AN219207

Inductive Sensing Design Guide

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Associated Part Family: PSoC® 4700
Software Version: PSoC Creator™ 4.2 or later
Related Application Notes: For a complete list, click here.

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AN219207 shows how to implement inductive sensing using PSoC® 4700 MCU family and tune it for desired performance. Inductive sensors are based on the principle of magnetic induction and are used for detecting non-contact position of target metal. Cypress inductive sensing solutions bring elegant, reliable, and easy-to-use inductive sensing functionality to your product.

Contents

1 Introduction

Inductive sensing is a low-cost, robust solution that seamlessly integrates with existing user interfaces, and is also used to detect the presence of metallic or conductive objects.

This application note helps you understand:

- Inductive Sensing Overview
- Designing an Inductive Sensing System
- Use Cases of MagSense
- Tuning MagSense Component Parameters

This guide assumes that you are familiar with developing applications for PSoC 4 MCUs using the Cypress PSoC Creator™ integrated design environment (IDE). If you are new to PSoC 4, see AN79953, Getting Started with PSoC® 4.

1.1 PSoC 4700 Inductive Sensing Features

Inductive sensing in the PSoC 4700 MCU has the following features:

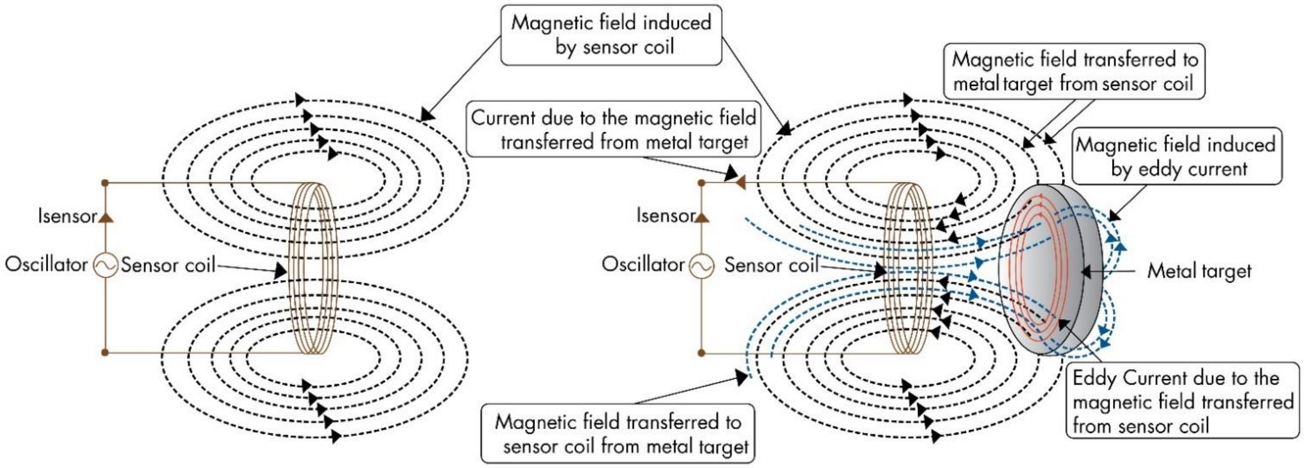
- Supports inductive sensing for excitation frequencies up to 3 MHz
- Operates at a measurement rate of up to 10 ksps
- Supports up to sixteen inductive sensor channels.
- Contains an integrated graphical tuner for tuning, testing, and debugging

2 Inductive Sensing Overview

Inductive sensing works on the principle of electromagnetic coupling between a sensor coil and the metal target to be detected. When the metal target enters the electromagnetic field induced by a sensor coil, some of the electromagnetic energy is transferred into the metal target as shown in Figure 1. This transferred energy causes a circulating electrical current called an eddy current. The eddy current flowing in the metal target induces reverse electromagnetic field on the sensor coil, which results in a reduction of the effective inductance of the sensor coil.

The sensor coil is placed in parallel with a capacitor. The parallel combination of sensor inductance and the external capacitor is called a tank circuit. The reduction in the sensor coil inductance causes an upward shift in the resonant frequency of the tank circuit. This shift in resonant frequency changes the amplitude of the signal across the sensor coil. The change in the amplitude of the sensor coil signal is measured by the PSoC 4 MCU to detect the presence of the metal target in the proximity-sensing distance. Note that the inductance of the sensor coil increases in the presence of ferromagnetic metal targets. An increase in the sensor inductance causes a down shift in the resonant frequency of the tank circuit.

Figure 1. Field Coupling Between Sensor and Metal Target



Typical applications for inductive sensing include the following:

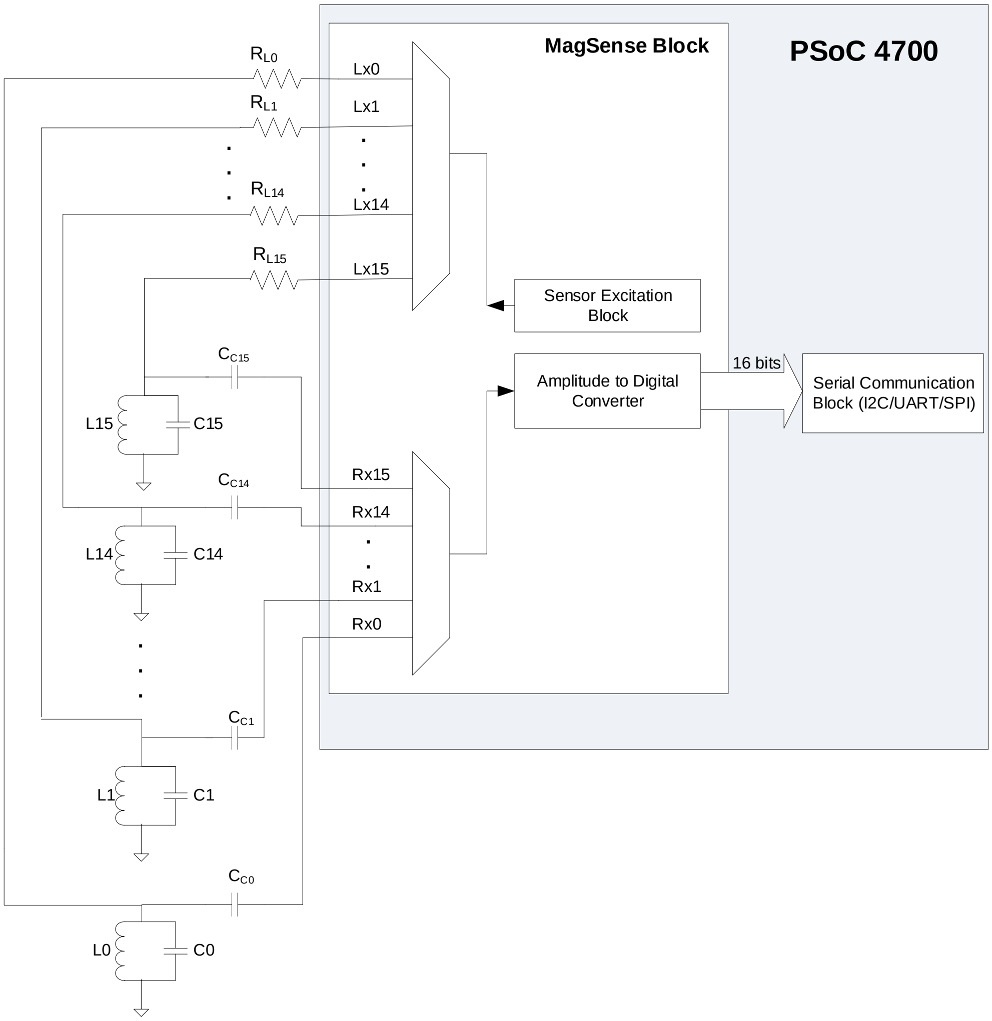
- Proximity detection
- Replacing mechanical open/close switches
- Buttons (industrial keypads and ON/OFF buttons)
- Rotation detection (flow meters, fan speed RPM detection, rotary control knob)
- Linear Encoder
- Spring compression detection

3 Designing an Inductive Sensing System

This section provides an overview of designing an inductive-sensing system. A block diagram of the inductive sensing system using a PSoC 4700 MCU is shown in Figure 2. A capacitor (C) is placed in parallel with the coil to create a parallel LC ‘tank’. The tank has a resonant frequency provided by the following equation:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad [1]$$

Figure 2. Block Diagram of the Inductive Sensing System with a PSoC 4700 MCU



The frequency of the Lx GPIO (sensor excitation pin) is set to the resonant frequency of the tank (f_0). This pin then drives the tank circuit through a resistor, R_{Lx}. The impedance of the tank circuit is the maximum at the resonant frequency, so a significant sinusoidal component with amplitude V_{Amp} (peak) appears across the tank circuit. This signal is AC-coupled into the Amplitude to Digital Converter through the capacitance C_C as shown in Figure 2 and is then converted into equivalent raw count. A change in inductance of the LC tank causes a change in V_{AMP} resulting in a change in the raw count of corresponding channels.

This system has the advantage that it excites the tank circuit to a known frequency. Multiple tanks can be set to resonate at different frequencies. Also, the frequency of operation of the tank circuit is controlled and can be designed for the best EMC performance.

The practical coil impedance is represented as an Inductance (L) with a series resistor (R_S) as shown in Figure 3.

Figure 3. LC Tank Resonance Circuit

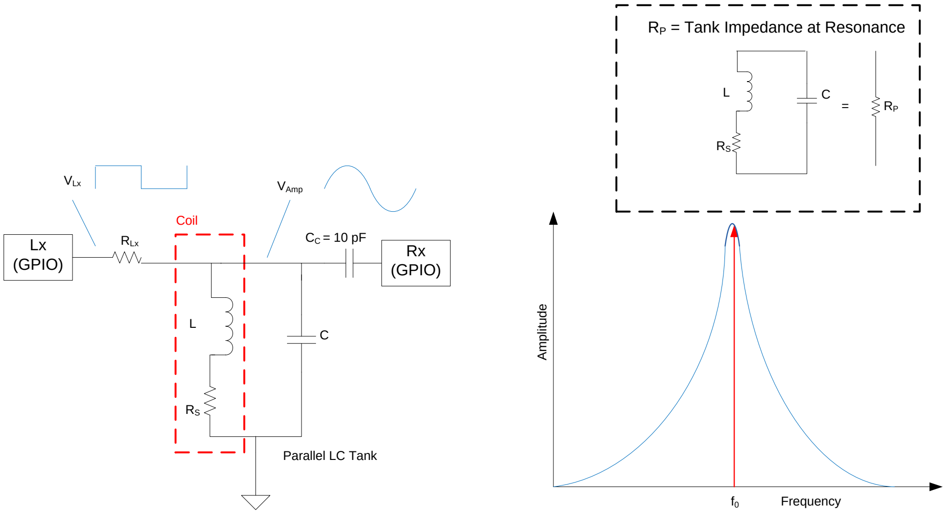


Figure 4 shows the steps for designing an inductive sensing system.

1. **Determine the design/size the coil:** Designing and sizing the coil required for your application is important. See Appendix A Sensor Design for further details.
2. **Determine/measure the inductance (L) and AC resistance (R_S) of the coil:** The coil inductance and AC resistance at a specific frequency can be measured with an LCR meter or estimated using a 2-D / 3-D coil modeling simulator. See section A.6.2 for example simulators. See the Sensor Design Spreadsheet section to calculate L and R_S.
3. **Choose C and f_0:** The resonant frequency of the tank (f_0) is set by Equation [2] considering the effect of AC resistance (**R_S**) of the coil. To select the resonant frequency, considering the coil parameters as well as the refresh rate and power consumption is important. Select the resonant frequency (f_0) in the range of 45 kHz to 3 MHz and select a discrete capacitance (C) that satisfies Equation [2].

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{(LC)} - \left(\frac{Rs}{L}\right)^2} \qquad [2]$$

4. **Determine the equivalent tank impedance (R_P) at resonance:** The impedance of the tank at resonance is required to determine R_{Lx}, the resistor in series with Lx pin. Use Equation [3] to estimate the value of R_P. See section A.2.1 for the details of R_S, the AC series resistance of coil.

$$R_P = \frac{1}{R_S}\,(2\pi f_0 L)^2 \qquad [3]$$

5. **Determine R_{Lx} and Cc:** The value of R_{Lx} can be found by substituting Equation [3] with Equation [4]. The value of C_C can be chosen based on the value of V_{AMP}. See Table 1 to select C_C. Higher value of V_{AMP} provides better SNR.

$$R_{Lx} = R_P * \left(\frac{VDDA}{V_{AMP}} - 1\right) \quad [4]$$

Where V_{DDA} = power supply voltage.

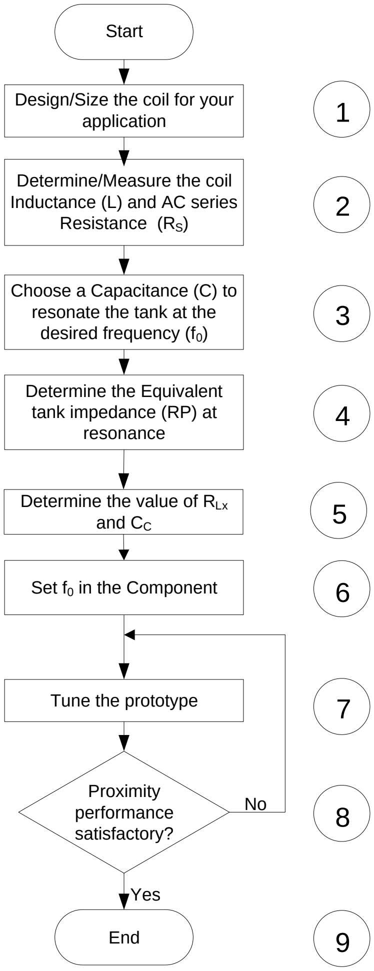
Table 1. Selection of C_C

V_{AMP} (V)	C_C (pF)
0.6	33
1.2	22
1.8	10

See Tuning Calculator to calculate the values of R_{Lx} and C_C.

6. **Set f_0 in the MagSense™ Component:** Set the value of f_0 from Equation [2] in the MagSense Component.
7. **Tune the prototype:** Tune the prototype board to achieve the required performance. See Tuning MagSense Component Parameters for more details. After tuning the sensor, check whether the inductive sensor performance meets your requirements. If the requirements are met, proceed to Step 9; otherwise continue with Step 8.
8. **Re-tune or redesign if necessary:** If the inductive sensor does not provide the required performance after you have set the optimum parameters, increase the sensor size or reduce the noise in the system by shielding the sensor from noise sources and repeat Step 7.
9. **End:** If the Inductive sensor meets the required performance, integrate it with your product.

Figure 4. Tuning Flow for Inductive Sensing Applications



4 Use Cases of MagSense

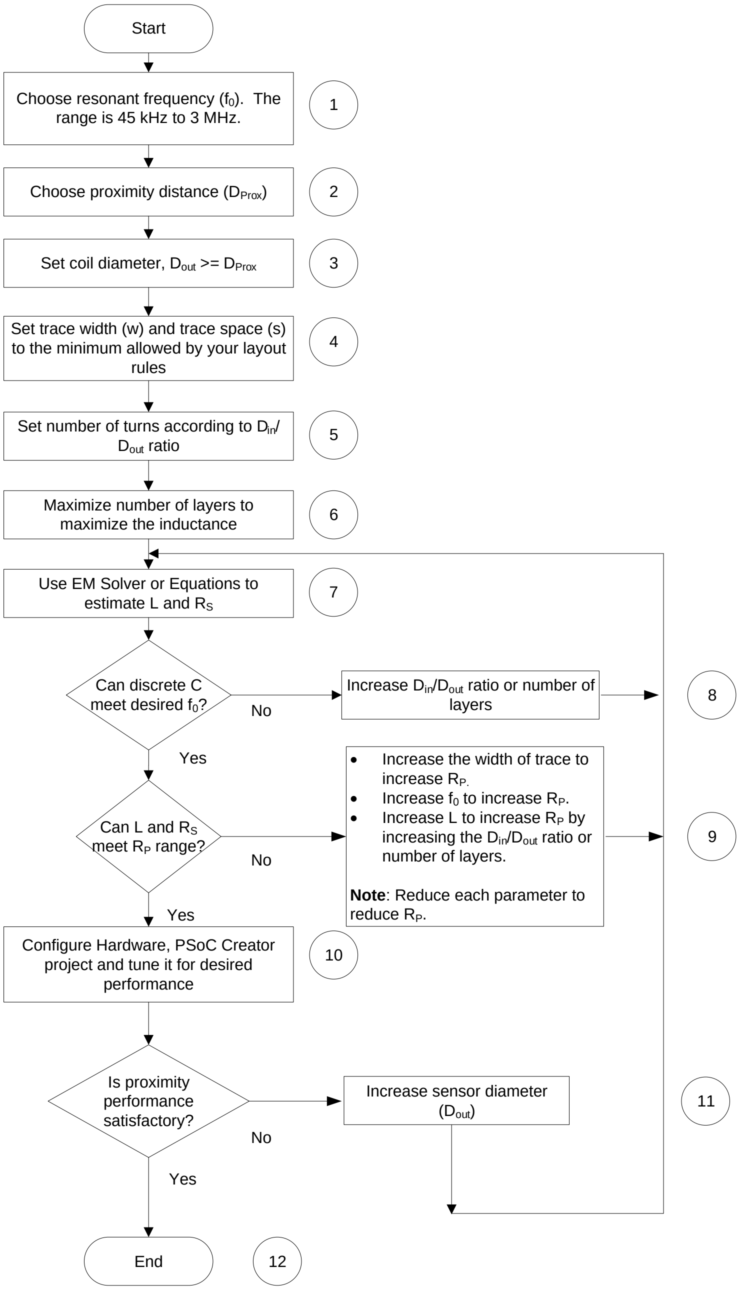
This section discusses the following use cases of MagSense based on PSoC 4700 MCU:

- Proximity Sensing
- Metal over Touch
- Rotary Encoder

4.1 Design Inductive Proximity Sensing System

The recommended sensor design flow for proximity application is outlined in Figure 5.

Figure 5. Sensor Design Flow



The detail of each step, shown in Figure 5 is outlined as follows:

1. **Choose f_0:** Choose the resonant frequency that best suits the system. The supported range is 45 kHz to 3 MHz.
2. **Choose proximity-sensing distance:** Determine the proximity-sensing distance (*Dprox*) needed by the system.
3. **Choose the Coil Diameter:** Set the coil diameter (*Dout*) to be greater than or equal to *Dprox*.
4. **Set Trace Width/Space:** Set the trace width (w) and space (s) to a minimum for the PCB design technology you are using.
5. **Set the number of turns:** Set the number of turns according to the *Din/Dout* ratio that you need. A guideline is to set *Din/Dout* > 0.3. A higher ratio will decrease L, but can improve sensitivity when sensing objects that are at a distance of the coil diameter from the coil.
6. **Maximize the number of layers:** Setting the number of layers to a maximum and choosing a series connection between layers will maximize the inductance and therefore, maximizes R_P to reduce coil loss.
7. **Calculate L and R_S:** Calculate the inductance (L) and the AC series resistance (R_S) at the resonant frequency (f_0) by using either an EM solver or Equations [19] and [20]. See the Sensor Design Spreadsheet section to calculate L and R_S.
8. **Optimize L:** Determine whether the value of L satisfies the chosen f_0 using Equation [2] for an available discrete capacitance, C. If not, you should optimize the Din/Dout ratio or the number of layers.
9. **Optimize R_P:** Calculate R_P from Equation [3]. If it does not satisfy the R_P range of 350 to 50,000 (see Figure 33) consider the following:
    a. **Increase R_P:** Increase R_P by increasing w, s, f_0, or L.
    b. **Decrease R_P:** Decrease R_P by decreasing w, s, f_0, or L
10. **Configure Hardware, PSoC Creator project, and tune it for desired performance:** Configure the hardware. Create a PSoC Creator project and tune it for desired performance. See the Tuning MagSense Component Parameters section to optimize SNR.
11. **Check the proximity-sensing distance:** Measure the proximity-sensing distance. If the proximity performance is not satisfactory, consider increasing the diameter of the sensor.
12. **End:** The proximity-sensing performance is satisfactory.

4.1.1 Sensor Self-Resonant Frequency (f_{SR})

The inductor itself has a parasitic capacitance due to the inter-winding capacitance of the coil. At a certain frequency, this parasitic capacitance resonates with the sensor inductance. A rule of thumb is to keep the sensor frequency (f_0) less than three times lower than the self-resonant frequency (f_{SR}) of the coil.

$$f_0 < 3 \cdot f_{SR} \qquad [5]$$

The self-resonant frequency can be measured with an impedance meter.

4.1.2 Additional Considerations

As a designer, you may require additional tuning when implementing inductive sensing:

- **Achieving a large distance:** A larger distance is achievable with a larger diameter coil.
- **Tuning R_{LX} for correct tank amplitude:** The tank amplitude (V_{AMP}) is determined by R_P of the tank at resonance and R_{Lx}, the drive resistance. If the measured tank amplitude differs from the calculated value, then R_{Lx} can be changed to bring the amplitude back to meet expectations. As the first step, use Equation [6] to estimate the actual R_P (R_{P_ACT}). Next, put the R_{P_ACT} value into Equation [7] to estimate the new value for R_{LX}.

$$R_{P\_ACT} = \frac{V_{AMP\_ACT} \cdot R_{Lx}}{(VDDA - V_{AMP\_ACT})} \qquad [6]$$

Where,

R_{P_Act} = actual (measured) value of R_P

V_{AMP_ACT} = actual (measured) tank amplitude

VDDA = power supply voltage

$$R_{Lx\_New} = R_{P\_ACT}\left(\frac{VDDA - V_{AMP}}{V_{AMP}}\right) \qquad [7]$$

R_{Lx_New} = new value of R_{Lx}

V_{AMP} = desired tank amplitude

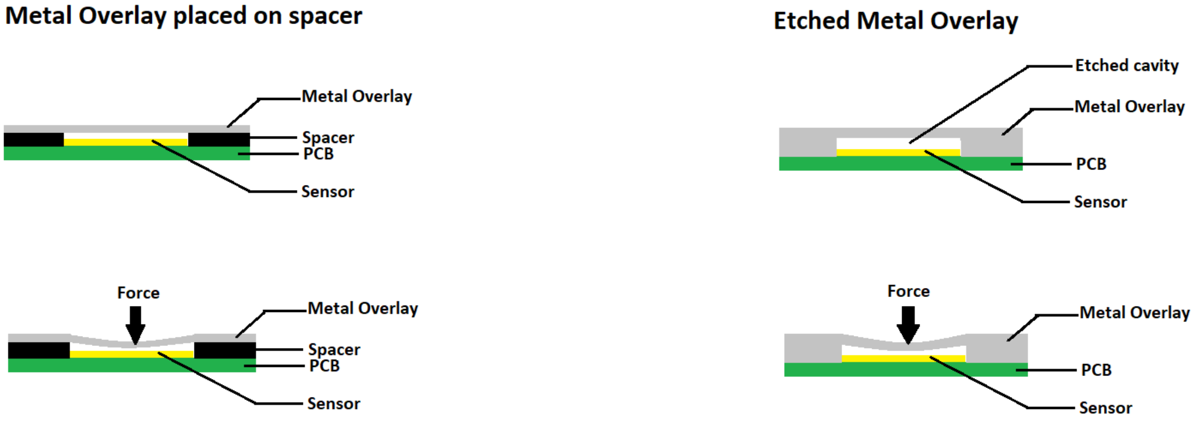
4.2 Design Metal Over Touch (MoT) System

Metal over Touch (MoT) involves detecting the deflection of a metal overlay upon a touch. MoT uses a metal overlay separated from the sensor using a thin spacer or etched surfaces of metal overlay as shown in Figure 6. When you touch the metal, the metal deflects. This deflection is detected by the inductive sensor. Figure 7 shows an example of front and back (with etched cavities) of a metal overlay. The sensitivity of touch detection depends on the following parameters.

- Amount of metal deflection
- Sensor dimensions
- Spacer thickness or depth of etched cavity
- Applied force

Note that the amount of metal deflection for the applied force depends on metal material, thickness, and flexural rigidity.

Figure 6. Metal Over Touch Arrangement



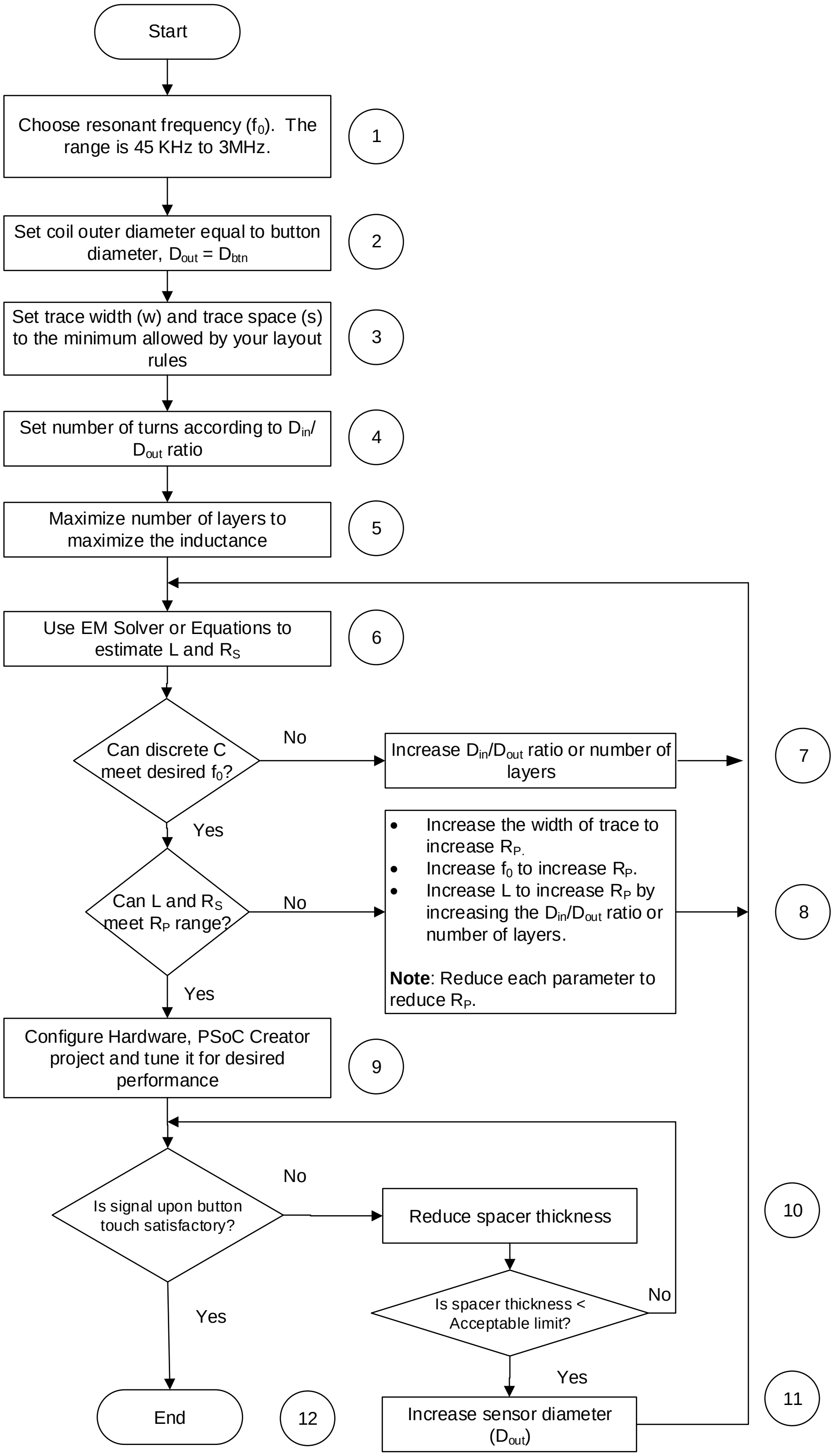
Metal Overlay placed on spacer

Etched Metal Overlay

Figure 7. Example Metal Overlay

The design of MoT involves the design of the sensor and the mechanical placement of the metal overlay. The sensor design flow is shown in Figure 8.

Figure 8. Sensor Design Flow of MoT



1. **Choose f_0:** Choose the resonant frequency that best suits the system. The supported range is 45 kHz to 3 MHz.
2. **Choose the Coil Diameter:** Set the coil diameter (*Dout*) to be equal to button diameter *Dbtn*.
3. **Set Trace Width/Space:** Set the trace width (w) and space (s) to a minimum for the PCB design technology you are using.
4. **Set the number of turns:** Set the number of turns according to the *Din/Dout* ratio that you need. A guideline is to set *Din/Dout* > 0.3.
5. **Maximize the number of layers:** Set the number of layers to a maximum and choose a series connection between layers to maximize the inductance and therefore, maximize R_P to reduce coil loss.
6. **Calculate L and R_S:** Calculate the inductance (L) and the AC series resistance (R_S) at the resonant frequency (f_0) by using either an EM solver or Equations [19] and [20]. See the Sensor Design Spreadsheet section to calculate L and R_S.
7. **Optimize L:** Determine whether the value of L satisfies the chosen f_0 using Equation [2] for an available discrete capacitance, C. If not, you should optimize the *Din/Dout* ratio or the number of layers.
8. **Optimize R_P:** Calculate R_P from Equation [3]. If it does not satisfy the R_P range of 350 to 50,000 (see Figure 33) consider the following:
   a. **Increase R_P:** Increase R_P by increasing w, s, f_0, or L
   b. **Decrease R_P:** Decrease R_P by decreasing w, s, f_0, or L
9. **Configure Hardware, PSoC Creator project, and tune it for desired performance:** Configure the hardware. Create a PSoC Creator project and tune it for desired performance. See the Tuning MagSense Component Parameters section to optimize SNR.
10. **Check the touch performance:** Measure the signal upon button touch and SNR. If the button performance is not satisfactory, consider reducing the spacer thickness.
11. **Increase sensor diameter:** If the spacer thickness becomes less than the acceptable limit, consider increasing the sensor diameter D_{out} and measure the performance of button touch.
12. **End:** The button performance is satisfactory.

5 Mechanical Design

For proper operation of the button, the PCB with the sensormust be fixed at a uniform offset from the metal surface. If the PCB is not held firmly, it could move or vibrate away from the metal surface, which could cause a false trigger of the buttons.

In most of the applications, the sensor coil can be part of the main PCB and mounting holes can be used to align the sensor to the outline of the metal button. The gap or spacing between the metal and the PCB will have the largest impact on the performance of the MagSense Button. Therefore, it is very important to have proper mechanical arrangement for proper MagSense button operation.

The mechanical factors affect the performance of the MagSense button:

- Target material selection
- Target thickness
- Target Conductivity
- Button Geometry
- Spacing between sensor and target

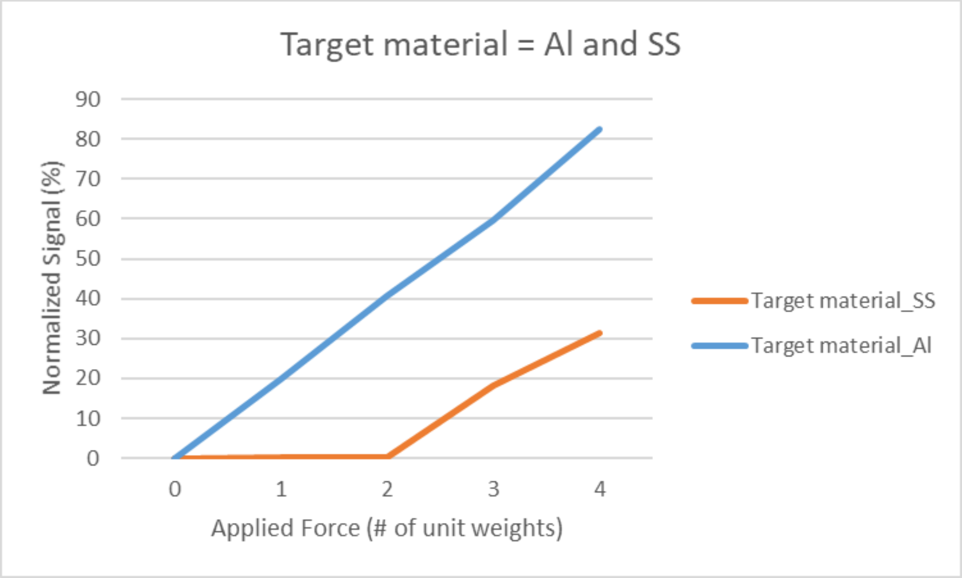
Note: To remove the dependency on the device setting that is used to tune for the given mechanical arrangement and to evaluate the impact of deflection performance between various mechanical arrangements, the parameter “Normalized Signal” is defined as below. This parameter represents the relative reflection of the target with respect to the deflection caused by the maximum force applied.

$$Normalized\ Signal = \frac{(Avg\ Rawcount\ with\ weight - Avg\ Rawcount\ without\ weight)}{(Avg\ Rawcount\ for\ max\ weight - Avg\ Rawcount\ without\ weight)} * 100$$

5.1 Target Material Selection

The amount of deflection for the given force at a distance depends on the elasticity of the target material. The Young's modulus of the material is the measure of elasticity of the material. Materials with lower Young's modulus are more flexible. Aluminum (AL6061-T6) and stainless steel (SS304) are the two commonly available materials that can be used as the target materials. Aluminum has Young's modulus of 68.9 GPa while stainless steel has Young's modulus of 203 GPa. Using aluminum as the target material provides more sensitivity for the given force compared to stainless steel, whereas using stainless steel as the target material brings in robustness to the touch application. Figure 9 shows the comparison of the normalized signal between aluminum and stainless steel targets.

Figure 9. Impact of Target Material on Normalized Signal



5.2 Target Thickness

Target thickness is one of the factors that affect deflection of the target for the applied force. The target with lesser thickness deflects more for the given force. Figure 10 shows the comparison of Normalized Signal for two different target thicknesses.

Figure 10. Impact of Target Thickness on Normalized Signal

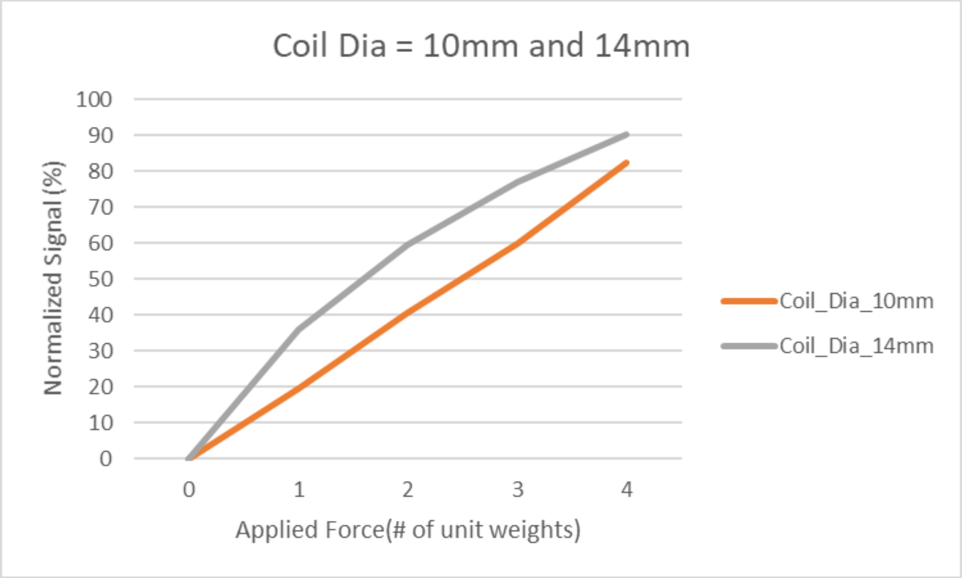
5.3 Material Conductivity

The change in the inductance of the sensor for a given target deflection depends on the conductivity of the target material as well. The material with higher conductivity has more induced eddy current on the surface of the target and therefore making more change in the sensor inductance for the given deflection of the target. Aluminum and stainless steel have a conductivity of 36.9×10^6 S/m and 1.37×10^6 S/m respectively. As aluminum has more conductivity and less Young’s modulus compared to stainless steel, aluminum is well suited for the inductive button application while stainless steel may be preferred in the case of robust button applications.

5.4 Button Geometry

The geometry of the inductive button (circular or rectangular, for example) is one of the factors that affects the performance of the button. For example, a circular button with 14-mm diameter will have more deflection than a button with 10-mm diameter. Figure 11 shows the comparison of Normalized Signal for two different button diameters.

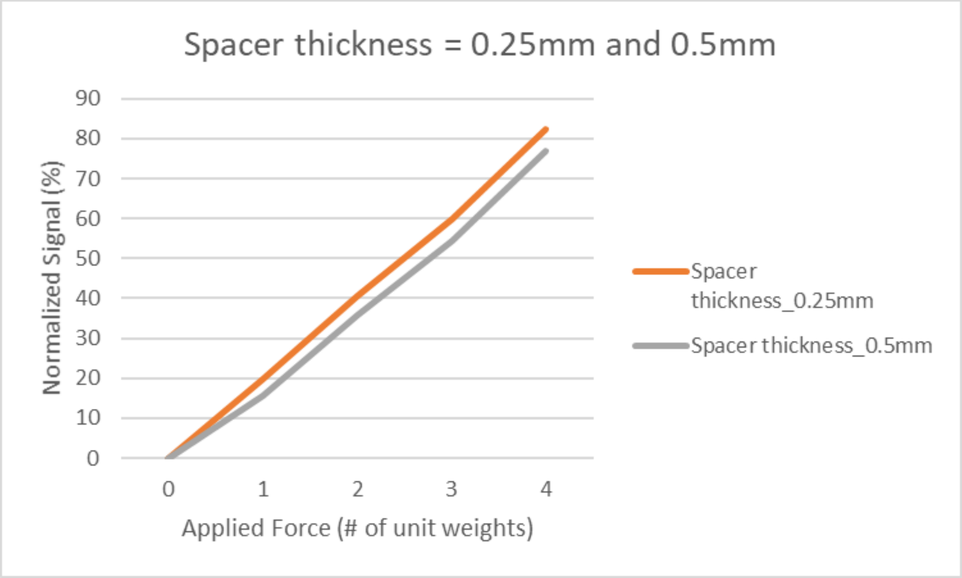
Figure 11. Impact of Coil Diameter on Normalized Signal



5.5 Spacing Between Sensor and Target

The distance of separation between the sensor and the target is also a parameter that affects the performance of the MagSense button. A uniform distance of separation between the sensor and target is established using a non-conductive spacer. Figure 12 shows the comparison of Normalized Signal for two different spacer thicknesses. As seen in the following plot, the smaller the spacer thickness, the better the Normalized Signal because the target is placed in the most sensitive region of operation from the coil.

Figure 12. Impact of Spacer Thickness on Normalized Signal



5.6 Methods of Mechanical Mounting

There are two methods for mounting the target separated from the sensor:

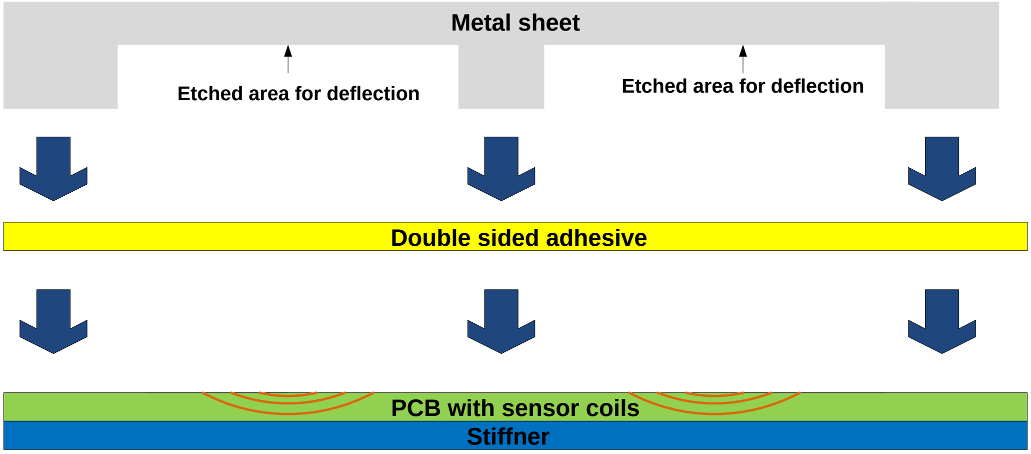
- Fixed edge support
- Simply supported

5.6.1 Fixed Edge Support

This method involves providing a metal panel with an etched area directly beneath the button on the bottom of the panel, which can be created by either milling or etching a cavity into the metal panel, as shown in Figure 13. In this case, the left-over areas act as standoffs that support the PCB and ensure that there is room for metal deflection above the sensor coil. Double-sided adhesive (such as 3M 300LSE adhesive tape), or epoxy can be used to attach the PCB to the metal panel.

If you use adhesive tape, bubbles in the adhesive can cause a non-uniform button response and potentially cause false detections. These air bubbles can be removed by using adhesive with micro-channels. When the button is touched, there is a chance that the PCB bends and causes false trigger. To minimize the effect of PCB bending, a stiffener can be added to the bottom side of the PCB as shown in Figure 13.

Figure 13. Fixed Edge Support



5.6.2 Simply Supported

A plastic spacer with cutouts can be placed between the metal panel and the PCB. This approach is useful in systems where a flat sheet of metal is used, and it is not possible to do additional cutouts or milling to the metal. The spacer provides the necessary air gap between the metal sheet and the sensor to allow for deflection. Therefore, the cut-outs are of the same dimension and location as the button itself.

When the button is touched, there is a chance that the PCB bends and causes a false trigger. To minimize the effect of PCB bending, a stiffener can be added to the bottom side of the PCB as shown in Figure 14.

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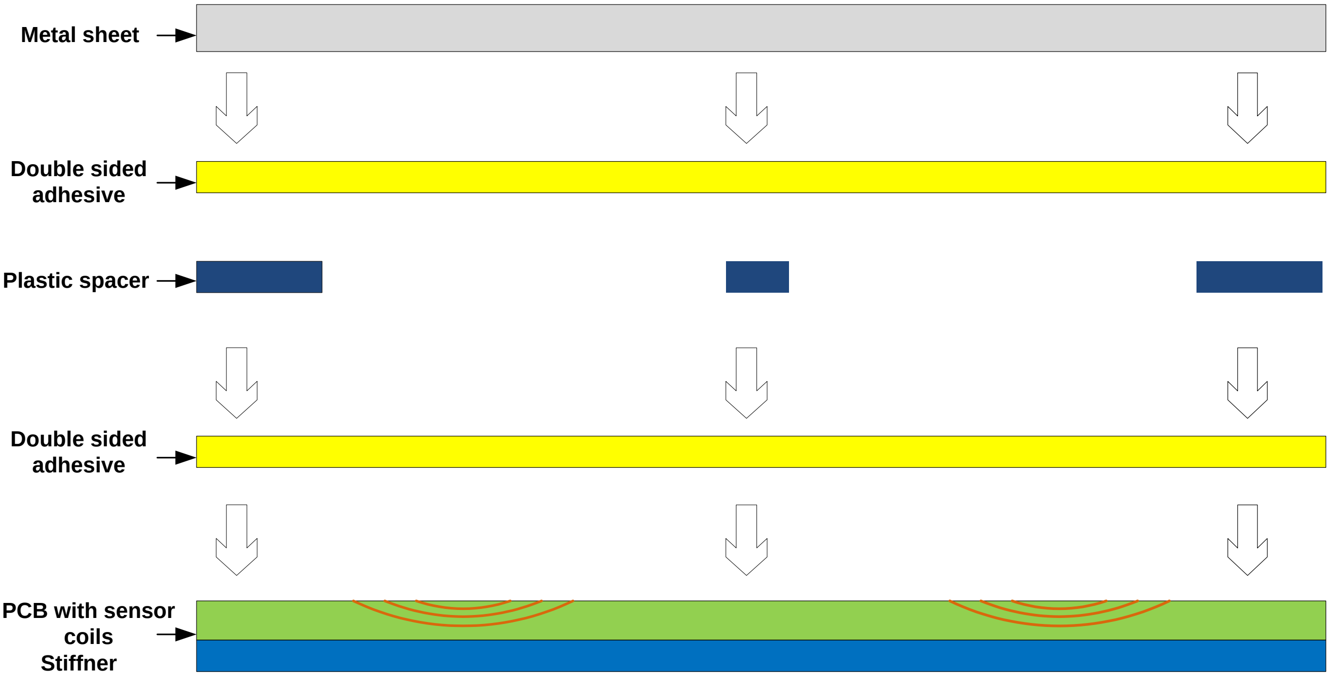
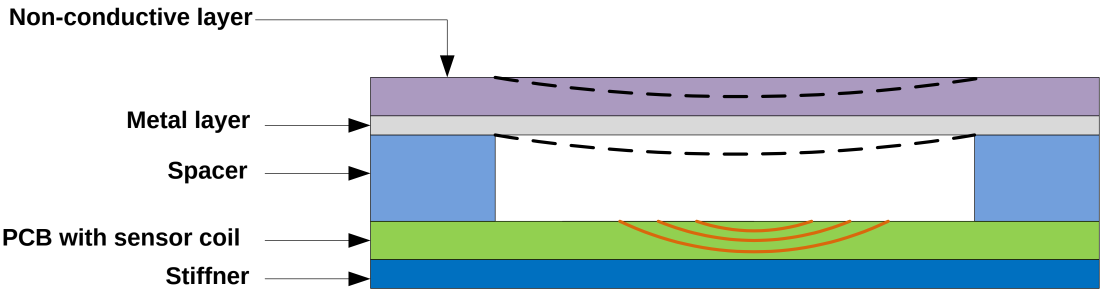
Figure 14. Simply Supported



5.7 Touch Over Non-conductive Overlays

In some applications, it is desired to have a non-conductive overlay. In such cases, a thin layer of metal can be affixed on the inner surface of the non-conductive layer and can be separated from the sensor coil using spacers as shown in Figure 15.

Figure 15. Touch Over Non-conductive Overlay



The dashed lines in Figure 15 shows deflection in non-conductive layer and metal layer.

5.8 Isolation of Buttons

In a multi-button system, the mechanical disturbance from the adjacent button can cause false trigger on the given button. To minimize the mechanical disturbance caused by the adjacent buttons, it is very important to provide proper isolation between the buttons. The following techniques can be used to provide proper mechanical isolation between the buttons.

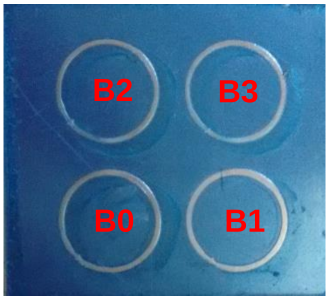
- Provide a groove around the button to allow the metal over the button to deflect more with reduced mechanical interference on the adjacent buttons.
- Use a thin metal target to allow it to deflect more for the button press which reduces the unintended deflection for the adjacent buttons.

- Separate adjacent coils at least by a distance equal to half the coil diameter.

5.9 Example MagSense Button Systems

An example 4-button system with 0.75 mm Aluminum target thickness, 0.25 mm spacer thickness, and 10 mm sensor outer diameter is shown in Figure 16.

Figure 16. Example 4-button System



Due to mechanical disturbance from adjacent buttons, there is a chance for the given button to get false triggered. By isolating each button from adjacent buttons using groves around the button and by reducing the sensitivity of the buttons using Lx clock frequency, number of sub-conversions and finger threshold parameters, you can achieve an optimum inductive button system that has more immunity for mechanical disturbance from adjacent buttons. The cross-sensitivity matrix of buttons for the given multi-button system can be used to tune the finger threshold of given button in Firmware to avoid the false trigger caused by adjacent buttons. The cross-sensitivity matrix (Table 2) provides the probability of the given button to get false triggered by the adjacent buttons. For example, the following table provides the cross-sensitivity matrix for a 4-button system.

$$\text{Probability for given Button to get false triggered by adjacent Button} = \frac{Interference\ Signal\ from\ adjacent\ Button}{Finger\ threshold\ of\ given\ Button}$$

Table 2. Cross-sensitivity Matrix

	By BTN1	By BTN2	BTN3
Probability for BTN0 to get false triggered	0.33	0.18	0

	By BTN0	By BTN2	BTN3
Probability for BTN1 to get false triggered	0.58	0.27	0.4

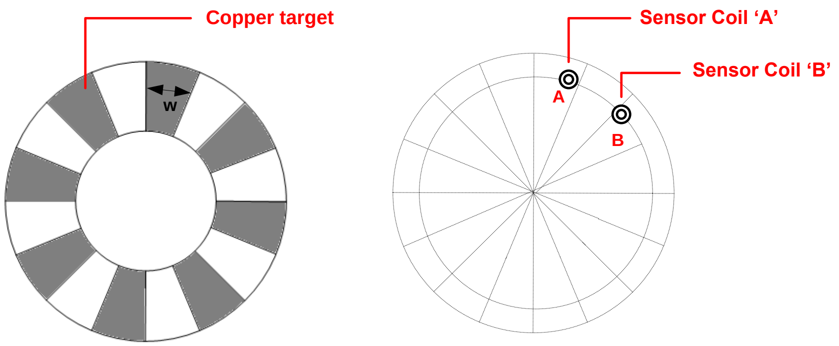
	By BTN0	By BTN1	BTN3
Probability for BTN2 to get false triggered	0.19	0	0.36

	By BTN0	By BTN1	BTN2
Probability for BTN3 to get false triggered	0.14	0.36	0.58

6 Design Rotary Encode System

Rotary Encode is another use case for inductive sensing. This section discusses the design of inductive rotary encoder. The construction of rotary encoder involves two sensor coils and N number of targets placed on the rotating platform as shown in Figure 17. To ensure a uniform separation between the base and rotating platforms of rotary encoder, a bush can be added along the shaft in the center of the rotary encoder.

Figure 17. Construction of Inductive Rotary Encoder



The number of targets (N) decides the angular resolution as shown in Equation [8].

$$Angular\ resolution = \frac{360}{(N * 4)} \qquad [8]$$

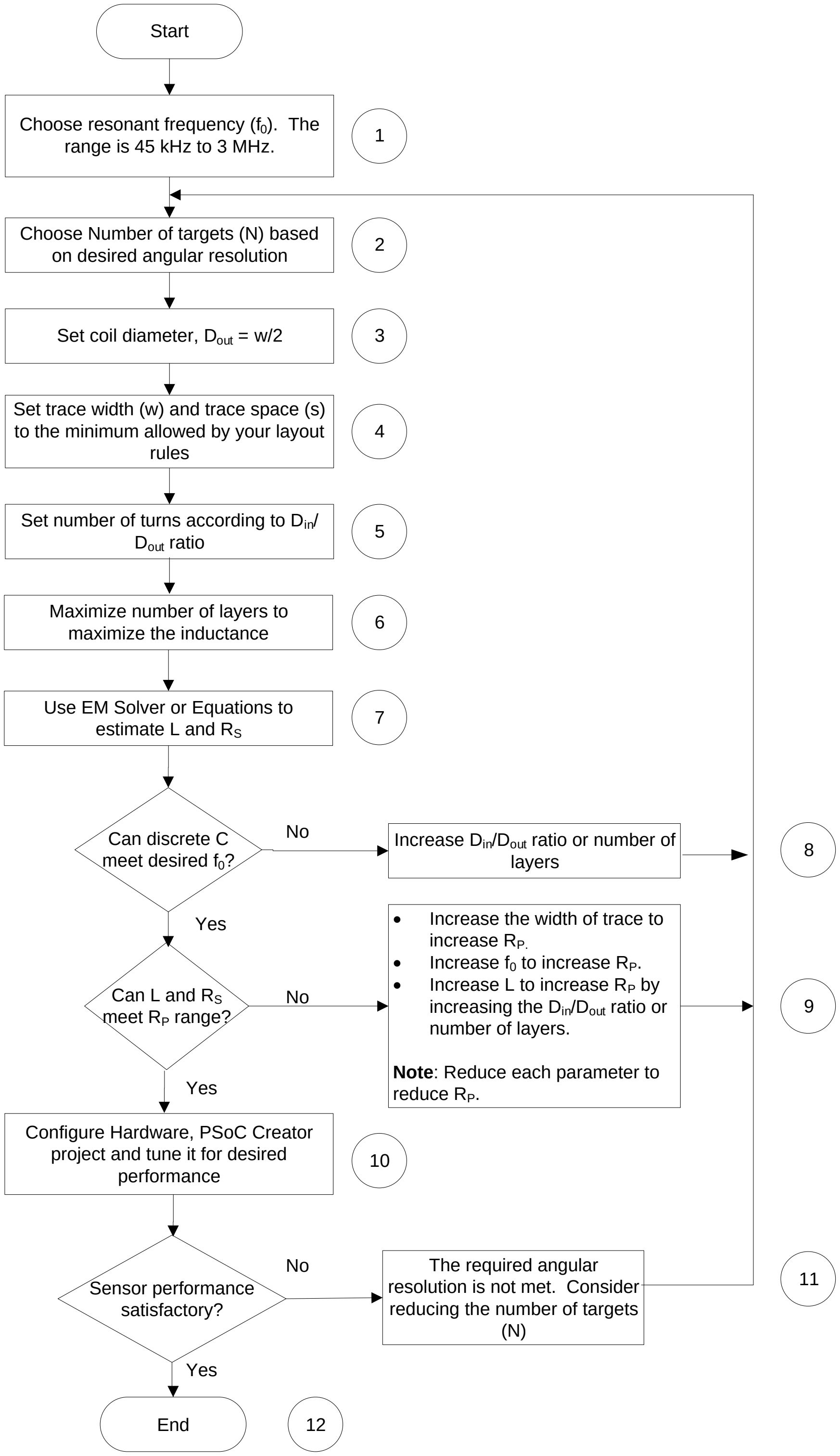
The sensor coils need to be separated at an angle twice the angular resolution. For example, if the number of targets N = 8, then the achievable angular resolution is 11.25° and the required spacing between sensor coils is 22.5°. The direction of rotation can be determined using the previous value of coil 'A' and the current value of coil 'B' as shown in Table 3. If the current value of coil 'B' and previous value of coil 'A' are same, it means the direction of rotation is anti-clockwise direction; if the values are different, then is the direction of rotation is clockwise.

Table 3. Direction of Rotation

Clockwise Direction		Anti-clockwise Direction	
A	B	A	B
1	1	1	1
1	0	0	1
0	0	0	0
0	1	1	0

The sensor design flow of inductive rotary encoder is provided in Figure 18.

Figure 18. Inductive Rotary Encoder – Sensor Design Flow



1. **Choose f_0:** Choose the resonant frequency that best suits the system. The supported range is 45 kHz to 3 MHz.
2. **Choose Number of targets:** Determine the number of targets (N) required to meet the desired angular resolution.

3. **Choose the Coil Diameter:** Set the coil diameter (*Dout*) to be equal to half of mean width of one target.
4. **Set Trace Width/Space:** Set the trace width (w) and space (s) to a minimum for the PCB design technology you are using.
5. **Set the number of turns:** Set the number of turns according to the *Din/Dout* ratio that you need. A guideline is to set Din/Dout > 0.3.
6. **Maximize the number of layers:** Set the number of layers to a maximum and choose a series connection between layers and maximize the inductance and therefore, maximize R_P to reduce coil loss.
7. **Calculate L and R_S:** Calculate the inductance (L) and the AC series resistance (R_S) at the resonant frequency (f_0) by using either an EM solver or Equations [19] and [20]. See the Sensor Design Spreadsheet section to calculate L and R_S.
8. **Optimize L:** Determine whether the value of L satisfies the chosen f_0 using Equation [2] for an available discrete capacitance, C. If not, you should optimize the *Din/Dout* ratio or the number of layers.
9. **Optimize R_P:** Calculate R_P from Equation [3]. If it does not satisfy the R_P range of 350 to 50,000 (see Figure 33) consider the following:
    a. **Increase R_P:** Increase R_P by increasing w, s, f_0, or L.
    b. **Decrease R_P:** Decrease R_P by decreasing w, s, f_0, or L
10. **Configure Hardware, PSoC Creator project and tune it for desired performance:** Configure the hardware. Create a PSoC Creator project and tune it for desired performance. See the Tuning MagSense Component Parameters section to optimize SNR.
11. **Check the sensor performance:** Measure the sensor signal. If the sensor does not yield significant signal change in the presence of the target, the desired angular resolution is not met; consider reducing the number of targets.
12. **End:** The system meets desired performance.

7 Tuning MagSense Component Parameters

After you have completed the inductive proximity sensor design and layout, the next step is to implement the firmware and tune the MagSense Component parameters to achieve optimum performance. PSoC Creator provides an inductive sense Component to simplify system design. See the MagSense Component datasheet for more details.

To detect a slight change in inductance, the MagSense circuitry should be tuned for high sensitivity, and the threshold parameters should be set to optimum values.

Tuning an inductive sensor in PSoC Creator has four high-level steps:

1. Getting Started with MagSense
2. MagSense Tuning Flow
3. Set MagSense Parameters
4. Set Optimum Threshold Parameters

7.1 Getting Started with MagSense

1. **Add an MagSense Component to your schematic.**

   In the PSoC Creator *TopDesign.cysch* window, search for the MagSense Component (Figure 20) and drop it onto your schematic.

2. **Add an inductive sensor to your design.**

   In the PSoC Creator *TopDesign.cysch* window, double-click the MagSense Component to configure the parameters. Starting with the basic configuration window shown in Figure 21, add a widget by clicking **+** under **Type** in the basic window. Currently the MagSense Component has three widgets - Button, Proximity Sensor, and Encoder Dial.

3. **Set the inductive sensor settings of the MagSense Component.**

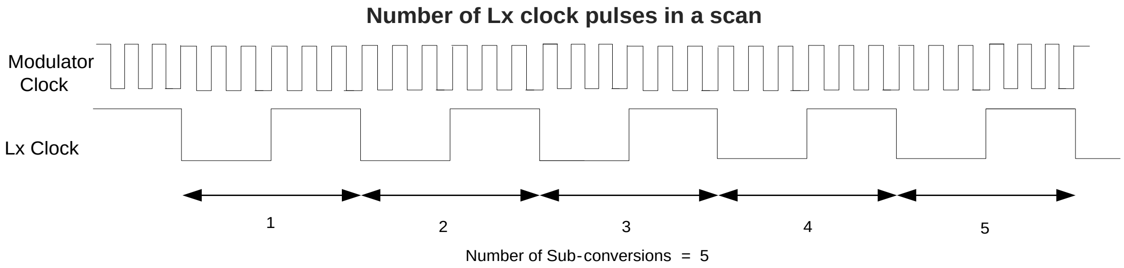
   The settings are explained in Table 5. It is recommended to set the modulator clock (clock to Amplitude to Digital Converter) to maximum value.

4. **Set the widget parameters in the MagSense Component.**

   The Widget details window is shown in Figure 23. Here, the Lx clock frequency (sensor excitation frequency) and number of sub-conversion parameters are set. The **Widget Threshold** parameters are described in the Set Optimum Threshold Parameters section of this document.

   The **Lx clock frequency** must be set to the resonant frequency of the tank circuit. Figure 19 illustrates the relationship between Modulator Clock, Lx Clock, and Sub-conversions (number of conversions per data sample).

Figure 19. Lx Clock, Modulator Clock, and Number of Sub-conversions Relationship



The Number of sub-conversions determines the sensitivity of the sensor.

$$Number\ of\ Subconversions < \left\{ \frac{2^{16} \cdot Lx\ clock}{Modulator\ clock} \right\} \qquad [9]$$

5. **Scan Order**

   The **Scan Order** tab (Figure 23) shows the order in which the widgets are scanned. An estimate of the total scan time is given in the lower right corner of this window.

Figure 20. Inductive Sense Component

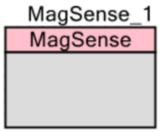
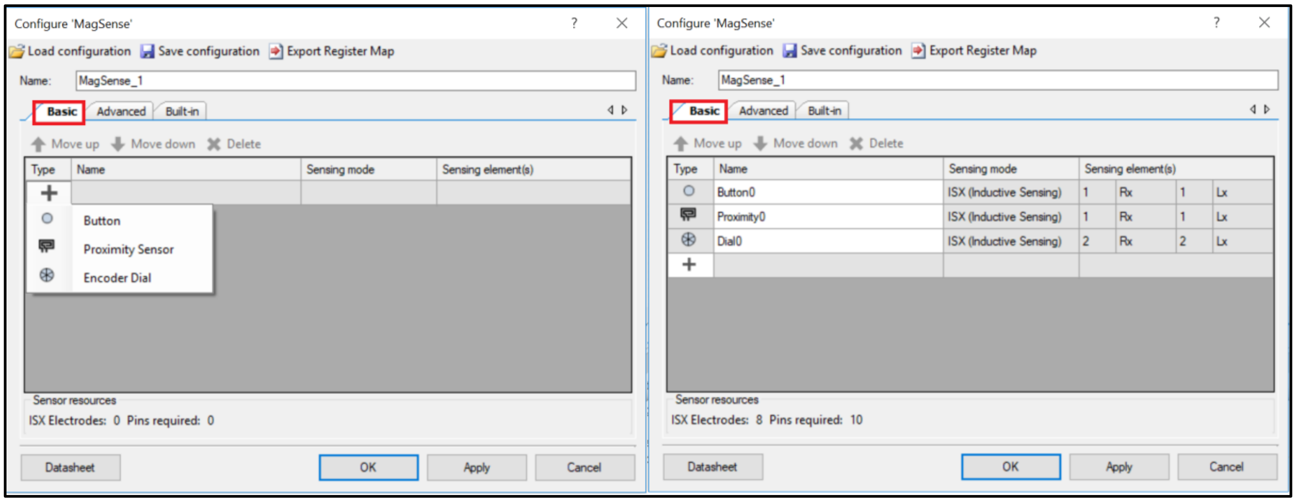


Figure 21. Basic Configuration Window



Name: MagSense_1

Type	Name	Sensing mode	Sensing element(s)			
+						

Sensor resources

ISX Electrodes: 0 Pins required: 0

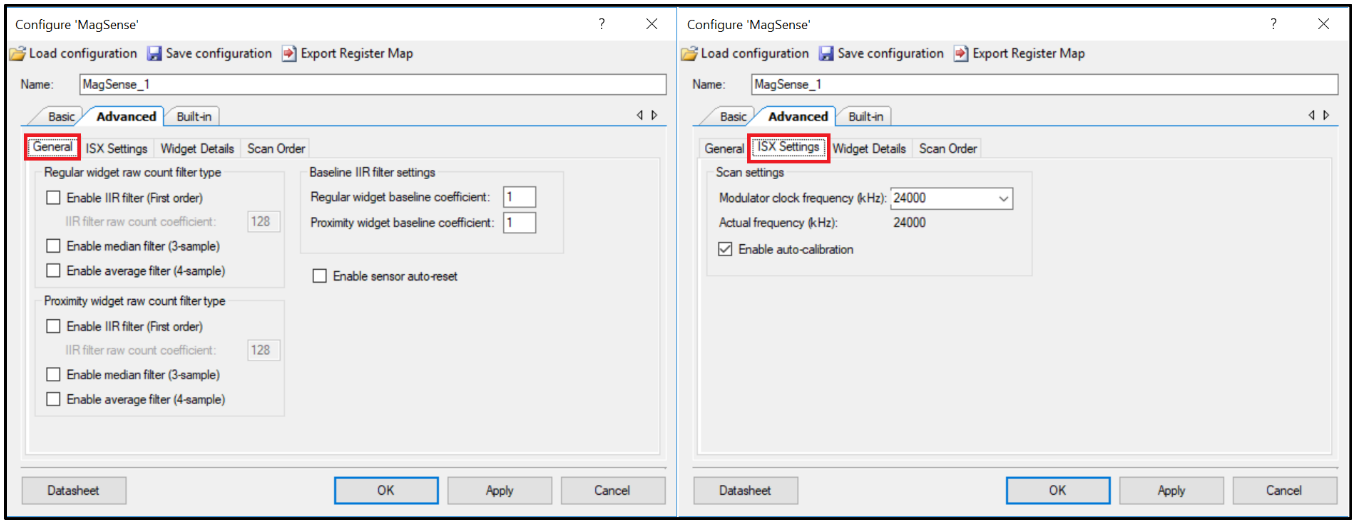
Name: MagSense_1

Type	Name	Sensing mode	Sensing element(s)			
○	Button0	ISX (Inductive Sensing)	1	Rx	1	Lx
	Proximity0	ISX (Inductive Sensing)	1	Rx	1	Lx
	Dial0	ISX (Inductive Sensing)	2	Rx	2	Lx
+						

Sensor resources

ISX Electrodes: 8 Pins required: 10

Figure 22. General and ISX (MagSense Crosspoint) Settings Configuration



Name: MagSense_1

Regular widget raw count filter type

☐ Enable IIR filter (First order)

IIR filter raw count coefficient: 128

☐ Enable median filter (3-sample)

☐ Enable average filter (4-sample)

Proximity widget raw count filter type

☐ Enable IIR filter (First order)

IIR filter raw count coefficient: 128

☐ Enable median filter (3-sample)

☐ Enable average filter (4-sample)

Baseline IIR filter settings

Regular widget baseline coefficient: 1

Proximity widget baseline coefficient: 1

☐ Enable sensor auto-reset

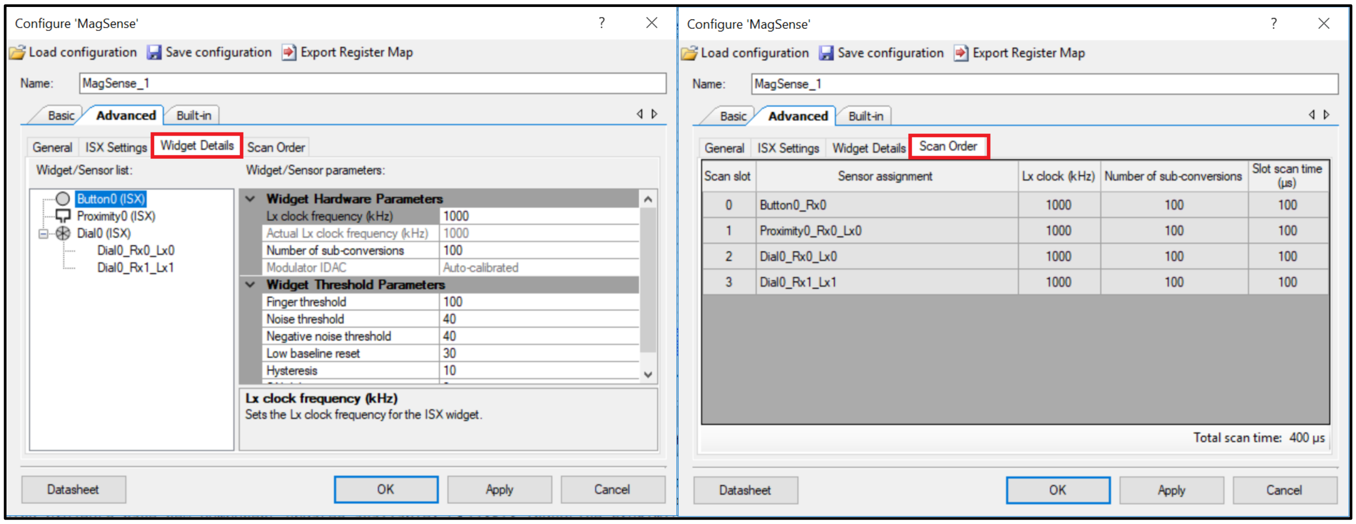
Scan settings

Modulator clock frequency (kHz): 24000

Actual frequency (kHz): 24000

☑ Enable auto-calibration

Figure 23. Widget Details and Scan Order Configuration



Name: MagSense_1

Widget/Sensor list:

- Button0 (ISX)
- Proximity0 (ISX)
- Dial0 (ISX)
  - Dial0_Rx0_Lx0
  - Dial0_Rx1_Lx1

Widget/Sensor parameters:

Widget Hardware Parameters	
Lx clock frequency (kHz)	1000
Actual Lx clock frequency (kHz)	1000
Number of sub-conversions	100
Modulator IDAC	Auto-calibrated
Widget Threshold Parameters	
Finger threshold	100
Noise threshold	40
Negative noise threshold	40
Low baseline reset	30
Hysteresis	10

Lx clock frequency (kHz)
Sets the Lx clock frequency for the ISX widget.

Scan slot	Sensor assignment	Lx clock (kHz)	Number of sub-conversions	Slot scan time (µs)
0	Button0_Rx0	1000	100	100
1	Proximity0_Rx0_Lx0	1000	100	100
2	Dial0_Rx0_Lx0	1000	100	100
3	Dial0_Rx1_Lx1	1000	100	100

Total scan time: 400 µs

7.2 MagSense Tuning Flow

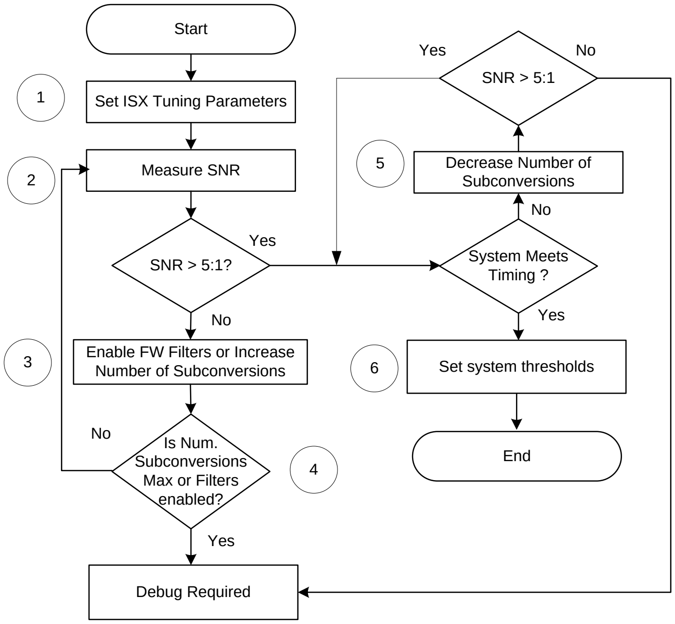
The inductive sensing tuning flow is shown in Figure 24.

1. **Set ISX Tuning parameters:** Set the tuning parameters outlined in the Getting Started with MagSense section. The most critical parameters are the Lx clock frequency and the number of sub-conversions, the number of conversions per data sample. Ensure that the Lx clock frequency is set to the resonant frequency of the LC tank (f_0).
2. **Measure SNR:** See Ensure SNR Is Greater Than or Equal to 5:1. If the SNR measured is greater than or equal to 5:1, proceed to Step 5; otherwise, enable filters and measure the SNR again.
3. **(SNR< 5:1) Enable FW filters or increase the number of sub-conversions**: See Table 4.

   Simple filters such as median, average, and infinite impulse response (IIR) filters may not be able to attenuate the higher noise amplitude in sensors, so you may need to use the advanced low-pass filter (ALP filter). The ALP filter is designed specifically for attenuating noise in the inductive sensor and providing a fast response time. See Advanced Low-Pass (ALP) Filter.

4. **Max sub-conversions/All filters used:** If all filters are enabled and the number of sub-conversions is set to a maximum, defined by Equation [9], debug is required to determine the reasons for the design not meeting SNR >= 5:1. See Design Debug.
5. **(SNR ≥ 5:1) System meets timing:** If SNR ≥ 5:1, it is important to check the system meets timing requirements. You might need to reduce the number of sub-conversions or remove filters if the SNR and scan time are high.
6. **Set the system thresholds:** After the scan time and SNR meet requirements, it is important to set the firmware thresholds for optimum detection of the target. See the following:
    - Table 7 for a list of these thresholds.
    - Figure 26 for a graphical representation of each threshold.
    - The Set Optimum Threshold Parameters section for optimum values for each threshold.

Figure 24. Inductive Sensing Tuning Flow



7.3 Set MagSense Parameters

Inductive sense parameters in each of the Widget windows are described in Table 4.

Table 4. MagSense Component General Configuration Parameters

Parameter	Value	Details
Proximity/Regular Widget raw count filter type	Median, Average, or IIR	1. **Median Filter:** A nonlinear filter that takes the three most recent samples and computes the median. $y[i] = median(x[i], x[i-1], x[i-2])$ 2. **Average Filter:** Takes the four most recent samples and computes the average. $y[i] = \frac{1}{4}(x[i] + x[i-1] + x[i-2] + x[i-3])$ 3. **First Order IIR Filter:** This filter has a step response similar to an RC low-pass filter, passing low-frequency signals from the sensor. The K value is fixed as 256. N is the IIR filter raw count coefficient. A lower N value results in lower noise. $y[i] = \frac{1}{K}(N \cdot x[i] + (K-N) \cdot y[i-1])$
IIR filter raw count coefficient	1 to 128	This parameter is the value N in the First Order IIR filter equation above.

Table 5. MagSense Component ISX Parameters

Parameter	Value	Details
Modulator Clock	48 MHz	The modulator clock drives the MagSense system and should be set to 48 MHz. Make sure to set HFCLK to 48 MHz in Design Wide Resources.
Auto Calibration	Enabled	Enable auto-calibration of the RX (recommended).

Table 6. MagSense Component Widget Details Configuration Parameters

Parameter	Value	Details
LX Clock Frequency	3 MHz	The LX clock can be set in the range from 45 kHz to 3 MHz; this must match the resonant frequency of the tank.
Num. of Sub-conversions	100	The number of sub-conversions defines the overall resolution that is measured. The higher the value, the higher is the resolution, but also the longer the response time. See Equation [9].
Finger threshold[1]	100	This threshold sets the touch level to determine the sensor state based on the signal.
Proximity threshold	100	This threshold detects the presence of a metal target at distance. This gives a proximity-sensing distance threshold.
Touch threshold	200	This is a second threshold used to detect the presence of a metal target within close proximity to the sensor coil
Noise threshold	40	The noise threshold decides whether the baseline is updated: If the signal is below the noise threshold, the baseline is updated. If the signal is above the noise threshold, the baseline is not updated.
Negative noise threshold	40	The negative noise threshold sets the raw count limit below which the baseline is not updated for the number of samples specified by the low baseline reset parameter.
Low baseline reset	30	Along with the negative noise threshold, this parameter counts the number of abnormally low raw counts required to reset the baseline.
Hysteresis	15	Hysteresis sets limits around the touch threshold within which the sensor is considered ON or OFF. See the description of parameter 'ON debounce' for more details.
ON debounce	3	Debounce sets the number of consecutive scans during which a sensor must be active to generate an ON state from the component: $Sensor\ State \begin{cases} PROX\ ON, & if\ (signal\ \geq Proximity\ threshold + Hysteresis) \geq debouce \\ PROX\ OFF, & if\ (signal\ \leq Proximity\ threshold - Hysteresis\ ) \\ PROX\ OFF\ , & if\ (Signal\ \geq Proximity\ threshold + Hysteresis)\ < debounce \end{cases}$ $Sensor\ State \begin{cases} TOUCH\ ON, & if\ (signal\ \geq Touch\ threshold + Hysteresis) \geq debouce \\ TOUCH\ OFF, & if\ (signal\ \leq Touch\ threshold - Hysteresis\ ) \\ TOUCH\ OFF\ , & if\ (Signal\ \geq Touch\ threshold + Hysteresis)\ < debounce \end{cases}$
Number of targets[2]	4	

Note: These parameters are graphically shown in Figure 26.

7.4 Ensure SNR Is Greater Than or Equal to 5:1

After hardware parameters are set, you need to measure the sensor SNR and ensure that it is greater than or equal to 5:1. An SNR of 5:1 ensures robust operation under all conditions.

SNR is the ratio of the sensor signal and the peak-to-peak noise counts, as shown in Equation [10].

$$SNR = \frac{Signal}{Peak\ to\ Peak\ Noise} \qquad [10]$$

Where,

Signal = Output count (Raw count) with metal target – Output count (Raw count) without metal target

Peak to Peak Noise = Peak-to-Peak raw count noise measured over 2,000 samples, as shown in Figure 25.

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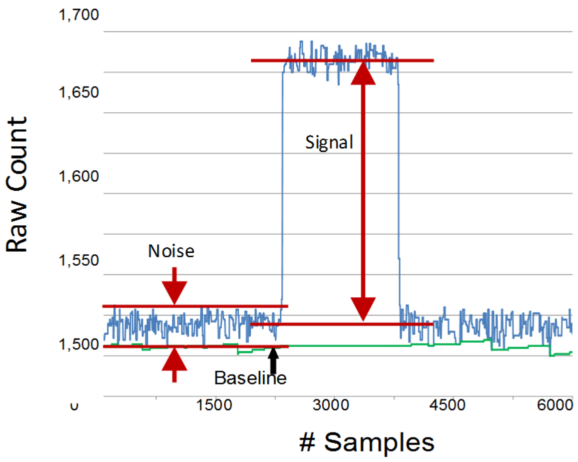
[1] Applicable to Button and Encoder Dial widgets only.

[2] Applicable to Encoder Dial widget only.

Figure 25. Computing SNR



To compute the SNR, acquire a fixed number of samples, for example 2,000 raw count samples, as Figure 25 shows, and measure the peak-to-peak noise count. Place your target at the required proximity-sensing distance and measure the shift in raw counts. The signal will be equal to the raw count (after placing the target) minus the average raw count (before placing the target.)

You can measure raw counts and compute the SNR using two methods:

- **MagSense Tuner:** Using the MagSense Tuner is the easiest method for computing the SNR. However, this method supports only I^{2}C communication to read the sensor data and requires you to run a specific set of APIs in the firmware. See the MagSense Tuner section in the PSoC 4 Inductive Sensing (MagSense) Component datasheet.
- **Bridge Control Panel (BCP):** BCP is a Cypress tool to read data from a slave device via an I^{2}C/SPI/UART interface.

Depending on your requirements, select a suitable method for measuring the SNR and implement the firmware. Appendix B implements both methods. You can use that the appendix section as a reference and implement the method for computing the SNR.

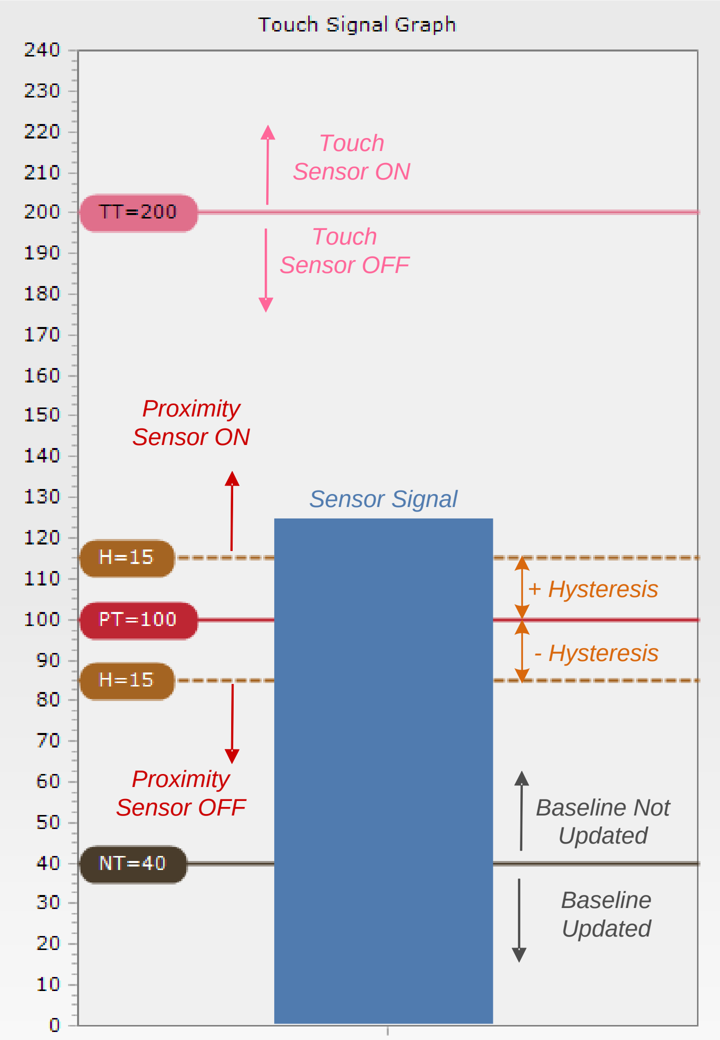
7.5 Set Optimum Threshold Parameters

If the SNR is greater than 5:1, and the scan time and power consumption requirements are met, set the threshold parameters to the recommended values listed in Table 7. See Figure 26 and the MagSense Component Widget Details Configuration section.

Table 7. Sensor Threshold Parameters

Threshold Parameter	Recommended Value
Proximity threshold	80 percent of proximity signal
Touch threshold	80 percent of touch signal
Finger threshold	80 percent of touch signal
Noise threshold	40 percent of proximity signal
Negative noise threshold	40 percent of proximity signal
Hysteresis	10 percent of proximity signal
Debounce	Set this parameter to ‘1’ if you are using the ALP filter; otherwise, set it to ‘3’
Low baseline reset	30

Figure 26. Thresholds

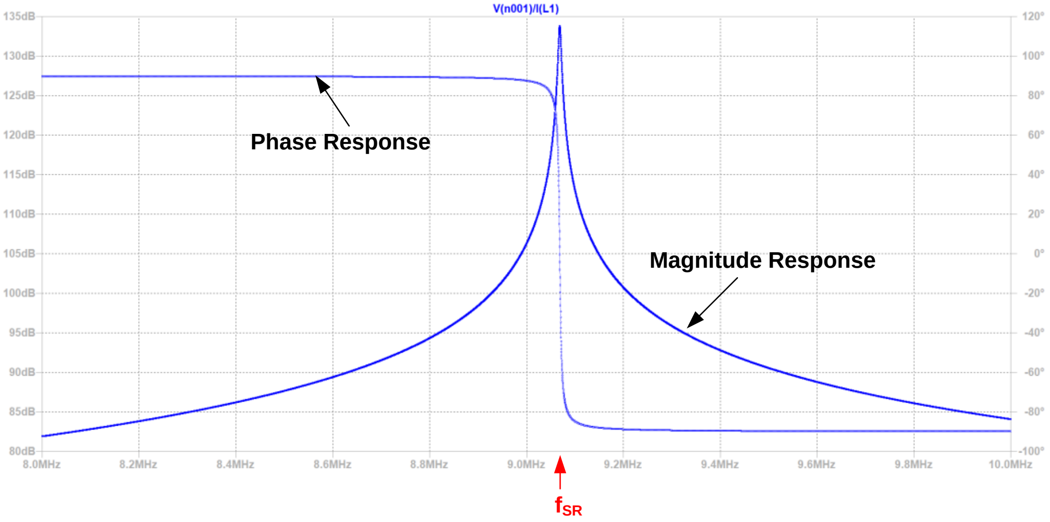


7.6 Design Debug

If you cannot tune the design, it indicates that debugging is required. Do the following:

- **Verify Tuning:** Measure the frequency of the Lx signal using an oscilloscope to verify whether it is where you expect it to be for your LC tank.
- **Measure the AC response of the LC tank:** Measure the tank response with an oscilloscope and ensure that the sine wave amplitude at resonance is the V_{AMP} that you expect.
- **Measure the tank f_{SR}:** Measure the self-resonant frequency of the coil (after disconnecting the capacitance C) with an impedance meter and make sure that it is at least three times larger than f_0. The phase of the inductor goes to 0º at the f_{SR} frequency.

Figure 27. Inductor Impedance Magnitude/Phase Response Over Frequency



8 Additional Firmware Filters to Reduce Noise

Filters help to reduce raw count noise and improve SNR. A high SNR implies a large proximity-sensing distance. The MagSense Component supports the following types of filters: median, average, and first-order IIR (as already outlined in Table 4).

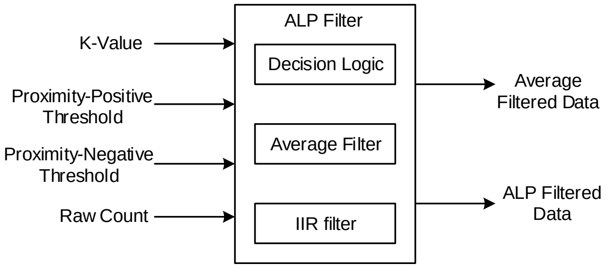
To achieve high noise attenuation and improve the response time, it is possible to use intelligent adaptive filters such as the ALP filter, as explained in the next section.

8.1 Advanced Low-Pass (ALP) Filter

The ALP filter is a combination of multiple low-pass filters specifically designed to attenuate noise in the proximity sensor raw count. Figure 28 shows the block diagram of the ALP filter. The ALP filter switches between multiple low-pass filters depending on the sensor signal and values of the threshold parameters to achieve maximum noise attenuation and provide a fast response time.

The ALP filter has a slow-response filter and a fast-response filter. The slow-response filter provides the maximum noise attenuation, but its response time is slow. On the other hand, the fast-response filter provides a fast response time but results in less noise attenuation.

Figure 28. ALP Filter Block Diagram



The inputs to the ALP filter are as follows:

- **Raw count:** The raw count of the sensor is the digital measurement of the LC tank amplitude.
- **K-value:** The K-value of the ALP filter determines the amount of noise attenuation in the proximity sensor raw count. The K-value can be one of the following:
  - IIR_K_16
  - IIR_K_32
  - IIR_K_64

  Noise attenuation decreases in the following order:

  IIR_K_64 > IIR_K_32 > IIR_K_16
- **Proximity-positive threshold:** This parameter determines the turn-on time of the proximity sensor when a target approaches it. When the sensor signal is greater than this value, the ALP filter switches to the fast-response filter from the slow-response filter.
- **Proximity-negative threshold:** This parameter determines the turn-off time of the proximity sensor when a target is withdrawn from it. When the sensor signal is less than this value, the ALP filter switches to the fast-response filter from the slow-response filter.

The outputs of the ALP filter are as follows:

- **Average filtered data:** Average filtered data is used to set the proximity-positive threshold and proximity-negative threshold parameters.
- **ALP filtered data:** The ALP filtered data is the final output of the filter, that is, the raw count with very low noise.

8.1.1 Adding an ALP Filter to the Project

See CE223813 Inductive Proximity Sensing to add an ALP filter to your project.

The ALP filter requires all the proximity sensors to occupy a scan order 0 through (n-1) in the MagSense Component. Here, 'n' is the total number of proximity sensors in the design. For proximity sensors to occupy the scan order from 0, place the proximity sensor widget first followed by other sensor widgets.

8.1.2 ALP Filter Tuning

The ALP filter requires you to specify the K-value, proximity-positive threshold, and proximity-negative threshold for proper operation. Follow these steps to set the ALP filter parameters.

1. Measure the peak-to-peak noise using the raw count without any nearby target object and filters.
2. Set the K-value per the mapping in Table 8.

Table 8. Selecting the K-Value

Peak-to-Peak Noise	Recommended K-Value
Less than 32 counts	IIR_K_16
Greater than 32 counts and less than 64 counts	IIR_K_32
Greater than 64 counts	IIR_K_64

3. Enable the ALP filter and program the device. Measure the peak-to-peak noise in the ALP filter’s average filtered data.

4. Set the proximity-positive threshold as equal to 1.5 × peak-to-peak noise of the average filtered data.
5. Set the proximity-negative threshold as equal to 0.5 × peak-to-peak noise of the average filtered data.
6. Set the proximity threshold parameter as equal to the proximity-positive threshold. After tuning the ALP filter, the proximity threshold parameter should be set to the value listed in Table 7.
7. Program the device with these settings and measure the peak-to-peak noise using the raw count for 3,000 samples.
8. Place the target at the required proximity-sensing distance and measure the signal, that is, the shift in the raw count when the target approaches the sensor.
9. Compute the SNR. If the SNR is greater than 5:1, check whether the sensor turn-off time is acceptable. If the sensor turn-off time is very slow, increase the proximity-negative threshold value. The maximum limit for the proximity-negative threshold parameter is equal to the proximity-positive threshold value.
10. If the SNR is greater than 5:1 and the sensor response time meets the requirements, proceed to set the threshold parameters listed in Table 7; otherwise, increase the proximity sensor size to increase the signal.

9 Other System Design Considerations

MagSense devices support proximity-sensing distances up to a distance that equals the diameter of the coil. In addition to the distance that can be sensed, there are other system design considerations:

- Dynamic Power Consumption
- Refresh Rate

9.1 Dynamic Power Consumption

The power consumed by the resonant tank is considered dynamic power consumption. The dynamic power dissipation consists of two components as given by Equation [11].

$$P_{diss\_dynamic} \le (V_{AMP} I_{TANK}) + (V_{DC} I_{DC}) \quad [11]$$

Where,

V_{AMP} = Amplitude (peak) of voltage across tank

I_{TANK} = AC Current flowing through tank

V_{DC} = DC voltage across tank

I_{DC} = DC current through flowing tank

The tank oscillation voltage amplitude (V_{AMP}) is governed by the AC impedance of the lossy tank at resonance and the DC voltage across the tank is governed by the DC resistance of the coil which can be approximated by Equation [12], where R_P is defined by Equation [3] and R_{DC} is the DC resistance of the coil.

$$V_{AMP} \approx R_P I_{TANK} \quad [12]$$

$$V_{DC} \approx R_{DC} \frac{VDDA}{R_{Lx}}$$

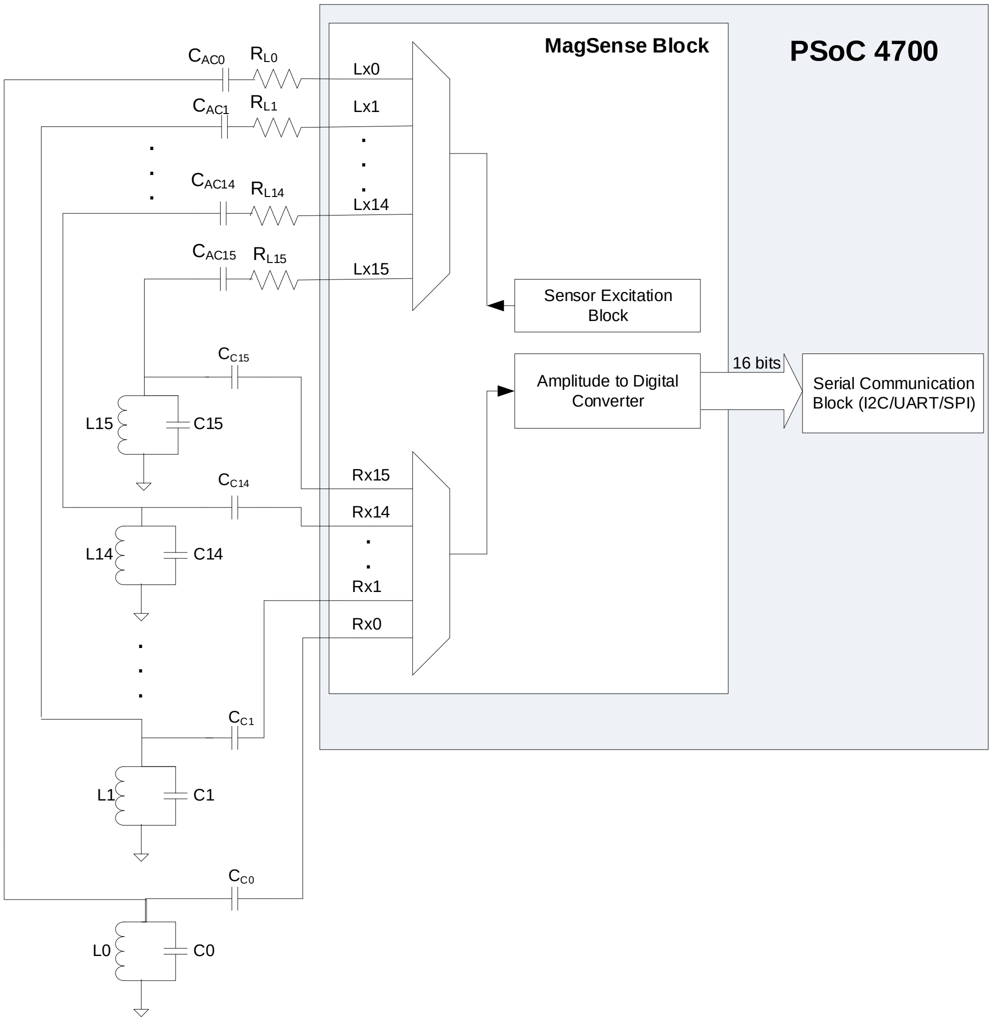
Because V_{AMP}, R_P, VDDA, R_{Lx} and R_{DC} are known, you can estimate the power consumed using Equation [13]. Considering the above parameters is important when designing your MagSense system and estimating the dynamic power consumption of the tank.

$$P_{diss\_dynamic} \le \left(\frac{{V_{AMP}}^2}{R_P} + R_{DC}(VDDA/R_{Lx})^2 \right) \quad [13]$$

By adding a DC blocking capacitor (100 nF) to the Lx line as shown in Figure 29, the second term (DC component) in Equation [13] can be eliminated. This reduces the total power consumption of the system.

Note: C_{AC0} to C_{AC15} are DC blocking capacitors in Figure 29.

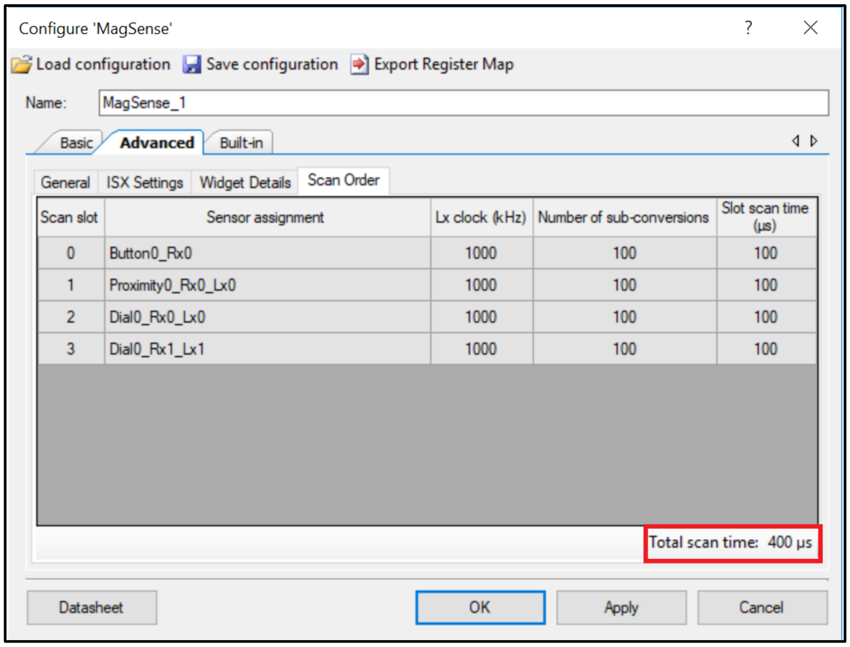
Figure 29. DC Blocking Capacitor on Lx line



9.2 Refresh Rate

The refresh rate can be estimated using the ‘Total scan time’ data in the **Scan Order** tab of the Advanced Window in the MagSense Component. In the example in Figure 30, four sensors are scanned and the total scan time is 400 us. The refresh rate decides the response time of the sensor.

Figure 30. Scan Order Window with Scan Time Estimate



Name: MagSense_1

Scan slot	Sensor assignment	Lx clock (kHz)	Number of sub-conversions	Slot scan time (µs)
0	Button0_Rx0	1000	100	100
1	Proximity0_Rx0_Lx0	1000	100	100
2	Dial0_Rx0_Lx0	1000	100	100
3	Dial0_Rx1_Lx1	1000	100	100

Total scan time: 400 µs

10 Related Application Notes

- AN79953 – Getting Started with PSoC 4
- AN86233 – PSoC 4 Low-Power Modes and Power Reduction Techniques

11 Bibliography

[Ref 1] Mohan, S. “Simple Accurate Expressions for Planar Spiral Inductances” in *IEEE Journal of Solid State Circuits*, vol. 34, no. 10, (Oct. 1999): pp 1419-1424.

[Ref 2] Howard Johnson, Martin Graham. “*High-Speed Digital Design: A Handbook of Black Magic*”.

Appendix A. Sensor Design

Sensor design plays a crucial role in achieving the required inductive proximity-sensing distance.

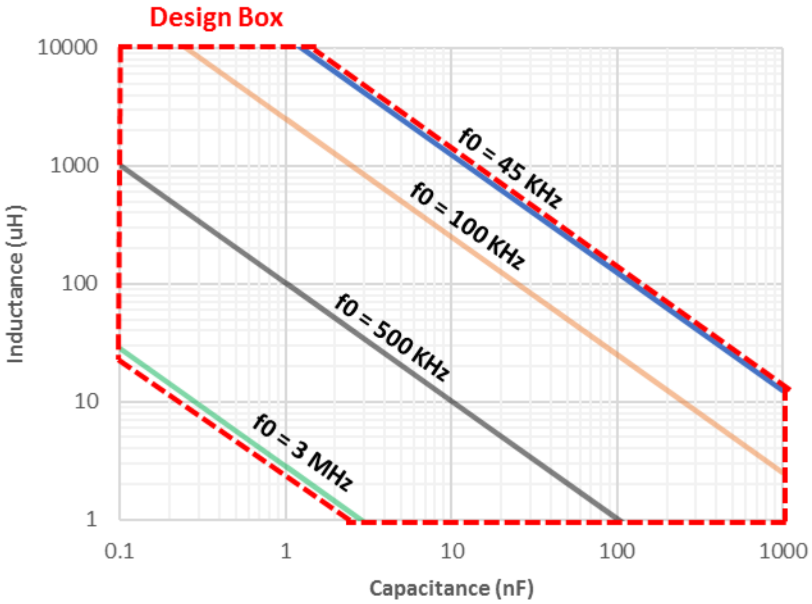
A.1 Sensor Resonant Frequency (f_0)

The sensor requires a capacitor (C) in parallel to form a parallel resonant circuit. The inductance and capacitance of that circuit determine the resonant frequency (f_0) according to the simplified expression in Equation [14].

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad [14]$$

The range of currently supported inductance is indicated by the graph in Figure 31, where the minimum resonant frequency of operation is 45 kHz and the maximum is 3 MHz.

Figure 31. Range of Supported Inductance and Capacitance Values



A.1.1 Capacitance Range

The supported capacitance range is 0.1 nF to 470 nF. The 0.1 nF lower limit is defined to reduce the effect of coil parasitic capacitance on the resonant frequency (f_0). The upper limit is based on the availability of NPO (also referred to as COG) grade capacitors, which are easy to obtain up to 470 nF.

A.1.2 Inductance Range

The supported inductance range is 1 µH to 10,000 µH. The 1 µH lower limit is defined by practical inductance values that can operate with the Lx frequency up to 3 MHz. **Inductances > 10 µH are preferred**.

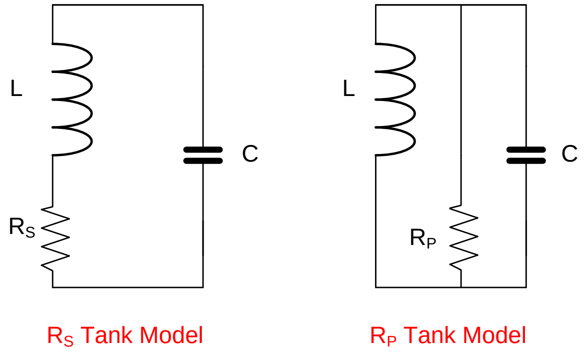
A.2 R_P and R_S Range

When designing the inductive coil, understanding the R_P and R_S values of the coil and how they impact the design is important. The definition of each is as follows:

- R_P is the parallel AC impedance of the tank at resonant frequency.
- R_S is the series AC resistance of the sensor at resonant frequency.

Figure 32 shows the series and parallel electrical model of the tank.

Figure 32. Electrical Model of Tank Circuit



A.2.1 R_S and the Skin Effect

The series resistance of the coil is driven by the skin effect. At lower frequencies, the series resistance of the coil is dominated by ohmic resistance. According to the skin effect, the AC current flow in a conductor is the largest near the surface of the conductor and decreases toward the core. The result is that the effective resistance of the conductor increases with frequency. The skin effect depends on the resistivity of the coil material, the length, width, and trace height of the coil, and the frequency. R_S should be minimized to reduce losses in the tank.

Use the following general rules for a Parallel (“tank”) LC circuit as guidelines:

- R in series with L: Resonant frequency is shifted *down*
- R in series with C: Resonant frequency is shifted *up*

Resonant frequency change with the skin effect R_S is estimated by Equation [15].

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{(LC)} - \left(\frac{R_S}{L}\right)^2} \quad [15]$$

A.2.2 R_P

The parallel resistance of the tank can be derived from the series resistance (R_S) according to Equation [16] and Equation [3].

$$R_P = \frac{1}{R_S}(2\pi f_0 L)^2 \quad [16]$$

A.2.3 R_P and Quality Factor (Q)

The Quality factor of an LC tank is defined by Equation [17].

$$Q = \omega_0 \frac{energy\ stored}{average\ power\ dissipated} \quad [17]$$

For a parallel LC tank, Equation [17] can be represented in terms of coil parameters (i.e., R_P, Q, f_0, and L). Equation [18] is the resulting expression for Q. Higher Q factor provides increased signal in the presence of metal target.

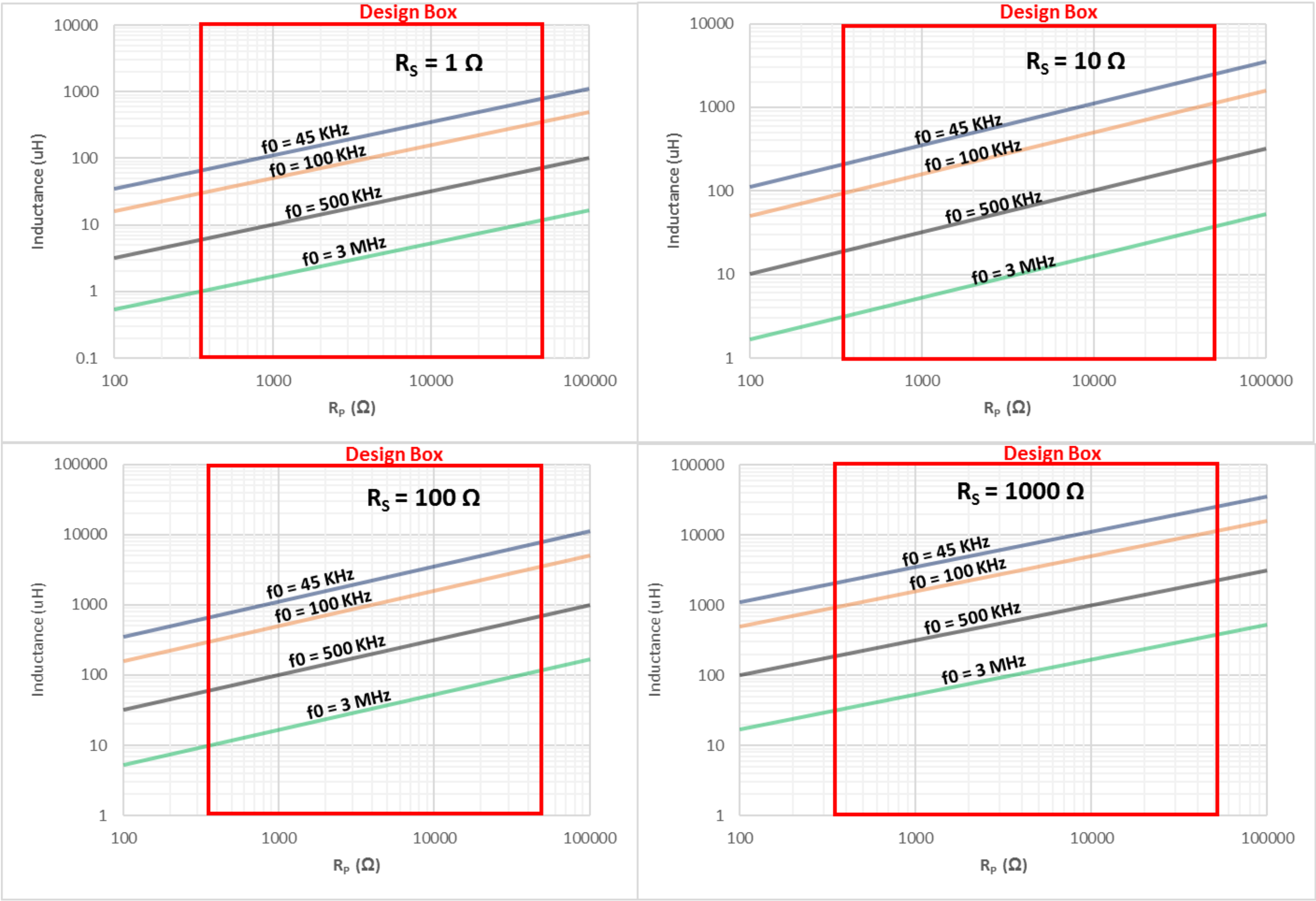
$$Q = \frac{2\pi f_0 L}{R_S} \quad [18]$$

A.2.4 R_P and R_S Range

Figure 33 plots the inductance and R_P for different resonant frequencies and different values of R_S.

The results in shown in Figure 33 give an indication of the values of R_S and R_P that can be supported over the range of resonant frequencies supported by the PSoC 4700 MCU. These plots are guidelines only; in practice, there are interdependencies between parameters L, R_S, and R_P. The supported R_P range is 350 Ω to 50,000 Ω.

Figure 33. Inductance Versus R_P over f_0 and R_S



A.3 Sensor Shape

The shape of the inductive sensor is important because it determines the shape of the generated magnetic field and therefore the change in inductance in the presence of a target metal object. The following are common shapes of PCB and flex coils:

- **Circular coil**: Circular coils are generally used when sensing a target object that is moving orthogonal to the sensor plane, as Figure 34 shows. The illustration also highlights the optimal plane of movement of the target for a circular sensor.

  Note: Non-circular coils have a higher R_S for the same Inductance.

- **Hexagonal coil:** Hexagonal coils are designed to approximate circular coils in cases where a circular coil is difficult to manufacture. See Figure 35 for an example of a hexagonal coil structure.
- **Square coil:** Square coil provides optimal performance with respect to sensitivity in both horizontal and vertical directions. See Figure 35 for an example.

- **Rectangular coil:** Rectangular coils can be used to detect movement along a preferred axis. Figure 36 shows an example of a rectangular coil with the axis for optimal detection of movement for this coil indicated in the diagram.

Figure 34. Circular Coil with Illustration Showing Optimal Plane of Movement

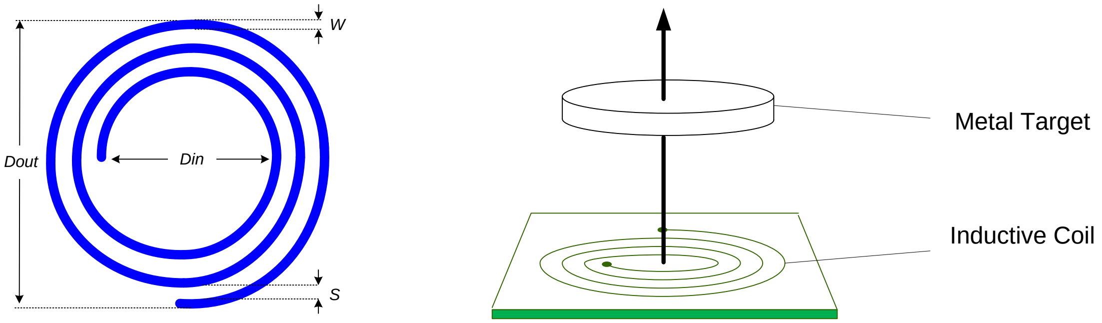


Figure 35. Hexagonal Coil and Square Coil Examples

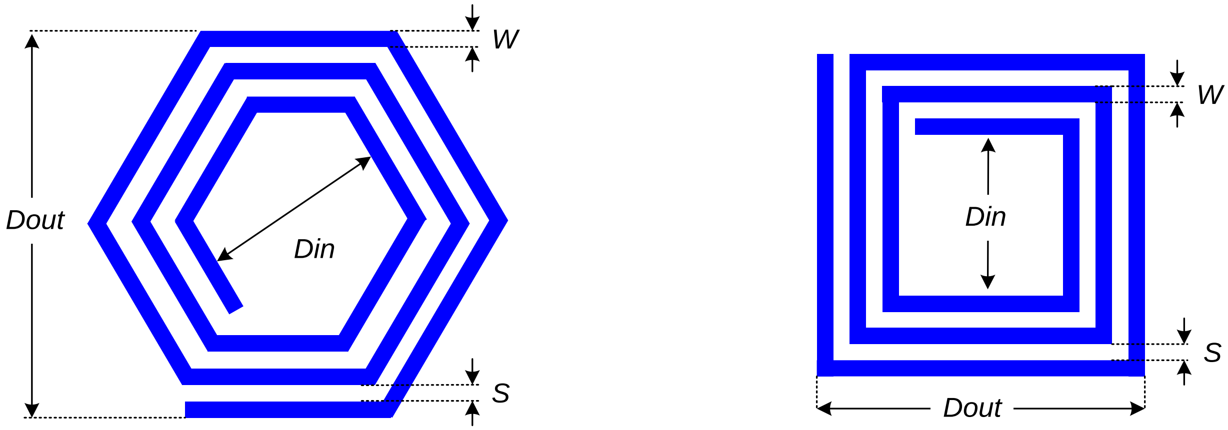
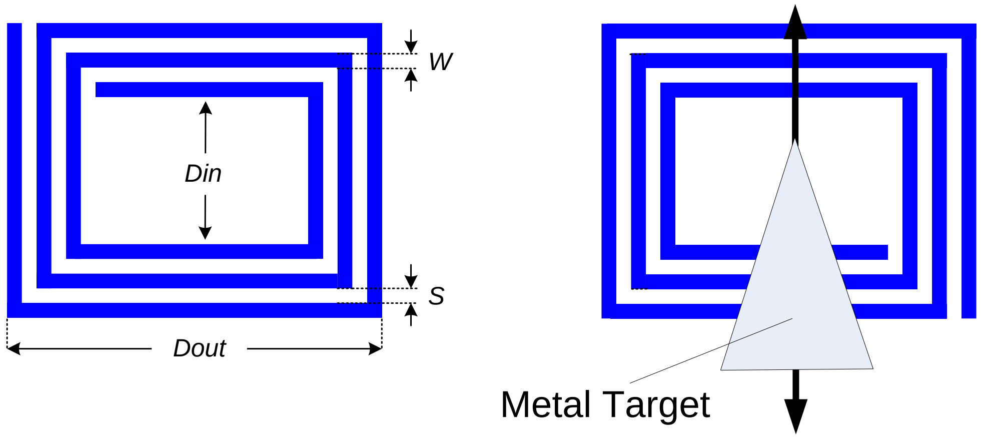


Figure 36. Rectangular with Illustration Showing Optimal Plane of Movement



A.4 Sensor Parameters

For a given shape, the sensor coil is specified by the following parameters, some of which are illustrated in Figure 34, Figure 35, and Figure 36:

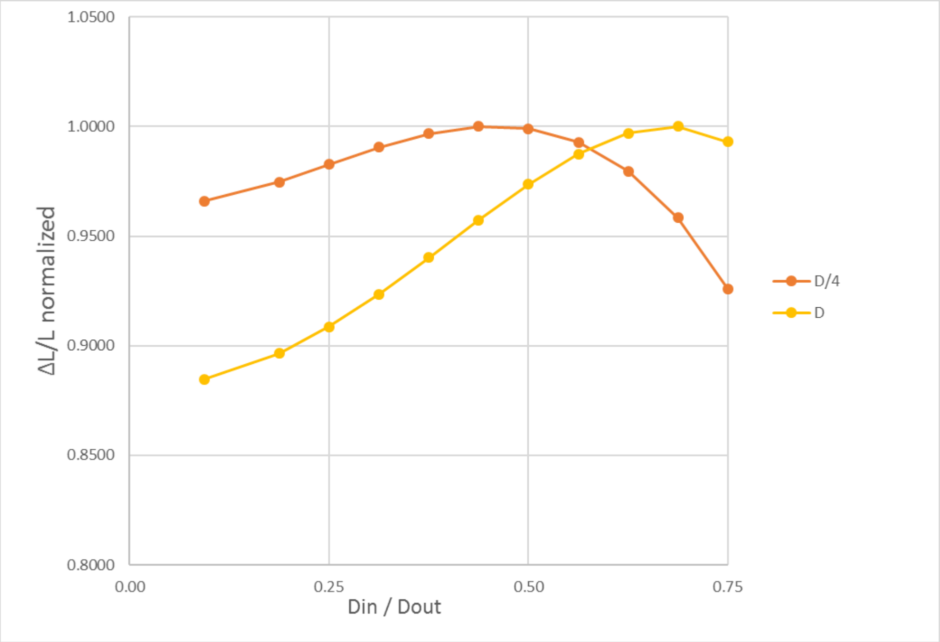
- *n*, the number of turns.
- *w,* the turn width.
- *s,* the turn spacing.
- *Din,* the inner diameter.
- *Dout,* the outer diameter – usually either *Din* or *Dout* needs to be specified; the other can be derived from other parameters

A.5 Sensor Dimensions

The extent of the magnetic field is decided by sensor physical dimensions; the outer diameter of the sensor, *Dout*, is the critical parameter. The Cypress solution aims for proximity-sensing distances up to a coil diameter from the coil while maintaining the signal-to-noise ratio (SNR) at greater than or equal to 5:1. See section 7.4 for details on signal-to-noise ratio (SNR).

If the metal target is near the coil, a small ratio of *Din/Dout* is optimal for the coil to give maximum change in inductance with distance. When the metal target is further away from the coil (*Dout*), outer windings contribute most to the electromagnetic field and windings near the center can be removed. Figure 37 shows the normalized change in inductance (ΔL/L) as the metal target is moved away from the coil at the distances *Dout* and *Dout*/4 with different coil *Din/Dout* ratios.

Figure 37. Normalized Inductance Change (ΔL/L) Versus *Din/Dout* Ratio for a 13-mm Diameter Coil



A.6 Sensor Modeling

The values L and R_S of the sensor need to be estimated for the tuning flow outlined in Figure 4.

A.6.1 Sensor Design – Approximate Equations

The following equations can be used to estimate the parameters of the inductor from coil dimensions.

Note: These expressions are not as accurate as a field solver, and are used for approximations only.

The Inductance of the coil can be estimated using the expression below derived in [Ref 1]. Equation [19] is based on a current sheet approximation.

$$L_{gmd} = \frac{\mu_0 n^2 D_{avg} C_1}{2}\left(ln\left(\frac{C_2}{\rho}\right) + C_3\rho + C_4\rho^2\right) \qquad [19]$$

C_1, C_2, C_3, C_4 = layout constant dependant on the shape of the coil. See Table 9.

Davg = $0.5 \cdot (Dout + Din)$

ρ = the fill factor = $(Dout - Din)/(Dout + Din)$

μ0 = the permeability of free space, 4π x 10^{-7}

n = the number of turns

Table 9. Coefficients for Current Sheet Method

Coil Shape	C_1	C_2	C_3	C_4
Square	1.27	2.07	0.18	0.13
Hexagonal	1.09	2.23	0.00	0.17
Circle	1.00	2.46	0.00	0.20

An expression to estimate the R_S of a conductor due to the skin effect has been derived in [Ref 2]. This equation provides an estimate of the AC resistance of the inductor in ohms/inch. Table 10 shows some values for ρ_R (the relative resistivity of the coil material, compared to copper). Note that the value of R_S calculated below is the unit value. To get the total value of R_S, the unit value needs to be multiplied by the length of the trace which can be measured from the PCB Design tool by making a sample coil of desired shape.

$$R_S = \frac{2.16x10^{-7} \cdot \sqrt{f\rho_R}}{2(w+d)} \qquad [20]$$

Where,

w = trace width, inches

d = trace height, inches

f_0 = frequency, Hz

ρ_R = relative resistivity, compared to copper = 1.00

R_S = AC resistance, ohms/inch

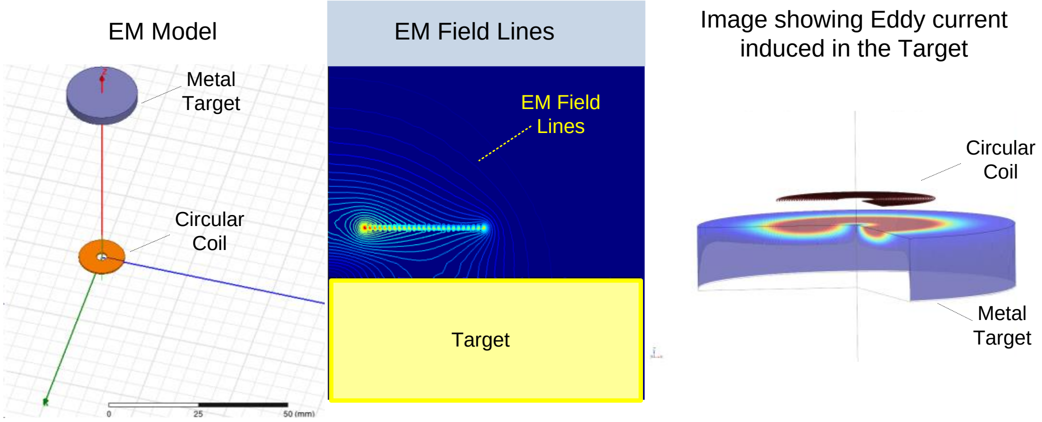
Table 10. Conductivity of Different Materials Compared to Copper

Metal	Resistivity (x 10^{-7} ohms inch)	Resistivity Relative to Cu
Copper	6.7879	1.000
Aluminum	10.3606	1.526
304 SS	302.847	44.616
Titanium Alloy	667.29	98.306

A.6.2 Sensor Design – 2D/3D EM Solver

An electromagnetic (EM) field solver tool such as from Comsol™ or Maxwell™ can be used to get a complete electrical model of the Inductor and understand its characteristics. Figure 38 shows an example of the coil modeling tool graphical outputs.

Figure 38. Examples of Output from an Electromagnetic Field Solver (Comsol)



A.7 Sensors with Multiple Layers

For a given diameter of the coil, there is a maximum limit to the number of turns due to the minimum allowable space between traces. If additional inductance is needed on a PCB, a multi-layer inductor can be designed using multiple layers of the PCB. The key consideration for multi-layer inductors is that the current flow on different layers is in the same direction so that it constructively adds to the EM field and does not destructively take from it. There are two configurations shown:

- **Series Inductors:** Inductors in a series configuration on multiple layers can help to achieve a larger inductance value. Figure 39 shows the electrical and layout model of this configuration. The arrows show the direction of current flow. This configuration increases the series resistance (R_S) of the overall inductor.
- **Parallel Inductors:** Inductors in a parallel configuration can be used to reduce the series resistance (R_S) of the overall inductor. Figure 40 shows the electrical and layout model of this configuration. The arrows show the direction of current flow.

Figure 39. Multi-Layer Inductors in a Series Configuration

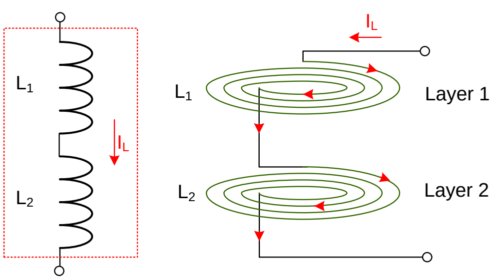
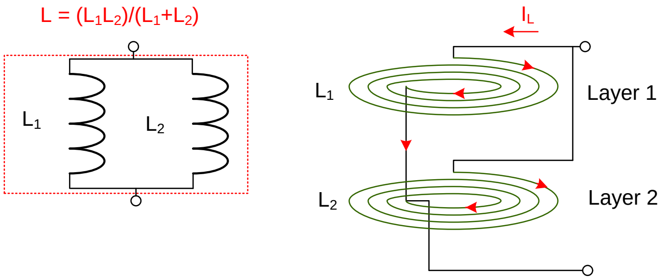


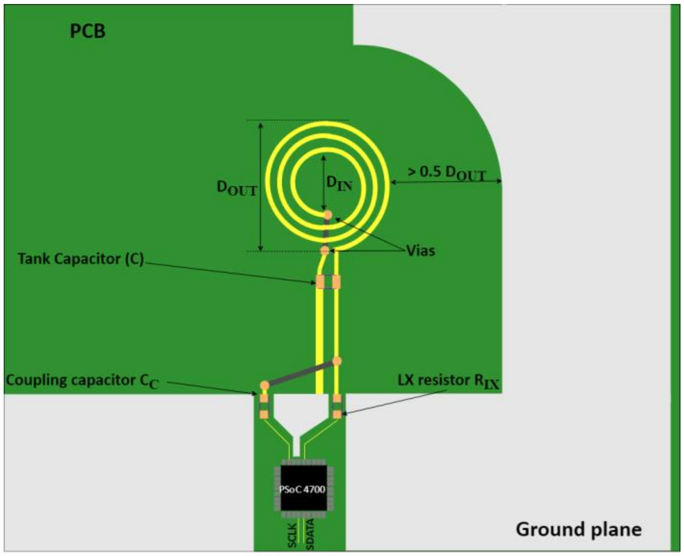
Figure 40. Multi-Layer Inductors in a Parallel Configuration



A.8 Sensor Layout Guidelines

This section highlights the layout guidelines to be considered during the physical design of an inductive sensing solution. Figure 41 provides a graphical summary of some key points.

Figure 41. Sensor Layout Considerations



A.8.1 Tank Considerations

Consider the following while laying out the LC tank:

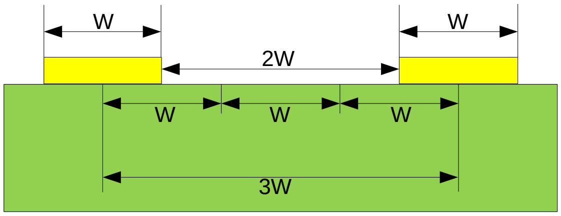
- Metal (routing, ground shields, and so on) should be kept away from the sensor as much as possible to maximize the signal from the sensor. If shielding is required behind the sensor, use a hatched ground and place the hatch on the bottom most PCB layer. You may have to increase the sensor diameter to compensate for some loss in signal.
- Place the metal traces 0.5*D_{OUT} away from the sensor where possible.
- Make sure that the ratio between the inner and outer diameter of the coil is > 0.3. ($D_{IN}/D_{OUT} > 0.3$)
- Make sure that the via size meets the recommended size of 15 mil.
- Place the vias close to the traces.
- Maximize the number of PCB layers used for the sensor to maximize the signal.

A.8.2 External Components

Consider the following while placing external components:

- Place the coupling capacitor (C_C) and the Lx resistor (R_{Lx}) as close as possible to the PSoC.
- Minimize the C_C trace width and length between the capacitor and the PSoC. This is a sensitive node and should not have interferers running beside it. Shield this trace from any Lx traces or sources of high frequency switching noise. If shielding is not possible, use the 3 W rule which states that “to reduce cross talk from adjacent traces, a minimum spacing of two trace widths should be maintained from edge to edge” as shown in Figure 42.

Figure 42. 3W Trace Spacing to Minimize Cross Talk



- Place the tank capacitor (C) as close to the coil as possible.
- Place the decoupling and CMOD capacitors as close as possible to the chip to keep the ground impedance and supply trace impedance as low as possible. It is important that the C_{MOD} capacitors and the chip ground have low ohmic connections.
- Place the components on the underside of the PCB to ensure the Z height does not infringe upon placement of a metal over touch overlay or proximity overlay.

A.8.3 Routing Considerations

Consider the following while routing signals:

- Place the Lx and Rx lines parallel to each other.
- Make sure that the Rx lines are not near any digital toggling line.
- Make sure that the Rx lines do not use the communications line port, for instance, the I2C or SWD ports as they may interfere with the signal.

A.8.4 Power and Ground

- Use both 1 µF and 0.1 µF decoupling capacitors on VDDD to VSS for PSoC 4700.
- Use both 10 µF and 0.1 µF decoupling capacitors on VDDA to VSSA for PSoC 4700 in mains-powered applications and use 1 µF and 0.1 µF decoupling capacitors on VDDA to VSSA for battery-powered applications.
- Use a 1 µF capacitor on VCCD to VSSD for the PSoC 4700.
- VDDIO noise couples with the LC tank through the IO, which resonates the tank. If supply noise is excessive in the system, consider a regulator or a filter on the VDDD supply.
- Make sure to use a low resistance ground plane to prevent any ground noise coupling into the LC tank.

A.9 Hardware Considerations

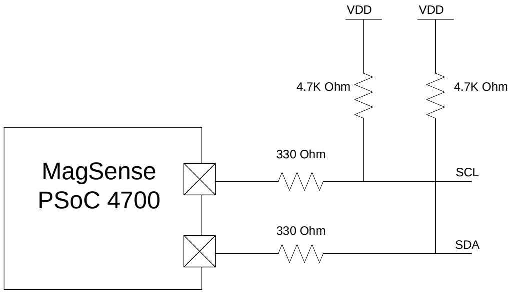
A.9.1 Ground Plane

A ground plane on the PCB reduces both RF emissions and interference. Solid grounds near MagSense sensors reduce the inductance. It is recommended to use hatched ground planes surrounding the sensor observing the distances outlined in section A.8.

A.9.2 Series Resistors on Digital Communications Lines

Communication lines, such as I^2C and SPI, can have long traces that act as antennae. They benefit from the addition of series resistance; 330 Ω is the recommended value as shown in Figure 43. The recommended pull-up resistor value for I^2C communication lines is 4.7 kΩ. If a series resistor of value greater than 330 Ω is placed in series with these lines, the V_{IL} and V_{IH} voltage levels may fall out of specifications, while 330 Ω will not affect I^2C operation as the V_{IL} level remains within the I^2C specification limit of 0.3 VDD when PSoC outputs a LOW.

Figure 43. Series Resistors on Communication Lines



A.9.3 Trace length

Long traces can pick up more noise than short traces. Long traces also add to C_P. Minimize the trace length whenever possible.

A.9.4 Current Loops

Another important layout consideration is to minimize the return path for currents. This is important as the current flows in loops. Unless there is a proper return path for high-speed signals, the return current will flow through a longer return path forming a larger loop, thus leading to increased emissions and interference.

If you isolate any MagSense ground hatch and ground fill around the device the sensor-switching current may take a longer return path. The MagSense sensors are switched at a high frequency, so the long return current may cause EMC issues. It is recommended to use a single ground fill to minimize the length of such a return path and any subsequent emissions.

A.10 Sensor Design Spreadsheet

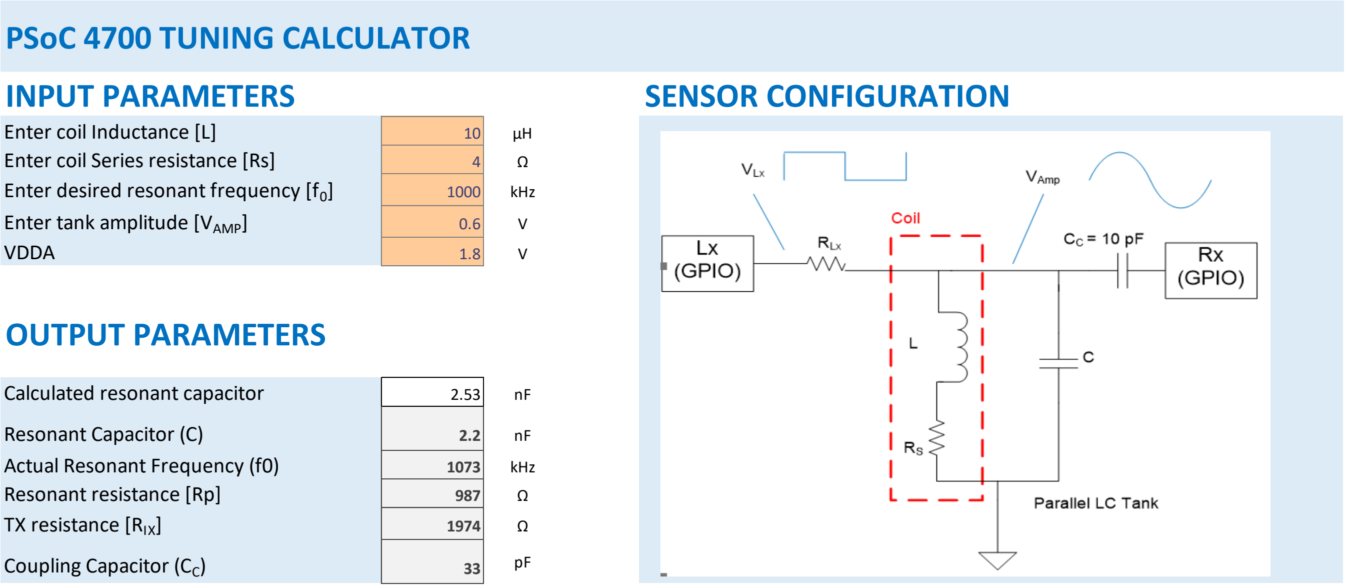
A Microsoft spreadsheet, *MagSense Toolkit.xlsx*, has been defined to assist with Inductive sensor design and is attached with this design guide. The spreadsheet has the following tabs:

- Tuning Calculator
- Simple Coil Designer
- Metal Deflection Estimator

A.10.1 Tuning Calculator

Figure 44 shows the **Tuning Calculator** tab. Using this tab, you can quickly estimate the tuning parameters for the PSoC 4700 family.

Figure 44. Simple Tuning Calculator Tab



PSoC 4700 TUNING CALCULATOR

INPUT PARAMETERS

Enter coil Inductance [L]	10	µH
Enter coil Series resistance [Rs]	4	Ω
Enter desired resonant frequency [f_0]	1000	kHz
Enter tank amplitude [V_{AMP}]	0.6	V
VDDA	1.8	V

OUTPUT PARAMETERS

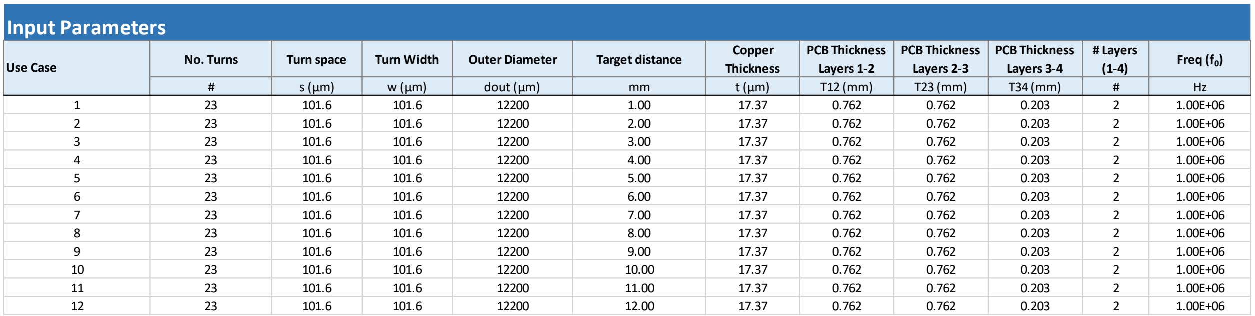
Calculated resonant capacitor	2.53	nF
Resonant Capacitor (C)	2.2	nF
Actual Resonant Frequency (f0)	1073	kHz
Resonant resistance [Rp]	987	Ω
TX resistance [R_{IX}]	1974	Ω
Coupling Capacitor (C_C)	33	pF

SENSOR CONFIGURATION

A.10.2 Simple Coil Designer

The coil designer is a tool used to design the sensor itself. A list of input parameters is shown in Figure 45. In metal proximity applications, the Target distance column can be used, which estimates the signal change with an Aluminum target at different distances from the coil. The signal change estimator is accurate to within a few percent in the proximity range from 0.1xDout to 1xDout. The output parameters are outlined in Figure 46.

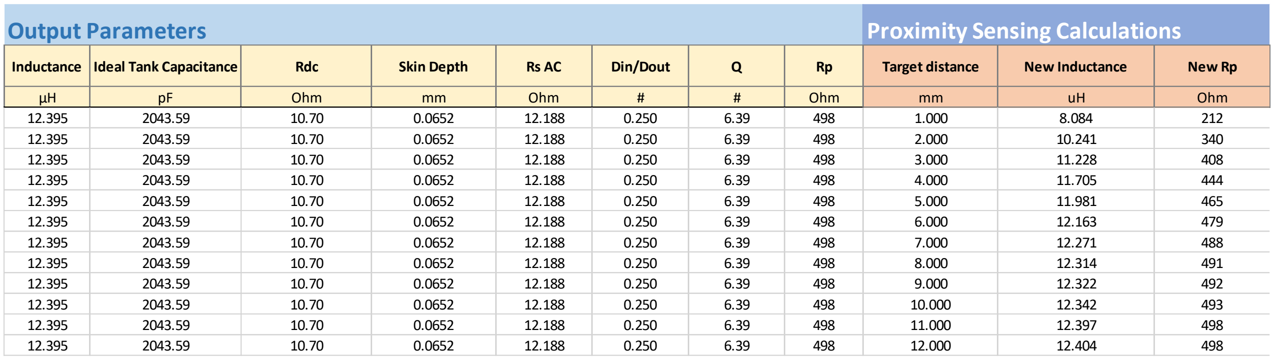
Figure 45. Coil Designer Spreadsheet Input Parameters



Input Parameters

Use Case	No. Turns	Turn space	Turn Width	Outer Diameter	Target distance	Copper Thickness	PCB Thickness Layers 1-2	PCB Thickness Layers 2-3	PCB Thickness Layers 3-4	# Layers (1-4)	Freq (f_0)
	#	s (µm)	w (µm)	dout (µm)	mm	t (µm)	T12 (mm)	T23 (mm)	T34 (mm)	#	Hz
1	23	101.6	101.6	12200	1.00	17.37	0.762	0.762	0.203	2	1.00E+06
2	23	101.6	101.6	12200	2.00	17.37	0.762	0.762	0.203	2	1.00E+06
3	23	101.6	101.6	12200	3.00	17.37	0.762	0.762	0.203	2	1.00E+06
4	23	101.6	101.6	12200	4.00	17.37	0.762	0.762	0.203	2	1.00E+06
5	23	101.6	101.6	12200	5.00	17.37	0.762	0.762	0.203	2	1.00E+06
6	23	101.6	101.6	12200	6.00	17.37	0.762	0.762	0.203	2	1.00E+06
7	23	101.6	101.6	12200	7.00	17.37	0.762	0.762	0.203	2	1.00E+06
8	23	101.6	101.6	12200	8.00	17.37	0.762	0.762	0.203	2	1.00E+06
9	23	101.6	101.6	12200	9.00	17.37	0.762	0.762	0.203	2	1.00E+06
10	23	101.6	101.6	12200	10.00	17.37	0.762	0.762	0.203	2	1.00E+06
11	23	101.6	101.6	12200	11.00	17.37	0.762	0.762	0.203	2	1.00E+06
12	23	101.6	101.6	12200	12.00	17.37	0.762	0.762	0.203	2	1.00E+06

Figure 46. Coil Designer Spreadsheet Output Parameters



Output Parameters								Proximity Sensing Calculations		
Inductance	Ideal Tank Capacitance	Rdc	Skin Depth	Rs AC	Din/Dout	Q	Rp	Target distance	New Inductance	New Rp
µH	pF	Ohm	mm	Ohm	#	#	Ohm	mm	uH	Ohm
12.395	2043.59	10.70	0.0652	12.188	0.250	6.39	498	1.000	8.084	212
12.395	2043.59	10.70	0.0652	12.188	0.250	6.39	498	2.000	10.241	340
12.395	2043.59	10.70	0.0652	12.188	0.250	6.39	498	3.000	11.228	408
12.395	2043.59	10.70	0.0652	12.188	0.250	6.39	498	4.000	11.705	444
12.395	2043.59	10.70	0.0652	12.188	0.250	6.39	498	5.000	11.981	465
12.395	2043.59	10.70	0.0652	12.188	0.250	6.39	498	6.000	12.163	479
12.395	2043.59	10.70	0.0652	12.188	0.250	6.39	498	7.000	12.271	488
12.395	2043.59	10.70	0.0652	12.188	0.250	6.39	498	8.000	12.314	491
12.395	2043.59	10.70	0.0652	12.188	0.250	6.39	498	9.000	12.322	492
12.395	2043.59	10.70	0.0652	12.188	0.250	6.39	498	10.000	12.342	493
12.395	2043.59	10.70	0.0652	12.188	0.250	6.39	498	11.000	12.397	498
12.395	2043.59	10.70	0.0652	12.188	0.250	6.39	498	12.000	12.404	498

Table 11 shows the comparison between the L and R_S values calculated by the toolkit and the measured values for few test coils.

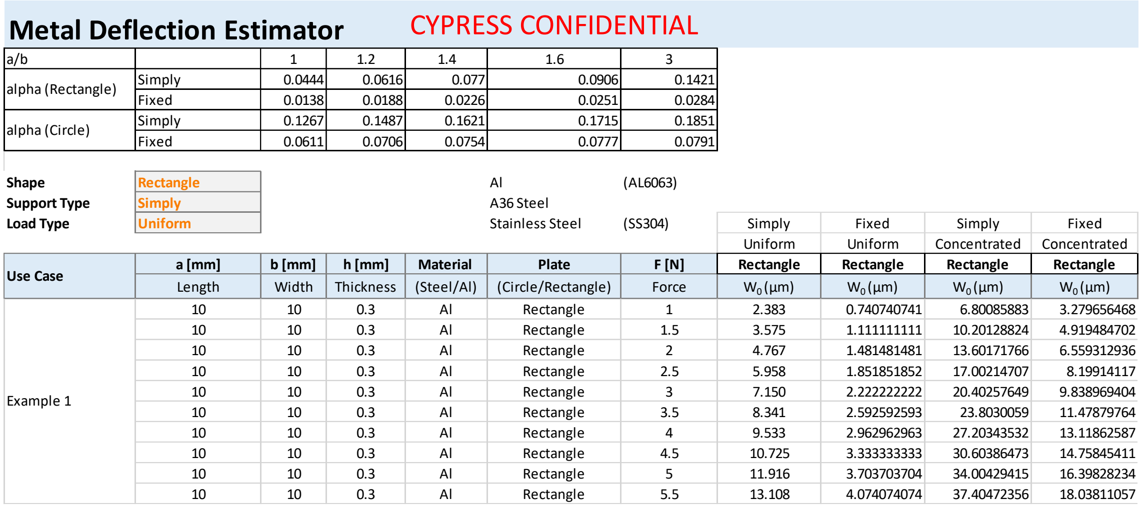
Table 11. Comparison of Measured and Calculated L and R_S

Coil Parameters											Measured Values		Calculated using Cypress MagSense Calculator		% Inductance Error	% Rs Error
Use Case	No. Turns	Turn space	Turn Width	Outer Diameter	Copper Thickness	PCB Thickness Layers 1-2	PCB Thickness Layers 2-3	PCB Thickness Layers 3-4	No. Layers	Frequency	Inductance	Rs	Inductance	Rs		
	#	s (mil)	w (mil)	dout (mm)	t (µm)	T12 (mm)	T23 (mm)	T34 (mm)	#	f_0 (kHz)	L (µH)	Ohm	L (µH)	Ohm		
Coil A	40	4	4	20	17.37	1.59	n/a	n/a	2	550	55.9	20	49.5	32	11.4	60
Coil B	24	4	4	13	17.37	0.2	1.15	0.2	4	550	55.6	18	52.6	26.5	5.4	47.2
Coil C	30	6	8	29	17.37	0.2	1.15	0.2	4	1000	274	50.4	186.2	38.5	32	23.6
Coil D	16	4	4	10	17.37	1.55	n/a	n/a	2	1000	20.6	10	5.7	7.6	72.3	24
Coil E	25	4	4	13	17.37	1.59	n/a	n/a	2	1000	14.1	7.3	13.7	13.9	2.8	90.4

A.10.3 Metal Deflection Estimator

In MoT applications, it is important to understand the required area and thickness of metal plate. The metal deflection estimator uses thin plate mechanics calculations to estimate the deflection of either a rectangular or circular metal plate. An example is shown in Figure 47.

Figure 47. Metal Deflection Estimator Spreadsheet



Metal Deflection Estimator CYPRESS CONFIDENTIAL

a/b		1	1.2	1.4	1.6	3
alpha (Rectangle)	Simply	0.0444	0.0616	0.077	0.0906	0.1421
	Fixed	0.0138	0.0188	0.0226	0.0251	0.0284
alpha (Circle)	Simply	0.1267	0.1487	0.1621	0.1715	0.1851
	Fixed	0.0611	0.0706	0.0754	0.0777	0.0791

Shape	Rectangle
Support Type	Simply
Load Type	Uniform

Al	(AL6063)
A36 Steel	
Stainless Steel	(SS304)

							Simply	Fixed	Simply	Fixed
							Uniform	Uniform	Concentrated	Concentrated
Use Case	**a [mm]**	**b [mm]**	**h [mm]**	**Material**	**Plate**	**F [N]**	**Rectangle**	**Rectangle**	**Rectangle**	**Rectangle**
	Length	Width	Thickness	(Steel/Al)	(Circle/Rectangle)	Force	W_0 (µm)	W_0 (µm)	W_0 (µm)	W_0 (µm)
Example 1	10	10	0.3	Al	Rectangle	1	2.383	0.740740741	6.80085883	3.279656468
	10	10	0.3	Al	Rectangle	1.5	3.575	1.111111111	10.20128824	4.919484702
	10	10	0.3	Al	Rectangle	2	4.767	1.481481481	13.60171766	6.559312936
	10	10	0.3	Al	Rectangle	2.5	5.958	1.851851852	17.00214707	8.19914117
	10	10	0.3	Al	Rectangle	3	7.150	2.222222222	20.40257649	9.838969404
	10	10	0.3	Al	Rectangle	3.5	8.341	2.592592593	23.8030059	11.47879764
	10	10	0.3	Al	Rectangle	4	9.533	2.962962963	27.20343532	13.11862587
	10	10	0.3	Al	Rectangle	4.5	10.725	3.333333333	30.60386473	14.75845411
	10	10	0.3	Al	Rectangle	5	11.916	3.703703704	34.00429415	16.39828234
	10	10	0.3	Al	Rectangle	5.5	13.108	4.074074074	37.40472356	18.03811057

Appendix B. Reading Sensor Debug Data in Bridge Control Panel

To tune the MagSense CSD parameters for a sensor, you need to view the sensor data such as the raw count, baseline, and difference count. For viewing the sensor data, you can use the MagSense Tuner available in the MagSense Component or use the Bridge Control Panel (BCP) tool.

Using the BCP tool, you can view other parameters in addition to the raw count, baseline, and difference count. The MagSense Tuner requires I^{2}C communication for viewing the sensor data, whereas the BCP tool supports both I^{2}C and UART communication for viewing the sensor data.

This appendix explains how to view the sensor data in the BCP tool through UART communication.

Table 12 lists the general structure of a UART TX packet sent to the BCP tool. The TX packet consists of a header (2 bytes), data (of variable length), and a tail (3 bytes).

Table 12. UART TX Data Packet Structure

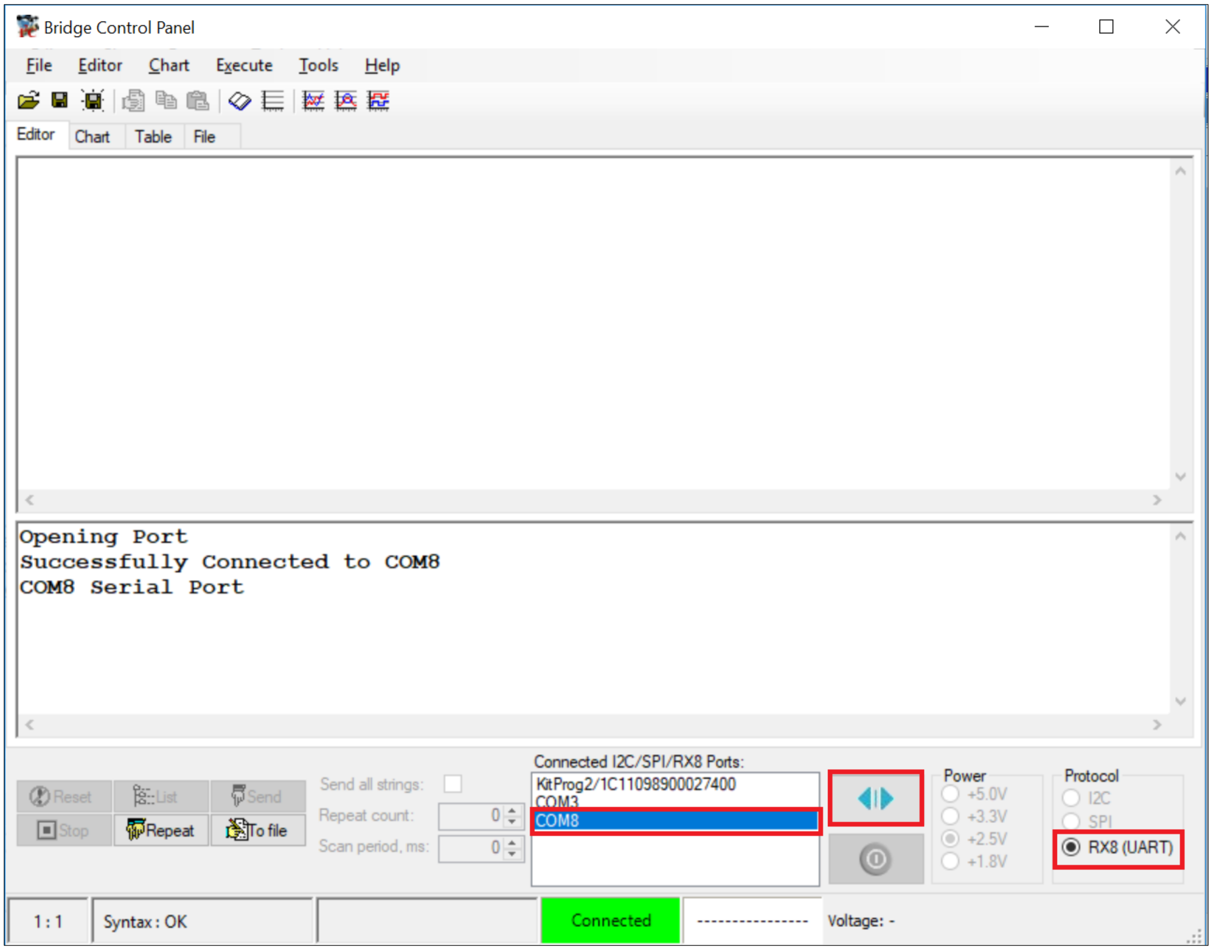
Header		Data	Tail		
0x0D	0x0A	Variable-length data	0x00	0xFF	0xFF

Note: To learn about the exact data for any example project, see the *.iic* file provided with it.

Follow these steps to set up the BCP tool for viewing the data:

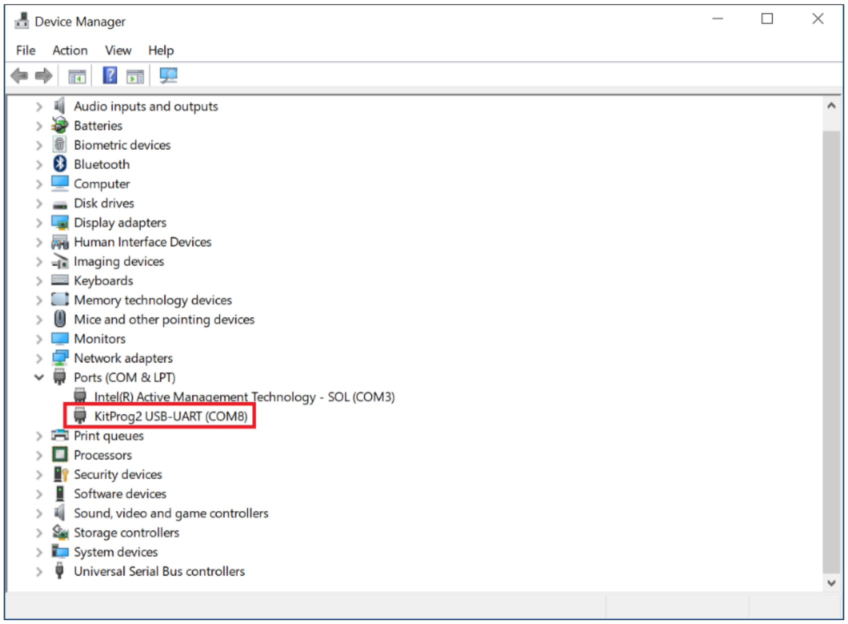
1. Connect CY8CKIT-148 to the PC using the USB cable (USB A to mini-B).
2. Press **Ctrl** + **F5** to program the CY8CKIT-148 kit.
3. Open the BCP tool (choose **Start** > **All Programs** > **Cypress** > **Bridge Control Panel <version>** > **Bridge Control Panel <version>**).
4. In the BCP tool, select the CY8CKIT-148 kit UART-bridge COM port in the Connected I2C /SPI/RX8 Ports window and set **RX8 (UART)** as its protocol, as Figure 48 shows. The CY8CKIT-148 kit UART-bridge COM port will be listed in the Device Manager, as Figure 49 shows.

Figure 48. Bridge Control Panel – COM Port and Protocol Selection



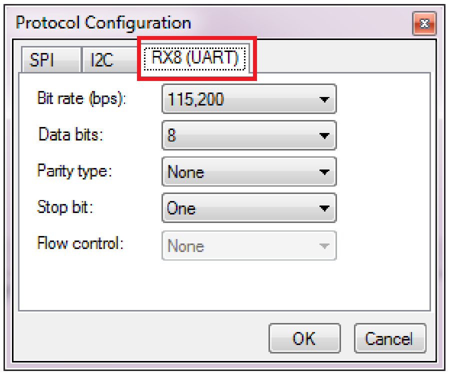
```
Opening Port
Successfully Connected to COM8
COM8 Serial Port
```

Figure 49. KitProg COM Port in Device Manager



5. Choose **Tools** > **Protocol Configuration** or press **F7** and configure the RX8 protocol parameters, as Figure 50 shows.

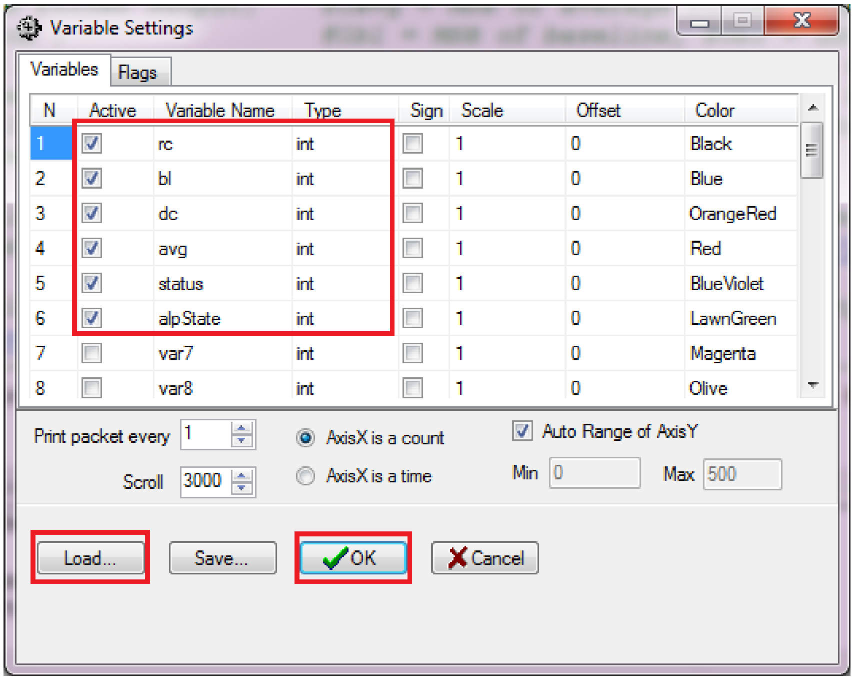
Figure 50. RX8 Protocol Configuration



Bit rate (bps): 115,200
Data bits: 8
Parity type: None
Stop bit: One
Flow control: None

6. Choose **Chart** > **Variable Settings** > **Load** and navigate to the example project directory. Select the *<Project_Name>.ini* file and click **Open**. Click **OK** to apply the settings and close the window, as shown in Figure 51.

Figure 51. Bridge Control Panel – Variable Settings

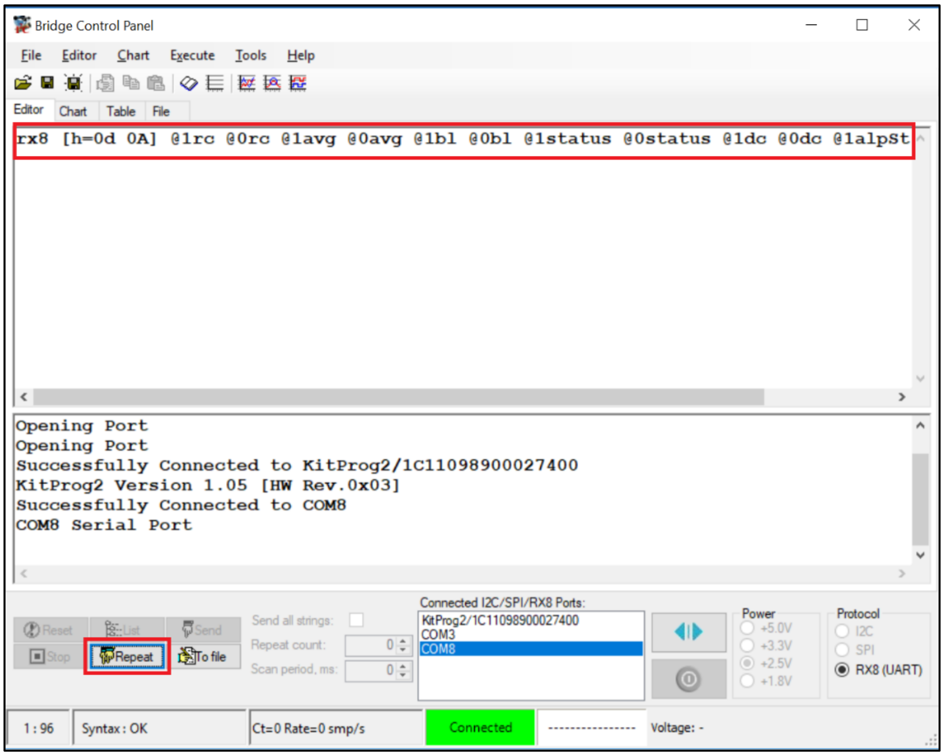


N	Active	Variable Name	Type	Sign	Scale	Offset	Color
1	☑	rc	int	☐	1	0	Black
2	☑	bl	int	☐	1	0	Blue
3	☑	dc	int	☐	1	0	OrangeRed
4	☑	avg	int	☐	1	0	Red
5	☑	status	int	☐	1	0	BlueViolet
6	☑	alpState	int	☐	1	0	LawnGreen
7	☐	var7	int	☐	1	0	Magenta
8	☐	var8	int	☐	1	0	Olive

Print packet every 1
Scroll 3000
● AxisX is a count
○ AxisX is a time
☑ Auto Range of AxisY
Min 0 Max 500

7. Choose **File** > **Open File** and select the *<Project_Name>.iic* file provided with the project and click **Open**.
8. Place the cursor on the command line and then click **Repeat**, as Figure 52, shows to start receiving the packets.
9. To view the sensor data in a graphical format, click the **Chart** tab. Uncheck the **Select All** option and check the **rc** and **bl** options to view the raw count and baseline, as shown in Figure 53. Similarly, you can view the difference count (**dc**) and the average filtered data

Figure 52. Reading Debug Data in Bridge Control Panel



```
rx8 [h=0d 0A] @1rc @0rc @1avg @0avg @1bl @0bl @1status @0status @1dc @0dc @1alpSt
```

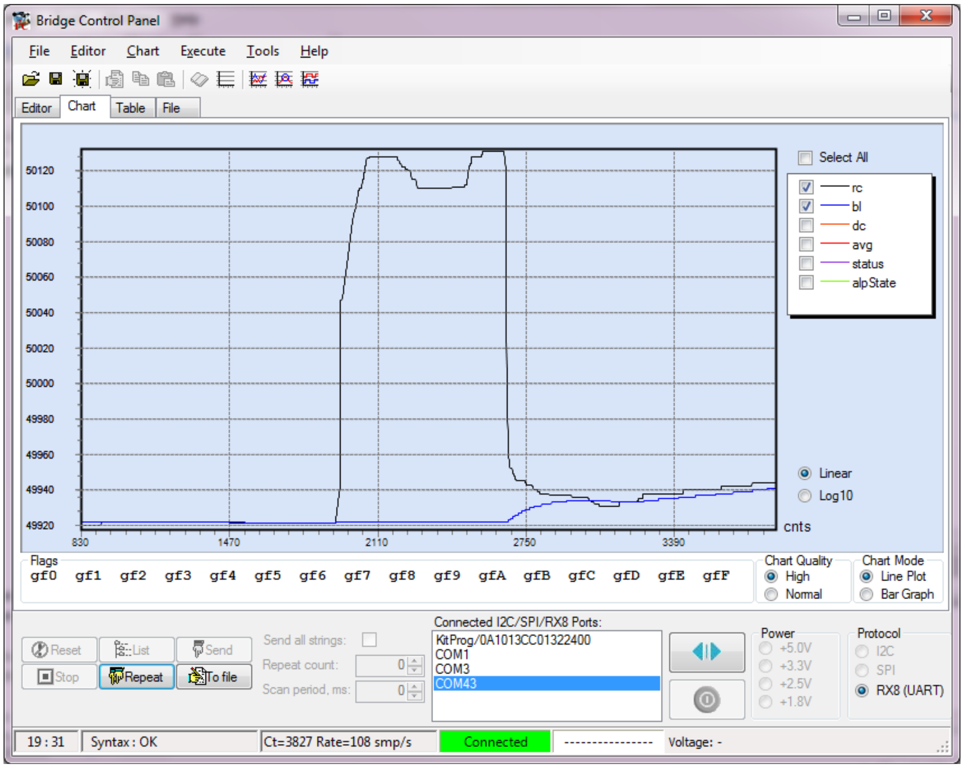
```
Opening Port
Opening Port
Successfully Connected to KitProg2/1C11098900027400
KitProg2 Version 1.05 [HW Rev.0x03]
Successfully Connected to COM8
COM8 Serial Port
```

Connected I2C/SPI/RX8 Ports: KitProg2/1C11098900027400, COM3, COM8 (selected)

Protocol: RX8 (UART)

1 : 96 | Syntax : OK | Ct=0 Rate=0 smp/s | Connected | --------------- | Voltage: -

Figure 53. Viewing MagSense Debug Data in Graphical Format in Bridge Control Panel



Connected I2C/SPI/RX8 Ports: KitProg/0A1013CC01322400, COM1, COM3, COM43 (selected)

19 : 31 | Syntax : OK | Ct=3827 Rate=108 smp/s | Connected | --------------- | Voltage: -

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**	6001001	PMW, DIMA	12/21/2017	New Draft Application Note for Inductive Sensing
*A	6212551	DIMA	06/20/2018	Added MoT and Rotary Encoder use cases Added DC blocking capacitor for power optimization Updated Component captures Updated Figure 2 and Figure 27 Added Sensor Design Toolkit and Layout guidelines
*B	6288116	DIMA	08/27/2018	Updated figures 12, 13,14 ,15, and 22.
*C	6533844	DIMA	04/01/2019	Added Mechanical Design consideration for buttons (section 4.2.1)

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