TI Designs
Inductive Proximity Switch BoosterPack

TI Designs

This design guide provides a foundation for building front-end circuits for an inductive proximity sensor with TI's inductance-to-digital converters. The document includes the methodology, testing, and design files to quickly evaluate and customize the system. TI Designs help *you* accelerate your time to market.

Design Resources

TIDA-00563	Design Folder
LDC1101	Product Folder
MSP430F5528	Product Folder
LP5951	Product Folder
TPD2E001	Product Folder
TPD1E10B06	Product Folder

TI E2E™ Community

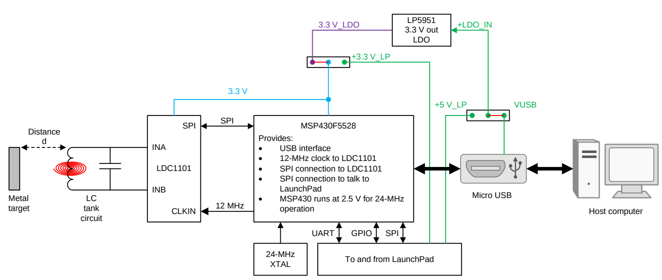
ASK Our E2E Experts

Design Features

- Inductive Sensing Technology
- Non-Contact Detection of Metallic Targets at Shorter Ranges
- Increased Flexibility and Performance Without Requiring Analog Trimming Techniques
- Operating Distance of 6 mm and Programmed for Hysteresis of 1 mm
- Insensitive to Environmental Contaminations
- More Reliable Operation Sensor Self-Diagnostic
- Replace Legacy Analog Only Solutions

Featured Applications

- Factory Automation and Process Control
- Sensors and Field Transmitters
- Building Automation
- Portable Instruments



An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.

1 Key System Specifications

Table 1. Key Specifications

PARAMETER	SPECIFICATION
Sensor type	Four-layer PCB circular coil with two parallel inductors (ϕ = 14 mm)
Target materials	Aluminum
Target size	1-mm thickness
Target approach direction	Axial
Operating distance	6 mm
Differential travel or hysteresis	1 mm
Power supply	5-V USB or external power

2 System Description

Sensors are like nervous system for any automated factory floors. They provide necessary information to the programmable logic controller (PLC). Even the best controllers cannot control the process without reliable sensors. When an application needs to detect a metallic target within an inch of the sensing surface, inductive proximity sensors are suitable for the task. Moreover, inductive sensors have a proven track record for operating reliably in harsh environmental conditions. The inductive sensors are an obvious choice due to their contactless, magnet-free sensing, contamination-resistant, and maintenance-free operation. Due to its high reliability, the inductive proximity switch has virtually replaced the mechanical switch.

TI offers highly integrated complete analog front end (AFE) inductance-to-digital converters (LDCs) optimized for use in industrial proximity sensors. This reference design uses the LDC1101, a 1.8- to 3.3-V high-resolution, high-speed inductance-to-digital converter. The LDC1101 provides a programmable decision threshold setting and a wide sensor frequency range. Due to its programmability, the LDC1101 can be used with a wide variety of external inductors, and its detections thresholds can be adjusted to the desired detection distance.

The scope of this design guide is to give system designers a head start in integrating TI's inductance-to-digital converter (LDC), ultra-low-power MCU, and power management devices into their end-equipment systems. This design guide describes the principle of operation and basic design process for building a high performance and highly reliable inductive proximity switch at a lower cost than other competing solutions. This design guide also addresses component selection, design theory, and test results of the TI Design system. All the relevant design files like schematics, BOM, layer plots, Altium files, Gerber, and MSP430 MCU firmware are provided.

2.1 Inductance-to-Digital Converter Selection

The LDC1101 is an inductance-to-digital converter that can simultaneously measure the impedance and resonant frequency of an LC resonator. The high-resolution measurement capability enables this device to directly measure changes in physical systems, allowing the resonator to sense the proximity and movement of conductive materials.

The LDC1101 measures the impedance and resonant frequency by regulating the oscillation amplitude in a closed-loop configuration at a constant level while monitoring the energy dissipated by the resonator. By monitoring the amount of power injected into the resonator, the LDC1101 can determine the parallel resistance of the resonator, R_P, which the LDC1101 returns as a digital value. In addition, the LDC1101 also measures the oscillation frequency of the LC circuit, which is then used to determine the inductance of the LC circuit. The LDC1101 is a high-resolution and low-cost device that enables contactless, short-range sensing even in harsh environments. Using a printed circuit board (PCB) coil as a sensor, the LDC1101 provides a way for system designers to achieve high performance and reliability at a lower system cost than other competing solutions. The LDC1101 was chosen because the device has the ability to measure inductance at a 16- or 24-bit resolution. The device has a simple four-wire serial peripheral interface (SPI). The power supply for the device can range from 1.8 V −5% to 3.3 V +5%.

2.2 Microcontroller Selection

TI Design system has relatively few requirements for the microcontroller. This TI Design requires one SPI to communicate with the LDC device, one SPI to communicate with the LaunchPad™ MCU, a USB to communicate with a LabVIEW™-based graphical user interface (GUI) running on a laptop or PC, and a few general purpose inputs and outputs (GPIOs) for interrupts, driving LEDs, and pushbutton switches.

The MSP430F5528 MCU was chosen as the central processor in this design as a means to demonstrate Texas Instruments' technology. This device is a fully-featured MCU with a wide variety of peripherals that more than fulfill the requirements of the TI Design system.

2.3 Power Management

The LP5951 low-dropout (LDO) regulator devices are the power management devices for the subsystem for several reasons. This particular subsystem is designed to power from a nominal input voltage of 5 V from a LaunchPad or from a standard USB port, which has a nominal voltage of 5 V. The LP5951 has a current limit of 150 mA and an adjustable output voltage range from 1.3 to 3.7 V at a low quiescent current of 29 µA (typical), which is significantly higher than the anticipated, maximum total operating load of the subsystem. Only one LP5951 device is used in this subsystem to regulate a 3.3-V output for the MSP430F5528 and LDC1101 devices.

The LDC and the MCU all require a 3.3-V voltage rail for their operation. Integrating the technology demonstrated in this design into an end-equipment system may necessitate a different power management configuration. The choice of devices for power management can change, depending on existing input voltage rails. If lower voltage point-of-load rails already exist, then different TI devices for power management may be chosen to suit the conditions of the system (see www.ti.com/power).

2.4 ESD Protection for Programming Interface

This TI Design system has robust protection against electromagnetic interference (EMI) on the Joint Test Action Group (JTAG) programming connector. The TPD1E10B06 single-channel, electro-static discharge (ESD) protection device was chosen to protect the Spy-Bi-Wire™ (SBW) programming interface. The device offers an over ±30-kV IEC air-gap, over ±30-kV contact ESD protection, and has an ESD clamp circuit with a back-to-back diode for bipolar or bidirectional signal support. The 10-pF line capacitance is suitable for a wide range of applications supporting data rates up to 400 millions of bits per second (Mbps). The 0402 package is an industry standard and convenient for component placement in space-saving applications. The TPD1E10B06 is characterized to operate over an ambient air temperature of –40°C to 125°C.

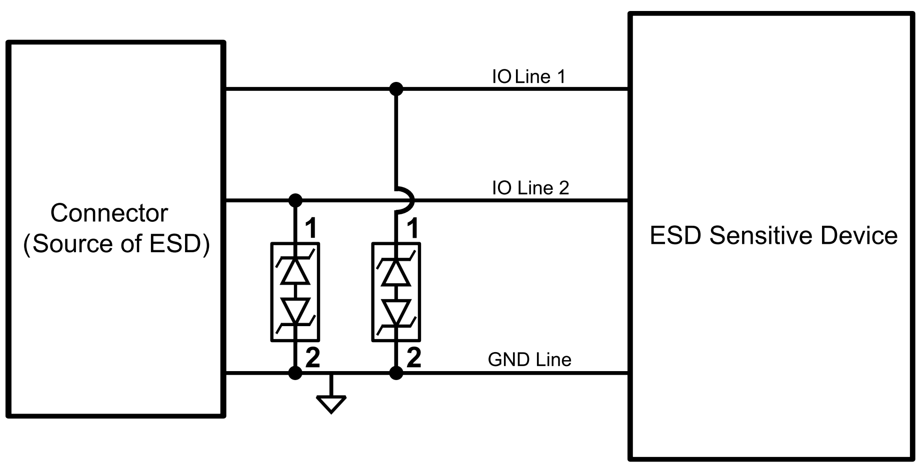


Figure 1. Functional Diagram of TPD1E10B06

2.5 ESD Protection for USB

This TI Design system has robust protection against electromagnetic interference (EMI), particularly on the USB power lines. The primary EMI protection circuitry is located on the USB jack.

The TPD2E001 is a unidirectional, dual-channel, ultra-low capacitance ESD-protection device. The device construction consists of a central ESD clamp that features two hiding diodes per line to reduce the capacitive loading. This central ESD clamp is also connected to V_{CC} to provide protection for the V_{CC} line. Each IO line is rated to dissipate ESD strikes above the maximum level specified in the IEC 61000-4-2 level 4 international standards. The TPD2E001 device's low-loading capacitance makes it ideal for protecting high-speed signal terminals like a USB.

The TPD2E001 is a passive integrated circuit that activates whenever voltages above V_{BR} or below the lower diode's $V_{FORWARD}$ (–0.6 V) are present during a transient event. During ESD events, voltages as high as ±15 kV can be directed to ground and V_{CC} through the internal diode network. As soon as the voltages on the protected lines fall below the trigger voltage of the TPD2E001 (usually within 10 seconds of nanoseconds) the device reverts back to a high impedance state.

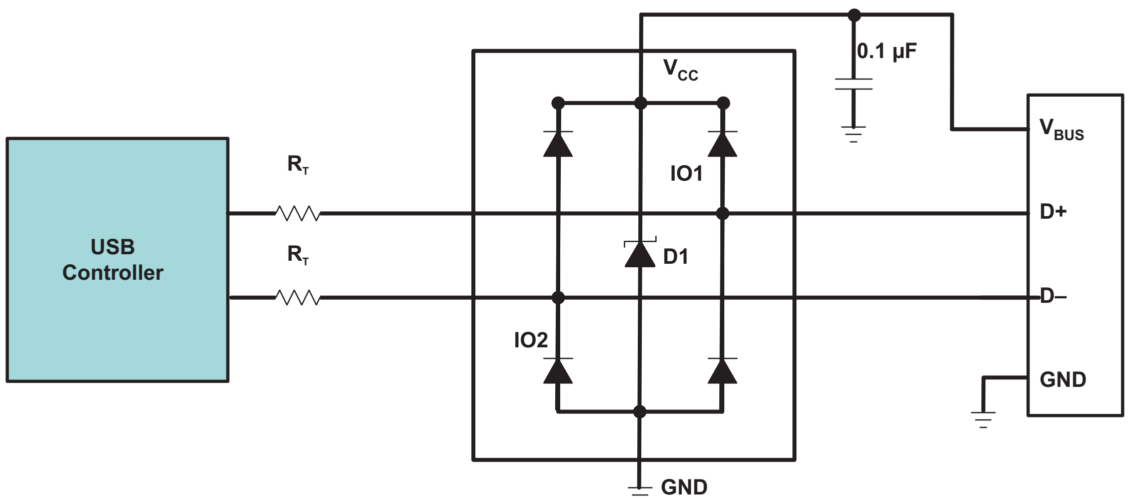


Figure 2. Functional Diagram of TPD2E001

3 Block Diagram

The system consists of the LDC1101 inductance-to-digital converter, the MSP430 MCU, and the supporting electronics. The MCU acts as a bridge between the LDC1101's SPI and the GUI's USB COM port. The MCU also provides non-volatile storage for the LDC1101's initial register values as well as the calibration data. The LDC1101EVM uses PC-based application software for device configuration and to retrieve conversion results. The conversion results may also be logged into a file for further processing. A 2-pin connector can easily connect to different sensor coils. The system is design in a standard 40-pin BoosterPack™ plugin module that fits on top of a LaunchPad evaluation kit.

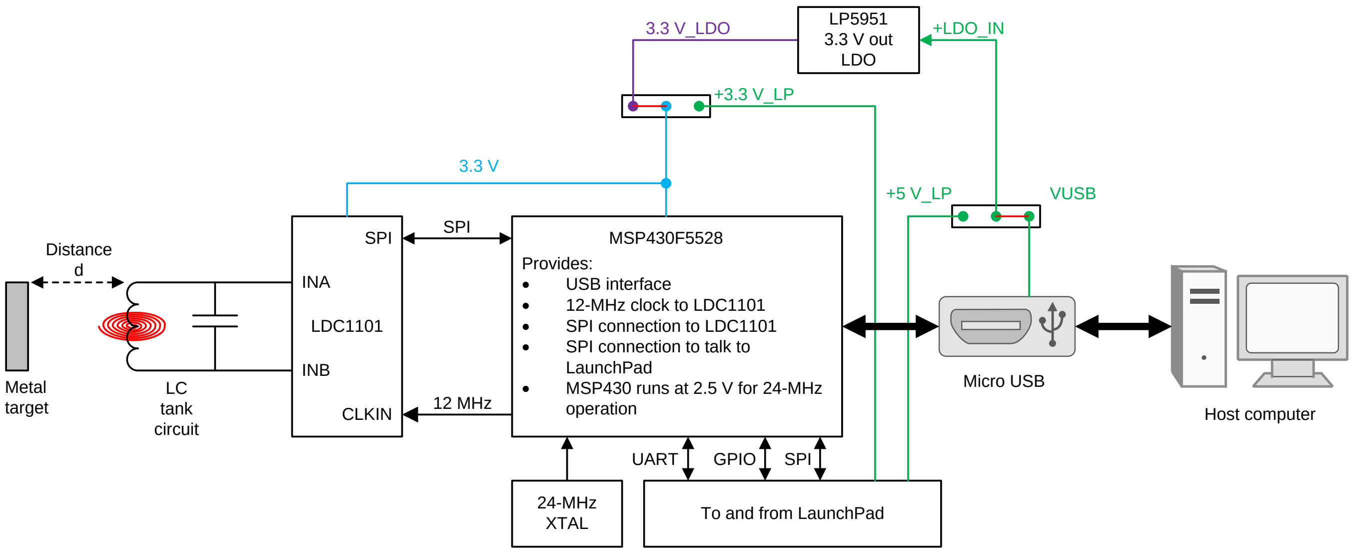


Figure 3. Block Diagram of TIDA-00563

3.1 *Highlighted Products*

The linear position sensing using inductive sensing reference design features the following devices:

- LDC1101: 1.8-V high resolution inductance-to-digital converter
- MSP430F5528: Ultra-low power MSP430 with 128KB Flash
- LP5951: Micro-power, 150-mA low-dropout CMOS voltage regulator
- TPD1E10B06: Single-channel ESD protection diode in 0402 package
- TPD2E001: Low-capacitance two-channel ESD-protection for high-speed data interfaces

For more information on each of these devices, see their respective product folders at www.ti.com.

3.1.1 LDC1101 Features

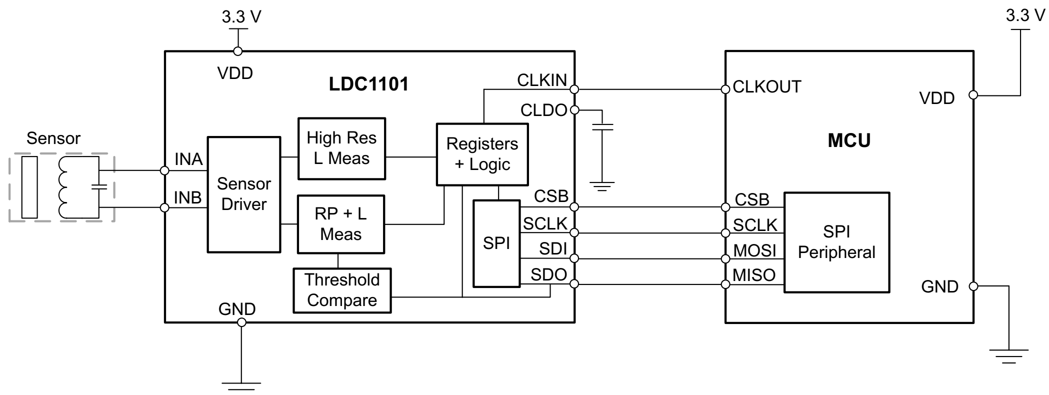


Figure 4. Functional Diagram of LDC1101

- R_P resolution: 16 bits
- L resolution: 16/24 bits
- 150-kSPS conversion rate
- Wide operating voltage range: 1.8 to 3.3 V
- Supply current:
  - 5-µA shutdown mode
  - 150-µA sleep mode
  - 2 mA (not including sensor current)
- Sub-micron resolution
- Adjustable sensing range (through coil design)
- Remote sensor placement; isolates the LDC from harsh environments
- Robust against environment interference such as dirt and dust
- Sensor frequency range: 500 kHz to 10 MHz
- Magnet-free operation

For more details, see the LDC1101 datasheet.

3.1.2 MSP430F5528 Features

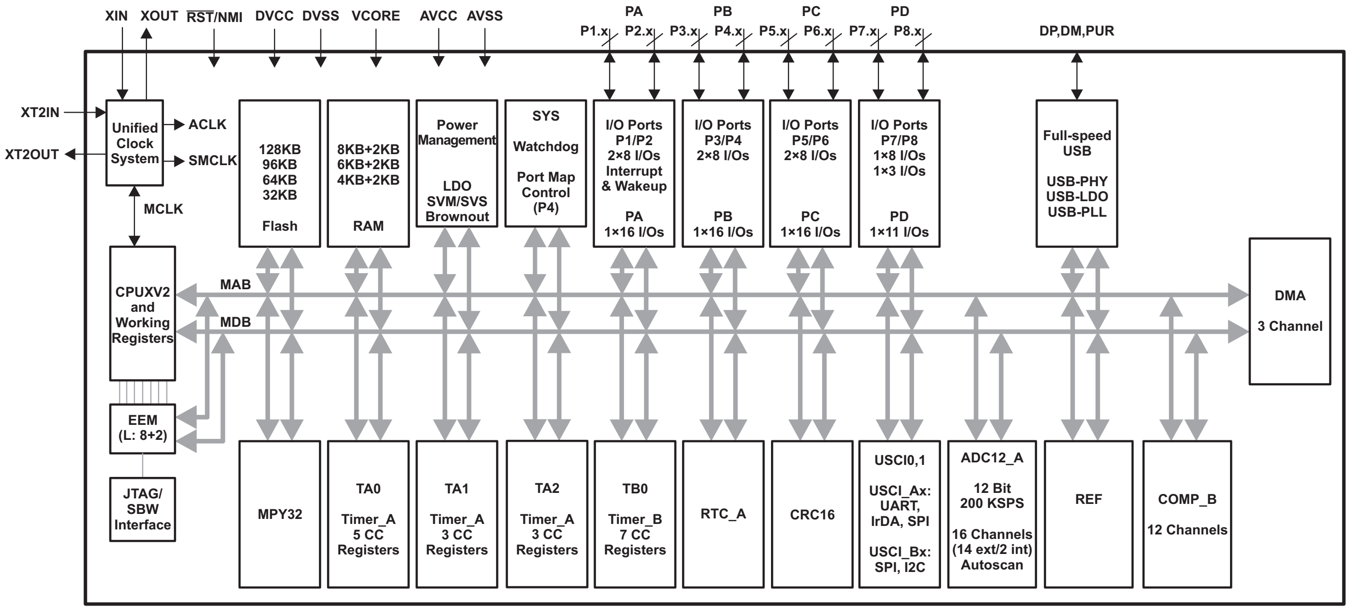


Figure 5. Block Diagram of MSP430F5528

- Low supply-voltage range: 3.6 V down to 1.8 V
- Ultra-low power consumption:
  - Active mode (AM):
    - All system clocks active
    - 290 µA/MHz at 8 MHz, 3.0 V, Flash program execution (typical)
    - 150 µA/MHz at 8 MHz, 3.0 V, RAM program execution (typical)
  - Standby mode (LPM3):
    - Real-time clock with crystal, watchdog, and supply supervisor operational, full RAM retention, fast wake-up:
      - 1.9 µA at 2.2 V, 2.1 µA at 3.0 V (typical)
      - Low-power oscillator (VLO), general-purpose counter, watchdog, and supply supervisor operational, full RAM retention, fast wake-up: 1.4 µA at 3.0 V (typical)
  - Off mode (LPM4):
    - Full RAM retention, supply supervisor operational, fast wake-up: 1.1 µA at 3.0 V (typical)
  - Shutdown mode (LPM4.5): 0.18 µA at 3.0 V (typical)
- Wake-up from standby mode in 3.5 µs (typical)
- 16-bit RISC architecture, extended memory, up to 25-MHz system clock
- Flexible power management system:
  - Fully integrated LDO with programmable regulated core supply voltage
  - Supply voltage supervision, monitoring, and brownout
- Unified clock system
  - Frequency-locked loop (FLL) control loop for frequency stabilization
  - Low-power, low-frequency internal clock source (VLO)
  - Low-frequency trimmed internal reference source (REFO)
  - 32-kHz watch crystals (XT1)
  - High-frequency crystals (XY1)
  - High-frequency crystals up to 32 MHz (XT2)

- 16-bit timer TA0, Timer_A with five capture/compare registers
- 16-bit timer TA1, Timer_A with three capture/compare registers
- 16-bit timer TA2, Timer_A with three capture/compare registers
- 16-bit timer TB0, Timer_B with seven capture/compare shadow registers
- Two universal serial communication interfaces
  – USCI_A0 and USCI_A1 each support:
    - Enhanced UART supports auto-baud rate detection
    - IrDA encoder and decoder
    - Synchronous SPI
  – USCI_B0 and USCI_B1 each support:
    - I^2C
    - Synchronous SPI
- Full-speed USB
  – Integrated USB-PLL
  – Integrated 3.3- and 1.8-V USB power system
  – Integrated USB-PLL
  – Eight input, eight output endpoints
- 12-bit analog-to-digital converter (ADC), for MSP430F552x device family only with internal reference, sample-and-hold, and auto-scan feature
- Comparator
- Hardware multiplier supporting 32-bit operations
- Serial on-board programming, no external programming voltage required
- Three-channel internal direct memory access (DMA)
- Basic Timer with real-time clock feature

For complete module descriptions, see the *MSP430x5xx and MSP430x6xx Family User's Guide* (SLAU208).

3.1.3 LP5951 Features

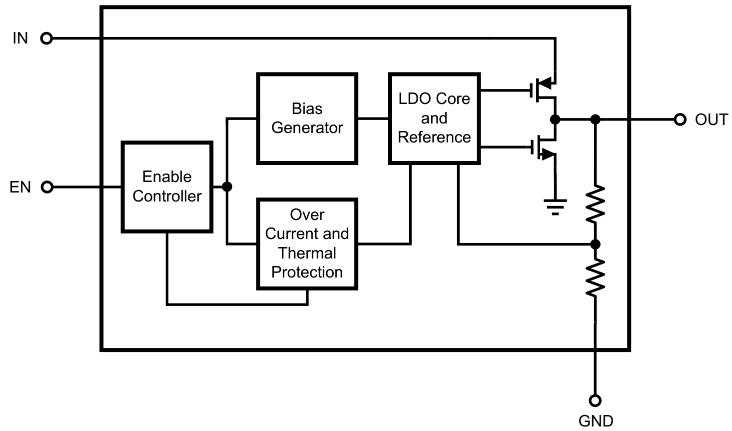


Figure 6. Block Diagram of LP5951

- Input voltage range: 1.8 to 5.5 V
- Output voltage range: 1.3 to 3.7 V
- Excellent line transient response: ±2 mV (typical)
- Excellent power supply rejection ratio (PSRR): –60 dB at 1 kHz typical
- Low quiescent current: 29 µA typical
- Small SC70-5 and SOT-23-5 packages
- Fast turn-on time of 30 µs (typical)
- Typical < 1-nA quiescent current in shutdown
- Ensured 150-mA output current
- Logic controlled enable 0.4 or 0.9 V
- Good load transient response of 50 mV_{PP} (typical)
- Thermal overload and short-circuit protection
- −40°C to 125°C junction temperature range

3.1.4 TPD1E10B06 Features

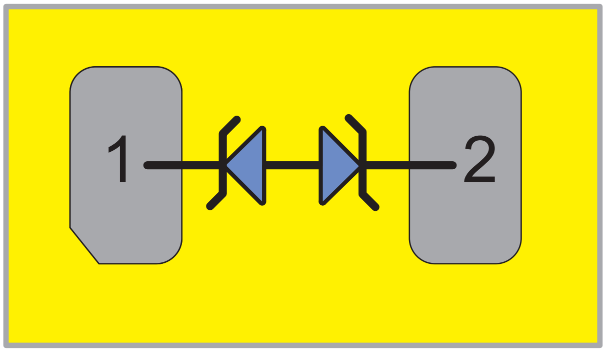


Figure 7. Block Diagram of TPD1E10B06

- Provides system-level ESD protection for low-voltage IO interface
- IEC 61000-4-2 level 4
- ±30-kV (air-gap discharge)
- ±30-kV (Contact discharge)
- IEC 61000-4-5 (surge): 6 A (8/20 μs)
- IO capacitance 12 pF (typical)
- RDYN 0.4 Ω (typical)
- DC breakdown voltage ±6 V (minimum)
- Ultra-low leakage current 100 nA (maximum)
- 10-V clamping voltage (maximum at IPP = 1 A)
- Industrial temperature range: –40°C to 125°C
- Space-saving 0402 footprint (1.0 × 0.6 × 0.5 mm)

3.1.5 TPD2E001 Features

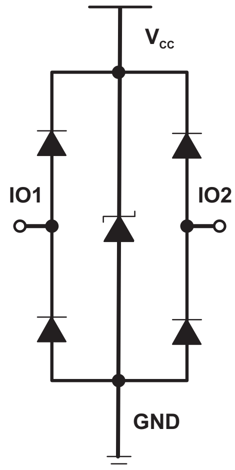


Figure 8. Block Diagram of TPD2E001

- IEC 61000-4-2 ESD protection (level 4)
  - ±8-kV contact discharge
  - ±15-kV air-gap discharge
- IO capacitance: 1.5 pF (typical)
- Low leakage current: 1 nA (maximum)
- Low supply current: 1 nA
- 0.9- to 5.5-V supply-voltage range
- Space-saving DRL, DRY, and QFN package options

4 System Design Theory

4.1 Working Principle

The basic principle of inductive linear position sensing is related to the phenomenon of eddy currents. Walter Pepperl and Ludwig Fuchs first employed inductive sensing in 1958 in Mannheim, Germany. They wanted to find a technology to replace mechanical contacts that would wear out in hostile environments or were simply dangerous in explosive atmospheres due to arching. The basic principle of inductive sensing remains the same as Pepperl and Fuchs' original design.

An alternating current flowing through a coil generates an AC magnetic field. If a user brings conductive material into the vicinity of the coil, such as a ferrous metal target, some of the energy from the oscillating magnetic field transfers to the metal target (see Figure 9). This transferred energy induces tiny circulating electrical currents (known today as eddy currents) on the surface of the target. The flowing eddy currents encounter electrical resistance as they try to circulate, which creates a small amount of power loss in the form of heat. These losses are known as eddy current losses. These eddy currents are a function of the distance, size, composition, and orientation of the target to the magnetic field. The induced eddy currents in target then generate their own magnetic field (counter field or secondary field) that reacts with the original field generated by the coil; this reaction changes the characteristics of the coil.

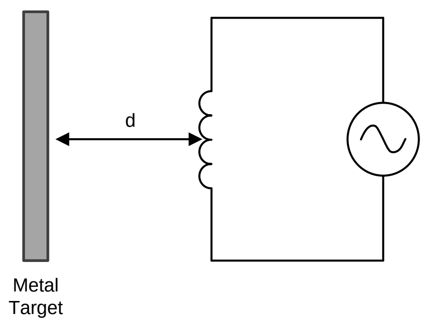


Figure 9. Inductor With Metal Target

This mechanism is best compared to a transformer, where the coil is the primary core and the eddy current is the secondary core. The inductive coupling between both cores depends on distance, shape, and the conductor's characteristics. Therefore, the resistance and inductance of the secondary core (eddy current) show up as a distant, dependent resistive and inductive component on the primary side (coil). The following figures show a simplified circuit model. In Figure 10, the inductance L_S is the coil's inductance and R_S is the coil's parasitic series resistance. The inductance L(d), which is a function of distance d, is the coupled inductance of the metal target. Likewise, R(d) is the parasitic resistance of the eddy currents.

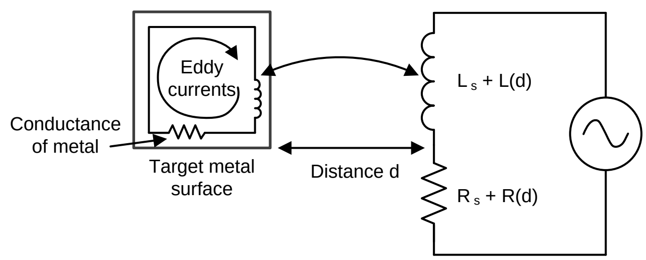


Figure 10. Metal Target Modeled as L and R With Circulating Eddy Currents

Generating an alternating magnetic field with just an inductor consumes a large amount of power. The user can reduce this power consumption by adding a parallel capacitor, turning the circuit into a resonator. In this manner, the power consumption is reduced to the eddy and inductor losses R_S + R(d) only. However, the LDC1101 does not measure the series resistance directly; instead, it measures the equivalent parallel resonance impedance, R_P. An equivalent, parallel R-L-C model of the sensor and target can be constructed, as shown in Figure 11.

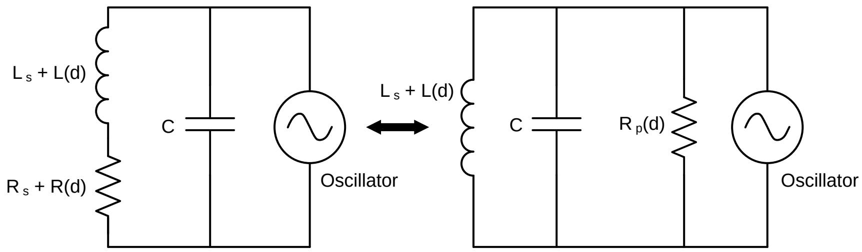


Figure 11. Series and Parallel LC Tank Circuits Connected With Oscillator

The conversions from the series inductance and resistance into their parallel counterpart are listed in Table 2.

Table 2. Converting Series Resonator into Parallel Resonator

	SERIES RESONATOR → PARALLEL RESONATOR	
INDUCTANCE	L_S	$L_P = L_S (1 + Q_S^{-2})$
RESISTANCE	R_S	$R_P = R_S (1 + Q_S^2)$
QUALITY FACTOR	$Q_S = \omega L_S / R_S$	$Q_P = R_P / \omega L_P$

The LDC1101 provides two independent measurement blocks to measure the impedance and resonant frequency of an attached sensor. The R_P+L block can simultaneously measure the impedance and resonant frequency of an LC resonator with up to 16 bits of resolution. The high resolution L (LHR) block only measures the sensor resonant frequency with up to 24 bits of resolution.

R_P Measurement

The LDC1101 accomplishes this task by regulating the oscillation amplitude in a closed-loop configuration to a constant level (see Figure 12) while monitoring the energy dissipated by the resonator. By monitoring the amount of power injected into the resonator, the LDC1101 can determine the value of R_P. When measuring R_P with the LDC1101, the intention is to measure only the eddy current losses on the target.

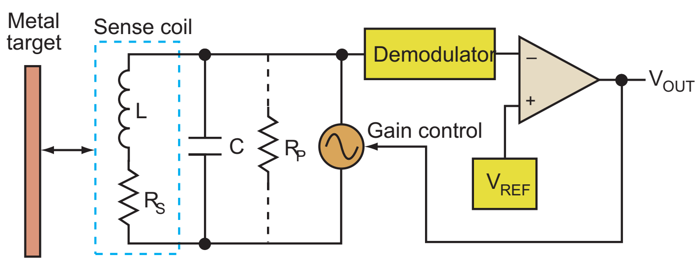


Figure 12. Oscillation Amplitude Regulation

Inductance Measurement

The LDC1101 measures the sensor's frequency of oscillation by using a frequency counter, as shown in Figure 13. The frequency counter timing is set by an external clock (12 MHz typical) from the MCU and is provided on the CLKIN pin. The sensor resonance frequency is derived from the frequency counter registers value (see registers 0x23 to 0x24 in R_P+L mode and registers 0x38 through 0x3A in LHR mode).

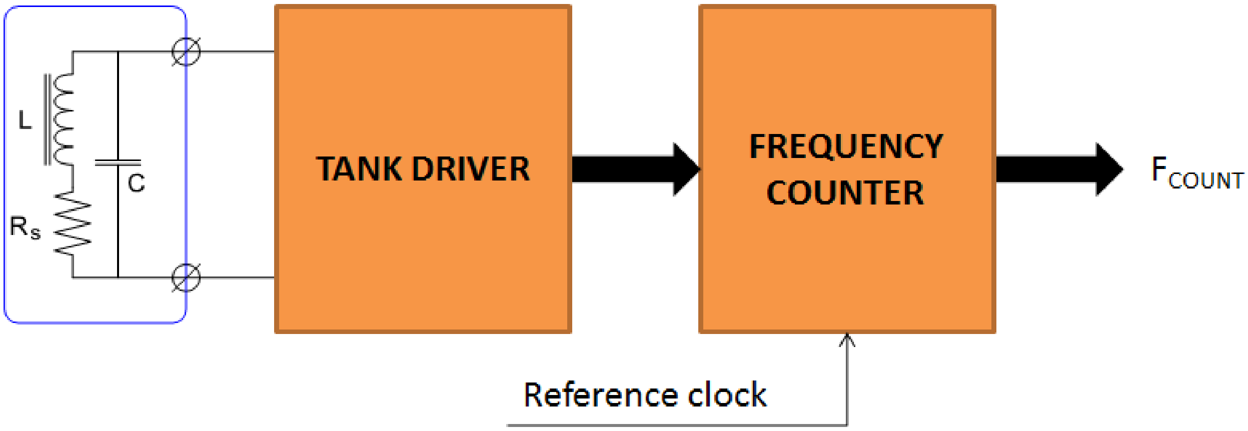


Figure 13. Sensor Frequency Measurement

4.2 Response Curve

To design an inductive sensing application, the first step is to convert the desired measurement into the amount of exposed metal from a target in the electromagnetic field generated by the coil. Commonly used sensor-target configurations are axial approach and radial approach, as Figure 14 shows. As the metal target moves closer to the sensor coil, or the metal target shape covers more of the sensor coil, a greater portion of the electromagnetic field is intercepted. The eddy currents increase as more electromagnetic field flux is intercepted, thereby decreasing the effective inductance of the coil generating the field and increasing the LC tank oscillation frequency. This series of events leads to a greater digital output value from the LDC1101. The LDC1101 has a built-in threshold compare function block as discussed in more detail in Section 4.6, which responds to an object only when it is in a defined area in front of the switch's sensing face. The point at which the LDC1101 recognizes an incoming target is the actuation point. The point at which an outgoing target causes the device to switch back to its normal state is called the de-actuation point. The distance between these two points is called the hysteresis width.

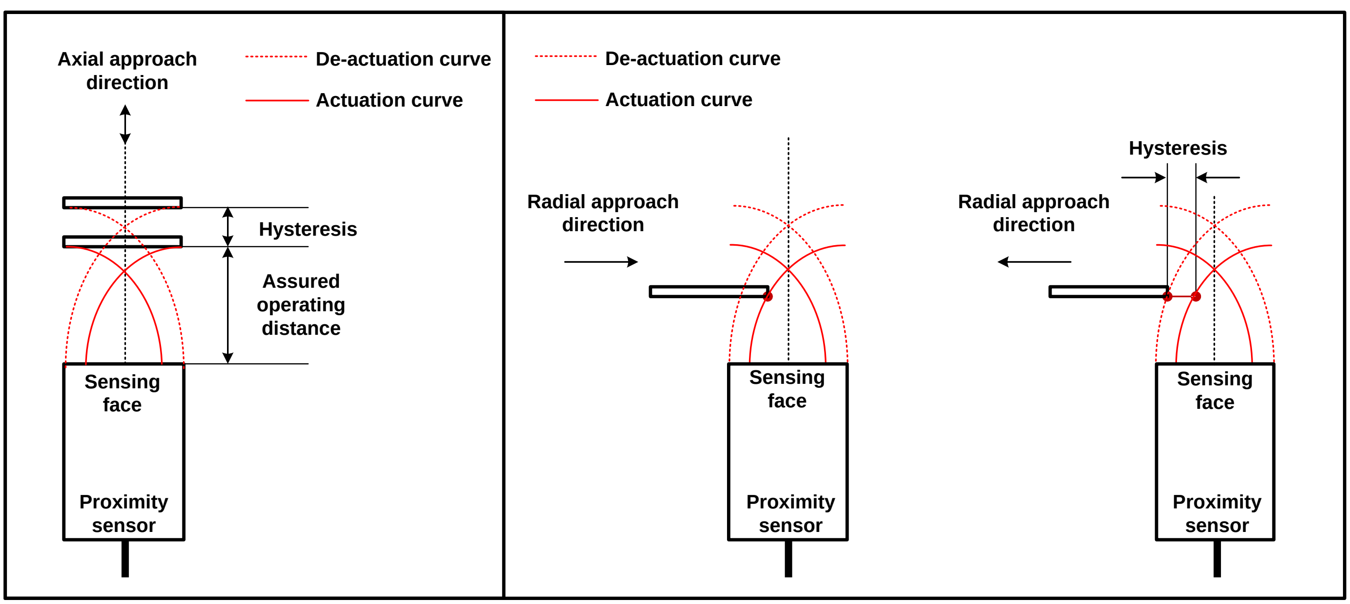


Figure 14. Commonly Used Sensor-Target Configurations

4.3 Target Metal: Composition and Thickness

Certain metal types perform better than other types in terms of creating a greater change in sensor output. These metals have high electrical conductivity and low magnetic permeability (for example, common aluminum (alloys) and copper (alloys)). The 300 series of non-ferrite stainless steel materials also work well, in that they cannot be picked up by a magnet.

Because alternating currents (such as eddy currents) tend to concentrate on the metal surface facing the sensor coil (known as the "skin effect"), a thin layer of metal usually works well enough. Table 3 shows the recommended minimum thickness for several commonly used metals.

Most metal types can be equally well-measured with L or R_P. However, there are some magnetic materials where the L response at certain frequencies is significantly smaller than the R_P response. For those materials, R_P is a more appropriate choice.

Table 3. Recommended Minimum Target Metal Thickness

TARGET METAL	SENSOR FREQUENCY (MHz)		
	1	**3**	**10**
Cooper	63	37	20
Silver	64	37	20
Gold	77	45	24
Aluminum	82	47	26
Aluminum alloy	99	57	31
Brass (yellow)	127	73	40
Solder	214	123	68
Non-ferritic stainless steel (3xx series)	421	243	133

4.4 Sensor Coil Design

The design of the sensor coil used with the LDC1101 is critical to achieve the desired metal detection performance. In this TI Design, the appropriate sensor coils were created using Altium script to detect axial movement. In end-equipment applications, the WEBENCH® Inductive Sensing Designer can be used to generate the sensor coils, based on the subsystem mechanical characteristics. The sensing coil design depends on the mechanical requirements for sensing distance, precision, and target size. Therefore, the sensing coil design depends on the end-equipment requirements. The sensor coil used for this TI Design is a four-layer circular coil with two parallel inductor paths with a 330-pF C0G/NP0 grade surface mount capacitor connected in parallel to form a LC tank circuit. This reduces the parasitic series resistance (R_S) of the sensor for improved parallel resonant impedance (R_P) measurement range. A 1-mm diameter un-plated through hole in the sensor center is available for mounting or alignment to an external assembly. The series resistance of the LC tank is plotted versus frequency in Figure 15.

Table 4. Sensor Coil Parameters

PARAMETER	EVM SENSOR VALUE
Outer diameter	551 mils (14.0 mm)
Inner diameter	191 mils (4.86 mm)
Number of turns	15
Trace width	6 mils (0.152 mm)
Trace spacing	6 mils (0.152 mm)
Number of layers	4
Trace thickness	1 oz-cu (35 µm)
Inductance at 3.27 MHz (no target)	7.2 µH
Sensor capacitance	330 pF
f_{SENSOR}	3.27 MHz
R_S at 3.27 MHz (no target)	1.9 Ω
R_P at 3.27 MHz (no target)	12.5 kΩ
Q at 3.27 MHz (no target)	75
Approximate CPARASITIC	3 pF
SRF	33 MHz

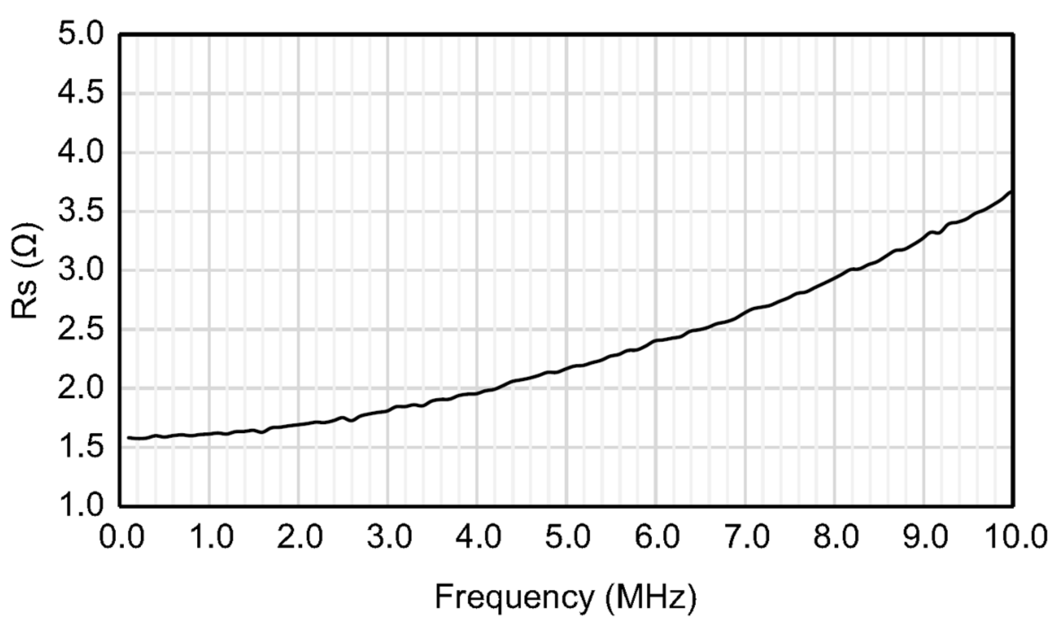


Figure 15. Sensor Coil Series Resistance versus Frequency

The wide range of oscillation frequency and the driving current of the LDC1101 provide great flexibility to the user when selecting the dimensions of the coil that best suits his or her specific mechanical system configuration. Follow these rules to properly operate the device:

- *LC tank resonant frequency*: The recommended sensor frequency range for LDC1101 devices is 500 kHz to 10 MHz.
- *Inductance of the sensor coil*: There is no absolute requirement on the value of the inductance as long as the range of the resonant frequency and R_P (the parallel loss resistance) are not violated.
- *Sensor oscillation amplitude*: The nominal sensor oscillation amplitude is 1.2 V. The maximum operating amplitude occurs when the target is either at its maximum distance from the sensor coil (axial approach) or the least amount of target area overlaps the coil (lateral approach). The minimum amplitude occurs when the target is at its closest point to the sensor (axial), or when it achieves maximum overlap with the coil (lateral). Maintain the minimum operating amplitude above 500 mV. As already explained, the sensor voltage is proportional to $R_P(d)$, which will vary as the target moves. Therefore, carefully design the coil to maintain a sufficient range of R_P over the operating range to ensure that the sensor oscillation does not collapse.
- *R_P (parallel loss resistance) of the LC tank*: The LC tank is "lossy" due to the inductor's loss and the energy dissipated by the target metal. This loss can be modeled by a parallel equivalent resistance R_P. The more the energy loss in the LC tank, the smaller is the value of R_P. The range of R_P values that the LDC1101 can be ranges from 1 to 128 kΩ. Different sensing applications may have different ranges of the resonance impedance R_P to measure. The LDC1101 measurement range of R_P is controlled by setting the RP_SET register: RP_MIN and RP_MAX bits. For a given application, R_P must never be outside the range set by these register values to avoid clipping the measured value. For optimal sensor resolution, the range of RP_MIN to RP_MAX must not be unnecessarily large.

Place the capacitors as close to the sensor coil as possible to reduce the parasitic inductance of the PCB traces. The trace length from the LC tank to the IC is less critical because they do not affect the resonance frequency. TI recommends using high quality capacitors such as the NP0/C0G grade ceramic capacitors or film capacitors with a tolerance of 1% to 5%. The tank capacitor is a 330-pF, NP0/C0G ceramic surface-mount device (SMD) part. These values make the tank oscillate at a resonant frequency of 3.27 MHz (no target), which is below the 10-MHz operation limit. The sensor coil that works at the highest possible frequency in precision applications is advantageous because these sensor coils would then require a fewer number of turns (frequency $\propto 1/N^2$). Also, fewer turns help to reduce the temperature drift of the frequency due to the target's resistance change.

4.5 Sensor Drive

The LDC1101 supports a wide range of LC combinations with oscillation frequencies ranging from 500 kHz to 10 MHz, and R_P lower and upper limits are programmable in the range from 1.25 to 90 kΩ to support a wide range of LC combinations. The nominal sensor amplitude is 1.2 V and kept constant within the R_P range of the LC tank. When the resonance impedance of the sensor, R_P, drops below the programed RP_MIN, the sensor oscillation may stop. This condition is reported by STATUS: NO_SENSOR_OSC (register 0x20-bit7). This condition could occur when a target comes too close to the sensor. The oscillator amplitude reduces and the LDC output will rail. This feature may be used to indicate the target over-travel or for sensor health monitoring.

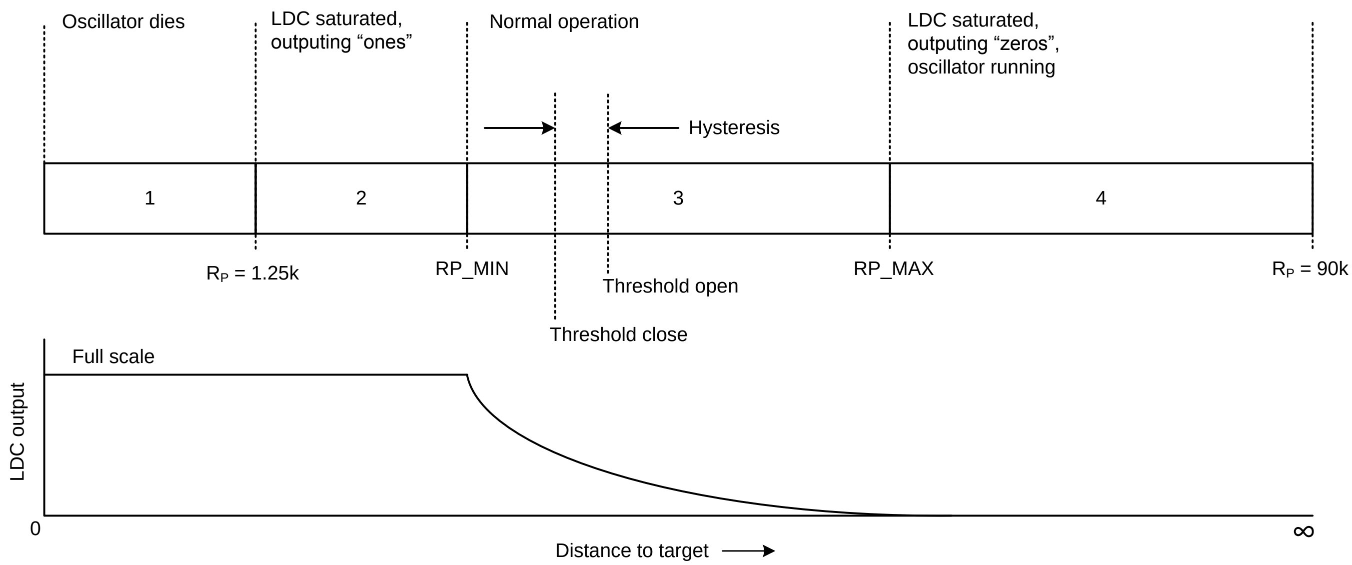


Figure 16. Operating Region

4.6 Detection

The threshold comparator block can compare the R_P+L conversion results versus a programmable threshold. With the threshold registers programmed and comparator enabled, the LDC1101 can provide a switch output, reported as a high/low level on the INTB/SDO pin and also in the STATUS register. Because the LHR conversion results cannot be used for comparator functionality, this reference design uses R_P+L measurement block to perform the intended function.

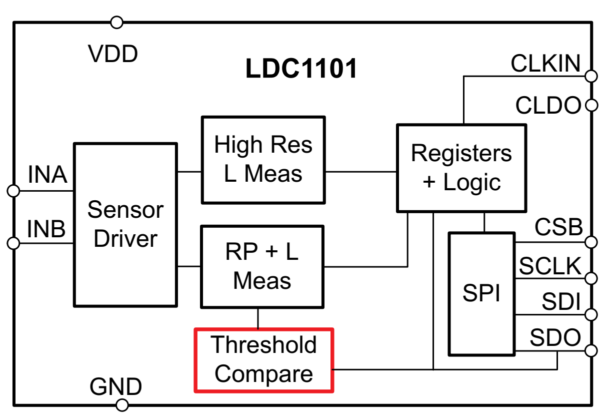


Figure 17. LDC1101 Block Diagram

	RP+L Mode	LHR Mode
R_P Measurement Resolution	16 bits	N/A
L Measurement Resolution	16 bits	24 bits
Sample Rate configuration	Varies with f_{SENSOR}, set by RESP_TIME	Fixed and set by RCOUNT field and f_{CLKIN}
Sample rate at highest resolution (SPS)	244	15.3
Maximum Sample Rate (kSPS)	156.25	183.9
L Resolution at Maximum Sample rate	6.7 bits	6.5 bits
Switch Output on SDO/INTB	Available for R_P or L output code	N/A

Figure 18. Comparison of Measurement Modes

In addition, the INTB signal can be asserted or de-asserted when the conversion results increase above a Threshold High (HI) or decreases below a Threshold Low (LO) register. In this mode, the LDC1101 essentially behaves as a proximity switch with programmable hysteresis. The threshold HI settings must be programmed to a higher value than the threshold LO registers. Either latching or non-latching functions can be reported on INTB/SDO. The INTB signal can report a latching signal or a continuous comparison for each conversion result.

FUNCTION	THRESHOLD HIGH	THRESHOLD LOW	STATUS REPORTING	INTB/SDO REPORTING
R_P Comparator with hysteresis	RP_THRESH_HI (registers 0x06 & 0x07)	RP_THRESH_LO (registers 0x08 & 0x09)	RP_HI_LON (bit 4)	RP_HI_LO (INTB_MODE:INTB_FUNC=b00'0010)
R_P High threshold only (Latching)	RP_THRESH_HI (registers 0x06 & 0x07)	N/A	RP_HIN (bit 5)	RP_TH_HI (INTB_MODE:INTB_FUNC=b00'0001) Note that INTB/SDO will latch.
L Comparator with hysteresis	L_THRESH_HI (registers 0x16 & 0x17)	L_THRESH_LO (registers 0x18 & 0x19)	L_HI_LON (bit 2)	L_HI_LO (INTB_MODE:INTB_FUNC=b01'0000)
L High threshold compare only (Latching)	L_THRESH_HI (registers 0x18 & 0x19)	N/A	L_HIN (bit 3)	L_TH_HI (INTB_MODE:INTB_FUNC=b00'1000) Note that INTB/SDO will latch.

Figure 19. Comparator Options

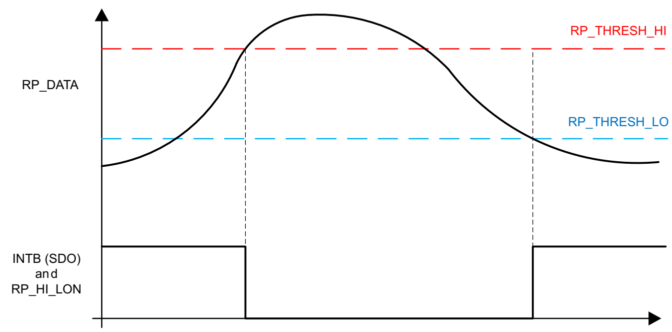


Figure 20. INTB/SDO Output Value for R_P Comparator With Hysteresis (INTB_FUNC = b00'0010)

5 System Design Considerations

The Inductive Proximity Switch TI Design detects the presence of metal targets within a certain area using inductive sensing technology from TI. The LDC1101 measures the inductance and R_P of an LC tank resonator, which consists of a PCB coil inductor and discrete capacitor. Whenever a metal target enters in the sensing range, both the inductance and R_P of the LC tank change. The design requirements is to detect the presence of a 1-mm thick aluminum target that moves from 1 to 7 mm axially with respect to the sensor coil as shown in Figure 21.

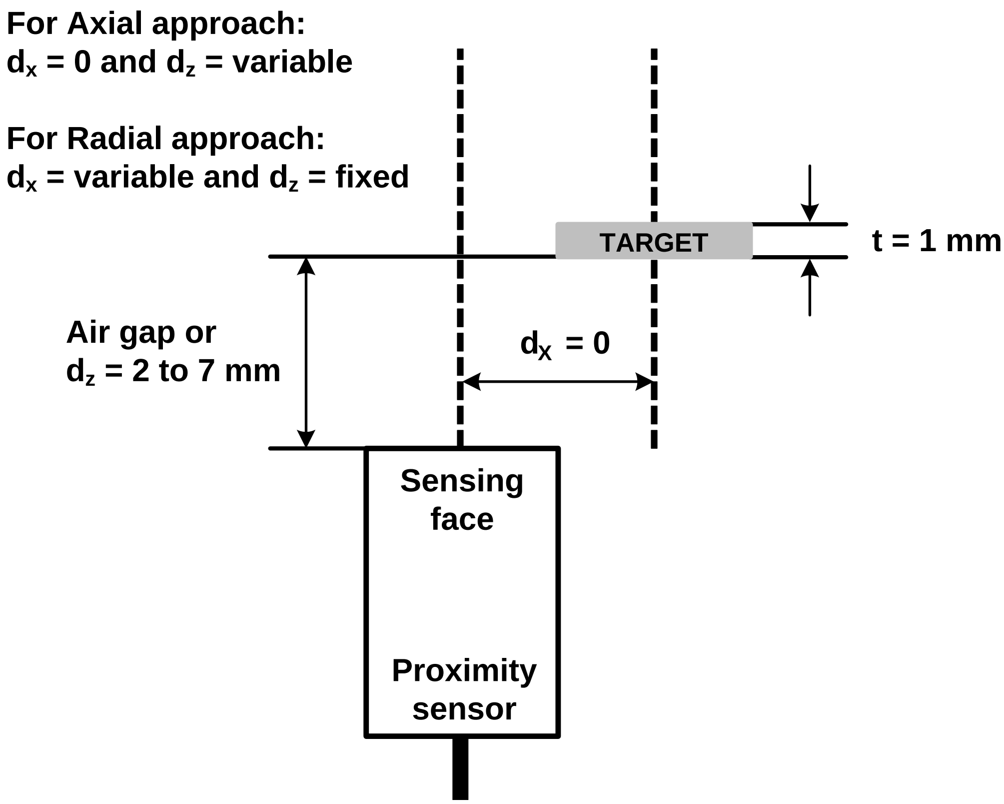


Figure 21. Axial Position Sensing

There are several considerations when designing the proximity switch using inductive sensing technology into an end-equipment system. The size of the desired sensing target should at least equal to 1.5 times the diameter of a circular sensing coil. In this TI Design, the sensor coils has a diameter of 14 mm. The sensor coil LC tank must be designed to resonate within the operating parameters of the LDC1101.

Another consideration is the distance between the sensing coil and the target. The maximum sensing range is similar for L- and R_P-measurements and depends primarily on coil diameter, resolution of the LDC and device configuration. A useful rule of thumb for precision applications is that an LDC requires a coil diameter of at least twice the maximum sensing range (for example, the user would need a 14-mm diameter coil to measure a target distance up to 7 mm).

A final consideration for the design of inductive proximity switch is the material of the sensing target. The sensing range, hysteresis, and so on are defined for a standard sensing target. The material for standard sensing object is iron. The current TI Design system uses a 1-mm thick aluminum surface, but different end-equipment systems may require different target materials or thicknesses.

5.1 Configure Device for R_P+L Measurements

Setting the RP_MIN and RP_MAX parameters is necessary for proper operation of the LDC1101; the LDC1101 may not be able to effectively drive the sensor with incorrect settings, as the sensor amplitude will be out of the valid operation region. The first step is to determine the appropriate RP_MIN or RP_MAX and TC1/2 settings.

For R_P measurements, set the following register settings as follows:

- ALT_CONFIG.LOPTIMAL (register 0x05-bit0) = 0
- D_CONFIG.DOK_REPORT (register 0x0C-bit0) = 0

Ensure that the sensor characteristics are within the sensor boundary conditions:

- 500 kHz < f_{SENSOR} < 10 MHz → 500 kHz < ~3.27 MHz < 10 MHz
- 500 kHz < C_{SENSOR} < 10 nF → 100 pF < 330 pF < 10 nF
- 1 µH < L_{SENSOR} < 500 µH → 1 µH < 7.2 µH < 500 µH

Measure the sensor's resonance impedance with minimal target interaction ($R_{PD\infty}$). The minimal target interaction occurs when the target is farthest away from the sensor for axial sensing solutions or when the target coverage of the sensor is at a minimum for rotational or lateral sensing. Select the appropriate setting for RP_MAX (register 0x01-bits [5:4]):

- $R_{PD\infty}$ < RP_MAX ≤ 2 $R_{PD\infty}$
- 12.5 kΩ ≤ RP_MAX ≤ kΩ → Set RP_MAX to 24 kΩ

Measure the sensor's resonance impedance with the target closest to the sensor (R_{PD0}) as required by the application. Select the largest RP_MIN setting that satisfies:

1. RP_MIN < 0.8 × R_{PD0}
2. If the required RP_MIN is smaller than 750 Ω, R_{PD0} must be increased to be compliant with this boundary condition. This can be done by one or more of the following:
   (a) increasing f_{SENSOR}
   (b) increasing the minimum distance between the target and the sensor
   (c) reducing the R_S of the sensor by use of a thicker trace or wire

0.8 × 2.10 kΩ = 1.68 kΩ → Set RP_MIN to 1.5 kΩ. Therefore, set RP_MIN = 1.5 kΩ.

Check if the worst-case sensor quality factor Q_{MIN} = RP_MIN × $\sqrt{(C_{SENSOR}/L_{SENSOR})}$ is within LDC1101's operating range:

1. 10 ≤ Q_{MIN} ≤ 400
2. If Q_{MIN} < 10, for a fixed f_{SENSOR}, increase C_{SENSOR} and decrease L_{SENSOR}.
3. If Q_{MIN} > 400, for a fixed f_{SENSOR}, decrease C_{SENSOR} and increase L_{SENSOR}.
4. Alternatively, the user may choose to not change the current sensor parameters, but to increase R_{PD0}.

Sensor Q is approximately 75, which is within the operating range of 10 to 400.

Set Time Constant 1 based on the minimum sensor frequency:
R1 × C1 = 0.75026 / 2.667 MHz = 2.8131E-7s

Starting with the largest C1 value of 6 pF for best noise performance results in R1 = 46.8854 kΩ. This is within the R1 range of 20.6 to 417.4 kΩ, and so C1 = 6 pF can be used. Picking the next higher programmable value for R1 → Set R1 = 59.44 kΩ. Next, set the Time Constant 2 based on RP_MIN setting: R2 × C2 = 2 × 1.5 kΩ × 270 pF = 9.9E-7s

Starting with the largest C2 value of 24 pF (once again, for best noise performance) results in R2 = 41.25 kΩ. This is within the programmable R2 value of 24.60 to 834.8 kΩ, so 24 pF can be used for C2. Picking the next higher programmable value for R2 → Set R2 = 43.26 kΩ.

Then, configure the MIN_FREQ field. The sensor minimum frequency is 2.667 MHz, which occurs with the minimum target interaction. Therefore, MIN_FREQ is set to 13, which configures the watchdog for 2.667 MHz. Next, set the response time. Setting 6144 will provide the highest resolution R_P measurement with this sensor. With 6144, the sample rate will be at least 2.01 kSPS.

All other device settings can be in their default values.

On power-up, the LDC1101 enters Sleep mode, which is a low-power mode used to configure the LDC. If the LDC1101 is actively converting, write 0x01 to START_CONFIG (address 0x0B) to stop conversions before writing the settings above.

Once the LDC1101 is configured, the process to retrieve R_P+L conversion results is:

1. Set the LDC1101 into conversion mode (active mode) by writing 0x00 to START_CONFIG (register 0x0B).
2. Poll STATUS.DRDYB (register 0x20:bit6) until it indicates a conversion result is present, or use the INTB signal.
3. If the desired measurement is R_P, then read back registers 0x21 and 0x22. The R_P output code is the contents of register 0x21 + 256 × (contents of register 0x22).
4. If the desired measurement is L, then read back registers 0x23 and 0x24. The L output code is the contents of register 0x23 + 256 × (contents of register 0x24). Reading both R_P and L is permitted, for a more efficient operation R_P and L registers can be retrieved in a single extended SPI transaction.
5. Process the conversion results on the MCU and repeat from Step 2 if additional conversions are desired. If no additional conversions are required, place the LDC1101 into Sleep mode or Shutdown mode.

Table 5. LDC1101 Register Settings for R_P+L Measurements

FIELD	FIELD SETTING	FIELD VALUE	REGISTER	REGISTER VALUE
RP_MAX_DIS	Disabled	b0	RP_SET (0x01)	0x26
RP_MAX	24.0 kΩ	b010		
RP_MIN	1.5 kΩ	b110		
C1	6 pF	b11	TC1 (0x02)	0xDC
R1	59.44 kΩ	b11100		
C2	24 pF	b11	TC2 (0x03)	0xFE
R2	43.26 kΩ	b111110		
MIN_FREQ	2.667 MHz	b1101	DIG_CONF (0x04)	0xD7
RESP_TIME	6144	b111		
FUNC_MODE	Active	b00	START_CONFIG (0x0B)	0x00

5.2 Programming Switching Point and Hysteresis

Program the switching point and hysteresis by putting the target metal at the desired sensing distance in front of the manufactured sensor system. The content of RP_DATA (at addresses 0x21 and 0x22) and L_DATA (at addresses 0x21 and 0x22) registers are read, and then RP_THRESH_LO (at addresses 0x08 and 0x09) and L_THRESH_LO (at addresses 0x18 and 0x19) registers are written with the values that sets the bits STATUS.RP_HI_LON (register 0x20: bit 4) and STATUS.L_HI_LON (register 0x20: bit 2). The metal target is then moved to another distance, farther away than the first distance, the content of RP_DATA (at addresses 0x21 and 0x22) and L_DATA (at addresses 0x21 and 0x22) registers are read again. Then RP_THRESH_HI (at addresses 0x06 and 0x07) and L_THRESH_HI (at addresses 0x16 and 0x17) registers are written with the values that resets the bits STATUS.RP_HI_LON (register 0x20: bit 4) and STATUS.L_HI_LON (register 0x20: bit 2). The Inductive Proximity Switch TI Design demonstrates both RP-measurement (RP_DATA) and L-measurement (L_DATA) capabilities of the LDC1101 to detect the presence of a metal object. However, in most of the cases designers may prefer L measurement for applications that require very high precision over wide system temperature range due to less temperature drift in L measurement. The LDC1101's RP_THRESH_LO, RP_THRESH_HI, L_THRESH_LO, and L_THRESH_HI registers are programmed to have a hysteresis of 1 mm by writing the following values as given in Table 6 and Table 7. Different end-equipment systems may require different hysteresis that can be easily programmed in similar fashion.

Table 6. Switching Point Programming Using L Threshold Registers

DISTANCE (mm)	L_DATA (MAX)	L_DATA (MIN)	VALUE WRITTEN TO L_THRESH_LO_MSB AND L_THRESH_LO_LSB	VALUE WRITTEN TO L_THRESH_HI_MSB AND L_THRESH_HI_LSB
5	7000	6999	6998 (0x1B56)	Default value
6	7058	7057	6998 (0x1B56)	7056 (0x1B90)

Table 7. Switching Point Programming Using R_P Threshold Registers

DISTANCE (mm)	RP_DATA (MAX)	RP_DATA (MIN)	VALUE WRITTEN TO RP_THRESH_LO_MSB AND RP_THRESH_LO_LSB	VALUE WRITTEN TO RP_THRESH_HI_MSB AND RP_THRESH_HI_LSB
5	50345	50338	50337 (0xC4A2)	Default value
6	50856	50851	50337 (0xC4A2)	50850 (0xC6A3)

6 Test Setup

The R_P and L measurements are obtained at each position with the test setup shown in Figure 22. A precision micrometer sets the accurate position. The precision micrometer is ideal for performing acceptance testing on proximity sensors. A probe mounting adapter holds the PCB sensor coil in the mounting base while the high precision micrometer moves the metallic target toward or away from the sensor coil from 2 to 7 mm in 0.1-mm increments. The RP_DATA and L_DATA values are recorded for every increment.

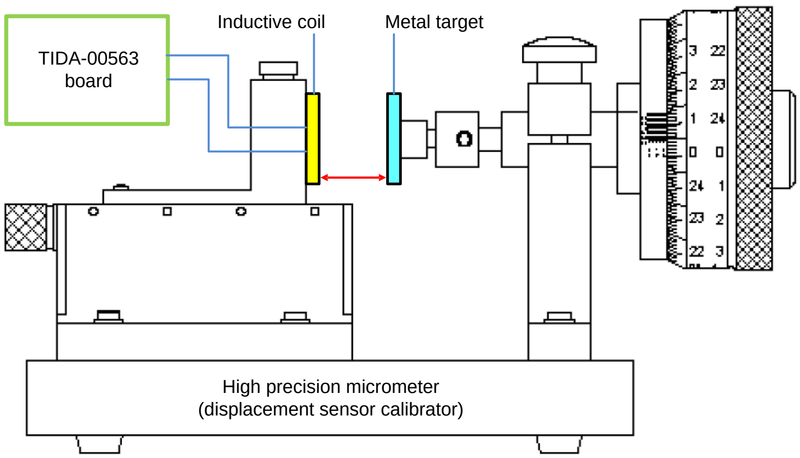


Figure 22. TIDA-00563 Test Setup

7 Test Data

NOTE: Unless otherwise noted, the test data in the following sections were measured with the system at room temperature.

NOTE: All of the measurements in this section were measured with calibrated lab equipment.

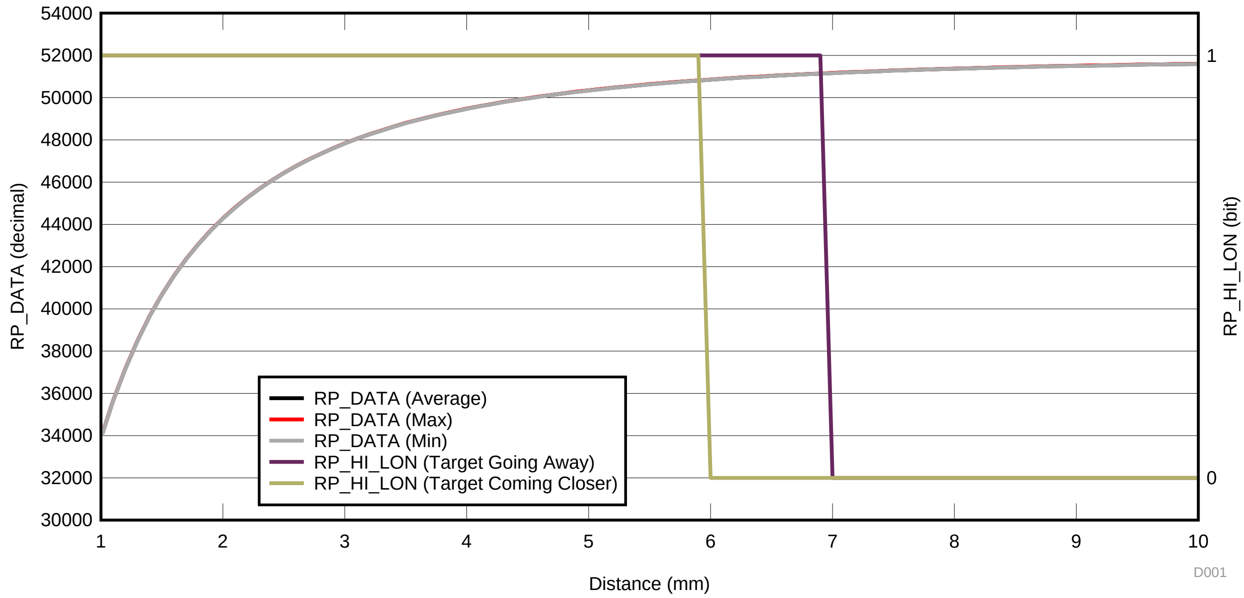


Figure 23. RP_DATA versus Distance

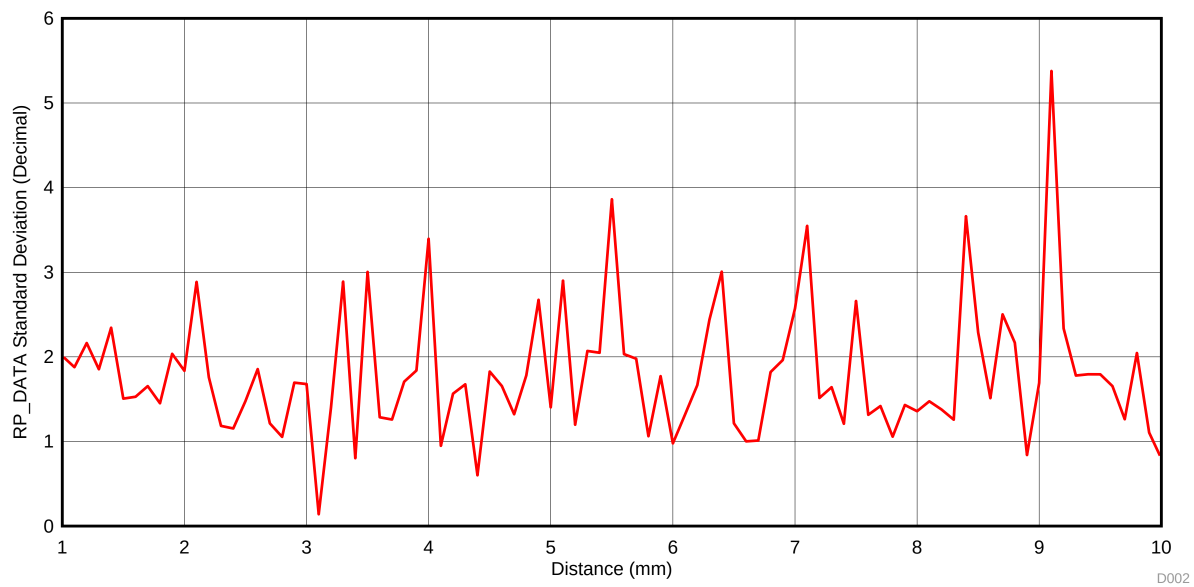


Figure 24. RP_DATA Standard Deviation

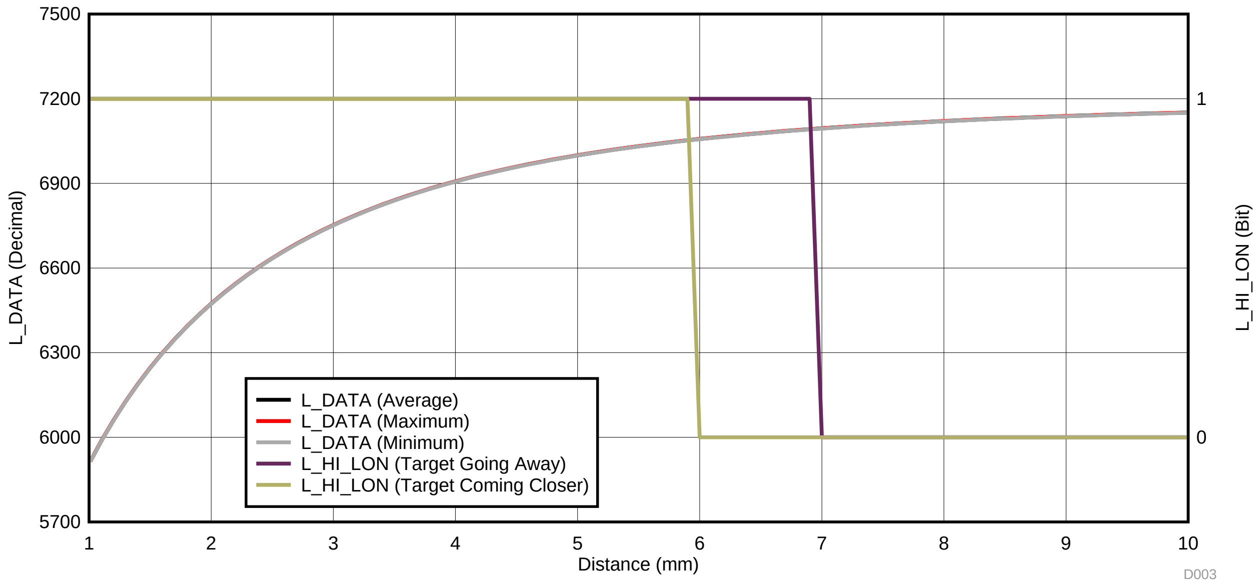


Figure 25. L_DATA versus Distance

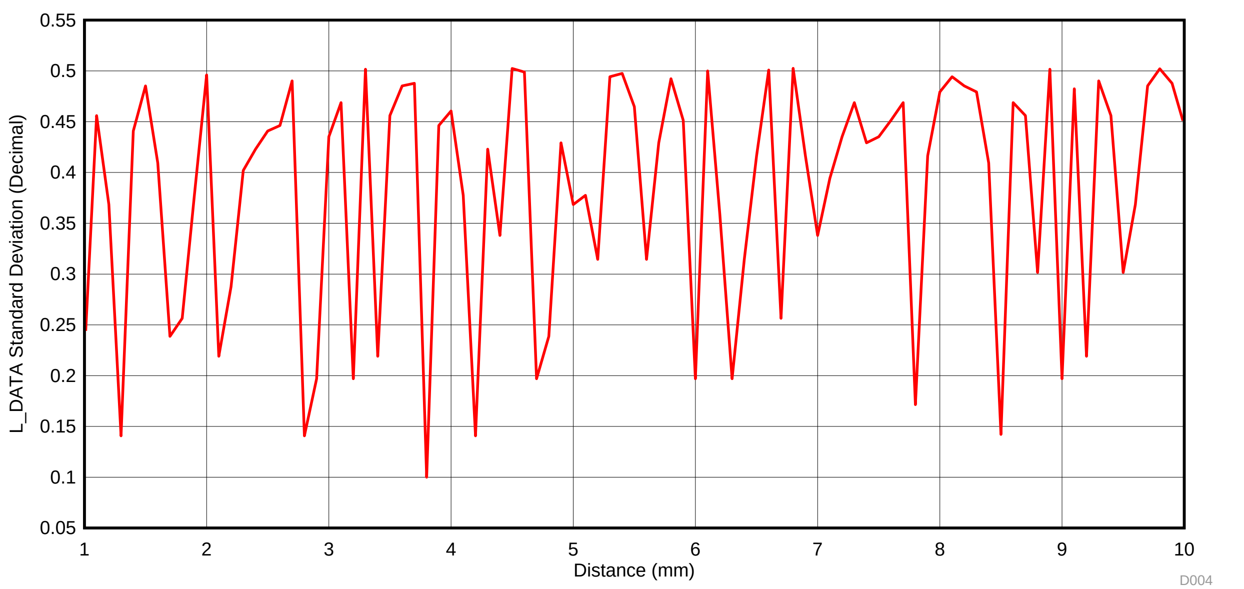


Figure 26. L_DATA Standard Deviation

8 Design Files

8.1 Schematics

To download the schematics, see the design files at TIDA-00563.

8.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00563.

8.3 Layout Prints

To download the layer plots, see the design files at TIDA-00563.

8.4 Altium Project

To download the Altium project files, see the design files at TIDA-00563.

8.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00563.

8.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-00563.

9 References

1. Texas Instruments, *LDC1101 1.8 V High-Resolution, High-Speed Inductance-to-Digital Converter*, LDC1101 Datasheet (SNOSD01).
2. Texas Instruments, *LDC1101EVM User's Guide* (SNOU137).
3. Texas Instruments, *Configuring Inductive-to-Digital-Converters for Parallel Resistance (RP) Variation in L-C Tank Sensors*, LDC1xxx Application Report (SNAA221).

Revision History

Changes from Original (November 2015) to A Revision	Page
• Changed from preview page	1

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

IMPORTANT NOTICE FOR TI REFERENCE DESIGNS

Texas Instruments Incorporated ("TI") reference designs are solely intended to assist designers (“Buyers”) who are developing systems that incorporate TI semiconductor products (also referred to herein as “components”). Buyer understands and agrees that Buyer remains responsible for using its independent analysis, evaluation and judgment in designing Buyer’s systems and products.

TI reference designs have been created using standard laboratory conditions and engineering practices. **TI has not conducted any testing other than that specifically described in the published documentation for a particular reference design.** TI may make corrections, enhancements, improvements and other changes to its reference designs.

Buyers are authorized to use TI reference designs with the TI component(s) identified in each particular reference design and to modify the reference design in the development of their end products. HOWEVER, NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY THIRD PARTY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT, IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI REFERENCE DESIGNS ARE PROVIDED "AS IS". TI MAKES NO WARRANTIES OR REPRESENTATIONS WITH REGARD TO THE REFERENCE DESIGNS OR USE OF THE REFERENCE DESIGNS, EXPRESS, IMPLIED OR STATUTORY, INCLUDING ACCURACY OR COMPLETENESS. TI DISCLAIMS ANY WARRANTY OF TITLE AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, QUIET ENJOYMENT, QUIET POSSESSION, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS WITH REGARD TO TI REFERENCE DESIGNS OR USE THEREOF. TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY BUYERS AGAINST ANY THIRD PARTY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON A COMBINATION OF COMPONENTS PROVIDED IN A TI REFERENCE DESIGN. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, SPECIAL, INCIDENTAL, CONSEQUENTIAL OR INDIRECT DAMAGES, HOWEVER CAUSED, ON ANY THEORY OF LIABILITY AND WHETHER OR NOT TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES, ARISING IN ANY WAY OUT OF TI REFERENCE DESIGNS OR BUYER’S USE OF TI REFERENCE DESIGNS.

TI reserves the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques for TI components are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

Reproduction of significant portions of TI information in TI data books, data sheets or reference designs is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards that anticipate dangerous failures, monitor failures and their consequences, lessen the likelihood of dangerous failures and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in Buyer’s safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed an agreement specifically governing such use.

Only those TI components that TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components that have ***not*** been so designated is solely at Buyer's risk, and Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265