDE COIL DESIGN
Sensor PCB Area	Small / Compact	Larger
Unidirectional Sensing	Yes	No
Switching Distance	Shorter, best limited to <10 mm	Longer
2-layer PCB Design	Complex layout, harder to ensure matching	Easy, coils can be duplicated
Temperature Robustness	Good	Better
WEBENCH Tools Available	Yes	Yes

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