TI Designs

Touch on Metal Buttons With Integrated Haptic Feedback

TI Designs

TI Designs provide the foundation that you need including methodology, testing, and design files to quickly evaluate and customize the system. TI Designs help *you* accelerate your time to market.

Design Resources

TIDA-00314	Design Folder
LDC1614	Product Folder
DRV2605L	Product Folder
DRV2667	Product Folder
HDC1010	Product Folder
MSP430F5528	Product Folder
LP5907	Product Folder
TS5A12301E	Product Folder
TPD2E2U06	Product Folder
TPD1E10B06	Product Folder

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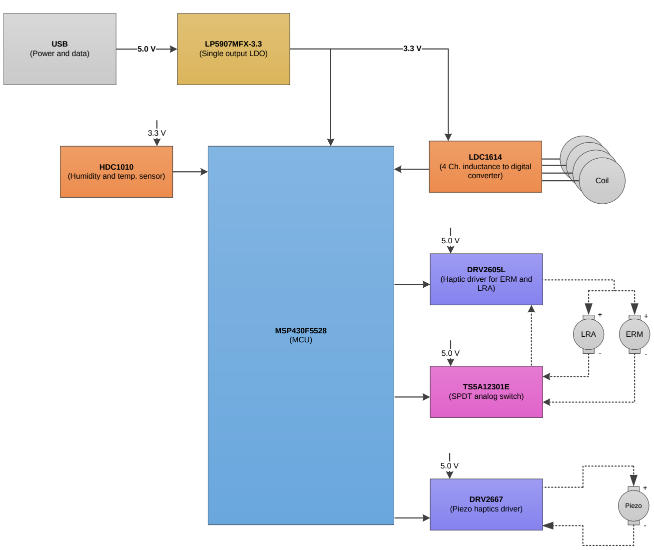
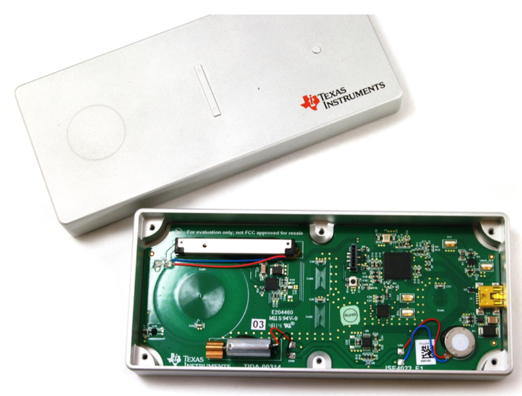


Design Features

- Replaces Mechanical Buttons With High-Resolution Inductive-Sensing Based Touch On Metal Detection
- Customizable Haptic Feedback and Waveforms Provide High Quality User Experience
- Programmable Button Sensitivity (from Light Touch to Hard Press)
- One Continuous Sheet of Metal Sealed and Grounded Against Electromagnetic Interference (EMI), Water, Oil, Dirt, and Other Contaminants.
- Works With Gloves, Underwater (if Sealed), and in Harsh Environments
- Can Be Used for Pressure and Multi-Step Button Press Sequences
- Three Button Options Implemented:
  – 20-mm Button
  – 3 × 10 mm (Two Buttons)
  – 3-mm Button
- Alternative Button Configurations Can Be Implemented With Different Mechanical Designs

Featured Applications

- Building Automation
- Industrial and Automotive Interfaces
- Mobile Device Interfaces
- Electronic Point of Sale
- Appliance Interfaces
- Mechanical Button Replacement



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1 Key System Specifications

PARAMETER	SPECIFICATION	DETAILS
Touch on metal sensor type	4 × PCB inductor coil	Section 2.2
Haptic actuator types	Piezo Linear resonance actuator (LRA) Eccentric rotating mass (ERM)	Section 2.4
Input voltage	5-V nominal (VBUS from USB)	Section 2.8
Calibration method	Auto-calibration of LRA and ERM actuators	Section 4.4
Operating temperature	–20°C to 70°C	Section 2.6
Working environment	Indoor or outdoor	Section 2.6
Environmental sensing	Temperature and humidity	Section 2.6
Thermal “shock”	No false button detections due to quick thermal changes	Section 6.6
Relative humidity “shock”	No false button detections due to quick humidity changes	Section 6.7
Adjacent button press	No false button detections on adjacent sensors	Section 6.2.1
Haptics influence on LDC1614	No false button detections due to haptic operations	Section 6.3
Total system current consumption	8.4 mA (peak) during LDC1614 measurement 408 mA (peak) during piezo actuator operation 580 mA (peak) during ERM actuator operation 216 mA (peak) during LRA actuator operation	Section 6.4
IEC 61000-4-2	Contact electrostatic discharge (ESD): ±4 kV on enclosure	Section 6.8.1
	Air ESD: ±8 kV on enclosure	
IEC 61000-4-3	Radiated immunity: 80 MHz to 2.7 GHz at 10 V/m	Section 6.8.2
IEC 61000-4-4	Electrical fast transients (EFT): ±2 kV on VBUS	Section 6.8.3
IEC 61000-4-5	Surge: 0.5 kV on VBUS	Section 6.8.4
IEC 61000-4-6	Conducted immunity: 3 V_{RMS} on VBUS	Section 6.8.5
Form factor	12.5 cm × 5.5 cm × 1.5 cm aluminum enclosure	Section 2.5

2 System Description

Many industrial, automotive, and consumer end-equipment systems and products currently require mechanical buttons to enable user input. However, mechanical buttons tend to add system cost, wear out after a set number of cycles, and complicate the implementation of sealing the system from environmental effects.

Enabled by Texas Instrument's inductive-to-digital and haptics technology, the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design demonstrates the touch on metal concept for mechanical button replacement, as well as integrated haptics to provide realistic feedback to the user.

At a high level, this TI Design system consists of an aluminum mechanical enclosure with four buttons built into the top part of the enclosure. The unique aspect of this design is that it is implemented in a single, monolithic piece of metal that forms the top part of the enclosure. The buttons are simply etched outlines or raised bumps on the metal surface. Using Texas Instruments' technology on the circuit board underneath the top part of the enclosure, the very small deflection of the aluminum (on the order of microns) is measured and then haptic feedback is activated, providing tactile feedback to the user similar to that of a mechanical button.

This design guide addresses component selection, design theory, and test results of the TI Design system. The scope of this design guide provides system designers with an advantage when integrating TI's inductance-to-digital converter and haptic driver technology into new applications that require high-resolution touch on metal button press detection with haptic feedback.

The following subsections describe the various blocks within the reference design system and the characteristics that are most critical to implementing the corresponding function.

2.1 Inductance-to-Digital Converter

The inductance-to-digital converter (LDC) detects button activation by measuring the deflection of the metallic surface used for the button. To detect a button press, the sub-system must be able to detect very small deflections of the metal surface in the order of microns, as shown in Figure 1.This system must have very low noise compared to the change measured by the button press itself. Also, the system must be able to distinguish between adjacent button presses to prevent false button press detections. In this TI Design configuration, the mechanical design is such that two of the buttons are immediately adjacent; therefore, when one button is pressed, the adjacent button should not detect a button press, and vice versa.

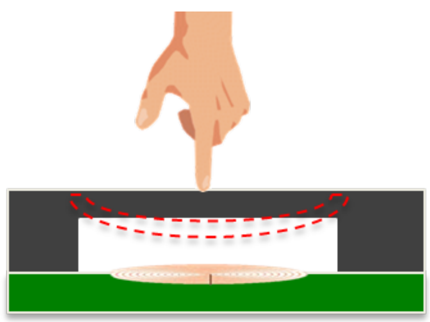


Figure 1. Mechanical Deflection Detail

Another consideration for the selection of the inductance-to-digital converter is the ability to handle measurement changes due to varying environmental conditions. This TI Design implements firmware filtering to mitigate environmental variations. In addition, a humidity and temperature sensor is included if more precision is required over environmental variations.

The LDC1614 device is an ideal component for this TI Design, as it combines high-resolution inductive sensing with four input channels. The high resolution of the LDC1614 enables the system to easily distinguish between adjacent button presses (Section 6.2.1 *Adjacent Button Press Performance*). Also, the low power consumption (Section 6.4 *Current Consumption*) and ease of use of the LDC1614 device allows for straightforward integration into an end-equipment. The high resolution of the LDC1614 device also enables the implementation of a pressure or multi-step button sequences, if the end equipment requires such an application.

2.2 Sensor Coil Design

The design of the sensor coil used with the LDC1614 device is critical to achieve the desired touch on metal button detection performance. In this TI Design, the appropriate sensor coils were manually created. The Big and Little buttons use round sensing coils to detect axial movement. The Down and Up buttons have rectangular sensing coils, which are typically used to detect lateral 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 for the distance from the sensing coil to the metal plate, button sensitivity, and button size.

2.3 Haptic Drivers

The selection of haptic drivers depends on the desired haptic actuators present in the system (see Section 2.4 *Haptic Actuators*).

For Linear Resonance Actuators (LRA) and Eccentric Rotating Mass (ERM)-type haptic actuators, the DRV2605L device provides a closed-loop actuator-control system for high-quality haptic feedback. The DRV2605L device offers a licensed version of TouchSense 2200™ software from Immersion, which eliminates the need to design haptic waveforms because the software includes over 100 licensed effects (six ERM libraries and one LRA library) and audio-to-vibe features.

For piezo actuators, the DRV2667 device integrates a 105-V boost switch, power diode, fully-differential amplifier, and digital front-end. These device characteristics make the DRV2667 ideal for driving both high-voltage and low-voltage piezo haptic actuators.

2.4 Haptic Actuators

To provide a broad overview of currently available haptics technology, the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design utilizes three types of haptic actuators: LRA, ERM, and piezo.

An LRA is a resonant system that produces vibration when exercised at or near its resonance frequency. LRAs tend to be of the coin type, but there are other form factors available. Technological innovation has made the shrinkage of LRA actuators possible down to heights of 2.5 mm or less, and diameters of 8 mm or less. This miniaturization trend makes LRA actuators one of the best choices for wearable devices. Because this device is typically run at resonance, the power consumption tends to be low when compared to other actuators.

An ERM is a DC motor with an off-center mass that spins to create vibrations. When the ERM rotates, the off-center mass results in a centripetal force; this kind of centripetal force causes displacement of the motor. People perceive this displacement as a vibration. The ERM vibrates because of rotation forces, so there is acceleration on two axes (X, Y, or Z axis). This acceleration creates losses in unintentional axes in some applications. Because this actuator is a DC motor, it requires more power to continue rotating when compared to other types of actuators.

Piezoelectric materials are a type of materials that deform (move) when a voltage is applied. Piezo haptic actuators enable precise actuation for high-definition haptics, which corresponds to a faster start-up time, a higher bandwidth of drive voltage, lower audible noise, and stronger vibrations when compared with ERMs and LRAs. Piezo actuators are available in two types: single-layer or multi-layer. The single-layer piezo requires higher voltage to move some distance because piezo actuators are capacitive loads. The multi-layer piezo type requires lower voltages but higher current. Piezo actuators bend when a voltage is applied and cause vibrations in one direction when a PWM or sinusoidal wave is provided. Overall, piezo actuators have stronger acceleration, faster response times, and low energy consumption.

[Table 1](#) compares the three haptic actuator types that are used in this TI Design system. For more information on the haptic actuator types, please see [SLOA194](#) and [SLOA207](#).

Table 1. Actuator Comparisons

ATTRIBUTE	ERM	LRA	LOW LAYER COUNT PIEZO	HIGH LAYER COUNT PIEZO
Performance	Good	Better	Best	Best
Acceleration (g)	Approx 1g	Approx 1–2g	Approx 3–5g	Approx 3–5g
Audible noise	Very noisy	Moderate noise	Silent	Silent
Response time	Approx 50 ms	Approx 30 ms	0.5 ms	0.5 ms
High-definition haptics	No	No	Yes	Yes
Cost	$	$$	$$	$$$

2.5 *Mechanical Design*

The mechanical design of the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design system consists of the aluminum enclosure, printed circuit board (PCB), and rubber grommets. The outside dimensions of the aluminum enclosure are approximately 12.5 cm × 5.5 cm × 1.5 cm.

The aluminum enclosure consists of the top and bottom parts. The top part contains four buttons: the *Big* button, which has an etched outline in the aluminum; the Down and Up buttons, which are on a single raised ridge in the middle of the top part; and the Little button, which is a raised bump on the aluminum. The top part of the enclosure is visible in the upper half of [Figure 2](#). The button layout is designed to provide examples for several different button configurations possible in end-equipment solutions. The PCB is fixed to the inside of the top part of the enclosure by means of double-sided tape (3M™ VHB™ Adhesive Transfer Tape F9460PC, please see [www.3m.com](#) for more information).

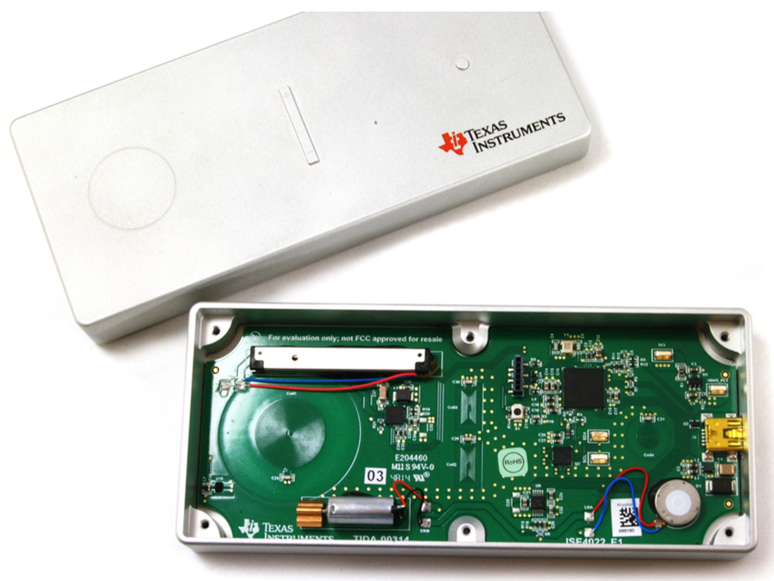


Figure 2. Touch on Metal Buttons With Integrated Haptic Feedback Mechanical Enclosure Detail

The bottom part of the enclosure is a simple aluminum plate, which is secured to the top part with six machine screws that pass through six rubber grommets, as Figure 3 shows. The purpose of the rubber grommets is to provide mechanical isolation between the top and bottom parts of the enclosure. The bottom part of the enclosure is intended to be mounted to a fixed surface, such as a desk or wall. The rubber grommets then allow the top part of the enclosure to move freely, when the haptic actuators are in operation. This movement best transfers the haptic energy to the finger of the end-user that is pressing one of the buttons on the top part of the enclosure.

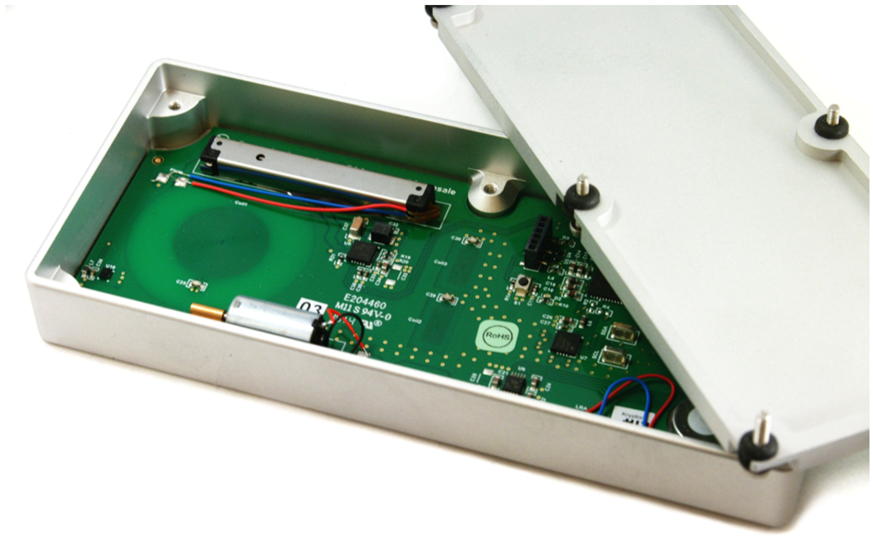


Figure 3. Touch on Metal Buttons With Integrated Haptic Feedback Mechanical Enclosure Detail

2.6 Environmental Sensor

Many industrial end-equipment systems operate in locations that experience high levels of environmental variations, including temperature and humidity changes.

The *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design reduces the impact from environmental variations by means of a firmware algorithm, but depending on the end-equipment requirements, active correction of environmental conditions can be used to achieve greater measurement precision. Please see Section 4.3 *Environmental Compensation Using Firmware Techniques* for more information on methods to deal with environmental effects on this TI Design system.

To further reduce the effects from environmental variations on the touch on metal measurements, this design has an HDC1010 device located on the PCB. The HDC1010 device measures both humidity and temperature at up to 14 bits of resolution with very low power consumption. The HDC1010 device has an operating temperature range of –20°C to 85°C and a functional range of –40°C to 125°C; however, the entire TI Design system is specified to operate from –20°C to 70°C due to the narrower temperature ranges of the various other components in the system. Because both humidity and temperature are monitored in this TI Design system, the operating environment can be either indoor or outdoor.

2.7 Microcontroller

The *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design system has relatively few requirements for the microcontroller. All of the devices used in the design communicate through I^2C and have no conflicting addresses. Therefore, only one I^2C module is required on the microcontroller. Several general-purpose inputs and outputs (GPIOs) for pin interrupts and analog switch control are required in the microcontroller. The only other main requirement for the selection of the microcontroller is that the processor speed be fast enough to process all four channels of LDC1614 device output data at the desired system refresh rate.

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

2.8 Power Management

To best demonstrate the performance of the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design system, the LP5907 low-dropout (LDO) regulator regulates the input voltage down to 3.3-V. The hardware of the design is powered from a standard USB port, which has a nominal voltage of 5-V. Also, the subsystem can be powered from the appropriate power rails if they already exist in the end equipment.

The inductance-to-digital converter, humidity and temperature sensor, and the microcontroller all require a 3.3-V voltage rail for operation. However, the haptic drivers and actuators operate directly from VBUS, the 5-V voltage rail provided at the input to the TI Designs system.

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). A low-noise power rail is ideal for optimal performance of the LDC1614 device. WEBENCH Designer is an excellent tool to determine the appropriate devices.

2.9 EMI Protection

The *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design system was designed to have robust protection against electromagnetic interference (EMI), particularly on the USB power lines. Because every end-equipment system can have a different power architecture (and thus a different protection scheme against EMI), this TI Design demonstrates that a real system can be built to comply with the various EMI standards (IEC61000). The EMI test results give confidence that Texas Instruments' technology can comply with EMI standards, given proper system design.

The primary EMI protection circuitry is located on the USB jack, as well as the Joint Test Action Group (JTAG) programming connector. There is a protection network of discrete devices on the main power input net. This network of devices consists of a high-voltage (2-kV) shunt capacitor to ground, transient voltage suppression (TVS) device, common-mode choke, fast bypass capacitor, and ferrite beads on both positive and return voltage rails. This network protects against transient voltages and currents on the main power input, in addition to reducing differential-mode and common-mode RF transients.

The TPD1E10B06 single-channel ESD protection device was chosen to protect the JTAG programming interface. The TPD2E2U06 dual-channel, high-speed ESD protection device was chosen to protect the data pins of the USB bus. See Section 6.8 *EMI Protection Performance* for more information on the performance of the EMI protection scheme used in this TI Design system.

3 Block Diagram

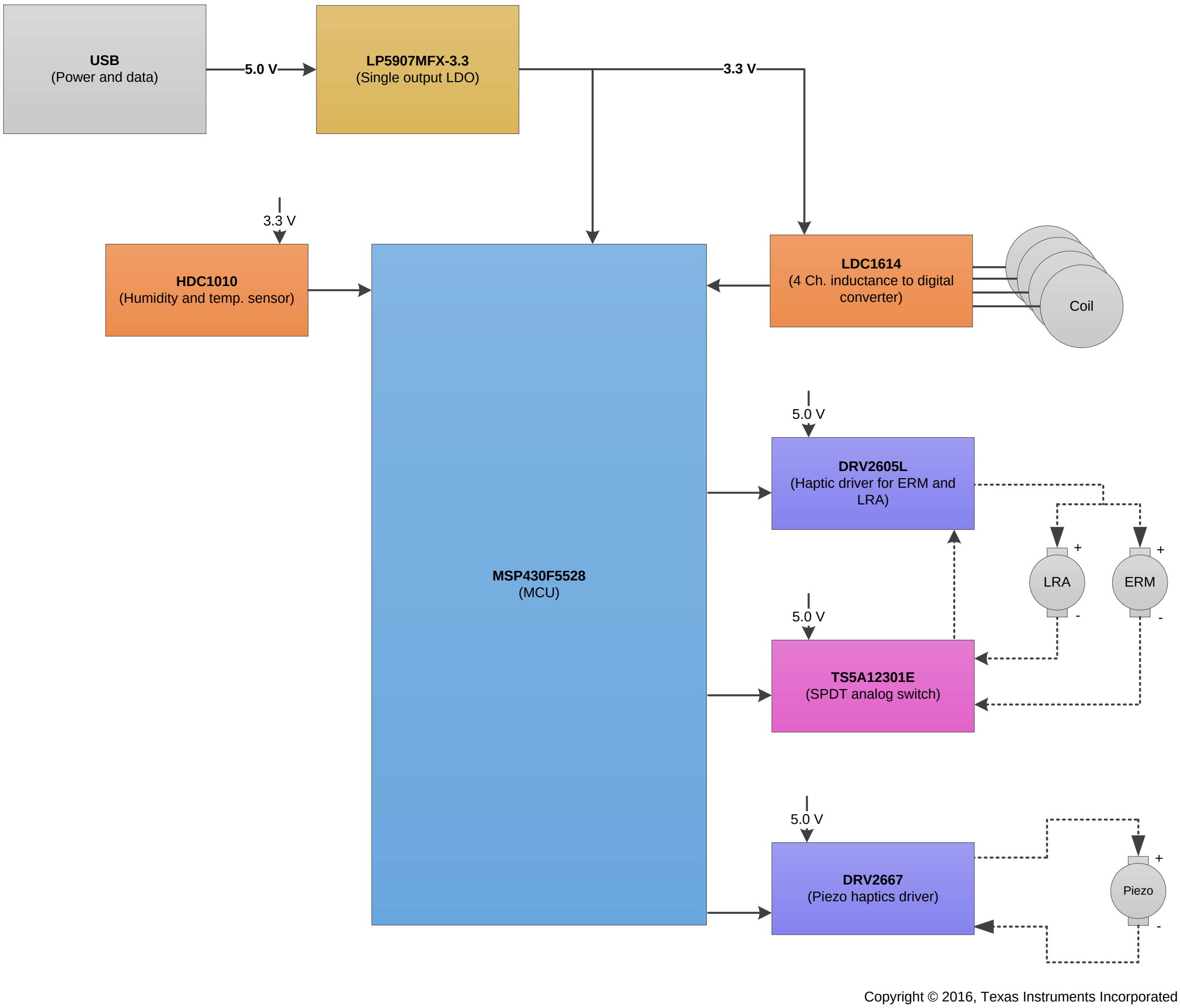


Figure 4. Touch on Metal Buttons With Integrated Haptic Feedback System Block Diagram

3.1 Highlighted Products

The *Touch on Metal Buttons With Integrated Haptic Feedback* reference design features the following devices:

- LDC1614 (Section 3.1.1): 4-channel, 28-bit inductance-to-digital converter with I^2C for inductive sensing
- DRV2605L (Section 3.1.2): Haptic driver for ERM and LRA with built-in library and smart loop architecture
- DRV2667 (Section 3.1.3): Piezo haptic driver with boost, digital front end, and internal waveform memory
- HDC1010 (Section 3.1.4): Low power, high accuracy digital humidity sensor with integrated temperature sensor
- MSP430F5528 (Section 3.1.5): 16-bit ultra-low power microcontroller, 128KB flash, 8KB RAM, USB, 12-bit ADC, two universal serial communication interfaces (USCIs), 32-bit HW MPY
- LP5907 (Section 3.1.6): 250-mA, ultra-low noise low-dropout regulator
- TS5A12301E (Section 3.1.7): IEC level 4 ESD protected, 0.75-ohm single-pole double-throw (SPDT) analog switch with 1.8-V logic compatible input logic
- TPD2E2U06 (Section 3.1.8): Dual-channel high-speed ESD protection
- TPD1E10B06 (Section 3.1.9): Single-channel ESD in 0402 package with 10-pF capacitance and 6-V breakdown
- For more information on each of these devices, see the respective product folders at www.ti.com.

3.1.1 LDC1614 Description

The LDC1312 and LDC1314 are 2- and 4-channel, 12-bit inductance to digital converters (LDCs) for inductive sensing solutions. With multiple channels and support for remote sensing, the LDC1312 and LDC1314 enable the performance and reliability benefits of inductive sensing to be realized at minimal cost and power. The products are easy to use and only require that the sensor frequency be within 1 kHz and 10 MHz to begin sensing. The wide 1-kHz to 10-MHz sensor frequency range also enables use of very small PCB coils, further reducing sensing solution cost and size.

The LDC1312 and LDC1314 offer well-matched channels, which allow for differential and ratiometric measurements. This enables designers to use one channel to compensate their sensing for environmental and aging conditions such as temperature, humidity, and mechanical drift. Given their ease of use, low power, and low system cost these products enable designers to greatly improve on existing sensing solutions and to introduce brand new sensing capabilities to products in all markets, especially consumer and industrial applications. Inductive sensing offers better performance, reliability, and flexibility than competitive sensing technologies at lower system cost and power.

The LDC1312 and LDC1314 are easily configured via an I^2C interface. The two-channel LDC1312 is available in a WSON-12 package and the four-channel LDC1314 is available in a WQFN-16 package The LDC1612 and LDC1614 are 2- and 4-channel, 28-bit inductance to digital converters (LDCs) for inductive sensing solutions. With multiple channels and support for remote sensing, the LDC1612 and LDC1614 enable the performance and reliability benefits of inductive sensing to be realized at minimal cost and power.

The high resolution channels allow for a much larger sensing range, maintaining good performance beyond two coil diameters. Well-matched channels allow for differential and ratiometric measurements, which enable designers to use one channel to compensate their sensing for environmental and aging conditions such as temperature, humidity, and drift.

Given their ease of use, low power, and low system cost these products designers to greatly improve performance, reliability, and flexibility over existing sensing solutions and to introduce brand new sensing capabilities to products in all markets, especially consumer and industrial applications.

These devices are easily configured via an I^2C interface. The two-channel LDC1612 is available in a WSON-12 package and the four-channel LDC1614 is available in a WQFN-16 package.

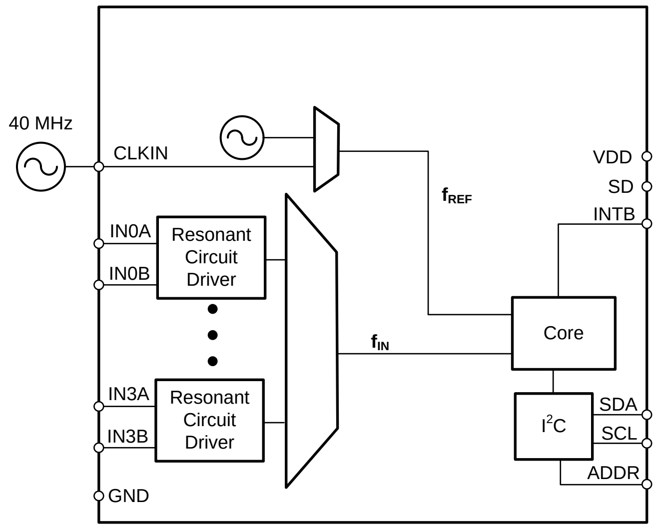


Figure 5. LDC1614 Functional Block Diagram

3.1.1.1 LDC1614 Features

- Easy-to-use—minimal configuration required
- Measure up to four sensors with one IC
- Multiple channels support environmental and aging compensation
- Multi-channel remote sensing provides lowest system cost
- Pin-compatible medium and high-resolution options
  - LDC1312/4: 2/4-ch 12-bit LDC
  - LDC1612/4: 2/4-ch 28-bit LDC
- Sensing range beyond two coil diameters
- Supports wide-sensor frequency range of 1 kHz to 10 MHz
- Power consumption:
  - 35-µA Low Power Sleep Mode
  - 200-nA Shutdown Mode
- 3.3 V operation
- Supports internal or external reference clock
- Immune to DC magnetic fields and magnets

3.1.2 DRV2605L Description

The DRV2605L device is a low-voltage haptic driver which includes a haptic-effect library and provides a closed-loop actuator-control system for high-quality haptic feedback for ERM and LRA. This schema helps improve actuator performance in terms of acceleration consistency, start time, and brake time and is accessible through a shared I^2C compatible bus or PWM input signal.

The DRV2605L device offers a licensed version of TouchSense 2200 software from Immersion, which eliminates the need to design haptic waveforms because the software includes over 100 licensed effects (6 ERM libraries and 1 LRA library) and audio-to-vibe features.

Additionally, the real-time playback mode allows the host processor to bypass the library playback engine and play waveforms directly from the host through PC.

The smart-loop architecture inside the DRV2605L device allows simple auto-resonant drive for the LRA as well as feedback-optimized ERM drive allowing for automatic overdrive and braking. This architecture creates a simplified input waveform interface as well as reliable motor control and consistent motor performance. The DRV2605L device also features automatic transition to an open-loop system in the event that an LRA actuator is not generating a valid back-EMF voltage. When the LRA generates a valid back-EMF voltage, the DRV2605L device automatically synchronizes with the LRA. The DRV2605L also allows for open-loop driving through the use of internally-generated PWM. Additionally, the audio-to-vibe mode automatically converts an audio input signal to meaningful tactile effects.

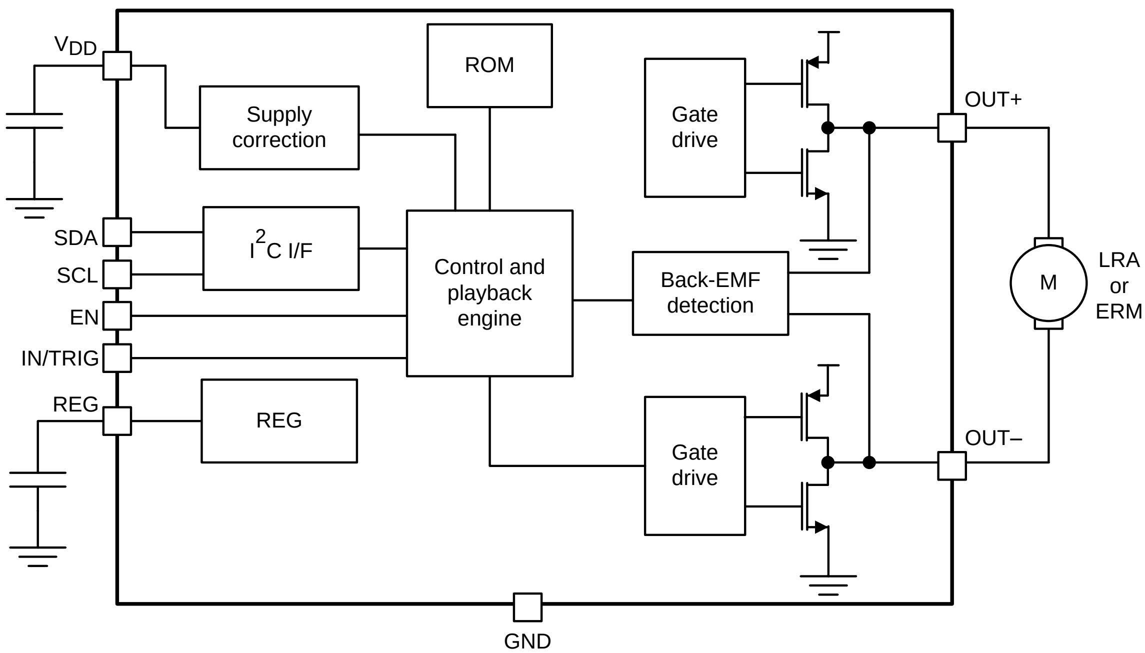


Figure 6. DRV2605L Functional Block Diagram

3.1.2.1 DRV2605L Features

- Qualified for automotive applications
- AEC-Q100 qualified with the following results:
  - Device temperature grade 0: –40°C to 150°C
  - Device HBM ESD classification Level 2
  - Device CDM ESD classification Level C4B
- Flexible haptic and vibration driver
  - LRA (Linear Resonance Actuator)
  - ERM (Eccentric Rotating Mass)
- I^2C-Controlled digital playback engine
  - Waveform sequencer and trigger
  - Real-time playback mode through I^2C
  - Internal RAM for customized waveforms
  - I^2C dual-mode drive (open and closed loop)
- Smart-loop architecture[(1)]
  - Automatic overdrive and braking
  - Automatic resonance tracking and reporting (LRA only)
  - Automatic actuator diagnostic
  - Automatic level calibration
  - Wide support for actuator models
- Licensed Immersion TouchSense® 3000-compatible 2200 features:
  - Integrated Immersion effect library
  - Audio-to-vibe
- Drive compensation over battery discharge
- Wide voltage operation (2 V to 5.2 V)
- Efficient differential switching output drive
- PWM input with 0% to 100% duty-cycle control range
- Hardware trigger input
- Fast start-up time
- 1.8 V compatible, V_{DD}-tolerant digital interface [(1)]

(1) Patent pending control algorithm

3.1.3 DRV2667 Description

The DRV2667 is a piezo haptic driver with an integrated 105-V boost switch, integrated power diode, integrated fully-differential amplifier, and integrated digital front end. This versatile device is capable of driving both high-voltage and low-voltage piezo haptic actuators. The input signal can be driven over the I^2C port or the analog inputs.

The DRV2667 digital interface is available through an I^2C-compatible bus. A digital interface relieves the costly processor burden of PWM generation or additional analog channel requirements in the host system. Any writes to the internal FIFO automatically wake up the device and begin playing the waveform after the 2-ms internal startup procedure. When the data flow stops (or the FIFO under-runs), the device automatically enters a pop-less shutdown procedure.

The DRV2667 also includes deep volatile waveform memory to store and recall waveforms with minimal latency, as well as an advanced waveform synthesizer to construct complex haptic waveforms with minimal memory usage. This provide a means of hardware acceleration, relieving the host processor of haptic generation duties as well as minimizing bus traffic over the haptic interface.

The boost voltage is set using two external resistors, and the boost current limit is programmable through the R_{EXT} resistor. A typical start-up time of 2 ms makes the DRV2667 an ideal piezo driver for fast haptic responses. Thermal overload protection prevents the device from being damaged when overdriven.

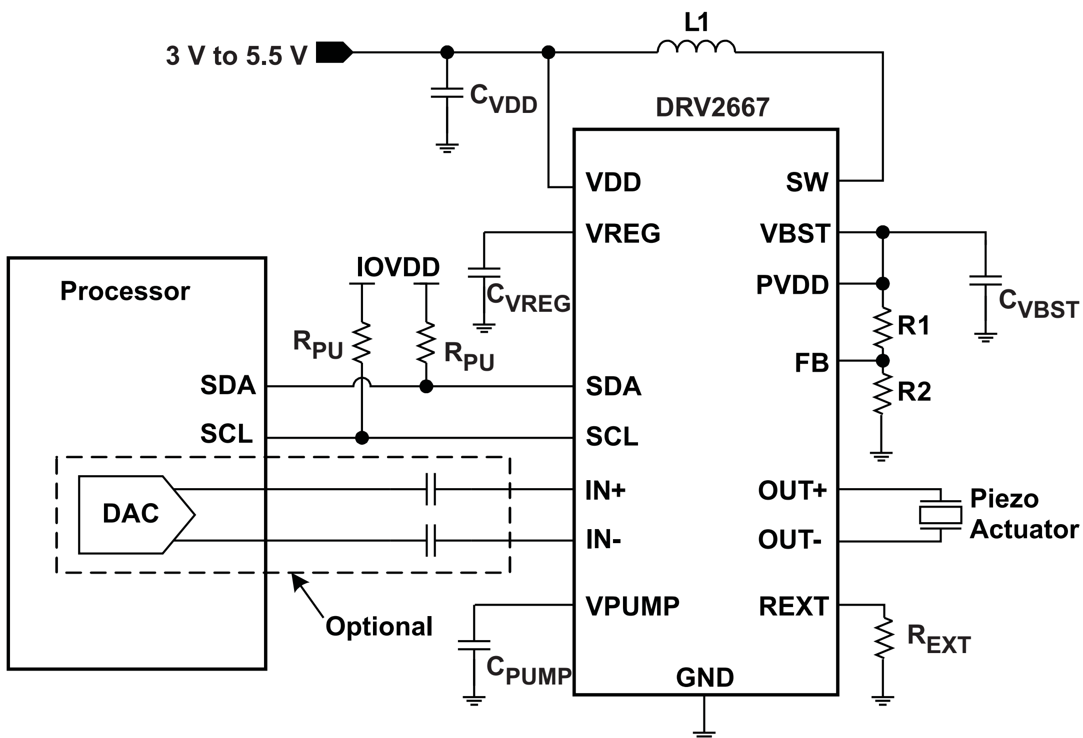


Figure 7. DRV2667 System Diagram

3.1.3.1 DRV2667 Features

- Integrated digital front end
  - I^2C bus control up to 400 kHz
  - Advanced waveform synthesizer
  - 2-kB internal waveform memory
  - Internal 100-byte first-in first-out (FIFO) interface
  - Immersion TS5000 compliant
  - Optional analog inputs
- High voltage piezo-haptic driver
  - Drives up to 100 nF at 200 V_{PP} and 300 Hz
  - Drives up to 150 nF at 150 V_{PP} and 300 Hz
  - Drives up to 330 nF at 100 V_{PP} and 300 Hz
  - Drives up to 680 nF at 50 V_{PP} and 300 Hz
  - Differential output
- Integrated 105-V boost converter
  - Adjustable boost voltage
  - Adjustable boost current limit
  - Integrated power field effect transistor (FET) and diode
  - No transformer required
- Fast start-up time of 2 ms (typical)
- Wide supply voltage range of 3 V to 5.5 V
- 1.8 V compatible, VDD-tolerant digital pins
- Available in a 4 mm × 4 mm × 0.9 mm QFN package (RGP)
- Pin-similar with DRV8662 and pin-compatible with DRV2665

3.1.4 HDC1010 Description

The HDC1010 is a digital humidity sensor with integrated temperature sensor that provides excellent measurement accuracy at very low power. The HDC1010 operates over a wide supply range, and is a low cost, low power alternative to competitive solutions in a wide range of common applications. The innovative Wafer Level Chip Scale Package (WLCSP) simplifies board design with the use of an ultra-compact package. The sensing element of the HDC1010 is placed on the bottom part of the device, which makes the HDC1010 more robust against dirt, dust, and other environmental contaminants. The humidity and temperature sensors are factory calibrated and the calibration data is stored in the on-chip non-volatile memory.

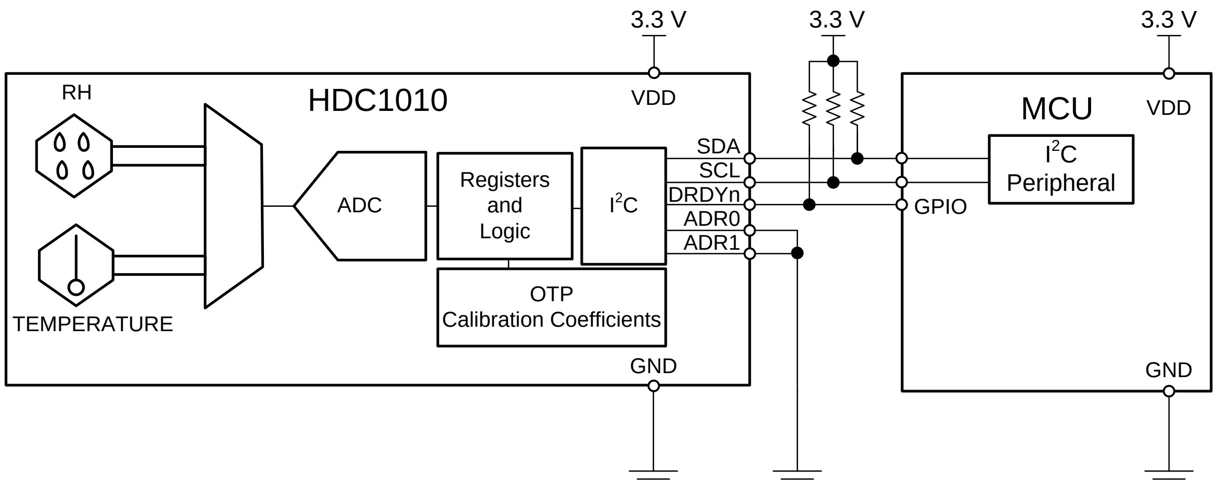


Figure 8. HDC1010 Functional Block Diagram

3.1.4.1 HDC1010 Features

- Relative humidity accuracy ±2% (typical)
- Temperature accuracy ±0.2°C (typical)
- Excellent stability at high humidity
- 14-bit measurement resolution
- 100-nA sleep mode current
- Average supply current:
  - 710 nA at 1 sps, 11-bit RH measurement
  - 1.3 µA at 1 sps, 11-bit RH and temperature measurement
- Supply voltage 2.7 to 5.5 V
- Tiny 2-mm×1.6-mm device footprint
- I^{2}C interface

3.1.5 MSP430F5528 Description

The Texas Instruments™ MSP430 family of ultralow-power microcontrollers consists of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with extensive low-power modes, is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows the devices to wake up from low-power modes to active mode in 3.5 µs (typical).

The MSP430F5529, MSP430F5527, MSP430F5525, and MSP430F5521 are microcontroller configurations with integrated USB and PHY supporting USB 2.0, four 16-bit timers, a high-performance 12-bit analog-to-digital converter (ADC), two universal serial communication interfaces (USCI), a hardware multiplier, DMA, a real-time clock (RTC) module with alarm capabilities, and 63 I/O pins. The MSP430F5528, MSP430F5526, MSP430F5524, and MSP430F5522 include all of these peripherals but have 47 I/O pins.

The MSP430F5519, MSP430F5517, and MSP430F5515 are microcontroller configurations with integrated USB and PHY supporting USB 2.0, four 16-bit timers, two universal serial communication interfaces (USCI), a hardware multiplier, DMA, an RTC module with alarm capabilities, and 63 I/O pins. The MSP430F5514 and MSP430FF5513 include all of these peripherals but have 47 I/O pins.

Typical applications include analog and digital sensor systems, data loggers, and others that require connectivity to various USB hosts.

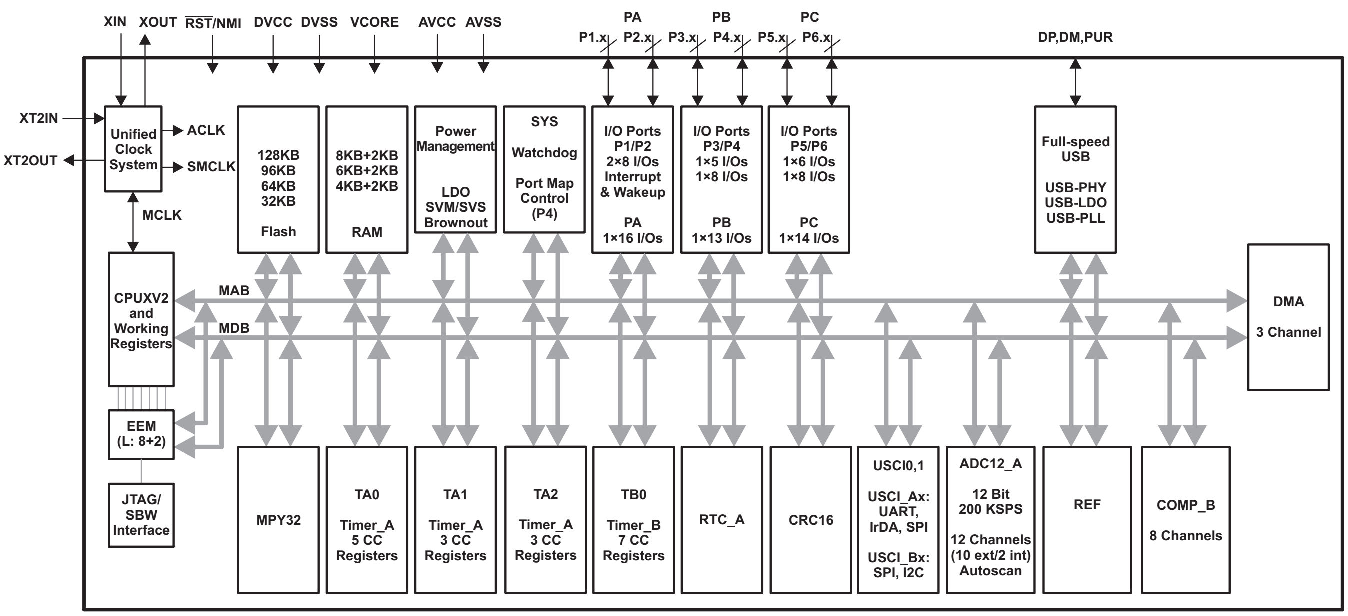


Figure 9. MSP430F5528 Functional Block Diagram

3.1.5.1 MSP430F5528 Features

- 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 (RTC) 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 reduced instruction set computing (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 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 universal asynchronous receiver/transmitter (UART) supports auto-baudrate detection
    - IrDA encoder and decoder
    - Synchronous serial peripheral interface (SPI)
  - USCI_B0 and USCI_B1 each support:
    - I^2C
    - Synchronous SPI

Full-speed universal serial bus (USB)
  - Integrated USB-PHY
  - Integrated 3.3-V and 1.8-V USB power system
  - Integrated USB-PLL
  - Eight input and eight output endpoints
- 12-bit analog-to-digital converter (ADC) (MSP430F552x only) with internal reference, sample-and-hold, and autoscan feature
- Comparator
- Hardware multiplier supports 32-bit operations
- Serial onboard programming, no external programming voltage needed
- Three-channel internal direct memory access (DMA)
- Basic timer with RTC feature
- Summarizes available family members
- For complete module descriptions, see the *MSP430x5xx and MSP430x6xx Family User's Guide* (SLAU208)

3.1.6 LP5907 Description

The LP5907 is a linear regulator capable of supplying a 250-mA output current. Designed to meet the requirements of RF and analog circuits, the LP5907 device provides low noise, high PSRR, low quiescent current, and low-line or load transient response figures. Using new innovative design techniques, the LP5907 offers class-leading noise performance without a noise bypass capacitor and the ability for remote output capacitor placement.

The device is designed to work with a 1-µF input and a 1-µF output ceramic capacitor (no separate noise bypass capacitor is required).

This device is available with fixed output voltages from 1.20 V to 4.50 V in 25-mV steps. Contact Texas Instruments Sales for specific voltage option needs.

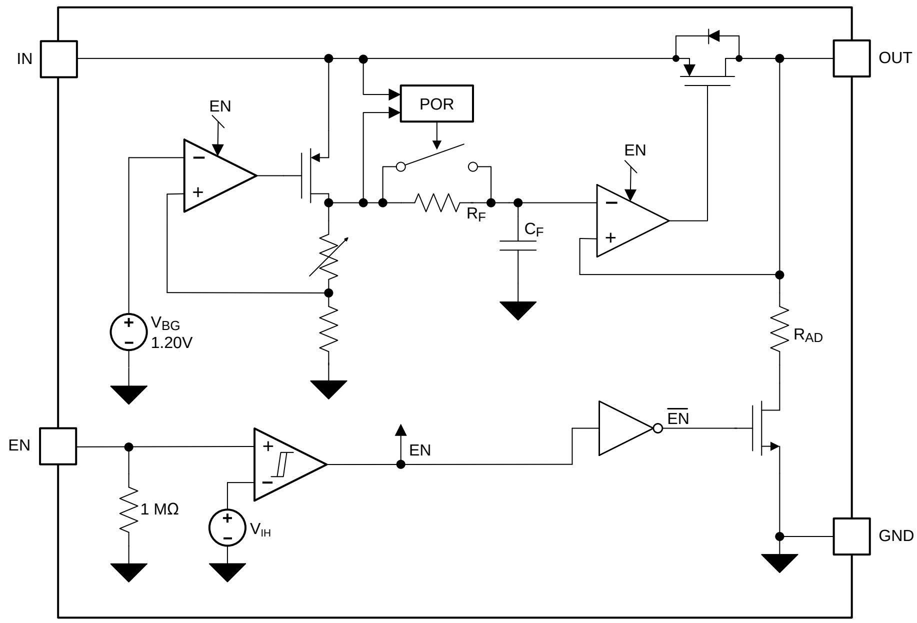


Figure 10. LP5907 Functional Block Diagram

3.1.6.1 LP5907 Features

- Input voltage range: 2.2 V to 5.5 V
- Output voltage range: 1.2 V to 4.5 V
- Output current: 250 mA
- Stable with 1-µF ceramic input and output capacitors
- No noise bypass capacitor required
- Remote output capacitor placement
- Thermal-overload and short-circuit protection
- –40°C to 125°C junction temperature range for operation
- Low output voltage noise: < 10 μV_{RMS}
- PSRR: 82 dB at 1 kHz
- Output voltage tolerance: ±2%
- Virtually zero IQ (disabled): < 1 µA
- Very low I_Q (enabled): 12 µA
- Start-up time: 80 µs
- Low dropout: 120 mV (typical)

3.1.7 TS5A12301E Description

The TS5A12301E is a single-pole double-throw (SPDT) analog switch that is designed to operate from 2.25 V to 5.5 V. The device offers a low ON-state resistance with an excellent channel-to-channel ON-state resistance matching, and the break-before-make feature to prevent signal distortion during the transferring of a signal from one path to another.

The device has excellent total harmonic distortion (THD) performance and consumes very low power. These features make this device suitable for portable audio applications. The control input (IN) pin can be connected to low-voltage GPIOs, allowing it to be controlled by 1.8-V signals.

The TS5A12301E has ±15-kV Air-Gap Discharge and ±8-kV Contact Discharge ESD protection for the COM port to GND, which make it compliant with the IEC Level 4 ESD standard (IEC 61000-4-2).

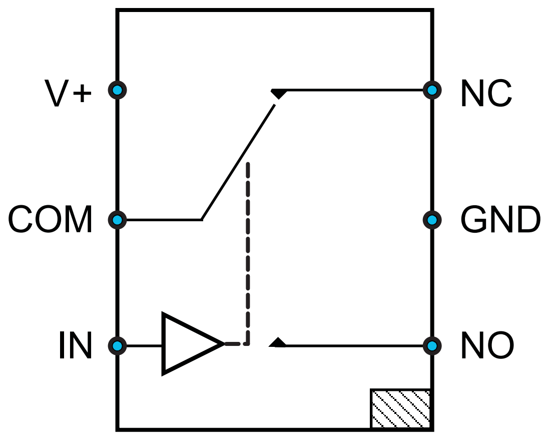


Figure 11. TS5A12301E Logic Diagram

3.1.7.1 TS5A12301E Features

- Low ON-state resistance (0.75 Ω)
- Low charge injection
- Excellent ON-state resistance matching
- Isolation in Power-Down Mode, $V_+ = 0$
- Specified break-before-make switching
- 2.25-V to 5.5-V power supply (V_+)
- 6-MΩ input pull-down allows control input (IN) to be unconnected
- 1.8-V compatible control input threshold independent of V_+
- Latch-up performance exceeds 100 mA per JESD 78, Class II
- ESD performance tested per JESD 22
  - 3000-V Human-Body Model (A114-B, Class II)
  - 1000-V Charged-Device Model (C101)
- ESD performance COM port to GND
  - 8000-V Human-Body Model (A114-B, Class II)
  - ±8-kV contact discharge (IEC 61000-4-2)
  - ±15-kV air-gap discharge (IEC 61000-4-2)

3.1.8 TPD2E2U06 Description

The TPD2E2U06 is a dual-channel ultra-low capacitance ESD-protection device. The device offers ±25-KV IEC contact and ±30-KV IEC air-gap ESD protection. The 1.5-pF line capacitance of the TPD2E2U06 makes the device suitable for a wide range of applications. Typical application interfaces are USB 2.0, LVDS, and I^2C.

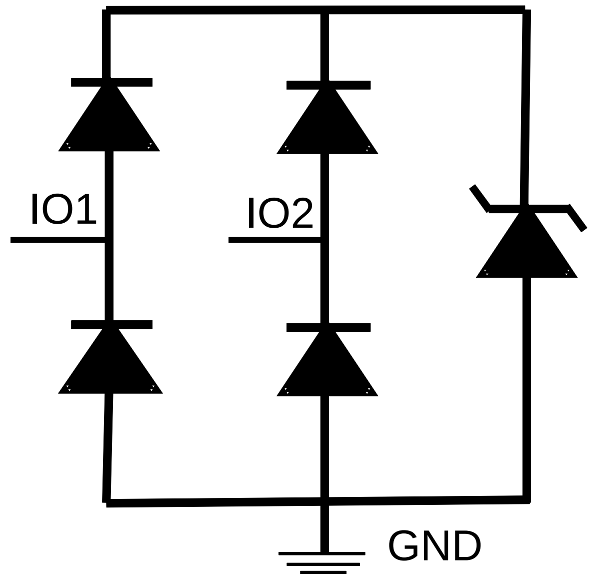


Figure 12. TPD2E2U06 Functional Block Diagram

3.1.8.1 TPD2E2U06 Features

- Provides system-level ESD protection for low-voltage IO interface
- IEC 61000-4-2 Level 4
  - ±25 kV (contact discharge)
  - ±30 kV (air-gap discharge)
- IO capacitance 1.5 pF (typical)
- DC breakdown voltage 6.5 V (minimum)
- Ultra-low leakage current 10 nA (maximum)
- Low ESD clamping voltage
- Industrial temperature range: –40°C to 125°C
- Small easy-to-route DRL package

3.1.9 TPD1E10B06 Description

The TPD1E10B06 is a single channel ESD protection device in a small 0402 package. The device offers 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 Mbps. Typical application areas of the TPD1E10B06 include audio lines (microphone, earphone, and speakerphone), SD interfacing, keypad or other buttons, and the VBUS pins of USB ports (ID).

The 0402 package is industry standard and convenient for component placement in space-saving applications. The TPD1E10B06 is characterized for operation over ambient air temperature of –40°C to 125°C.

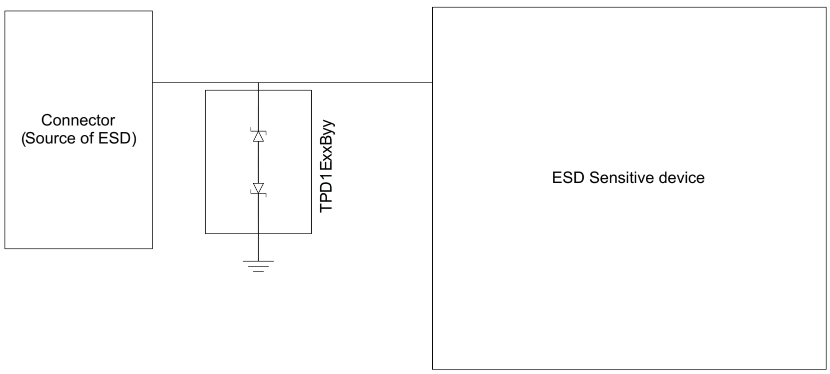


Figure 13. TPD1E10B06 Device Configuration

3.1.9.1 *TPD1E10B06 Features*

- 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): 6A (8/20 µs)
- IO capacitance 12 pF (typical)
- R_{DYN} 0.4 Ω (typical)
- DC breakdown voltage ±6 V (minimum)
- Ultra low leakage current 100 nA (maximum)
- 10-V clamping voltage (maximum at I_{PP} = 1 A)
- Industrial temperature range: –40°C to 125°C
- Space-saving 0402 footprint
  (1mm x 0.6mm x 0.5mm)

4 System Design Theory and Considerations

4.1 Touch on Metal Button Press Detection Design Considerations

The *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design detects a physical touch on a metal surface using inductive sensing technology from TI. The LDC1614 device measures the inductance of an L-C tank resonator, which consists of a PCB coil inductor and discrete capacitor. Whenever a user's finger deflects the top part of the metal enclosure, the inductance of the L-C tank changes. The aluminum of the enclosure actually deflects by several microns and the LDC1614 device can easily detect this change.

For more information on the operation of the LDC1614 device, please see the device datasheet (SNOSCY9).

There are several considerations when designing the touch on metal using inductive sensing technology into an end-equipment system. First, the sensor coils must be designed to match the desired button shape. In this TI Design system, the sensor coils match the shapes of the four buttons that are etched or embedded into the top part of the enclosure. The sensor coil L-C tank must be designed to resonate within the operating parameters of the LDC1614 device.

Another consideration is the distance between the sensing coil and the metal enclosure or surface. The maximum recommended distance is approximately ½ the diameter of the sensing coil. In this TI Design, the PCB with the sensing coils is attached to the top part of the enclosure by means of double-sided tape (3M™ VHB™ Adhesive Transfer Tape F9460PC, please see www.3m.com for more information). In an end-equipment solution, it may be desirable to have the PCB with sensing coils slightly separated from the metal surface containing button locations. The LDC1614 device can handle a separation of up to a few millimeters easily and still maintain the measurement resolution required to reliably detect button presses on the metal surface.

When designing the metal surface that contains the buttons, care must be taken to ensure that the buttons have sufficient mechanical isolation, ensuring that the LDC1614 device can distinguish between adjacent button presses. The Up and Down buttons on this TI Design show an example of how mechanically-linked buttons are distinguishable from each other by the LDC1614 device (see Section 6.2.1 *Adjacent Button Press Performance* for more information).

A final consideration for the design of touch on metal button press detection is the material of the metal surface containing the buttons. The current TI Design system uses a 1-mm thick aluminum surface, but end-equipment systems may require different materials or thicknesses. As long as the material is conductive, the LDC1614 device is able to detect any button presses, assuming that the metal thickness allows sufficient deflection when pressed. If the thickness of the metal is too great, an end user pressing on the surface with just a touch of the finger would not be able to deflect the metal enough for the LDC1614 device to measure. However, the LDC1614 device can achieve sub-micron sensing resolution; so, with the proper system design, inductive sensing technology from TI can replace existing mechanical or capacitive switches

4.2 Haptics Design Considerations

The first design consideration for the implementation of haptics technology in an end-equipment system is the selection of the haptic actuator type. This TI Design system incorporates three different haptic actuator types for easy evaluation of the various technologies available. Please see Table 1 for a detailed comparison of haptic actuators.

Upon selecting a haptic actuator, be sure to choose the proper haptic driver. For ERM and LRA actuators, the DRV2605L device is an excellent choice. For piezo actuator designs, the DRV2667 device handles the high-voltage driving very well.

The final design consideration for haptics integration is the mechanical design of the enclosure, or touch surface. If the end equipment is a fixed, mounted application (not handheld), take care to ensure that the mechanical design provides mechanical isolation between the mounting point and the user-interface surface. For instance, in this TI Design system, the top part of the enclosure is mechanically isolated from the bottom part by rubber grommets. When the bottom of the enclosure is fixed to a surface, the top part is free to vibrate without transferring the majority of the haptic energy into the surface on which the unit is mounted.

4.3 Environmental Compensation Using Firmware Techniques

In the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design system, only the relative change in the value of the LDC1614 output data is used to determine if a button has been pressed. This determination is accomplished by the use of an infinite impulse response (IIR) filter-based, moving average algorithm to post-process the data. Therefore, if environmental variations cause the baseline output data from the LDC1614 to change, firmware can compensate by means of averaging.

The actual algorithm used takes the following form in Equation 1:

$$MA[n] = \frac{MA[n-1] \times N - MA[n-1] + X[n]}{N} \tag{1}$$

Where the variables represent the following values:

- MA[n]: new moving average value
- MA[n - 1]: previous moving average value
- N: number of samples to average over (must be a power of two to operate efficiently on a microcontroller processor)
- X[n]: current LDC sample

The algorithm is optimized for use on low-power microcontrollers because the response of the IIR filter is tunable with a single variable (N), and operates using only bit-shift and addition operations. The actual IIR filter response has an exponential response, which emphasizes the most recent samples from the LDC1614 device.

If the absolute value of the LDC1614-device output data is required information for a specific end-equipment application, then the output data of the HDC1010 device can be used to actively compensate based on the measured humidity and temperature conditions at runtime. This compensation is done with a gain and offset algorithm if the environmental variation is linear, or possibly a look-up table routine if the environmental variation is some non-linear function.

4.4 Firmware Control

The *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design hardware is preloaded with firmware to control all of the components in the system. The MSP430F5528 device is programmed to control the LDC1614, HDC1010, DRV2605L, and DRV2667 devices using the USCI_B1 universal serial communication interface in I^2C mode. The firmware initializes the communication module, timer module, as well as the clock system of the MSP430F5528.

The LDC1614, DRV2605L, and DRV2667 all have several control and configuration registers that must be set in order to operate properly in this TI Design. The register details are all described in the respective datasheets.

After the microcontroller GPIOs are configured for the lowest power consumption at startup, the clock system is initialized. A 24-MHz crystal is used to drive XT2 as the main clock source for ACLK, SMCLK, and MCLK. ACLK is sourced directly to a GPIO, which drives LDC_CLKIN, the main clock source for the LDC1614 device. SMCLK is sourced by XT2, but divided by eight, because SMCLK is used to drive the Timer_A0 module at a slow rate.

The I^2C and USB modules are initialized, and then the DRV2605L device is initialized and set to perform auto-calibration for both the ERM and LRA actuators. Auto-calibration is a feature of the DRV2605L device that determines various operating parameters of the individual haptic actuator. This procedure optimizes performance of the DRV2605L device for the specific actuator that is being driven. The DRV2667 device is initialized and the waveform library loads into the device RAM.

The HDC1010 device is then configured to perform 11-bit resolution temperature and humidity measurements.

The LDC1614 device is configured to operate in continuous measurement mode (sequential) on all four channels sequentially. The LDC1614 is then set to start converting inductances on all four channels to digital output data. See Table 2 for the LDC1614 channel assignments.

Table 2. LDC1614 Channel Assignments

LDC1614 CHANNEL	CORRESPONDING BUTTON NAME
0	*Down* button
1	*Up* button
2	*Big* button
3	*Little* button

By default, the raw output data from the LDC1614 device is averaged 16 times using an IIR filter to reduce noise; this result is called the “instantaneous average”. Then, the slow-moving average is updated with 256 samples of the “instantaneous average” through the same IIR filter. If the “instantaneous average” is greater than the sum of the slow-moving average and the individual channel threshold (determined experimentally), a flag is set. This flag indicates that the individual channel has detected a button press. During the main firmware loop, the haptics assigned to that specific button are activated.

If low power consumption is a primary end-equipment constraint, then the LDC1614 device can be duty-cycled to reduce the overall system current consumption. This method yields a lower overall sample rate, reducing the signal-to-noise ratio; but given the high signal-to-noise ratios shown in Section 6.2.2 *Baseline LDC1614 Performance*, there is room to make that system tradeoff.

The HDC1010 device is set to measure temperature and humidity once per second, by means of the Timer_A0 module.

The USB module is used to communicate with the graphical user interface (GUI).

4.5 Graphical User Interface

This graphical user interface communicates with the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design hardware using the USB module.

The GUI supports the following features:

- LDC data output and threshold graph display from all four channels
- Temperature and relative humidity display
- Enclosure highlights when buttons are pressed
- USB firmware upgrade
- Firmware configuration settings
  - LDC filter length configuration
  - Haptic Effects mode configuration
  - Threshold mode configuration
  - Button effects
    - First threshold
    - Haptic actuator on first threshold
    - Haptic effect on first threshold
    - Second threshold
    - Haptic actuator on second threshold
    - Haptic effect on second threshold

5 Getting Started

5.1 Hardware Overview

Figure 14 and Figure 14 show the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design hardware. The piezo haptic actuator is located in the upper left quadrant of the PCB; the ERM is located in the lower left quadrant; and the LRA actuator is located in the lower right quadrant. Each actuator is fixed to the PCB with a quick-set epoxy adhesive.

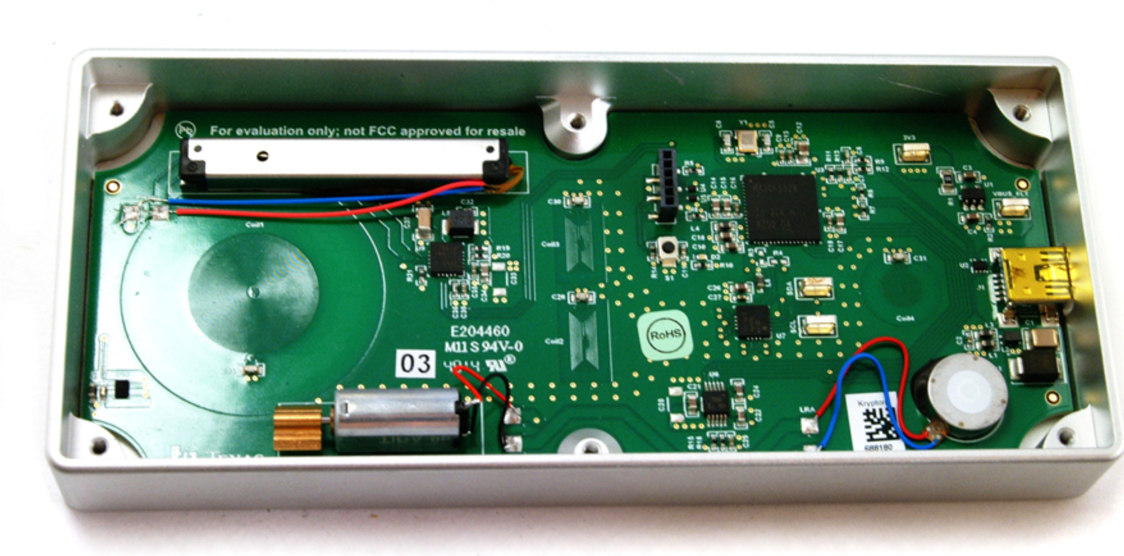


Figure 14. Touch on Metal Buttons With Integrated Haptic Feedback Reference Design Hardware

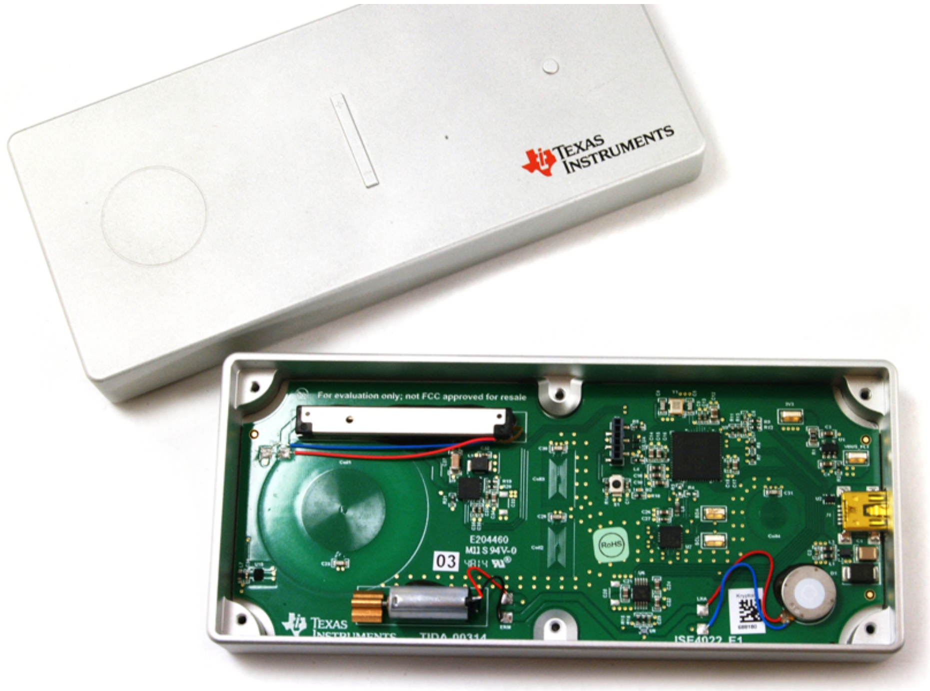


Figure 15. Touch on Metal Buttons With Integrated Haptic Feedback Reference Design Hardware

The Big button sensor coil is located in the middle left of the PCB, the Down and Up button sensor coils are in the center of the PCB, and the Little button sensor coil is in the right side of the PCB.

The DRV2667 device is located close to the piezo actuator, and the DRV2605L device is located in between the ERM and LRA actuators.

The LDC1614 device is located between the Down and Up buttons and the Little button is located immediately below the MSP430F5528 microcontroller.

All components are placed on one side of the PCB, as the underside is directly fixed to the top part of the aluminum enclosure.

J2 is the JTAG programming header and is designed to work with an adapter board to the standard 14-pin JTAG programming port.

There are test points located on the PCB for the I^2C communication lines, as well as for VBUS_FLT and 3V3 voltage rails.

When first powering up the TI Design hardware, it is necessary to wait five seconds to allow the slow-moving average thresholds to adapt to the specific hardware. Initial guesses at appropriate values are inserted into the firmware, but there is some tolerance between each unit of hardware.

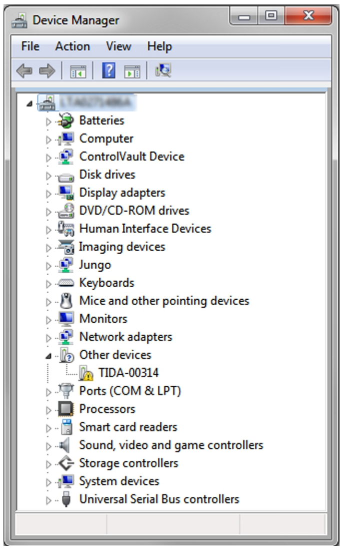
5.2 System Setup

The GUI is not required for proper TI Design operation; however, it can be used to visualize the LDC channels and configure the firmware settings.

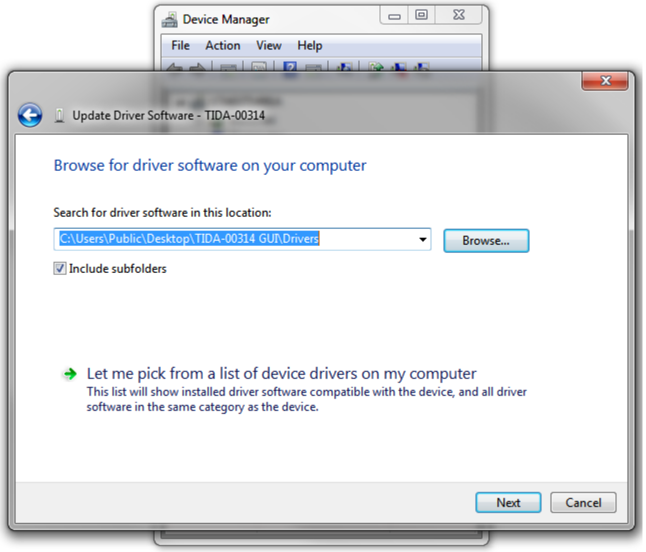
The GUI is written with Microsoft Visual Studio 2013®, so Microsoft .Net Framework 4.5 or higher is required to run the application. If these drivers are missing, install from the Microsoft website or install vcredist_x86.exe from the *Drivers* folder.

The user must also install the MSP430 CDC Windows driver to communicate with the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design. Utilize the following steps to set up the USB driver.

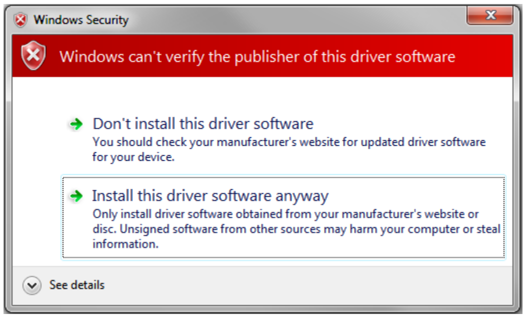
1. Plug in the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design into the PC.
2. Open the PCs *Device Manager*. Find “TIDA-00314” under *Other devices*.



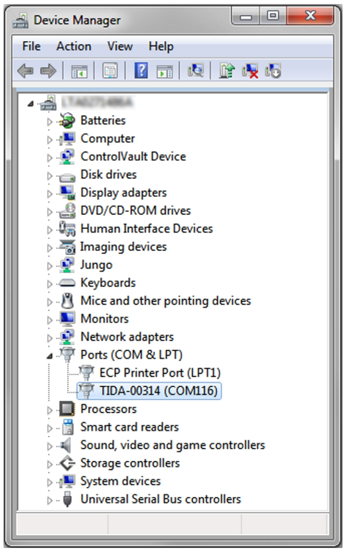
3. Right-click "TIDA-00314" and select “Update Driver Software…”.
4. Select “Browse my computer for driver software”.
5. For the location, browse to the *TIDA-00314_GUIs Drivers*.



6. Click "Next".
7. If a warning prompts that "Windows can't verify the publisher of this driver software", click "install this driver software anyway".



8. After installation, "TIDA-00314" is listed under the *Port* section with a valid COM port number. Note the COM port number, because this is to be used in the TIDA-00314_GUI.



5.3 GUI Features and Operations

The following sections describe the features and how to operate the TIDA-00314_GUI.

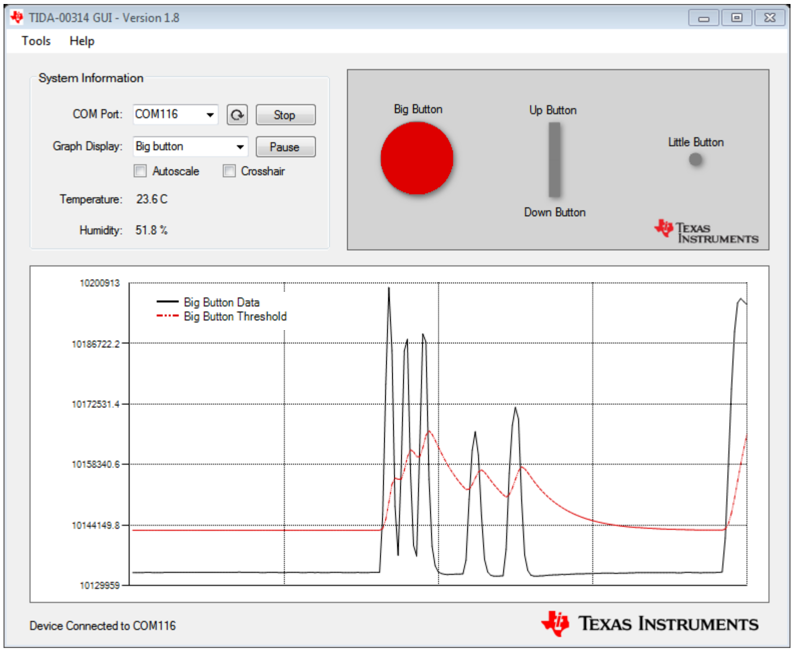


Figure 16. TIDA-00314_GUI

5.3.1 Starting the GUI

1. Navigate to the TIDA-00314_GUI folder
2. Double-click the icon for *TIDA-00314_GUI.exe*.

When the GUI runs, the following occurs:

- By default, the firmware does not send out a USB stream until the GUI connects.
- When the *Start* button is pressed, the GUI sends out a data packet to trigger the firmware to start the USB stream.
- When the *Stop* button or the GUI is closed, the GUI notifies the firmware to stop the USB stream.

5.3.2 Select the COM Port

From the COM port drop down menu, select the COM port of the TIDA-00314 reference design. If required, use the *Device Manager* to find the COM port number.

If the COM port number is not visible under the drop-down menu, press the refresh button to re-scan for COM ports.

As soon as the correct COM port is selected, click the *Start* button to start updating the graph, environment data, and enclosure button graphic. This step also enables the USB firmware upgrade feature.

5.3.3 Graph Display

Use the graph display drop-down menu to select the data to show on the graph. There are five options: the *Down* button, *Up* button, *Big* button, *Small* button, and *Down/Up* buttons.

The black solid line represents the LDC data output. The red line represents the threshold for button press detection. If the LDC data output exceeds the threshold, a button press is detected.

Sixteen samples per second are sent from the MSP430. The y-axis values dynamically increase according to the data received.

5.3.4 Temperature and Relative Humidity Data

Under system information, the temperature and relative humidity data from the HDC1010 device is displayed.

5.3.5 Enclosure Button Graphic

When a button press is detected, the button turn reds.

5.3.6 Firmware Upgrade

The GUI has the ability to upgrade the MSP430 firmware using the USB boot loader (BSL). To start the firmware upgrade, run *Tools* > *Flash Firmware*.

1. The TIDA-00314_GUI notifies MSP430 to enter BSL mode.
2. The MSP430 waits for three seconds. During this time, the TIDA-00314_GUI processes any remaining data and closes the COM port.
3. After the three-second wait, the MSP430 disables the USB peripheral and enters BSL.
4. When the BSL starts, the MSP430s USB registers as an HID device (VID / PID = 0x2047 / 0x0200).
5. The TIDA-00314_GUI launches the *Firmware Upgrade* utility.

To do a firmware upgrade, utilize the following steps:

1. Click *Browse* and open the firmware files (in TI-TXT format).
2. Wait for the BSL device to be detected.
3. If the BSL device is detected and the file has been specified, then the *Update* button is enabled.
4. Click the *Update* button.
5. The flashing takes about five seconds to complete.
6. When done, a “No devices in BSL found” message appears in the log window, because the application has restarted with the new firmware and is now registered as a COM device.
7. Close the *Firmware Upgrade* utility.
8. Select the COM port and click *Start*.

5.3.7 Firmware Configuration Settings

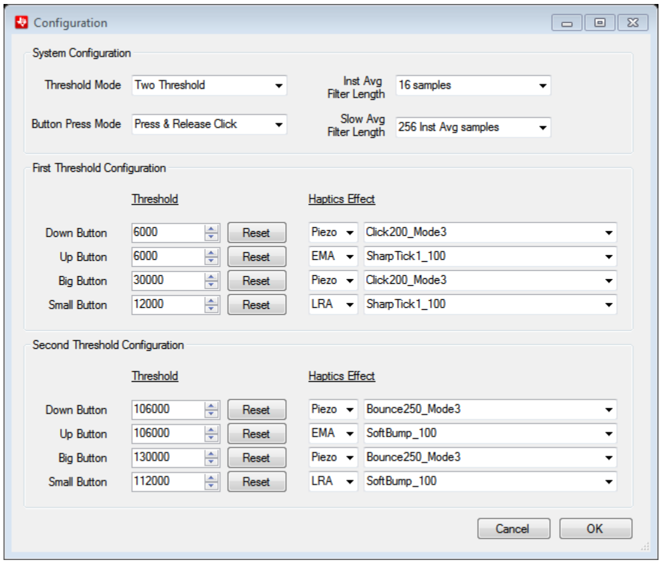


Figure 17. Firmware Configuration

The firmware can be configured remotely using the GUI. Configuring the firmware is only required if the user wants to alter the firmware default settings.

NOTE: The configuration does not save after HW restart. Restarting the HW sets the firmware back to default values.

The following Table 3 and Table 4 describe the various firmware configurations.

Table 3. System Configurations

SYSTEM CONFIGURATION	DESCRIPTION	PARAMETER
Threshold mode	Configure the number of thresholds to detect	Valid options: one threshold, two threshold Default: one threshold
Button press mode	Configure when to use haptics during button press	Press click: Haptics only on the down press Press and release click: Haptics on both the down and up press (default)
Inst avg filter length	Change the number of samples in the instant average filter	Valid options: 1, 2, 4, 8, 16, 32, 64, 128, and 256 samples Default: 16 samples
Slow avg filter length	Change the number of samples in the slow average filter	Valid options: 1, 2, 4, 8, 16, 32, 64, 128 and 256 instant average samples Default: 256 instant average samples

Table 4. Threshold Configurations

THRESHOLD CONFIGURATION	DESCRIPTION	PARAMETER
First threshold	Change the first threshold for button detection	Valid options: 1 to 999,999 Press the reset button to set back to default *Down* button: 6,000 *Up* button: 6,000 *Big* button: 30,000 *Small* button: 12,000
Second threshold	Change the second threshold for button detection	Valid options: (first threshold) to 999,999 The 2nd threshold must always be higher than the first. Press the reset button to set back to default. *Down* button: 106,000 *Up* button: 106,000 *Big* button: 130,000 *Small* button: 112,000
Haptic effect	First drop down selects the actuator Second drop down selects the waveform	Valid actuators: LRA, ERM, and piezo Valid waveforms are listed in the drop down

6 Test Data

NOTE: The test data in the following sections was measured with the system at room temperature, unless otherwise noted. All of the measurements in this section were measured with calibrated lab equipment.

6.1 Overview

The *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design has been characterized for both functional usage (button press, haptics, and power performance) as well as the impact of environmental variations and electromagnetic interference (EMI).

The results of testing and characterization are shown in the following sections. Any plots of the output data from the LDC1614 device was produced through a UART output stream to an external PC. Data formatting and analysis is performed using Microsoft Excel®.

6.2 Touch on Metal Button Press Performance

6.2.1 Adjacent Button Press Performance

The primary goal of the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design is to provide high-resolution detection of a press on a metal surface. An important characteristic of this design is the rejection of mechanical cross-talk between adjacent button presses. In other words, because the press-able surface is a continuous sheet of metal with multiple button sensors underneath, each button sensor may detect the inductance change due to an adjacent button press. This TI Design must be able to separate out false presses due to an adjacent button being pressed.

To determine how well the TI Design rejects adjacent button presses, a test sequence of button presses was performed over a time period of approximately 13 seconds. Table 5 shows the event sequence performed; the Down button was pressed twice, and then the Up button twice, and so forth.

Table 5. Adjacent Button Press Test Sequence

EVENT NUMBER	EVENT DESCRIPTION
1	*Down* button press
2	*Down* button press
3	*Up* button press
4	*Up* button press
5	*Big* button press
6	*Big* button press
7	*Small* button press
8	*Small* button press

The output data from all four channels of the LDC1614 device was then recorded during this button press test sequence and each event is labelled on Figure 18, Figure 19, Figure 20, and Figure 21.

Each of the following four figures show the slow-moving average threshold, which determines if a button press is detected.

The blue dots, labeled in the legend as "ChX Button Press?", on all of the figures indicates if a button press has been detected, where a value of 1 indicates a button press, and a value of 0 indicates that no button press has been detected.

What these four figures show is that when an adjacent button is pressed, the LDC1614 is sensitive enough to record the change. However, the LDC1614 device has enough resolution and sensitivity to distinguish between an adjacent button press and an actual button press.

For example, in Figure 18, which shows the LDC1614 data for Ch0 (Down button), the TI Design correctly records a button press on the Down button for Events 1 and 2, but does not record a button press for the other events, as they do not exceed the threshold. Referring to the previous Table 5, it is visible that Events 1 and 2 are Down button presses.

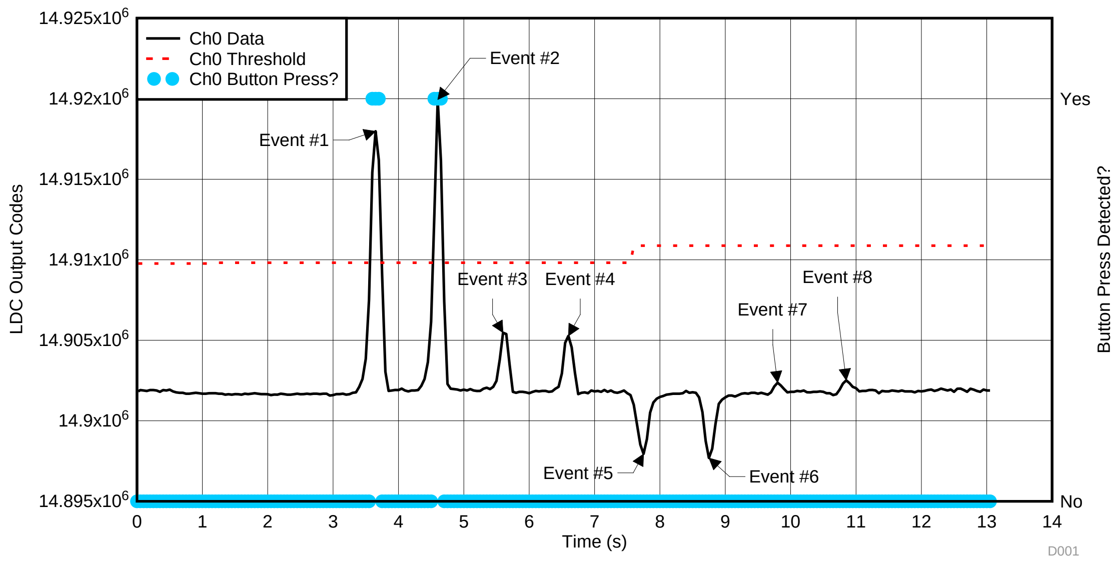


Figure 18. LDC Ch0 Data – *Down* Button Channel

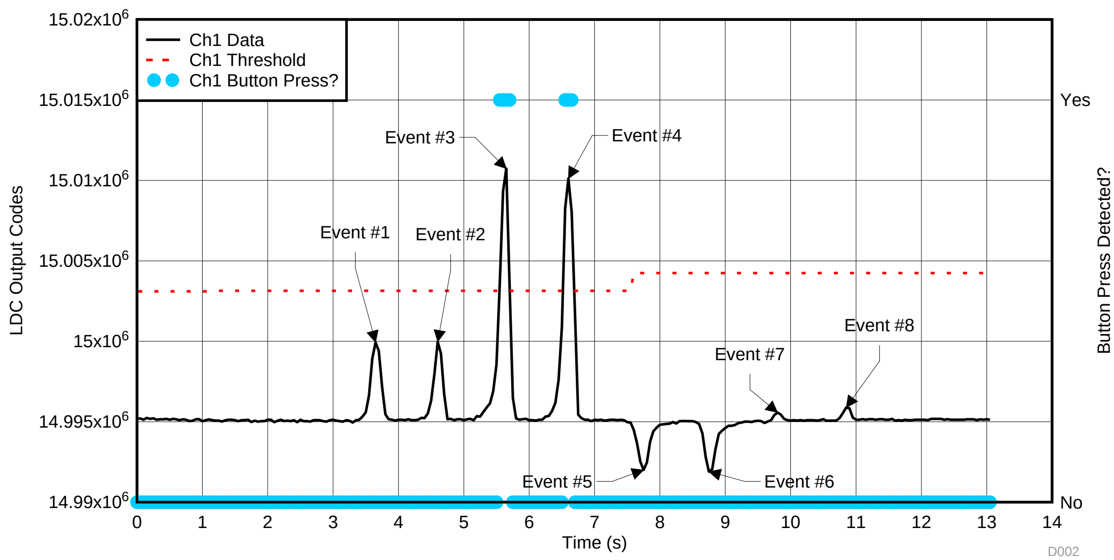


Figure 19. LDC Ch1 Data—*Up* Button Channel

The mechanical design of the enclosure is such that the Down button and Up button have significant mechanical coupling. So the mechanical cross-talk is at the worst case between these two buttons. However, Figure 18 and Figure 19 show that the LDC1614 device has plenty of resolution and sensitivity to distinguish between Up and Down button presses.

Figure 20 shows minimal mechanical cross-talk on the *Big* button channel of the LDC1614 device, which is due to several factors. The first factor is that the sensor coil on the Big button channel is much larger than the other three channels, which increases the channel sensitivity. The second factor is that the Big button sensor coil is at the end of the mechanical enclosure, reducing the actual mechanical linkage.

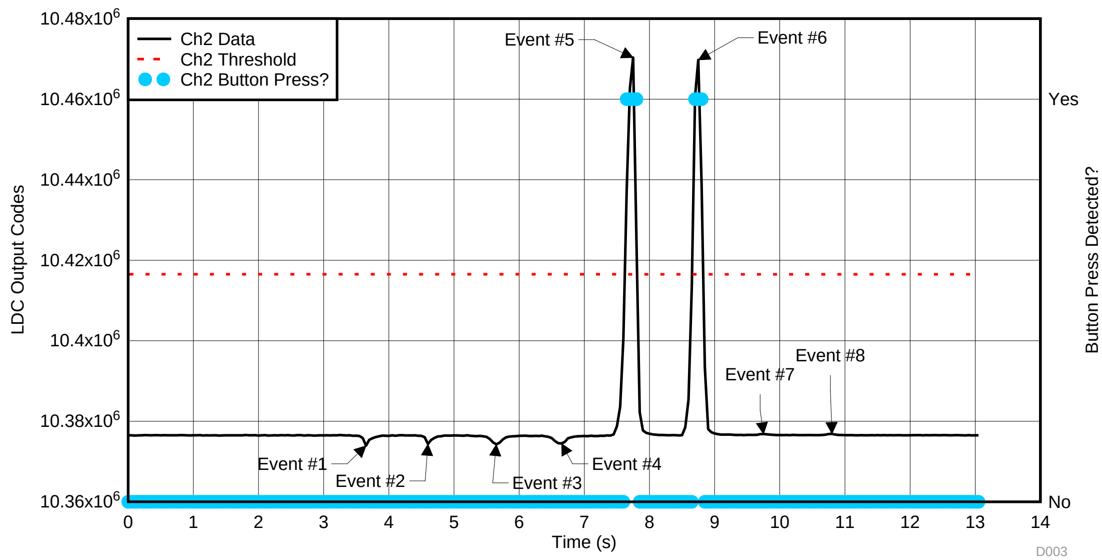


Figure 20. LDC Ch2 Data—*Big* Button Channel

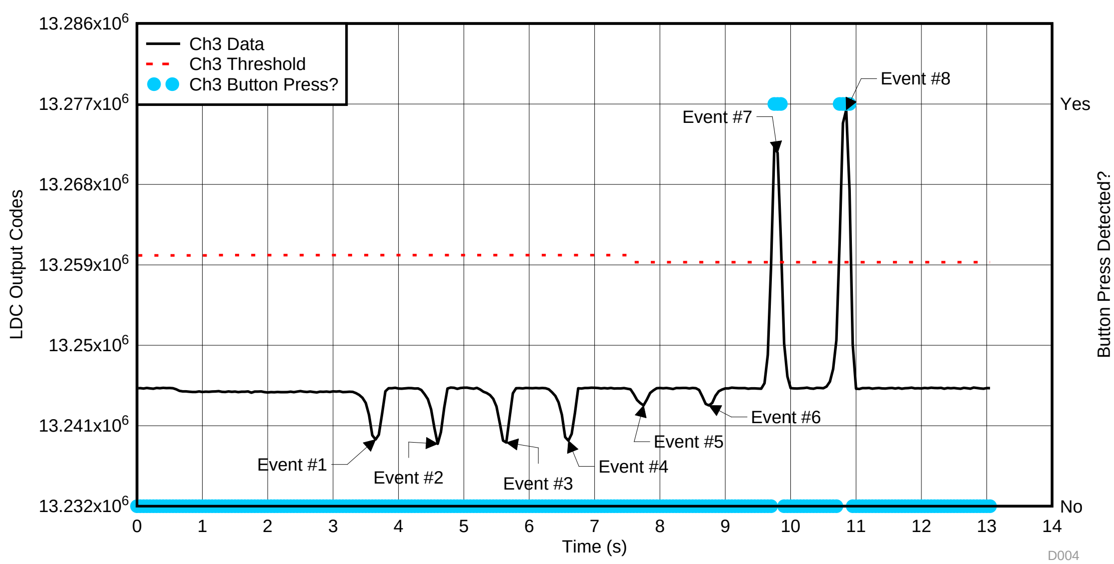


Figure 21. LDC Ch3 Data—*Little* Button Channel

Several of the four previous figures show the ChX threshold moving slightly during the test sequence. This movement is due to the impact of the actual button presses on the slow-moving average algorithm. As programmed, if a button is held down for greater than the update rate of the slow-moving average threshold value, a button press would cease to be registered, because the slow-moving average would adjust to the new, “constant” value. The intent with this feature is to eliminate “stuck” buttons due to metal deformation (for instance, the metal surface being hit with a hammer). If this feature is not the desired behavior of the end-system, the algorithm and firmware logic can be easily adjusted for other scenarios.

Also, several of the data output channels of the LDC1614 device show negative peaks during various events. This result is due to the mechanical enclosure flexing away from the sensor instead of towards the sensor. Because the magnitude of these negative peaks is not large compared to the actual button press event, the ChX threshold does not move significantly.

6.2.2 Baseline LDC1614 Performance

The LDC1614 device outputs data that represents the oscillation frequency of the LC sensor tank. For the purposes of detecting a button press on a metal surface, only the relative change in this oscillation frequency is required. Thus, a key performance parameter of the system is the baseline noise level compared to the change in the LDC1614 output code due to a button press. This parameter is effectively the signal-to-noise ratio (SNR) of the system. Table 6 summarizes the measured noise, change in codes due to button presses, and the calculated signal-to-noise ratio in decibels. The data in Table 6 is taken from one unit of the TI Designs hardware.

Table 6. Summary of System Signal-to-Noise Ratio

LDC1614 CH	BASELINE NOISE (CODES PEAK-TO-PEAK)	Δ CODES DUE TO BUTTON PRESS	SIGNAL-TO-NOISE RATIO (dB)
0	202	24111	41.5
1	315	21486	36.7
2	276	80119	49.3
3	209	23274	40.9

As Table 6 shows, the noise levels for all four LDC1614 channels are comparable. The main difference in the signal-to-noise ratio data comes from the greatly increased value of the LDC1614 Ch2 Δ Codes due to Button Press. The value is much higher because the coil for the Big Button channel is significantly larger than the sensor coils for the other three buttons, while still maintaining the same distance from the metal target. Therefore, the gap-to-coil diameter ratio for the Big button is very small, leading to a much higher sensitivity than the other three buttons.

All four LDC1614 channels are measured sequentially in this system. Figure 22 shows the sequence of measurements where Ch0 is read, followed by Ch1, Ch2, and Ch3. All four channels are measured and then the sequence repeats. Each acquisition of all four channels takes approximately 3.1 ms, yielding an overall sample rate of 325 Hz.

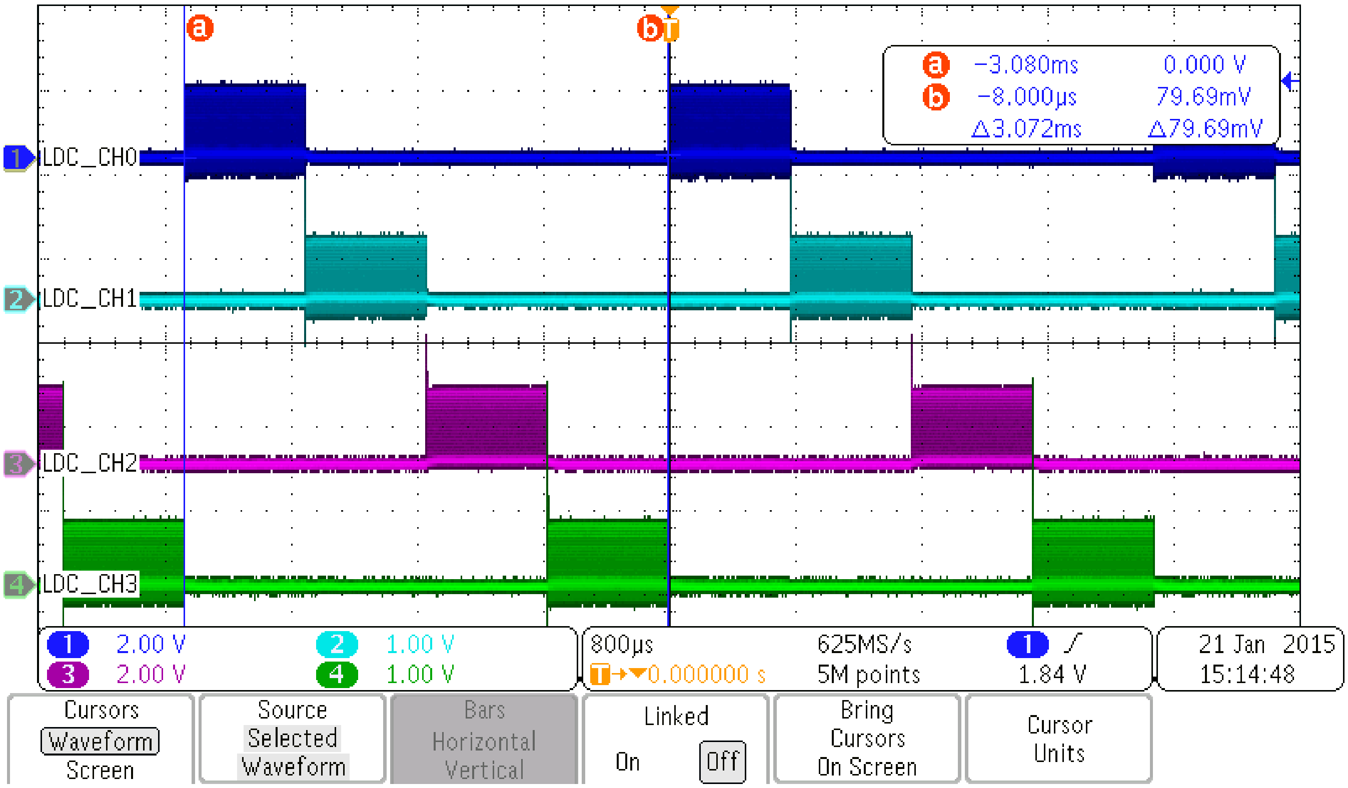


Figure 22. LDC1614 Measurement Sequence

As described in Section 4.1 *Touch on Metal Button Press Detection Design Considerations*, the baseline resonant frequency of the LC tank needs to be within the LDC1614 device operating parameters (1 kHz to 10 MHz). Table 7 summarizes the resonant frequencies for all four sensor coils. Since the Up and Down buttons share the same exact coil footprint, the measurements confirm that the resonant frequencies are identical, with small variations due to the parallel capacitor variation, as well as manufacturing tolerance on the sensor coil itself. Figure 23, Figure 24, Figure 25, and Figure 26 show the waveform on all four sensor coils.

Table 7. Summary of Sensor Coil Resonant Frequencies

LDC1614 CHANNEL	CORRESPONDING BUTTON NAME	MEASURED RESONANT FREQUENCY (MHz)
0	*Down* button	9.8
1	*Up* button	9.9
2	*Big* button	1.8
3	*Little* button	9.4

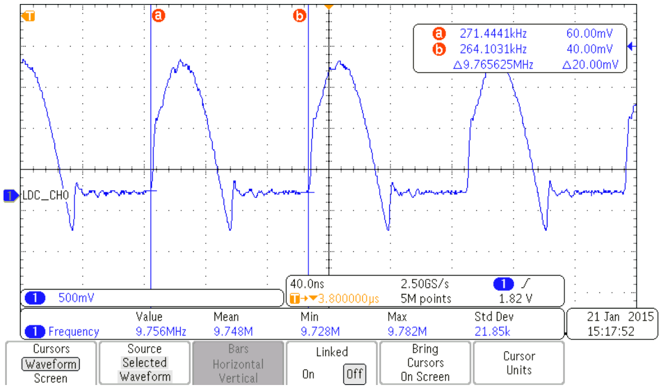


Figure 23. LC Tank Baseline Resonant Frequency—Ch0 (*Down* Button)

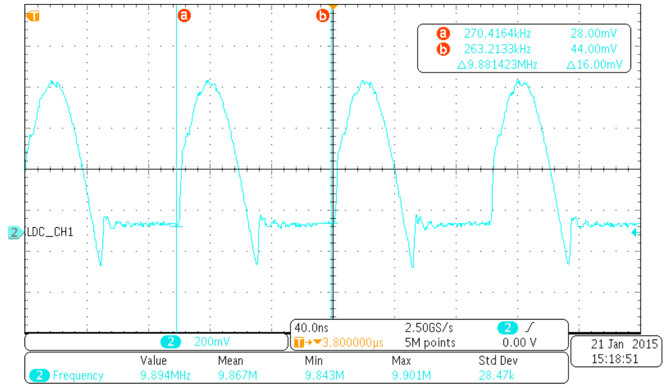


Figure 24. LC Tank Baseline Resonant Frequency—Ch1 (*Up* Button)

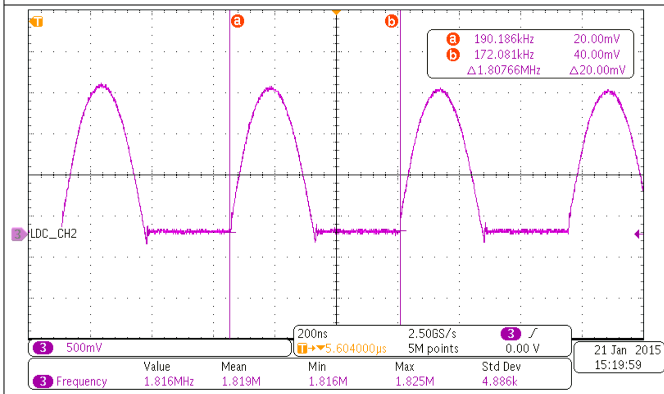


Figure 25. LC Tank Baseline Resonant Frequency—Ch2 (*Big* Button)

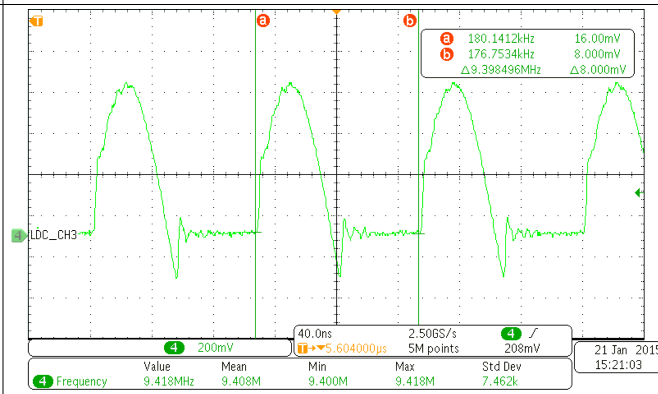


Figure 26. LC Tank Baseline Resonant Frequency—Ch3 (*Little* Button)

6.3 Haptics Performance

Because the primary purpose of the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design is to detect a button press on a metal surface and then provide haptic feedback to the user, it is critical that the activation of the haptics does not affect the determination of a button press. Therefore, in this test setup, the LDC1614 device output for all four channels was recorded while each of the three available haptic actuators were activated separately. Each actuator type was set to operate approximately once per second.

The only scenario where the haptics affected the LDC1614 device measurement was in the case of the piezo actuator. There was some impact on the LDC1614 Ch2 reading because the piezo actuator is located physically close to the Big button sensor coil, and also because the Big button sensor coil is the largest—and therefore most sensitive—of the four sensor coils. However, as Figure 29 shows, the excursion due to the piezo activation was just over 2000 codes, which is well under the threshold of 40000 codes in place for the Big button sensor channel. Each event labeled in Figure 29 represents an activation of the piezo actuator. As is easily seen, the impact of the piezo activation is insignificant when compared with the threshold required to trigger a button press. In addition, the piezo activation causes the LDC1614 device output to move in the negative direction, away from the button press detection threshold.

No events are labeled on the figures showing operation during the ERM or LRA activation because no discernable effect was produced on the LDC1614 data output.

All other channels are essentially unaffected by the piezo actuator and all channels are essentially unaffected by the ERM and LRA actuators.

Table 8 summarizes the noise levels during all three haptic actuator operations.

Table 8. Summary of LDC1614 Noise During Haptic Actuator Operation

CHANNEL	NOISE DURING PIEZO ACTIVATION (CODES PEAK-TO-PEAK)	NOISE DURING ERM ACTIVATION (CODES PEAK-TO-PEAK)	NOISE DURING LRA ACTIVATION (CODES PEAK-TO-PEAK)	Δ CODES DUE TO BUTTON PRESS
0	256	114	256	24111
1	310	252	176	21486
2	**2407**	218	222	80119
3	229	260	190	23274

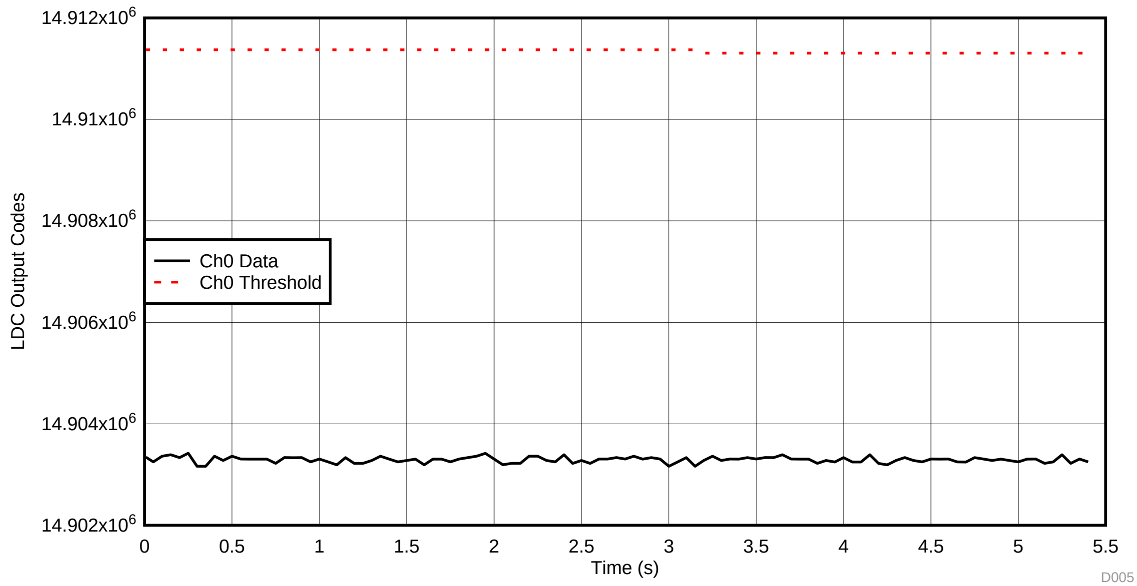


Figure 27. LDC Ch0 Data During Piezo Activation—*Down* Button Channel

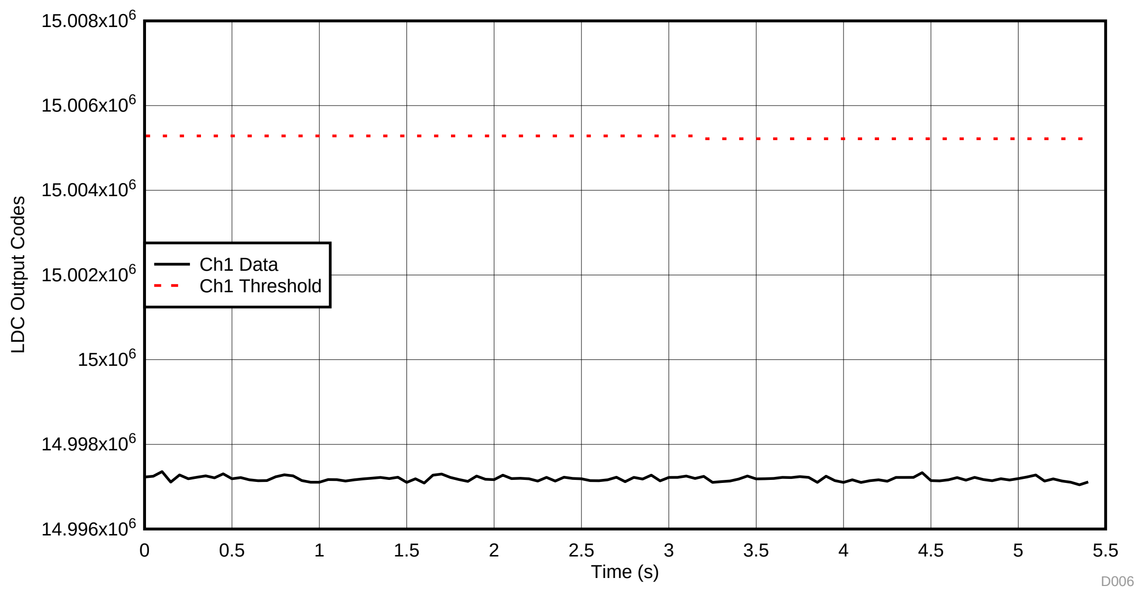


Figure 28. LDC Ch1 Data During Piezo Activation—*Up* Button Channel

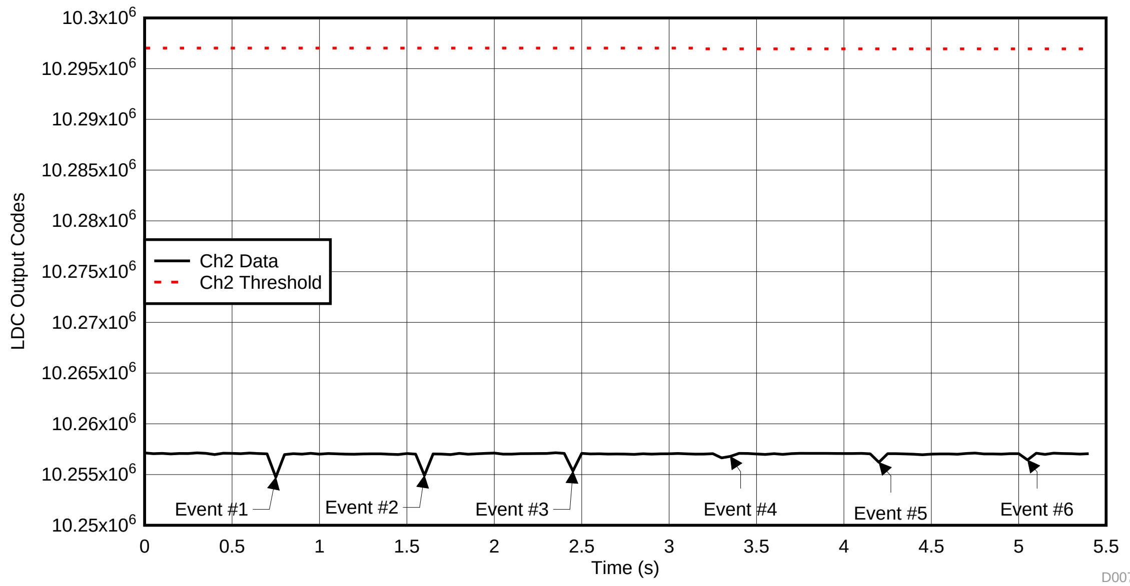


Figure 29. LDC Ch2 Data During Piezo Activation—*Big* Button Channel

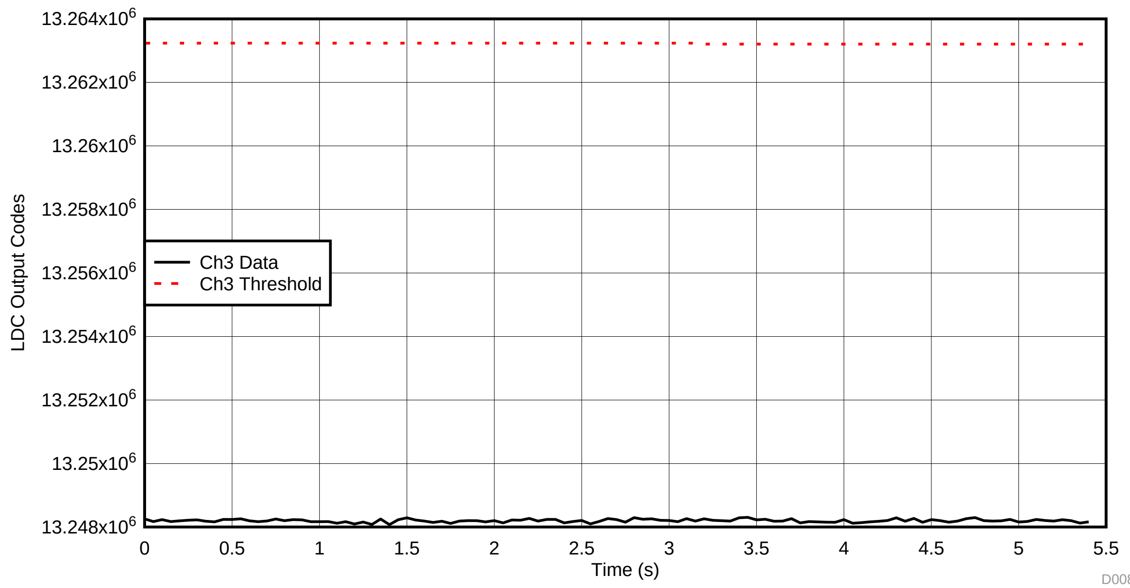


Figure 30. LDC Ch3 Data During Piezo Activation—*Little* Button Channel

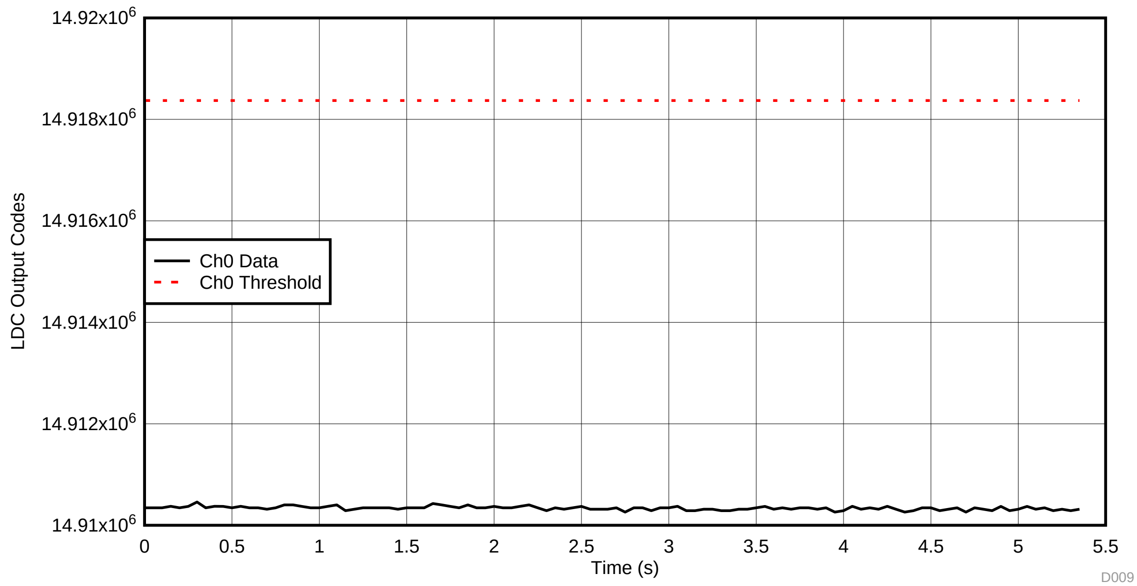


Figure 31. LDC Ch0 Data During ERM Activation—*Down* Button Channel

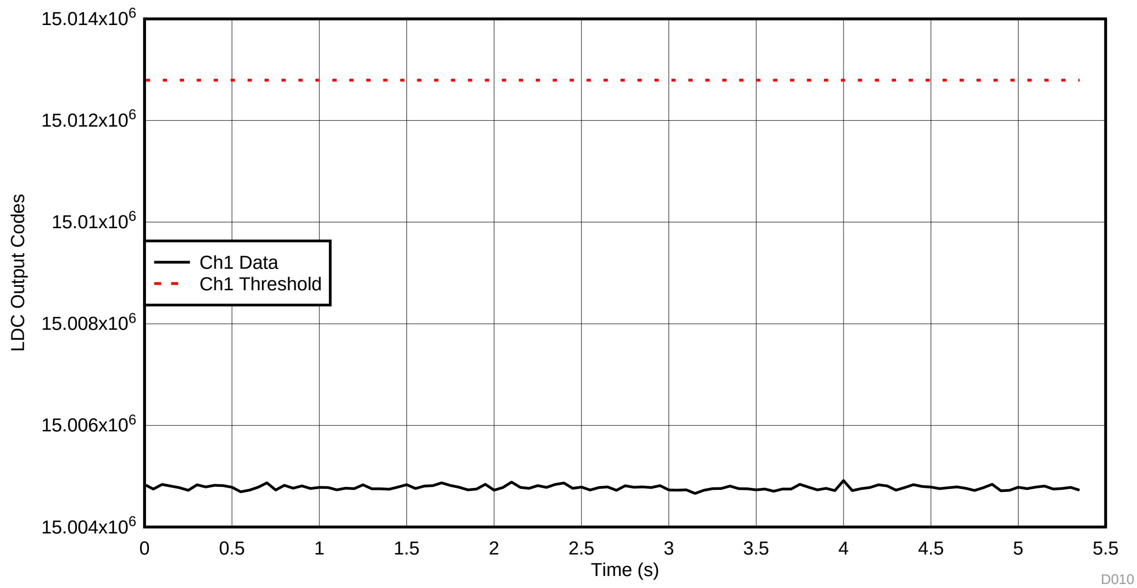


Figure 32. LDC Ch1 Data During ERM Activation—*Up* Button Channel

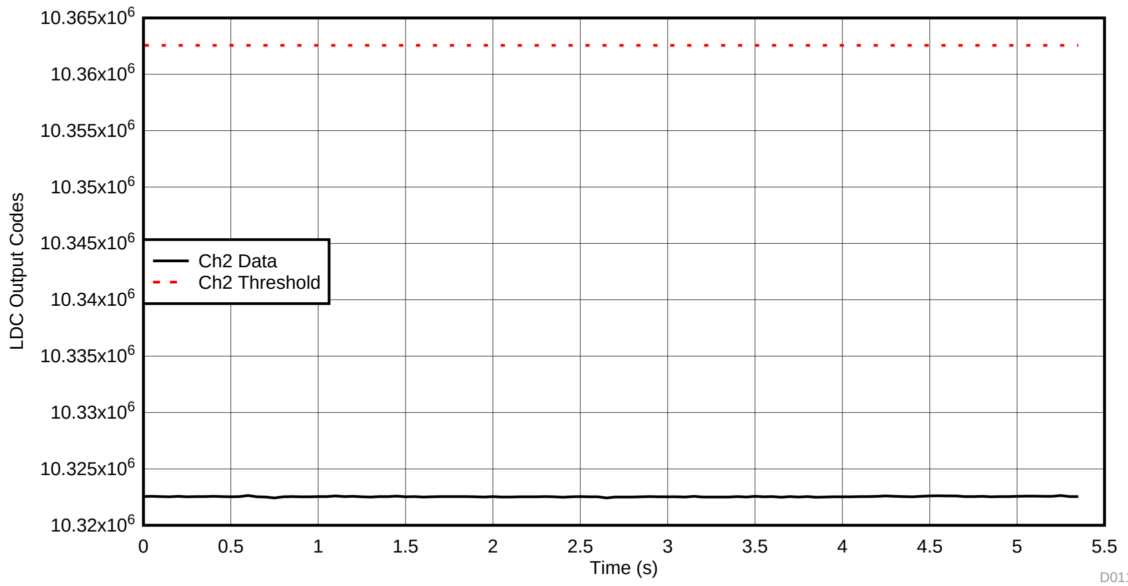


Figure 33. LDC Ch2 Data During ERM Activation—*Big* Button Channel

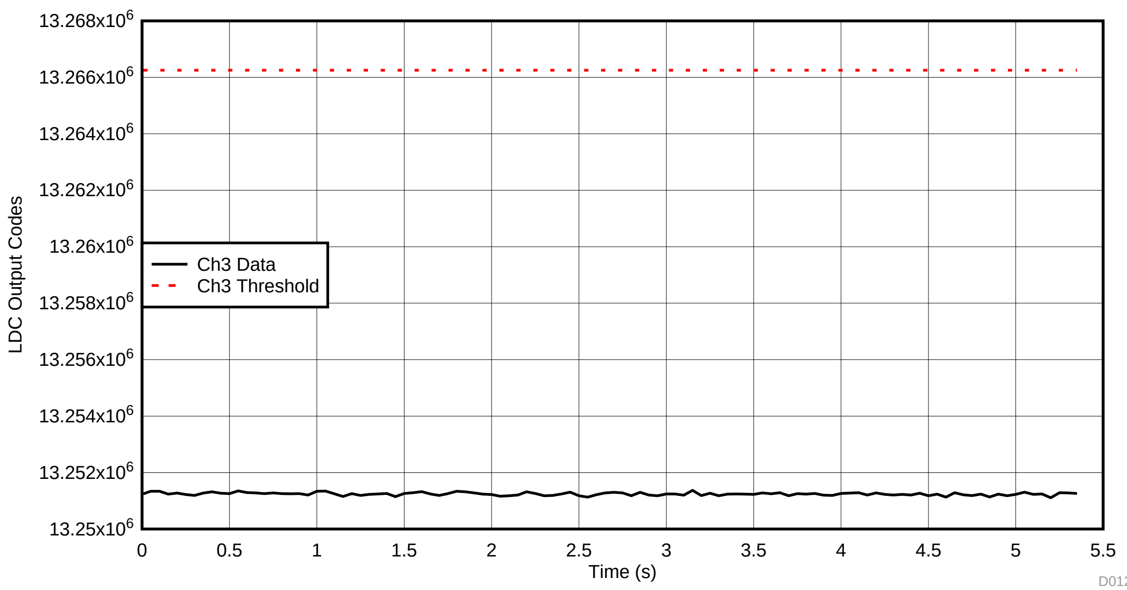


Figure 34. LDC Ch3 Data During ERM Activation—*Little* Button Channel

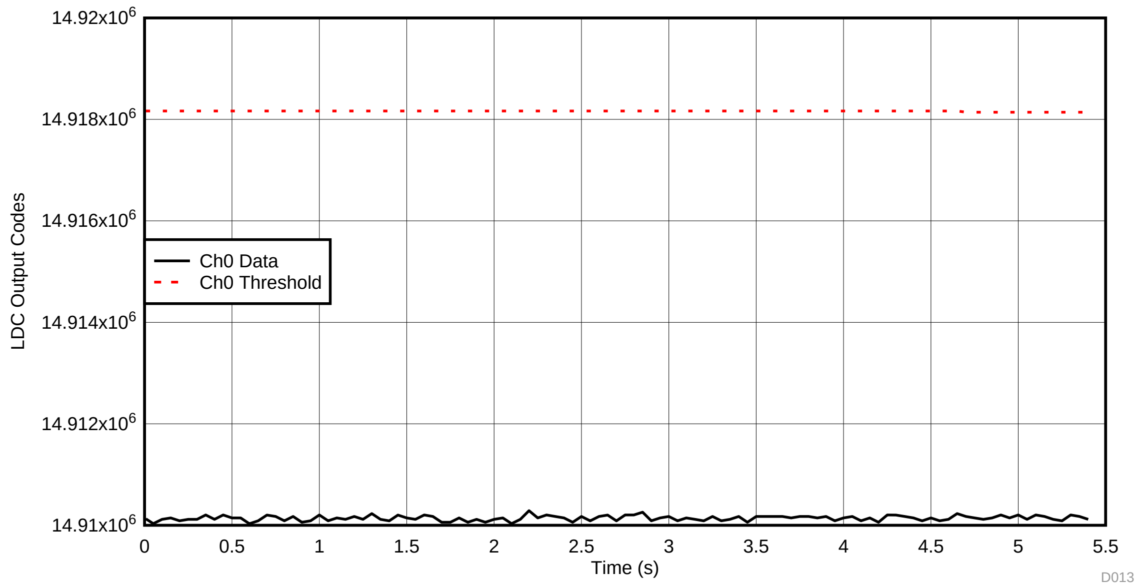


Figure 35. LDC Ch0 Data During LRA Activation—*Down* Button Channel

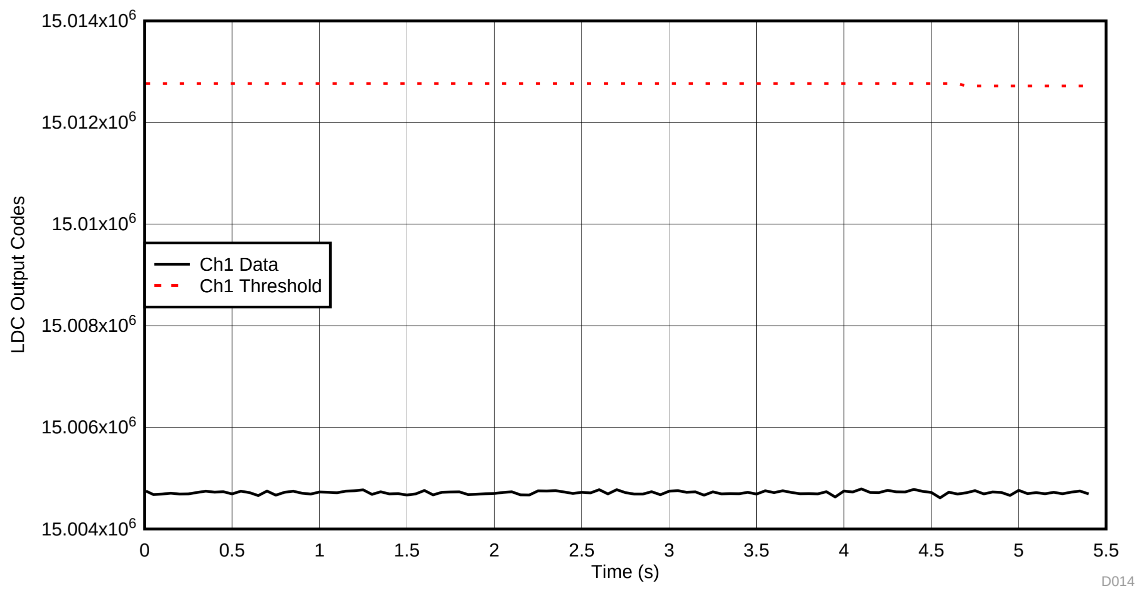


Figure 36. LDC Ch1 Data During LRA Activation—*Up* Button Channel

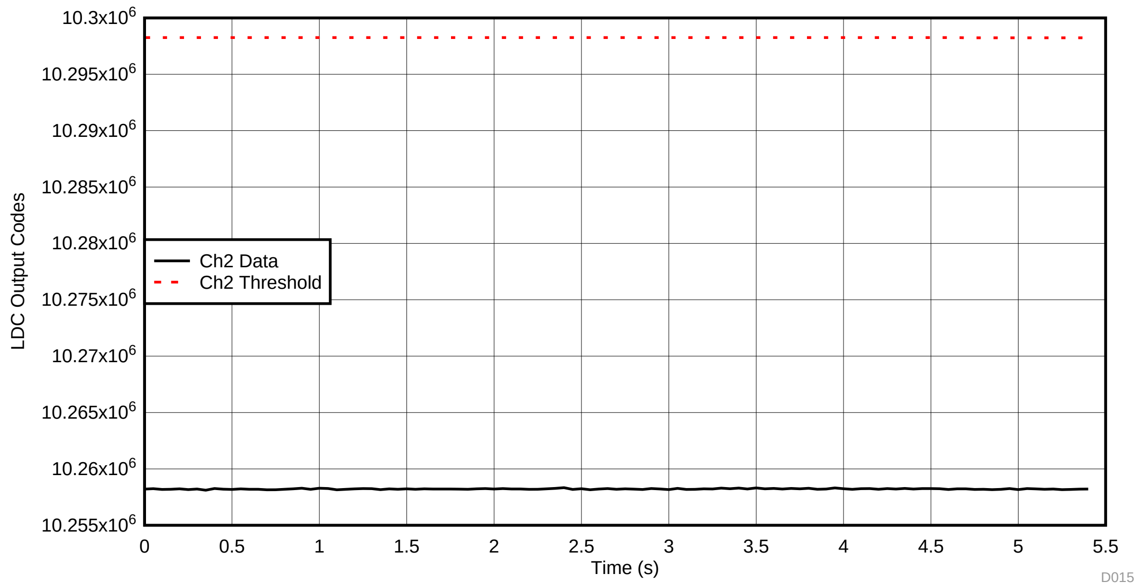


Figure 37. LDC Ch2 Data During LRA Activation—*Big* Button Channel

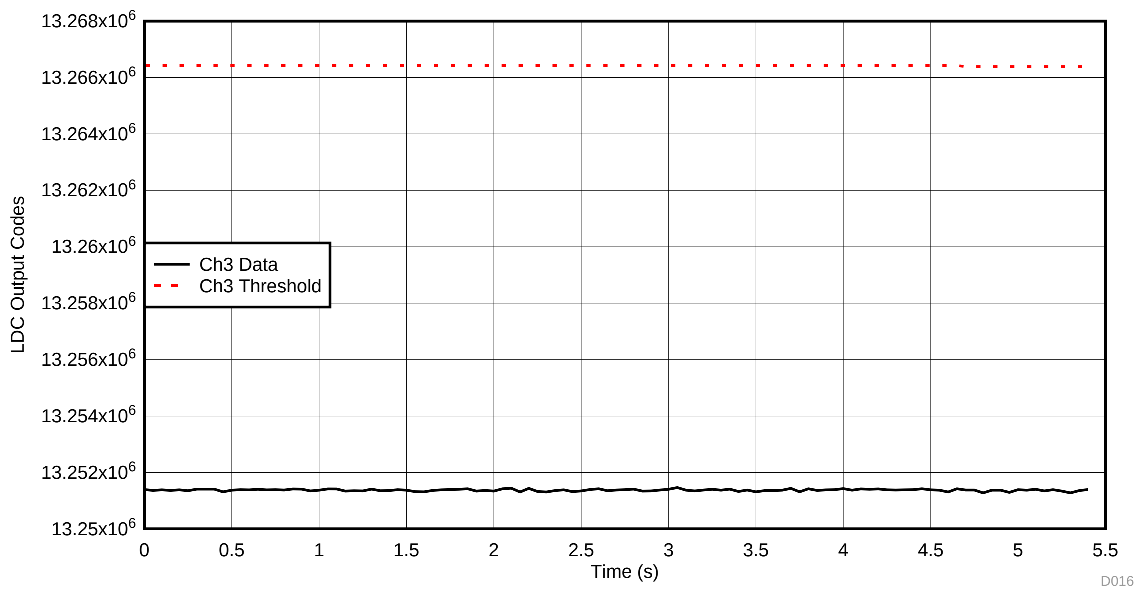


Figure 38. LDC Ch3 Data During LRA Activation—*Little* Button Channel

6.4 Current Consumption

One of the key design considerations for the integration of the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design into end-user systems is the overall system current consumption. Because there are several modes of operation, test data has been collected showing the total system current consumption during each mode.

The modes include the LDC1614 measurement (default mode, occurs continuously), piezo actuator operation, ERM actuator operation, and LRA actuator operation. Figure 39, Figure 40, Figure 41, and Figure 42 show the VBUS input (5-V from USB), VBUS_FLT (5-V after EMI protection circuitry), 3V3 (3.3-V output from the LP5907 device), and I_VBUS (current at the input of the system) during the respective modes of operation. Table 9 summarizes the current draw for each of these four modes of operation. The vast majority of the time, the system runs in the LDC1614 measurement mode, which operates continuously. The three operation modes for the haptic actuators only occur when a button press is detected. The average system power consumption then depends on the usage profile, which varies based on the end-user system expectations.

The current during HDC1010 device operation is not significant compared to the LDC1614 device measurement during operation. This result occurs because the HDC1010 device is set to take measurements only once per second, and at that rate, the average supply current is approximately 1.2 μA, much less than the other devices in the TI Design system.

Table 9. Summary of Total System Current Consumption During Modes of Operation

MODE OF OPERATION	I_VBUS CURRENT CONSUMPTION (mA)
LDC1614 measurement (default mode)	8.4 (peak)
Piezo actuator operation	408 (peak)
ERM actuator operation	580 (peak)
LRA actuator operation	216 (peak)

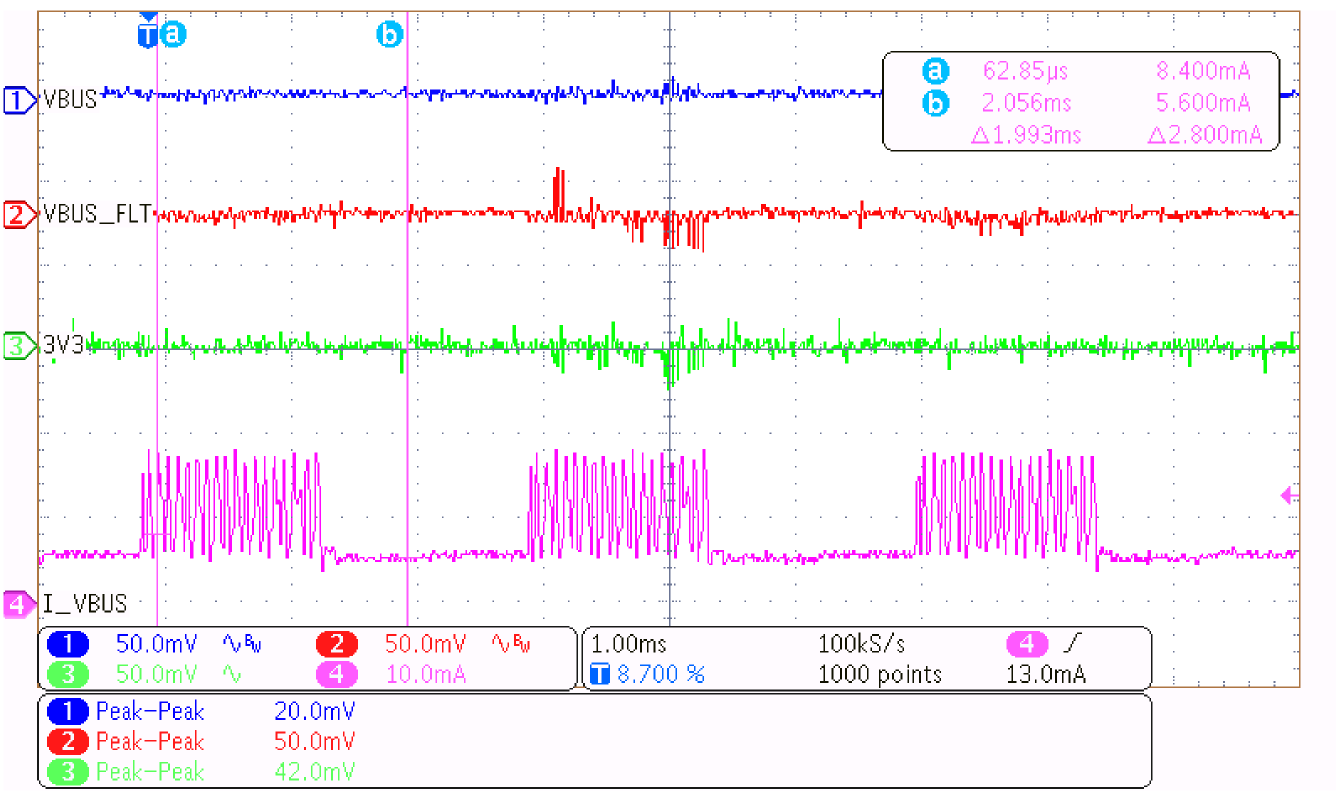


Figure 39. Power Data During LDC Measurement

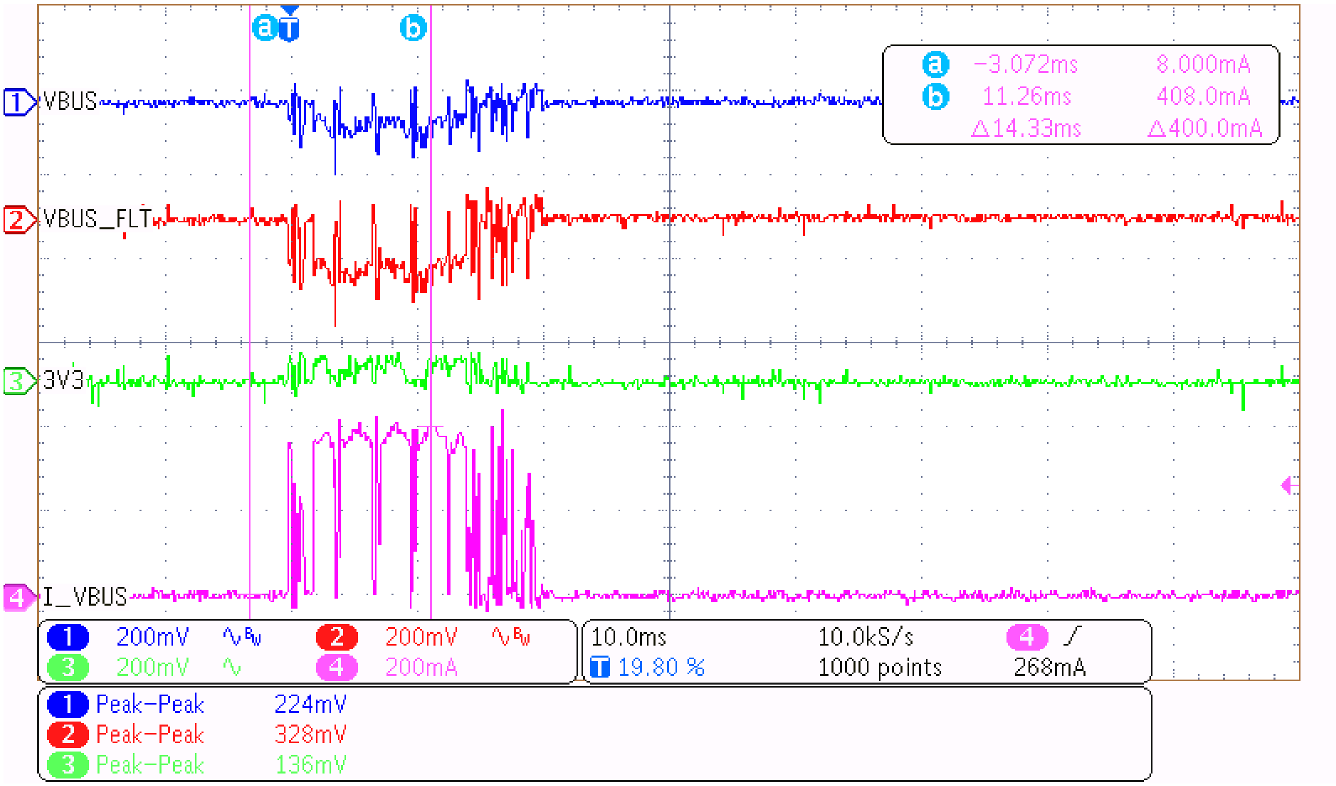


Figure 40. Power Data During Piezo Actuator Operation

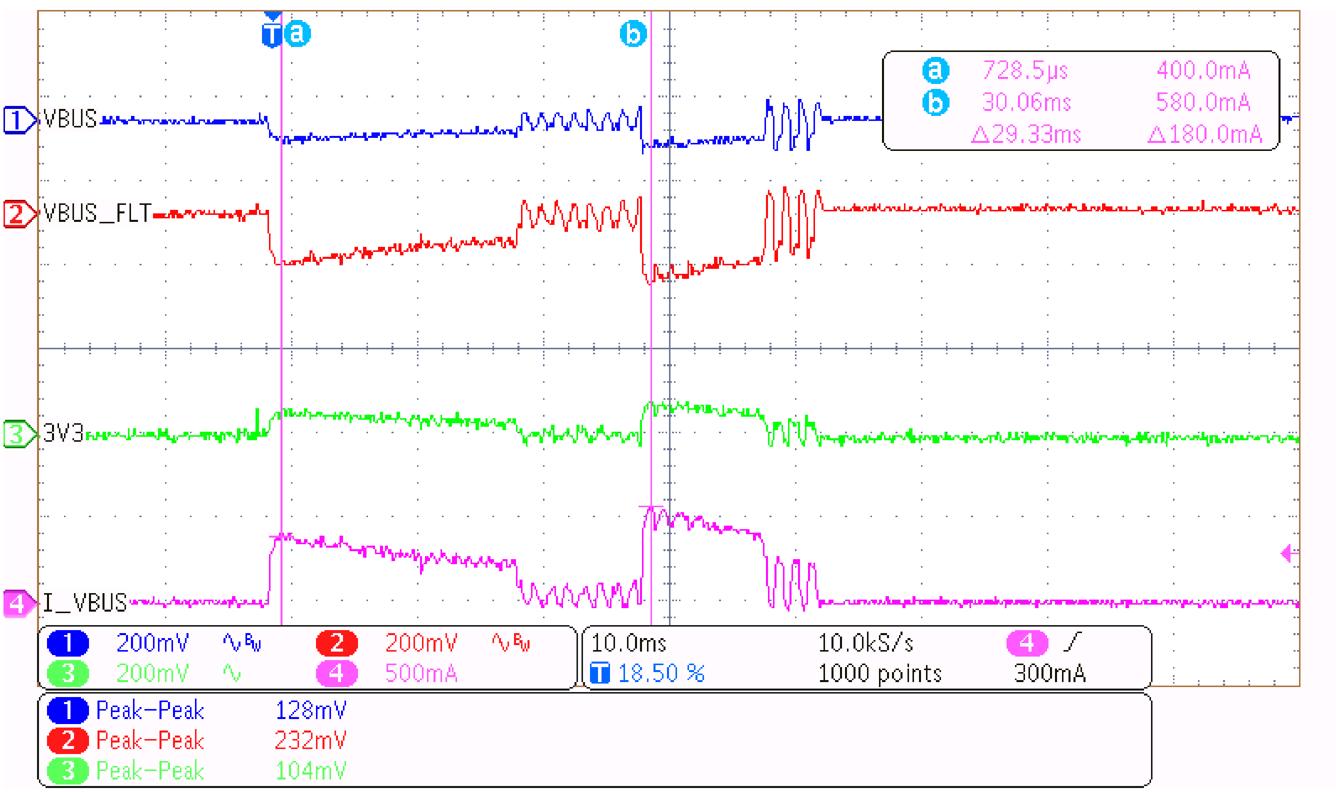


Figure 41. Power Data During ERM Actuator Operation

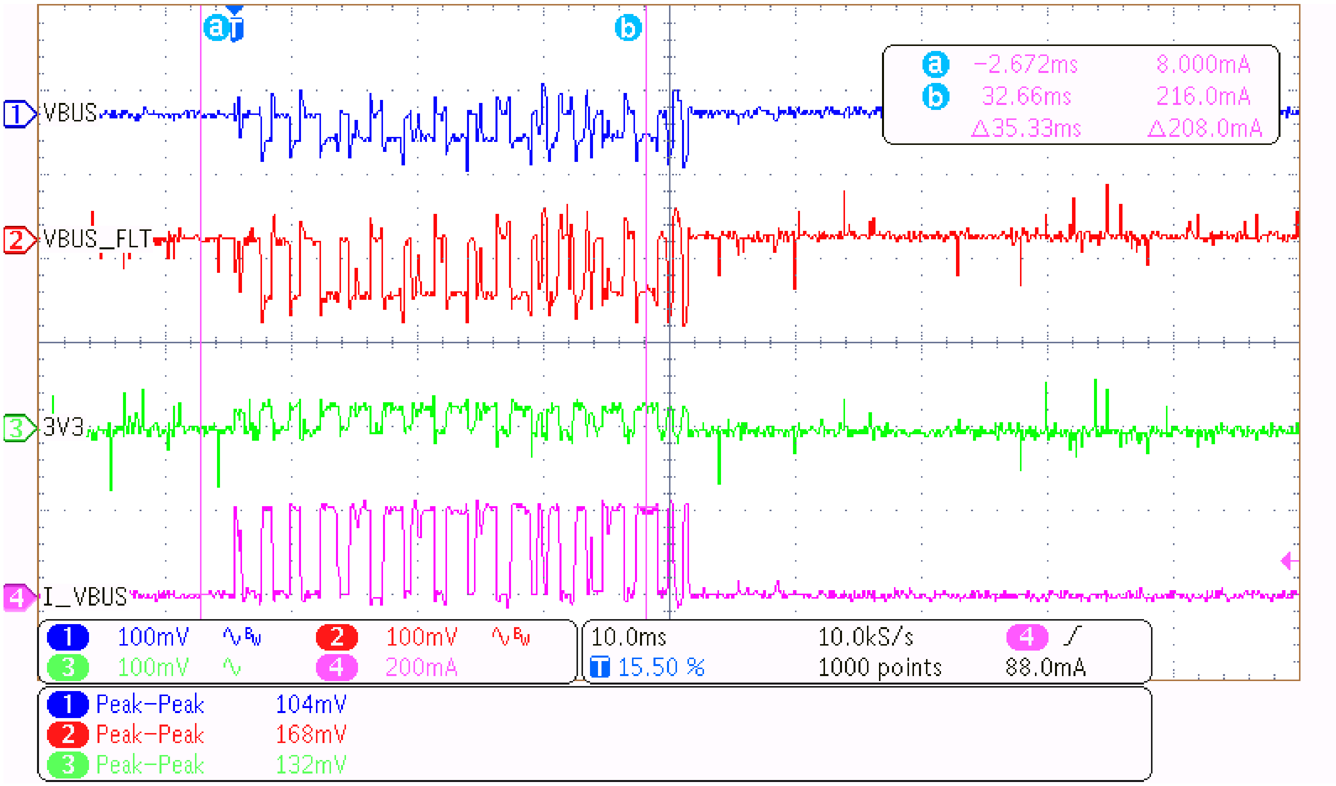


Figure 42. Power Data During LRA Actuator Operation

6.5 Water Droplet Characterization

A water droplet characterization was performed to test the performance of the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design performance when environmental contaminants cover the surface of the enclosure.

Several water droplets were placed on the enclosure using a water dropper, while the debug data was collected through a UART connection to a PC. No changes occurred in the output data before, during, or after the water droplet test.

This test result is easily explained because the LDC1614 works by generating a magnetic field, which only penetrates the aluminum enclosure to a specific skin depth. The skin depth for Equation 2 is:

$$\delta = \sqrt{\frac{\rho}{\pi \times f \times \mu}}$$

where

- δ = skin depth in m
- ρ = resistivity in Ω × m
- μ = permeability of the metal in H/m. (2)

Because the enclosure is made of aluminum, the permeability in Equation 3 is equal to:

$$\mu = 4\pi \times 10^{-7} \times 1.000022 = 1.256665 \times 10^{-6} \text{ H/m} \quad (3)$$

Furthermore, the resistivity of aluminum is equal to 28.2 nΩ × m at 20°C.

Because skin depth is maximized when operating frequency is minimized, the resonant frequency of the *Big* button L-C tank (1.8 MHz, see Table 7) yields the deepest skin depth.

Therefore, the deepest skin depth in this system is equal to:

$$\delta = \sqrt{\frac{28.2 \times 10^{-9}}{\pi \times 1.8 \times 10^{6} \times 1.256665 \times 10^{-6}}} = 62.995\mu m \quad (4)$$

Because the aluminum enclosure is 1 mm thick, even the magnetic field of the *Big* button channel does not penetrate the top half of the enclosure completely. Therefore, water droplets, dust, grease, or any other contaminant does not affect the LDC1614 measurements, unless they are heavy enough to physically flex the aluminum enclosure.

6.6 Temperature Characterization

Because the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design relies on the LDC1614 device output to determine if a button has been pressed, the output of the LDC1614 device must be characterized over the expected operating temperature range.

To better understand how the TI Design system responds to varying temperatures, the hardware was placed in a TestEquity 1007H Temperature/Humidity Chamber (http://www.testequity.com/products/1104/) with power and UART connections routed outside the chamber to a PC for data collection, as Figure 43 shows. The temperature was then set to 25°C and soaked until the HDC1010 reading settled. The LDC1614 device output data was then recorded for one minute. The temperature was then incrementally increased up to 70°C, then incrementally decreased to –20°C, and finally incrementally increased back to 25°C.

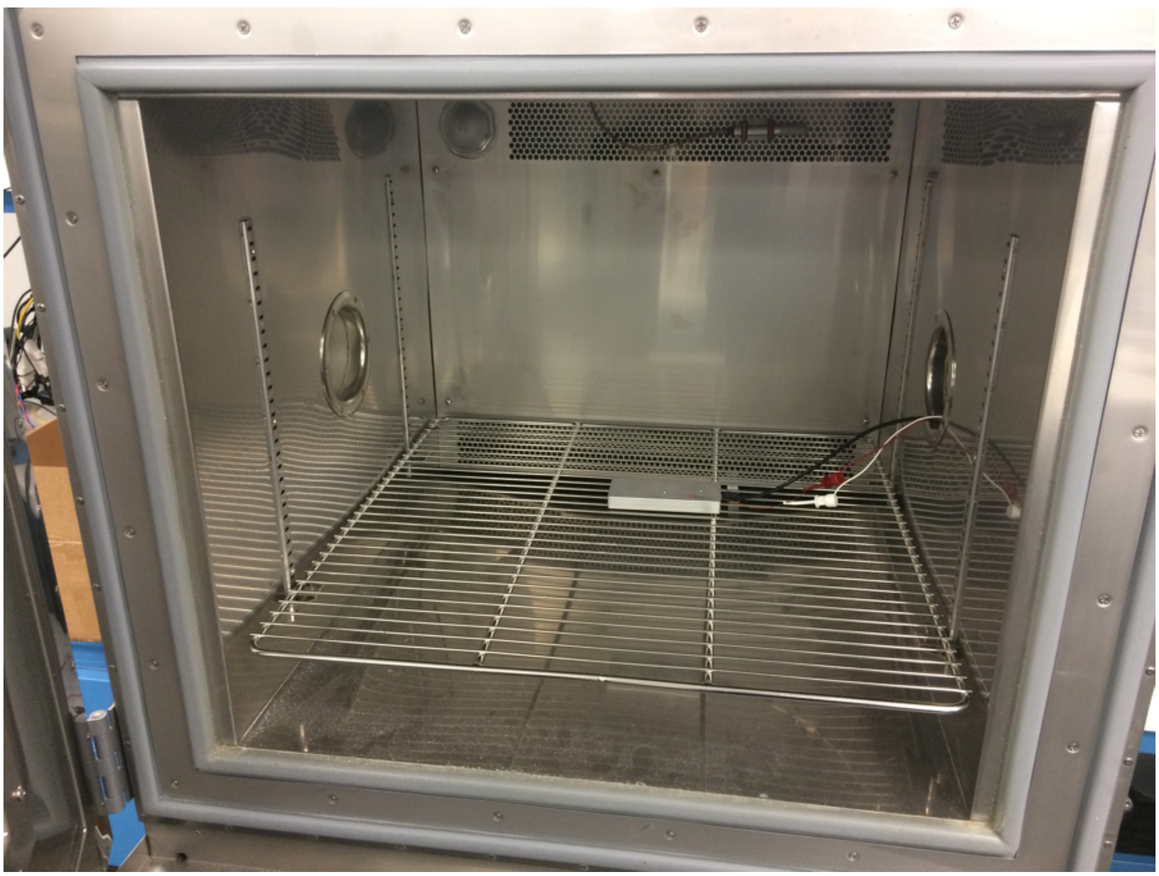


Figure 43. Temperature and Relative Humidity Test Setup

Figure 44 shows the LDC1614 device output for all four channels over the tested temperature range. Although the outputs do change over temperature, the changes are linear and change by less than ±1% over the entire tested temperature range.

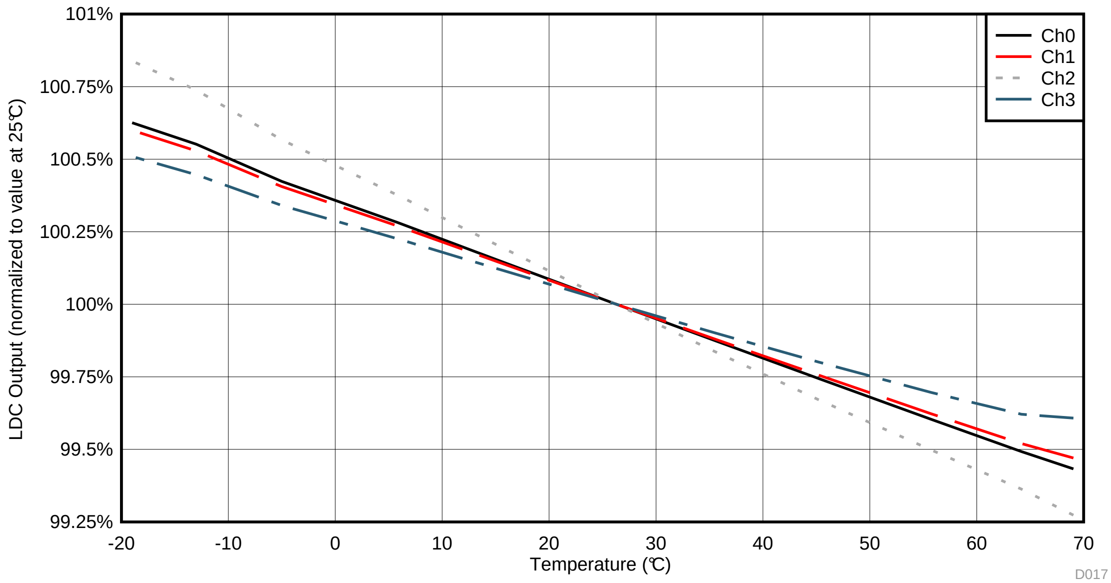


Figure 44. LDC1614 Data Over Temperature—All Channels

As discussed in Section 4.3 *Environmental Compensation Using Firmware Techniques*, this TI Design system does not implement any separate temperature compensation, as the IIR filter-based, slow-moving average accounts for any drift due to temperature. If the absolute value of the LDC1614 device output is critical to the end-user application, then separate compensation for temperature is required, either with a gain and offset linear compensation algorithm or a look-up table algorithm.

A “thermal shock” test was performed on this TI Design system to prove the robustness of the IIR filter-based, slow-moving average firmware technique. The system was placed in the TestEquity 1007H Temperature/Humidity Chamber with the temperature set to –20°C. Once the system settled at this temperature, the chamber was set to ramp up the temperature to 70°C as quickly as possible and then decreased back to –20°C as quickly as possible. Figure 45, Figure 46, Figure 47, and Figure 48 show the following for all four LDC1614 device channels: the chamber temperature over time, output data from the LDC1614 device, slow-moving average threshold, and the variable that flags whether or not a button press has been detected. The button-press detection flag equals 0 when no press is detected and 1 when a press is detected. This detection flag is set to 1 only if the LDC1614 device output data exceeds the slow moving average threshold.

Figure 45, Figure 46, Figure 47, and Figure 48 show no button press detections for all four LDC1614 device channels over the entire tested temperature range, proving that the slow-moving average algorithm successfully compensates for temperature variations. The performance of the algorithm is shown by the ChX Button Press? (blue dots) data trace being equal to 0 during the entire duration of the test, indicating no false button press detections.

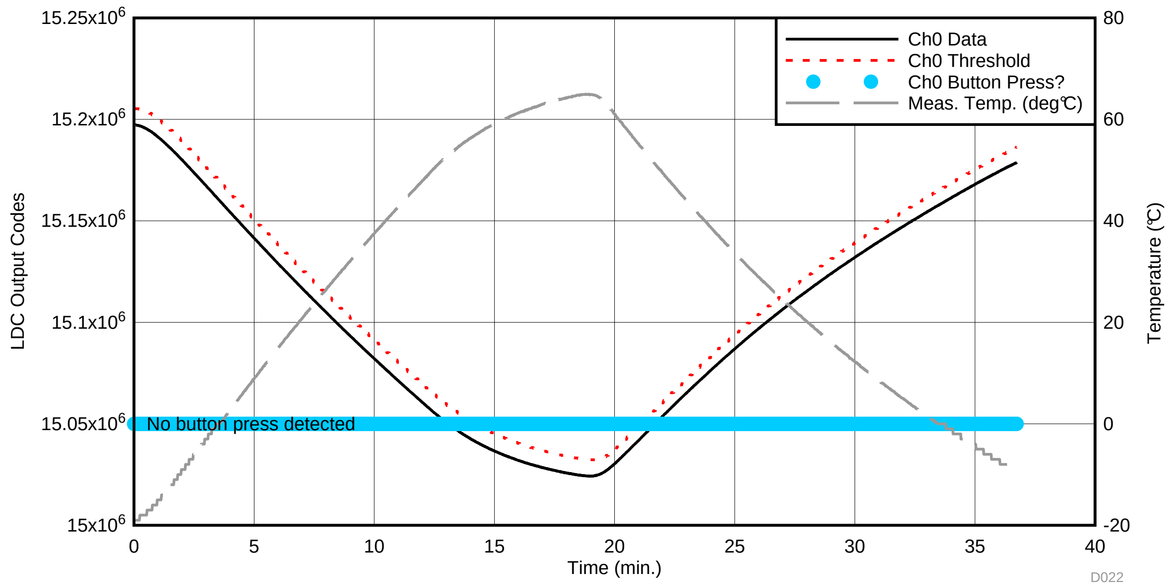


Figure 45. LDC Ch0 Data During Thermal "Shock" Test—*Down* Button Channel

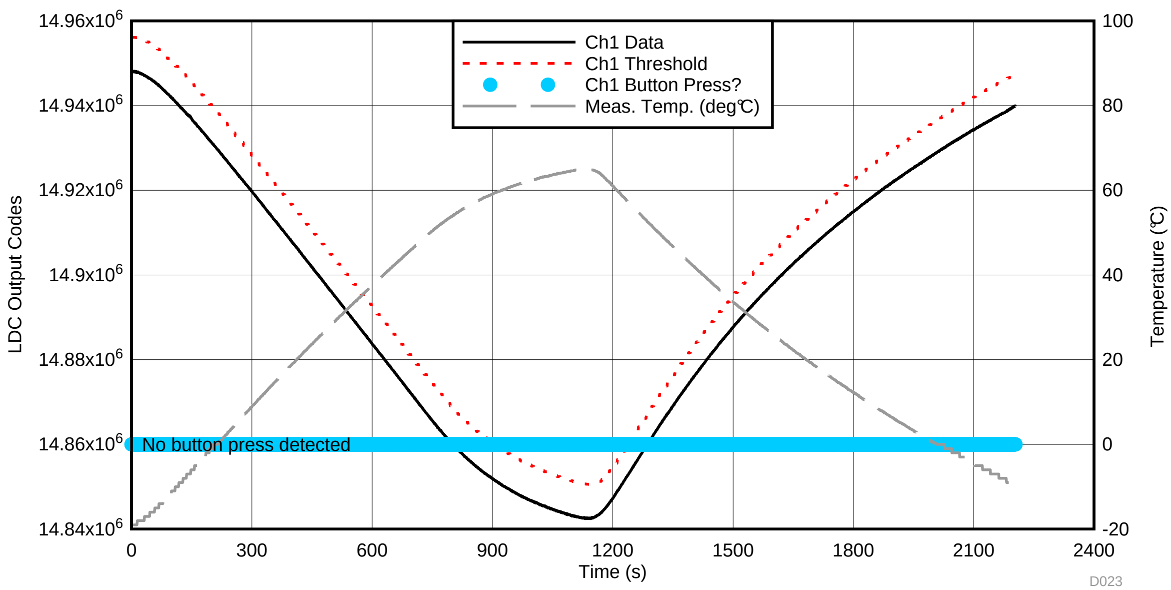


Figure 46. LDC Ch1 Data During Thermal "Shock" Test—*Up* Button Channel

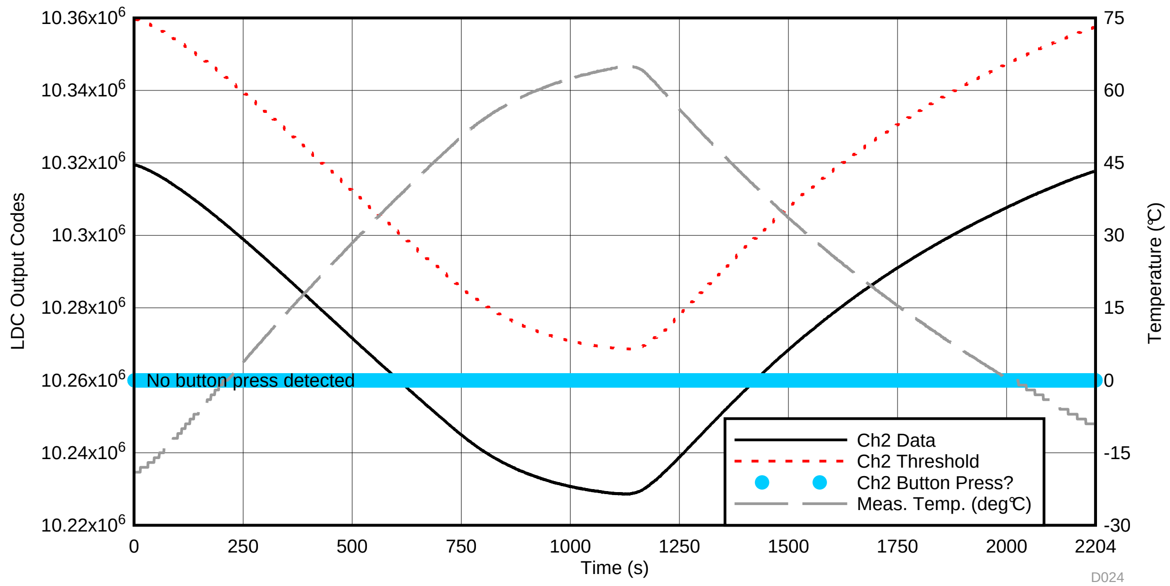


Figure 47. LDC Ch2 Data During Thermal "Shock" Test—*Big* Button Channel

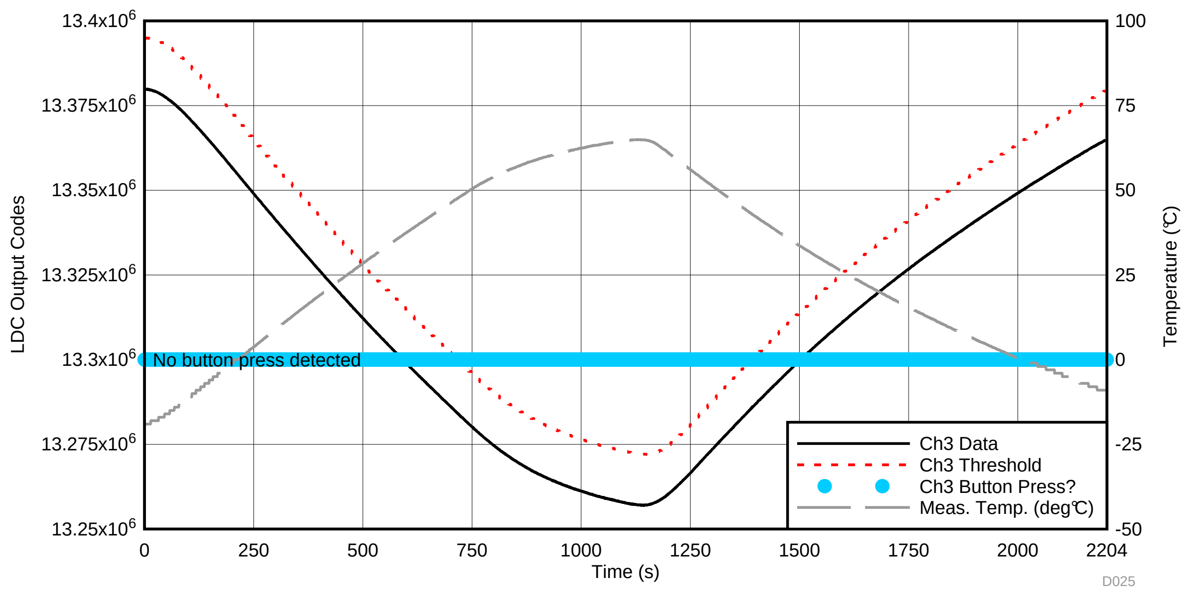


Figure 48. LDC Ch3 Data During Thermal "Shock" Test—*Little* Button Channel

6.7 Humidity Characterization

Because the *Touch on Metal Buttons with Integrated Haptic Feedback* TI Design relies on the LDC1614 device output to determine if a button has been pressed, the output of the LDC1614 device must be characterized over the expected operating relative humidity range.

To better understand how the TI Design system responds to varying relative humidity levels, the hardware was placed in a TestEquity 1007H Temperature/Humidity Chamber with the power and UART connections routed outside the chamber to a PC for data collection, as Figure 43 shows. The relative humidity level was then set to 20% and soaked until the HDC1010 reading settled. The LDC1614 device output data was then recorded for one minute. The relative humidity was then incrementally increased up to 80% and then incrementally decreased back to 20%.

Figure 49 shows the LDC1614 device output for all four channels over the tested relative humidity range. Although the outputs do change over relative humidity levels, the variations are very slight and change by less than ±0.05% over the entire tested relative humidity range. If the absolute value of the LDC1614 output data is critical to the end-equipment system, the variation due to humidity is easily correctable in firmware by implementing a gain and offset linear compensation algorithm or a look-up table algorithm.

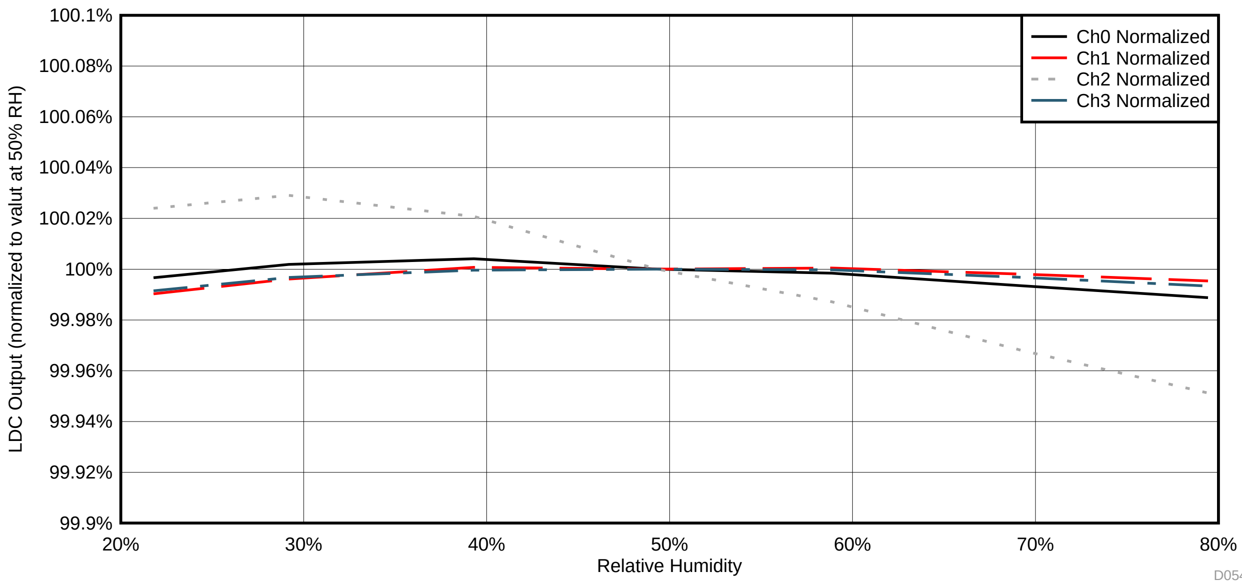


Figure 49. LDC1614 Data Over Relative Humidity—All Channels

A “relative humidity shock” test was performed on this TI design system to prove the robustness of the IIR filter-based, slow-moving average firmware technique. The system was placed in the TestEquity 1007H Temperature/Humidity Chamber with the humidity level set to 20%. Once the system settled at this relative humidity level, the chamber was set to ramp up the relative humidity to 80% as quickly as possible and then decreased back to 20% as quickly as possible. Figure 50, Figure 51, Figure 52, and Figure 53 show the following for all four LDC1614 device channels: chamber relative humidity over time, output data from the LDC1614 device, slow-moving average threshold, and the variable that flags whether or not a button press has been detected. The button-press detection flag equals 0 when no press is detected and 1 when a press is detected. This detection flag is set to 1 only if the LDC1614 device output data exceeds the slow moving average threshold.

Figure 50, Figure 51, Figure 52, and Figure 53 show no button press detections for all four LDC1614 device channels over the entire tested relative humidity range, proving that the slow-moving average algorithm successfully compensates for temperature variations. The performance of the algorithm is shown by the ChX Button Press? (blue dots) data trace being equal to 0 during the entire duration of the test, indicating no false button press detections.

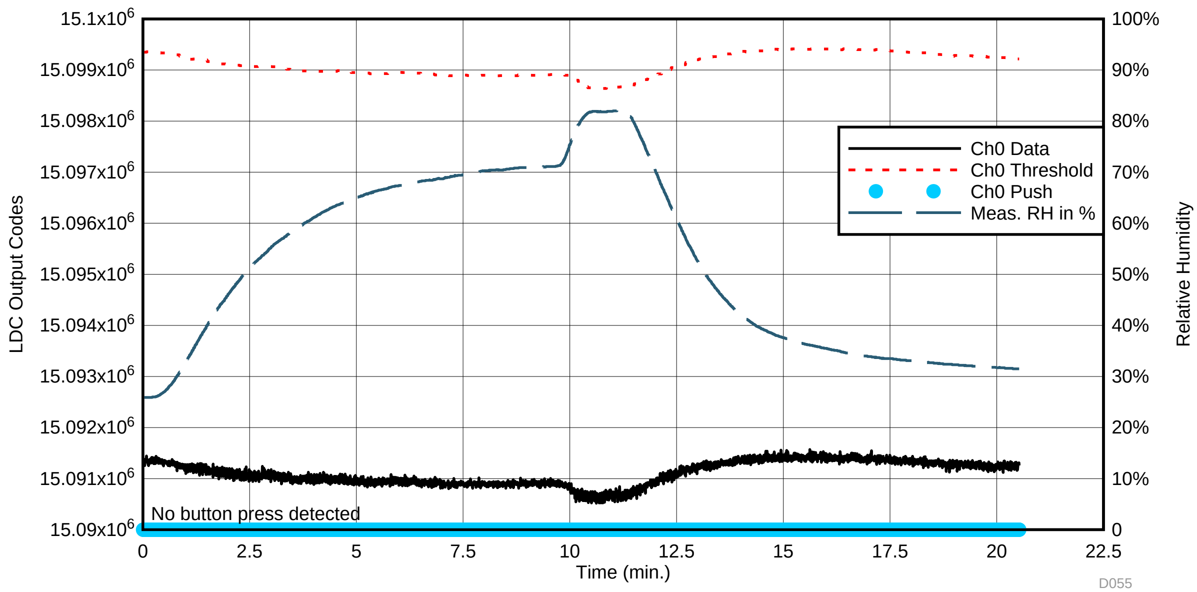


Figure 50. LDC Ch0 Data During Relative Humidity "Shock" Test—*Down* Button Channel

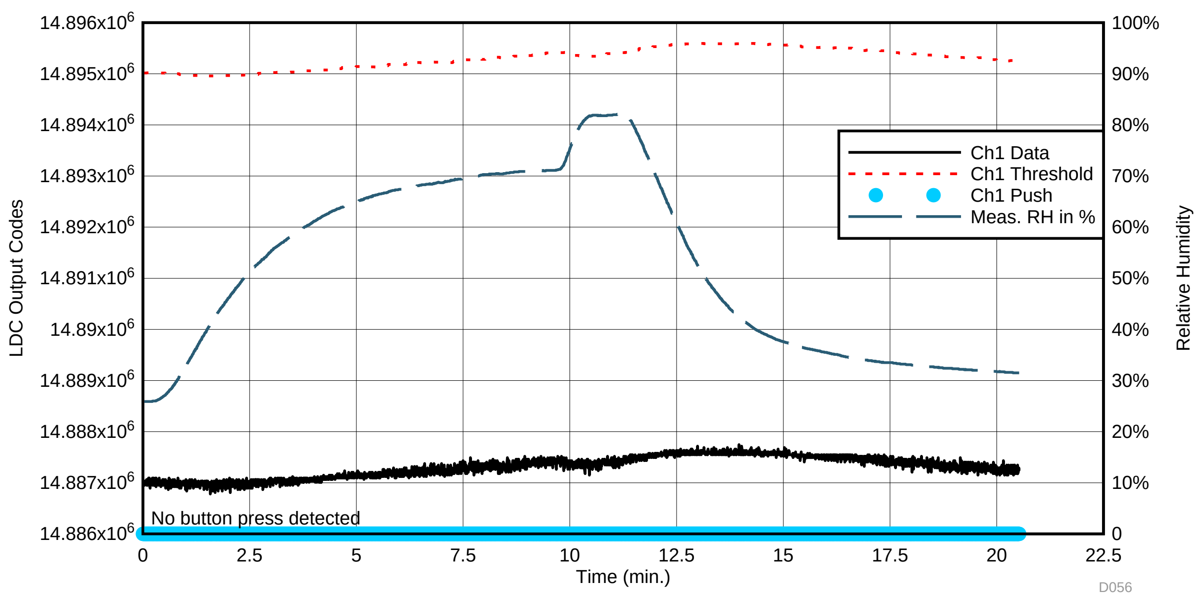


Figure 51. LDC Ch1 Data During Relative Humidity "Shock" Test—*Up* Button Channel

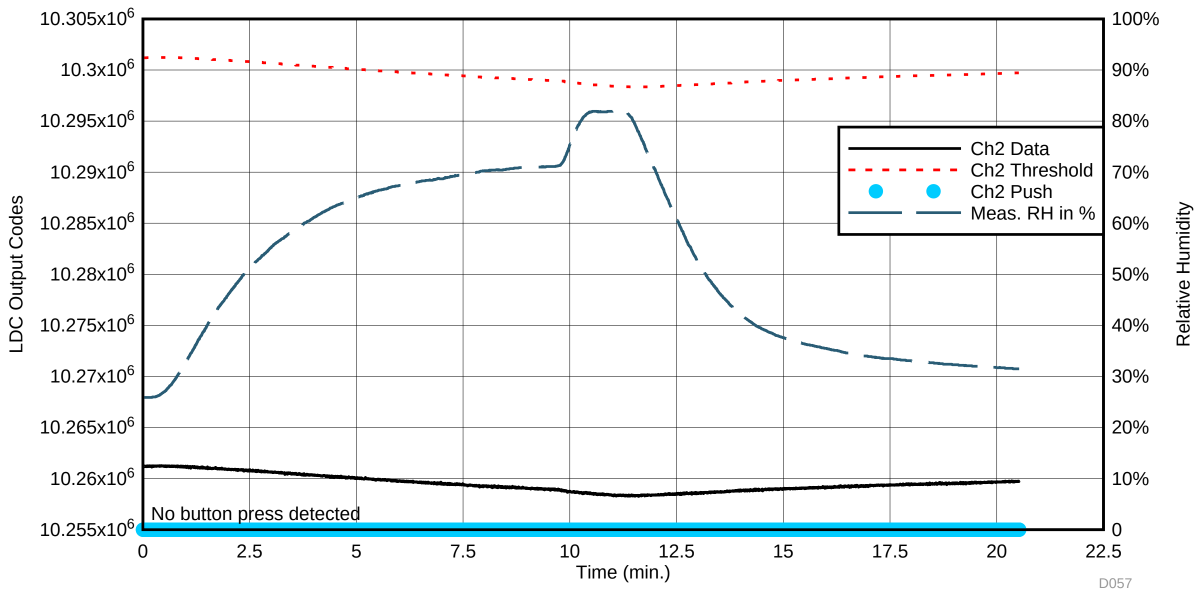


Figure 52. LDC Ch2 Data During Relative Humidity "Shock" Test—*Big* Button Channel

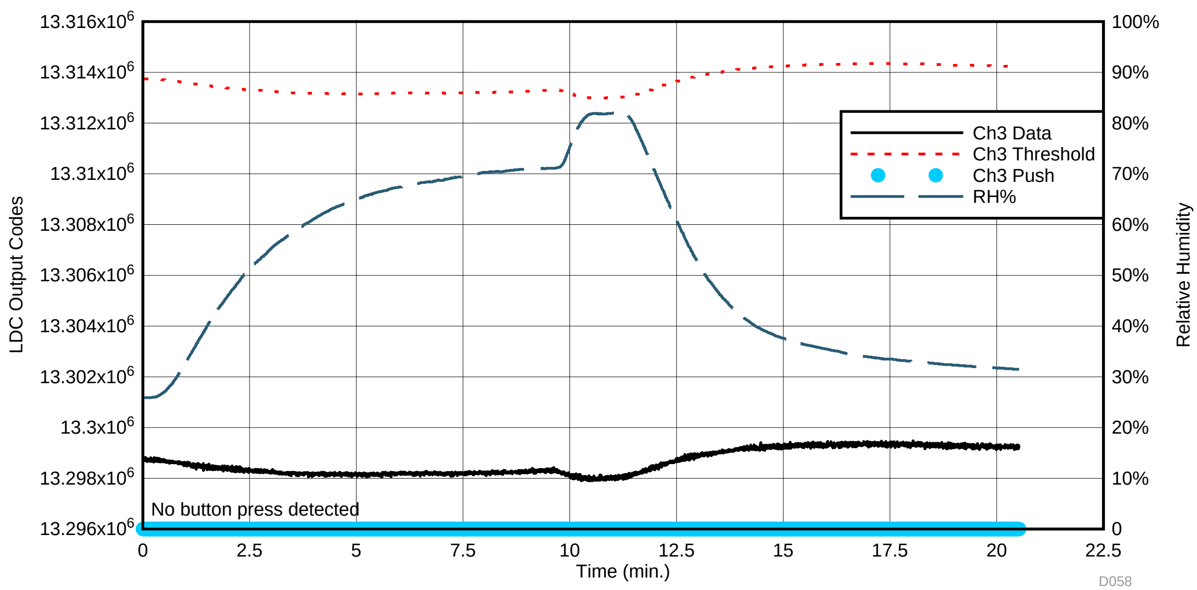


Figure 53. LDC Ch3 Data During Relative Humidity "Shock" Test—*Little* Button Channel

6.8 EMI Protection Performance

The *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design was characterized through pre-compliance and engineering tests for ESD, radiated immunity, EFT, surge, and conducted immunity performance. Each test was accorded a pass criteria rating, according to the definitions found in Table 10.

Table 10. Criteria and Performance as Per IEC61131-2

CRITERIA	PERFORMANCE (PASS) CRITERIA
A	The system continues to operate as intended with no loss of function or performance, even during the test.
B	Temporary degradation of performance is accepted. After the test, the system continues to operate as intended without manual intervention.
C	During the test, loss of functions is accepted, but no destruction of hardware or software. After the test, the system must continue to operate as intended automatically, after a manual restart, powering off, or powering on.

6.8.1 IEC 61000-4-2 (ESD) Performance

For the IEC 61000-4-2 pre-compliance test, the system was powered and all four channels of the LDC1614 device output data, slow-moving average threshold, button-press detection flag, as well as the temperature and humidity data were recorded through a UART stream before, during, and after the test conditions were applied. Figure 54 shows the setup for ESD testing.

Figure 54. IEC 61000-4-2 ESD Test Setup

The TI Design system performed as expected, with a class A passing criteria on all ESD tests, as the following Table 11 shows.

Table 11. IEC 61000-4-2 (ESD) Test Results

IEC 61000-4-2 (ESD) TEST CONDTION	RESULT(1)
±4-kV vertical coupling plane	A
±4-kV horizontal coupling plane	A
±4-kV contact discharge on aluminum enclosure	A
±8-kV air discharge above aluminum enclosure	A

(1) See Table 10 for details.

6.8.2 IEC 61000-4-3 (Radiated Immunity) Performance

For the IEC 61000-4-3 pre-compliance test, the system was powered and all four channels of the LDC1614 device output data, slow-moving average threshold, button-press detection flag, as well as the temperature and humidity data were recorded through a UART stream before, during, and after the test conditions were applied. Figure 55 and Figure 56 show the setup for radiated immunity testing.

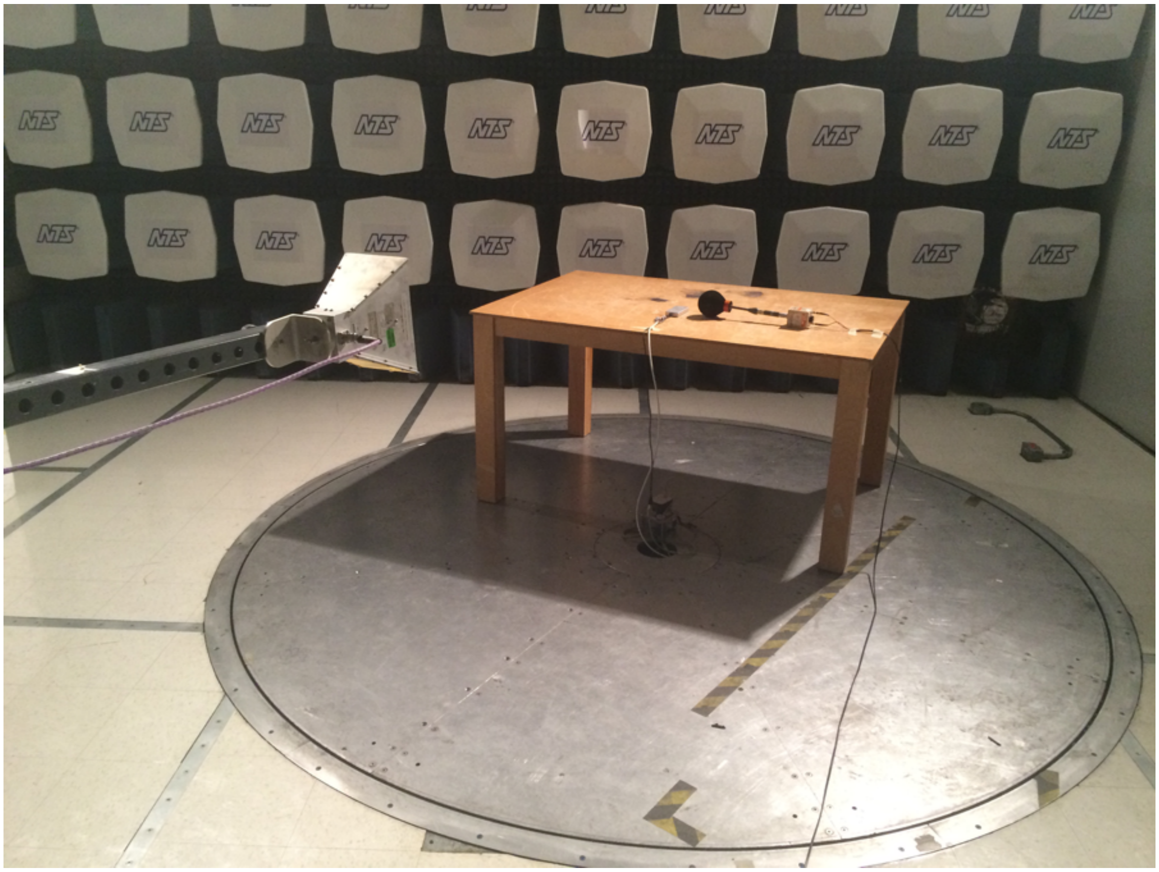


Figure 55. IEC 61000-4-3 Radiated Immunity Test Setup

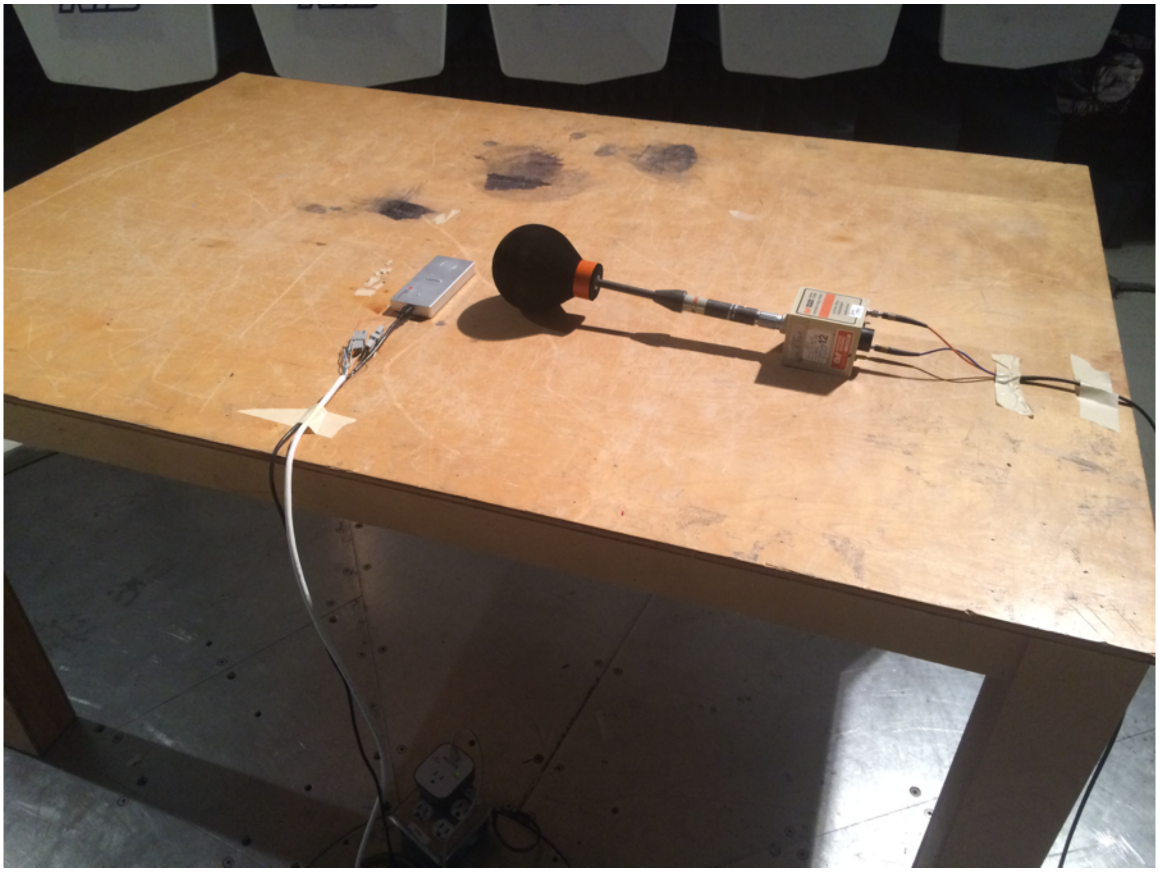


Figure 56. IEC 61000-4-3 Radiated Immunity Test Setup

The system was tested over the standard high-frequency range of 80 MHz to 2.7 GHz at a field strength of 3 V/m. The system output data during this test is shown in the figures listed in Table 12.

A slow drift and some noise in the data are shown in some of the figures as the noise frequency was swept from 80 MHz to 2.7 GHz. However, the IIR filter-based, slow-moving average feature of the TI Design eliminates any false triggering of the system. As is shown in the figures below, the LDC1614 device output never exceeds the slow-moving average threshold, resulting in no false button-press detections and proving a resilience to radiated immunity effects.

The TI Design system performed as expected, with a class A passing criteria on all radiated immunity tests, as Table 12 shows below.

Table 12. IEC 61000-4-3 (Radiated Immunity) Test Results

IEC 61000-4-3 (RADIATED IMMUNITY) TEST CONDTION	RESULT(1)
80 MHz to 1 GHz (horizontal polarization)	A (see Figure 57, Figure 58, Figure 59, and Figure 60)
80 MHz to 1 GHz (vertical polarization)	A (see Figure 60, Figure 62, Figure 63, and Figure 64)
1 GHz to 2.7 GHz (horizontal polarization)	A (see Figure 64, Figure 66, Figure 67, and Figure 68)
1 GHz to 2.7 GHz (vertical polarization)	A (see Figure 69, Figure 70, Figure 71, and Figure 72)

(1) See Table 10 for details.

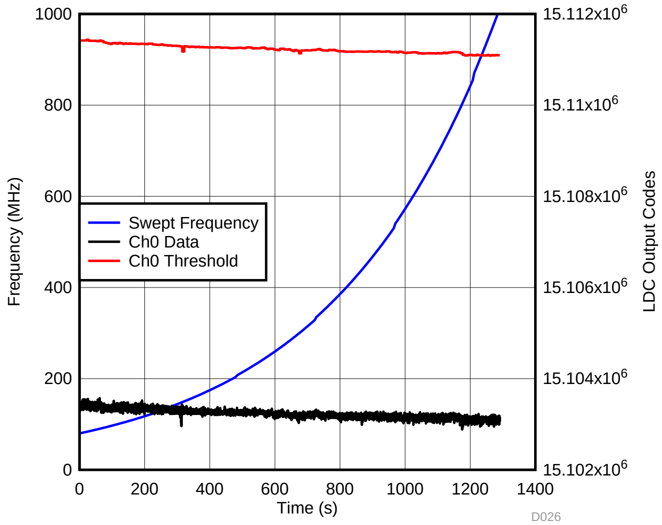


Figure 57. LDC Ch0 Data During Radiated Immunity (80 MHz – 1 GHz, Horizontal Polarization) Test—*Down* Button Channel

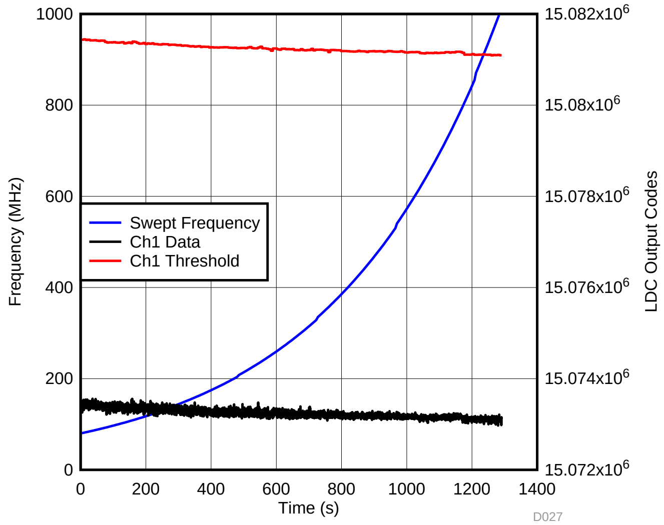


Figure 58. LDC Ch1 Data During Radiated Immunity (80 MHz – 1 GHz, Horizontal Polarization) Test—*Up* Button Channel

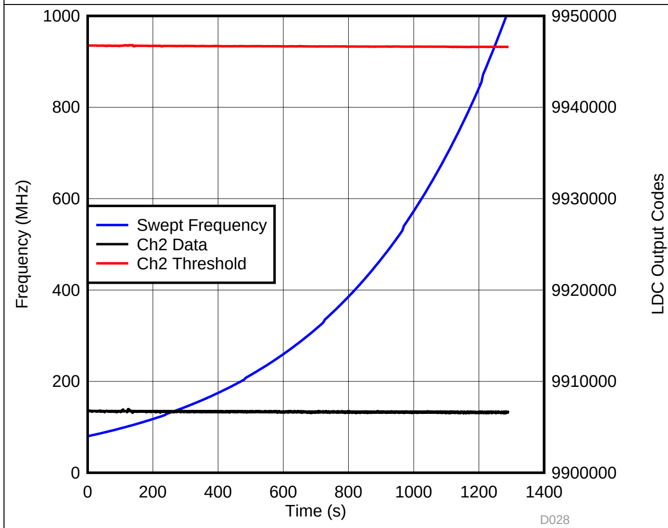


Figure 59. LDC Ch2 Data During Radiated Immunity (80 MHz – 1 GHz, Horizontal Polarization) Test—*Big* Button Channel

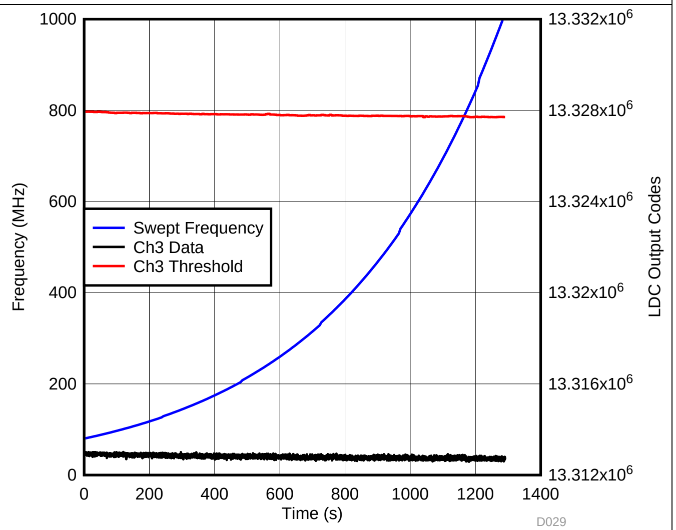


Figure 60. LDC Ch3 Data During Radiated Immunity (80 MHz – 1 GHz, Horizontal Polarization) Test—*Little* Button Channel

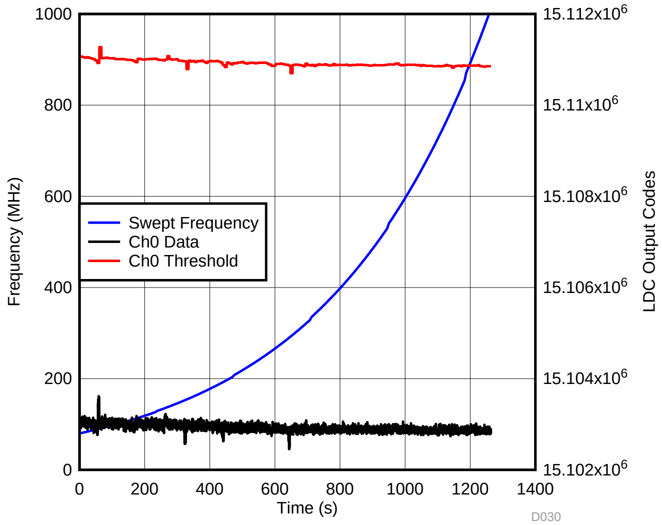


Figure 61. LDC Ch0 Data During Radiated Immunity (80 MHz – 1 GHz, Vertical Polarization) Test—*Down* Button Channel

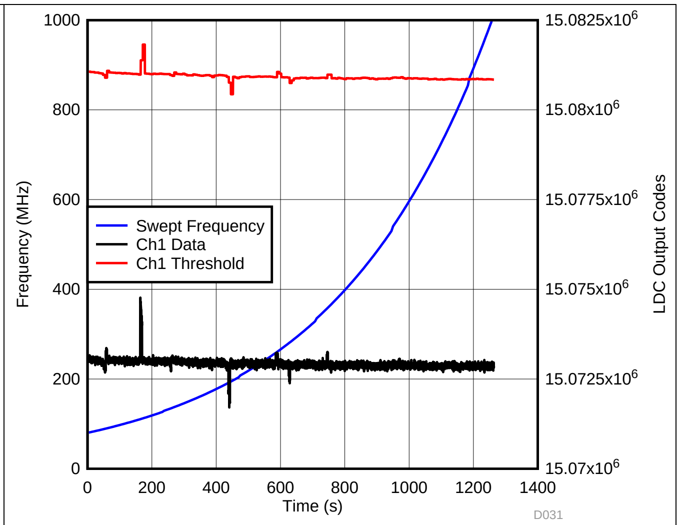


Figure 62. LDC Ch1 Data During Radiated Immunity (80 MHz – 1 GHz, Vertical Polarization) Test—*Up* Button Channel

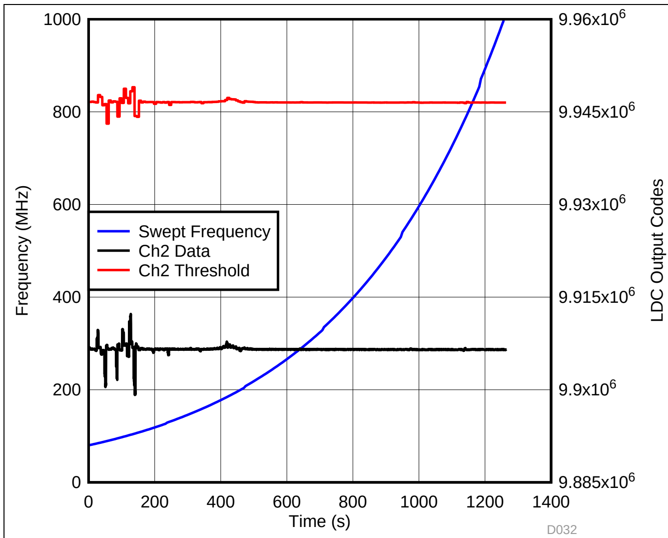


Figure 63. LDC Ch2 Data During Radiated Immunity (80 MHz – 1 GHz, Vertical Polarization) Test—*Big* Button Channel

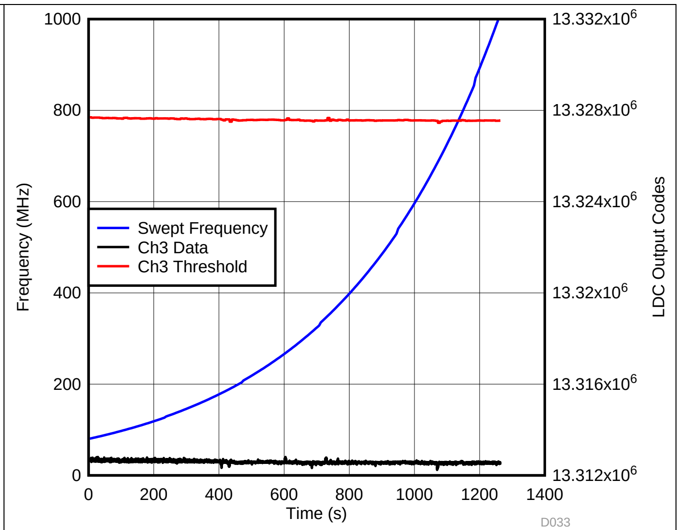


Figure 64. LDC Ch3 Data During Radiated Immunity (80 MHz – 1 GHz, Vertical Polarization) Test—*Little* Button Channel

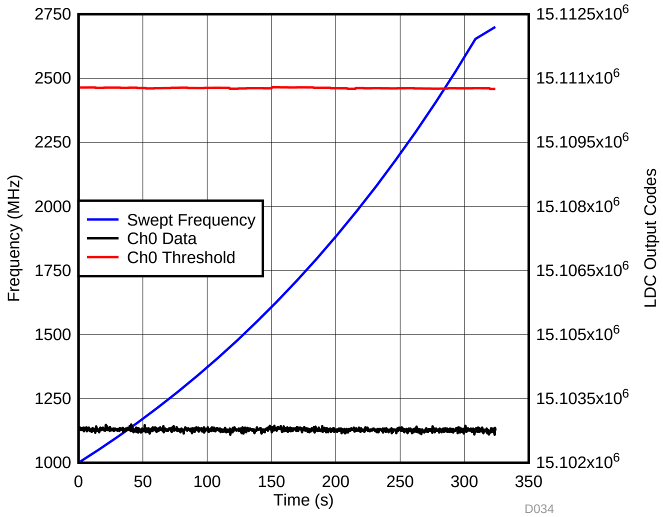


Figure 65. LDC Ch0 Data During Radiated Immunity (1 GHz – 2.7 GHz, Horizontal Polarization) Test—*Down* Button Channel

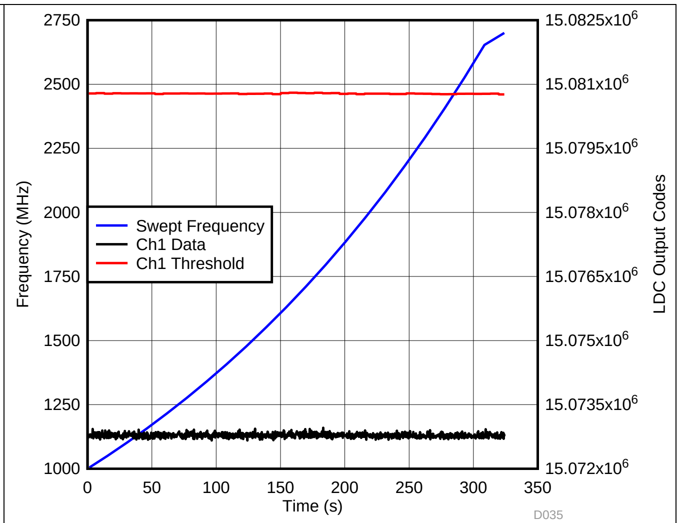


Figure 66. LDC Ch1 Data During Radiated Immunity (1 GHz – 2.7 GHz, Horizontal Polarization) Test—*Up* Button Channel

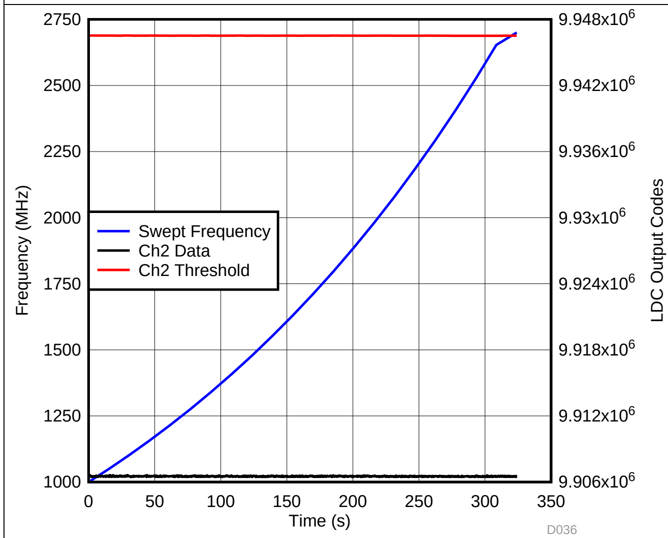


Figure 67. LDC Ch2 Data During Radiated Immunity (1 GHz – 2.7 GHz, Horizontal Polarization) Test—*Big* Button Channel

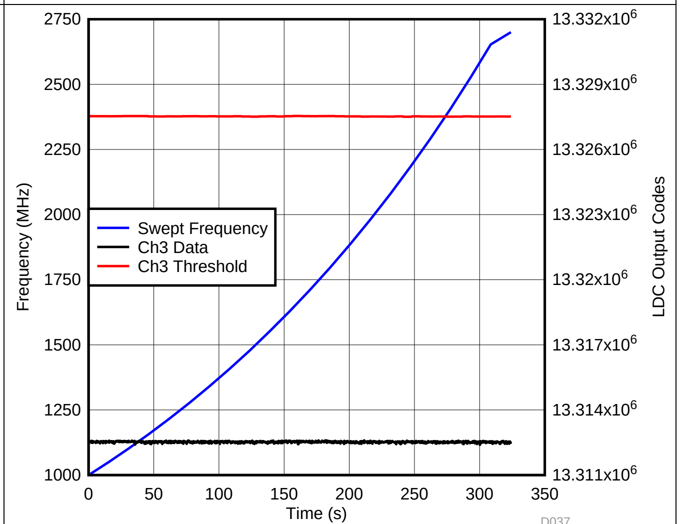


Figure 68. LDC Ch3 Data During Radiated Immunity (1 GHz – 2.7 GHz, Horizontal Polarization) Test—*Little* Button Channel

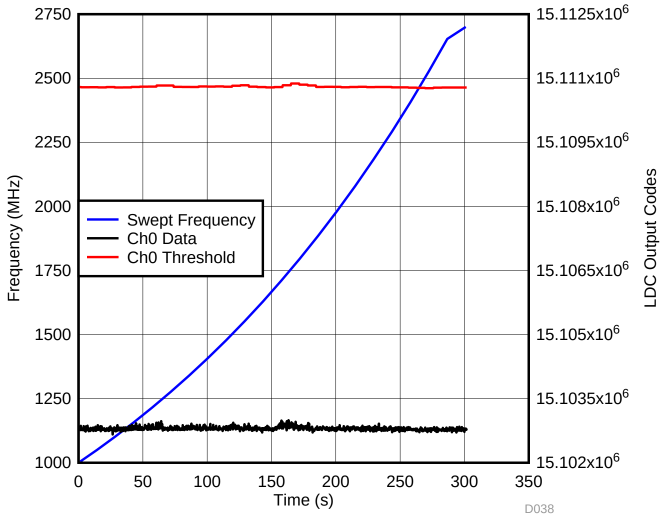


Figure 69. LDC Ch0 Data During Radiated Immunity (1 GHz – 2.7 GHz, Vertical Polarization) Test—*Down* Button Channel

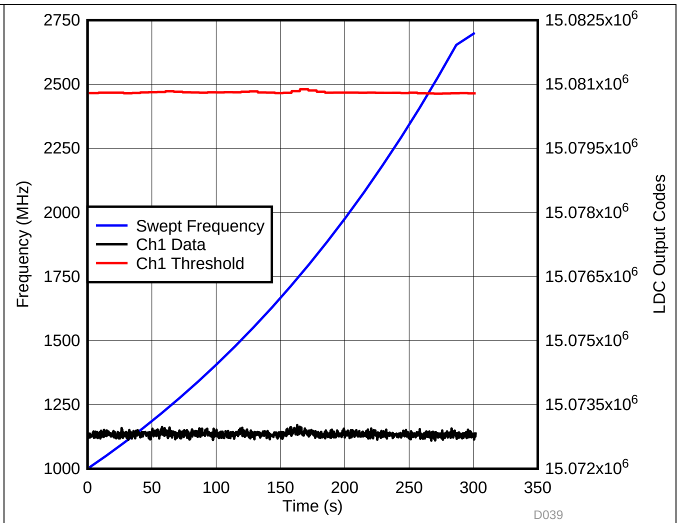


Figure 70. LDC Ch1 Data During Radiated Immunity (1 GHz – 2.7 GHz, Vertical Polarization) Test—*Up* Button Channel

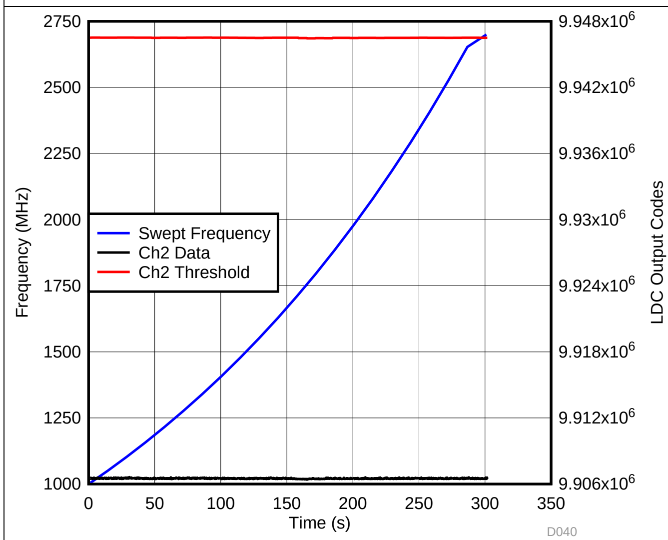


Figure 71. LDC Ch2 Data During Radiated Immunity (1 GHz – 2.7 GHz, Vertical Polarization) Test—*Big* Button Channel

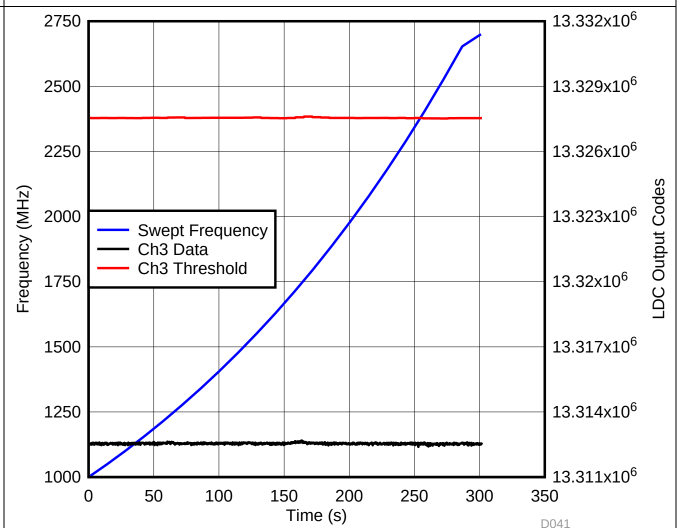


Figure 72. LDC Ch3 Data During Radiated Immunity (1 GHz – 2.7 GHz, Vertical Polarization) Test—*Little* Button Channel

6.8.3 IEC 61000-4-4 (EFT) Performance

For the IEC 61000-4-4 pre-compliance test, the system was powered and all four channels of the LDC1614 device output data, slow-moving average threshold, button-press detection flag, as well as the temperature and humidity data were recorded through a UART stream before, during, and after the test conditions were applied. Figure 73 shows the setup for EFT testing.

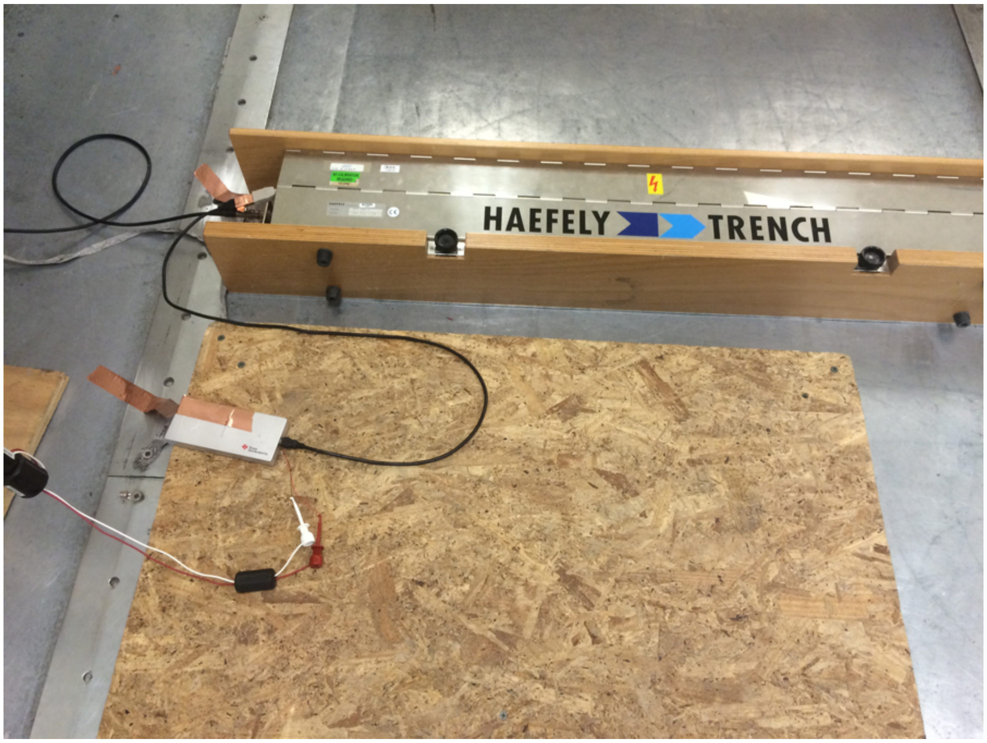


Figure 73. IEC 61000-4-4 EFT Test Setup

The system was tested over the standard test levels of ±0.5 kV, ±1.0 kV, and ±2.0 kV. The aluminum chassis of the TI Design system was connected to earth ground by means of copper tape. Ferrite beads were used to keep the UART debugging data from corrupting.

The TI Design system performed as expected, with a class A passing criteria on all EFT tests, as the following Table 13 shows. The output data plots are not shown to be concise because there were no significant noise artifacts measured.

Table 13. IEC 61000-4-4 (EFT) Test Results

IEC 61000-4-4 (EFT) TEST CONDITION	RESULT(1)
±0.5 kV (on USB power cable)	A
±1.0 kV (on USB power cable)	A
±2.0 kV (on USB power cable)	A

(1) See Table 10 for details.

6.8.4 EC 61000-4-5 (Surge) Performance

For the IEC 61000-4-5 pre-compliance test, the system was powered and all four channels of the LDC1614 device output data, slow-moving average threshold, button-press detection flag, as well as the temperature and humidity data were recorded through a UART stream before, during, and after the test conditions were applied. Figure 74 shows the setup for surge testing.

Figure 74. IEC 61000-4-5 Surge Test Setup

The system was tested at the standard test level of ±0.5 kV. The aluminum chassis of the TI Design system was connected to earth ground by means of copper tape. Ferrite beads were used to keep the UART debugging data from corrupting.

The TI Design system performed as expected, with a class A passing criteria on all surge tests, as the following Table 14 shows. To be concise, and because the VBUS to GND test conditions represent the worst case scenario, only the output data plots for that test condition are shown.

Table 14. IEC 61000-4-5 (Surge) Test Results

IEC 61000-4-5 (SURGE) TEST CONDITION	RESULT[(1)]
+0.5 kV (from GND to earth)	A
-0.5 kV (from GND to earth)	A
+0.5 kV (from VBUS to earth)	A
-0.5 kV (from VBUS to earth)	A
+0.5 kV (from VBUS to GND)	A (see Figure 75, Figure 76, Figure 77, and Figure 78)
-0.5 kV (from VBUS to GND)	A (see Figure 79, Figure 80, Figure 81, and Figure 82)

(1) See Table 10 for details.

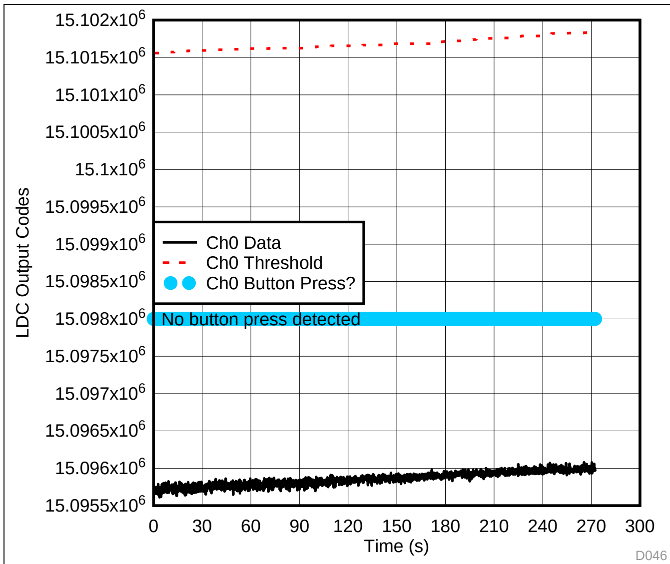


Figure 75. LDC Ch0 Data During Surge (+0.5 kV, From VBUS to GND) Test—*Down* Button Channel

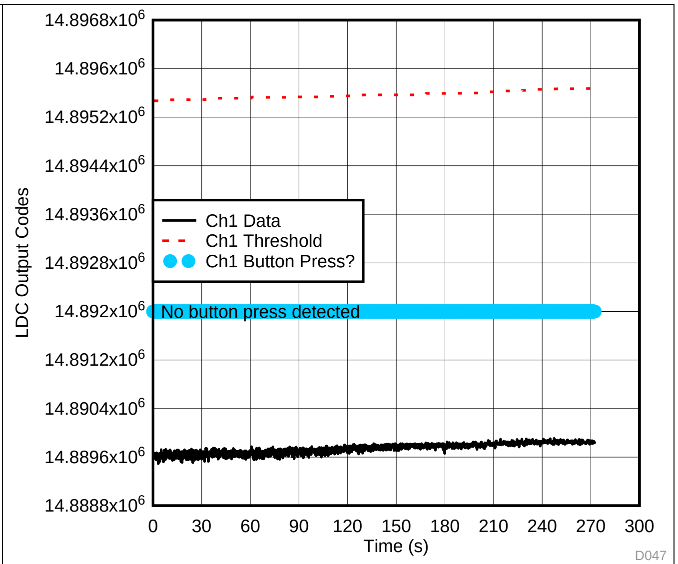


Figure 76. LDC Ch1 Data During Surge (+0.5 kV, From VBUS to GND) Test—*Up* Button Channel

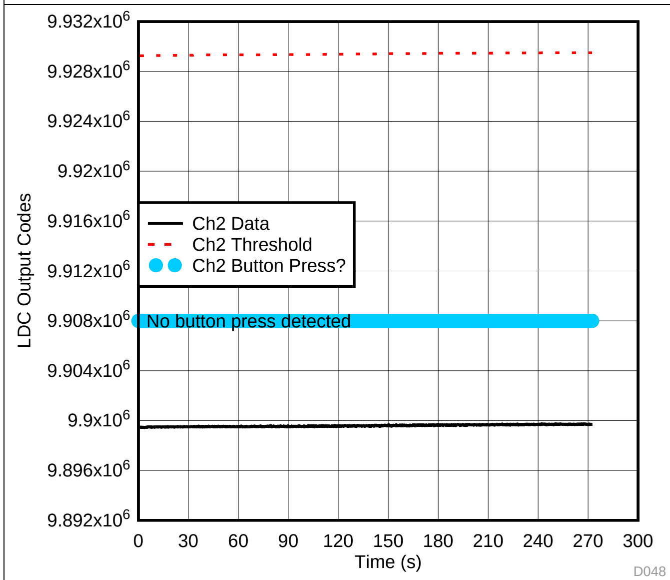


Figure 77. LDC Ch2 Data During Surge (+0.5 kV, From VBUS to GND) Test—*Big* Button Channel

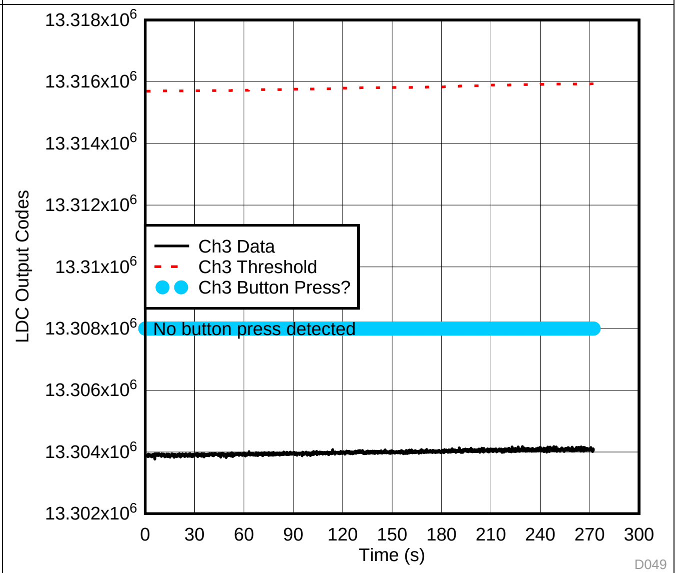


Figure 78. LDC Ch3 Data During Surge (+0.5 kV, From VBUS to GND) Test—*Little* Button Channel

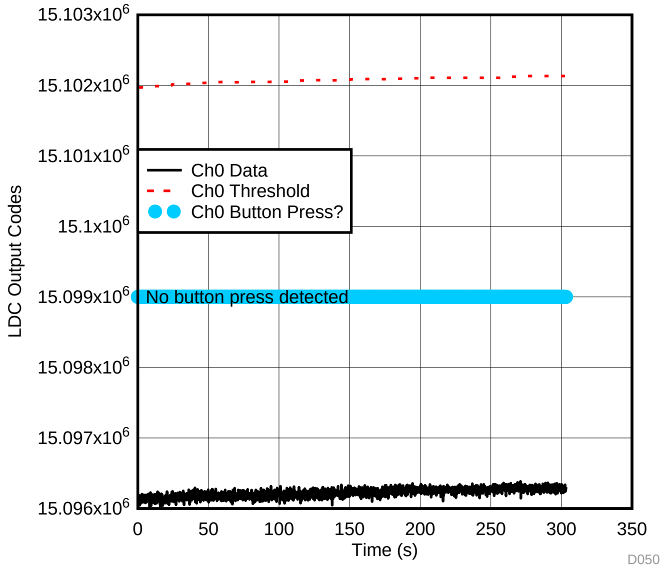


Figure 79. LDC Ch0 Data During Surge (–0.5 kV, From VBUS to GND) Test—*Down* Button Channel

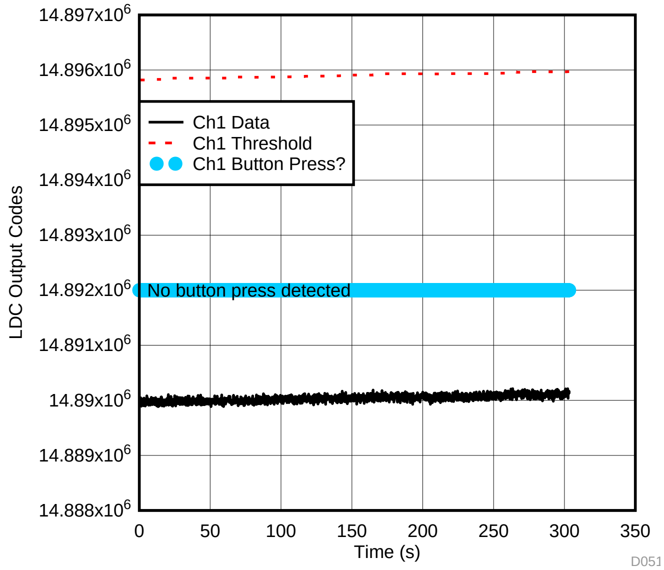


Figure 80. LDC Ch1 Data During Surge (–0.5 kV, From VBUS to GND) Test—*Up* Button Channel

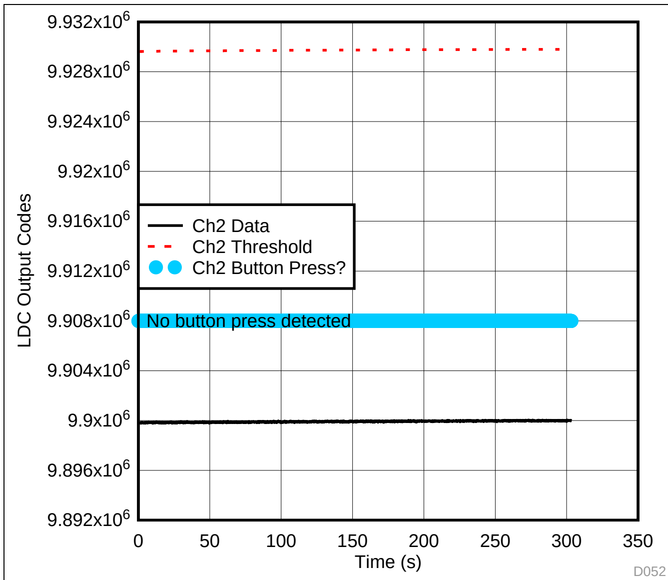


Figure 81. LDC Ch2 Data During Surge (–0.5 kV, From VBUS to GND) Test—*Big* Button Channel

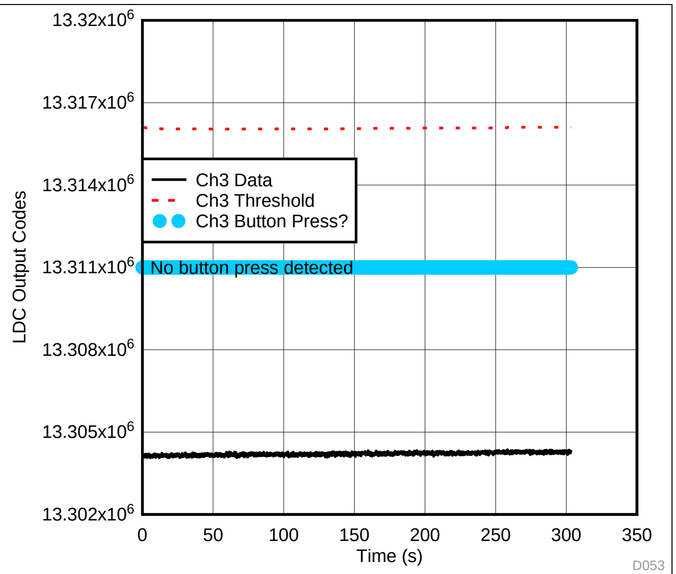


Figure 82. LDC Ch3 Data During Surge (–0.5 kV, From VBUS to GND) Test—*Little* Button Channel

6.8.5 IEC 61000-4-6 (Conducted Immunity) Performance

For the IEC 61000-4-6 pre-compliance test, the system was powered and all four channels of the LDC1614 device output data, slow-moving average threshold, button-press detection flag, as well as the temperature and humidity data were recorded through a UART stream before, during, and after the test conditions were applied. Figure 83 shows the setup for conducted immunity testing.

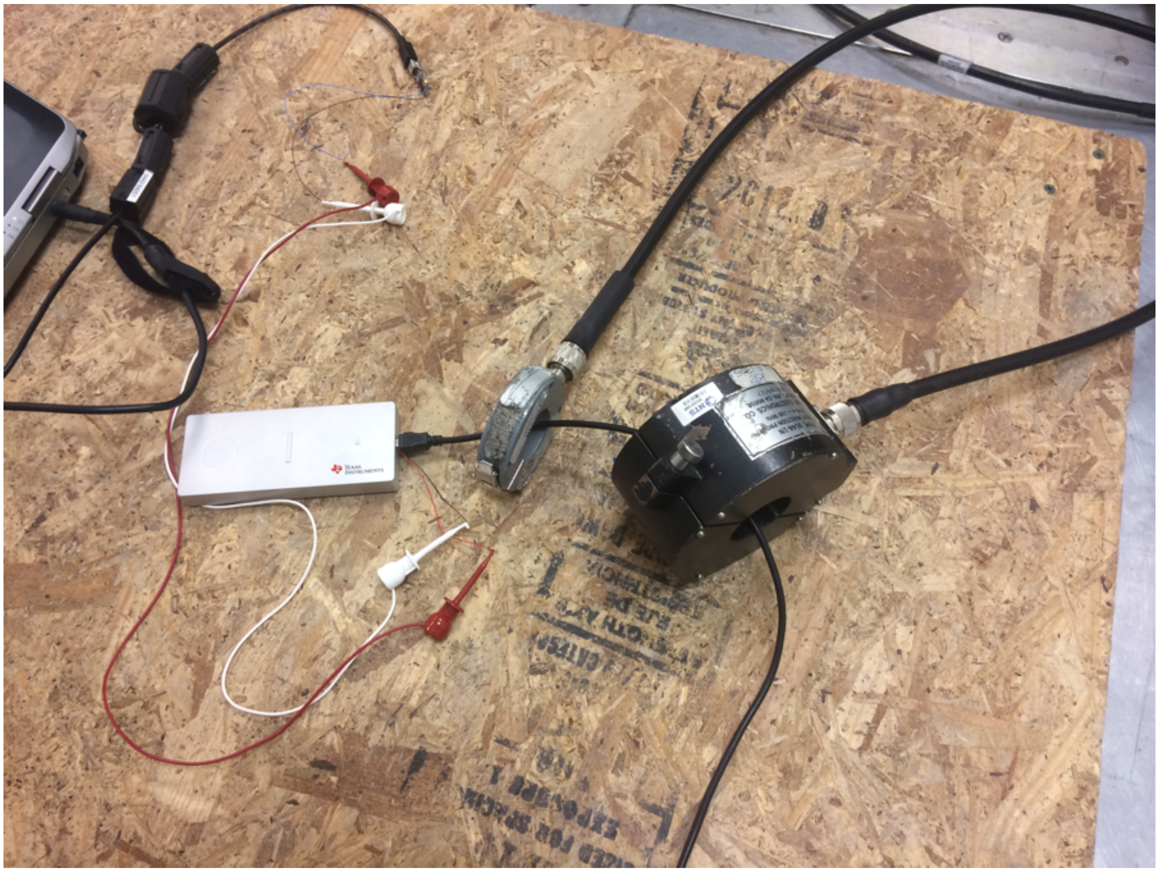


Figure 83. IEC 61000-4-6 Conducted Immunity Test Setup

The system was tested over the standard frequency range of 150 kHz to 80 MHz at a field strength of 3 VRMS. The system output data during this test is shown in the figures listed in Table 15. Ferrite beads were used to keep the UART debugging data from corrupting due to the test.

A slow drift and some noise in the data are shown in some of the figures as the noise frequency was swept from 150 kHz to 80 MHz. However, the IIR filter-based slow-moving average feature of the TI Design eliminates any false triggering of the system. As the figures below show, the LDC1614 device output never exceeds the slow-moving average threshold, resulting in no false button press detections and proving resilient to conducted immunity effects.

The TI Design system performed as expected, with a Class A passing criteria on the conducted immunity test, as the following Table 15 shows.

Table 15. IEC 61000-4-6 (Conducted Immunity) Test Results

IEC 61000-4-6 (CONDUCTED IMMUNITY) TEST CONDITION	RESULT(1)
150 kHz to 80 MHz (at 3 V_{RMS})	A (see Figure 84, Figure 85, Figure 86, and Figure 87)

(1) See Table 10 for details.

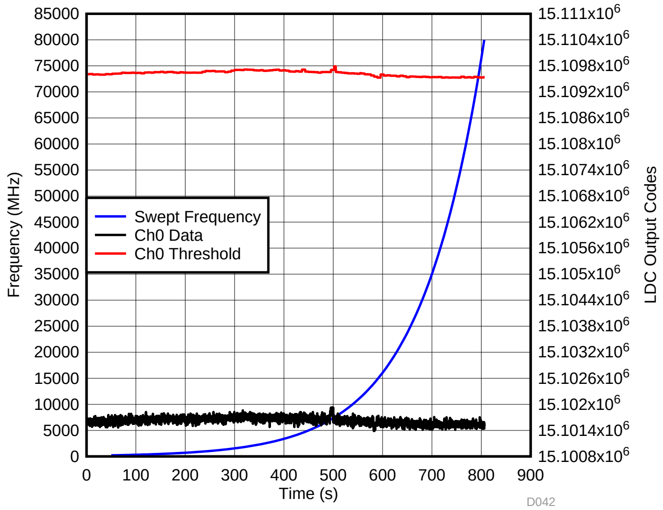


Figure 84. LDC Ch0 Data During Conducted Immunity Test—*Down* Button Channel

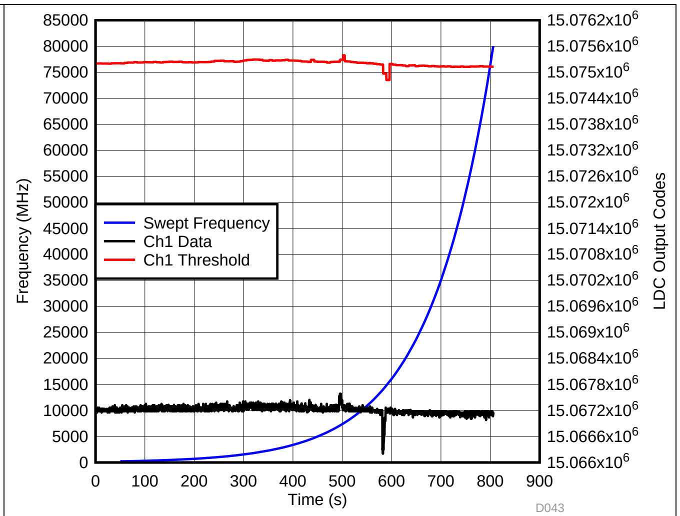


Figure 85. LDC Ch1 Data During Conducted Immunity Test—*Up* Button Channel

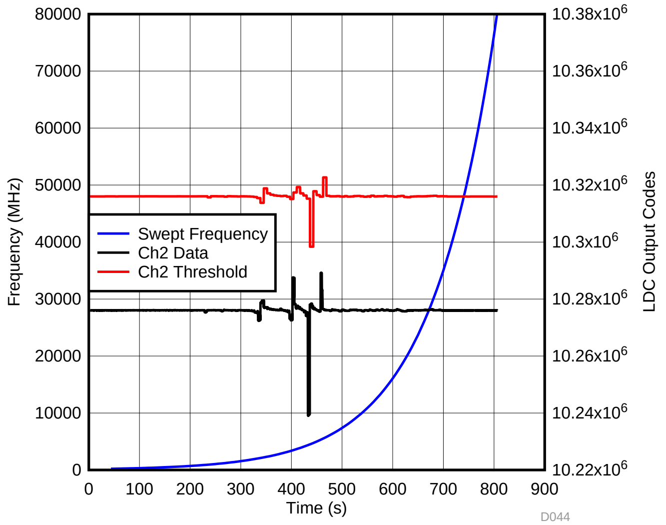


Figure 86. LDC Ch2 Data During Conducted Immunity Test—*Big* Button Channel

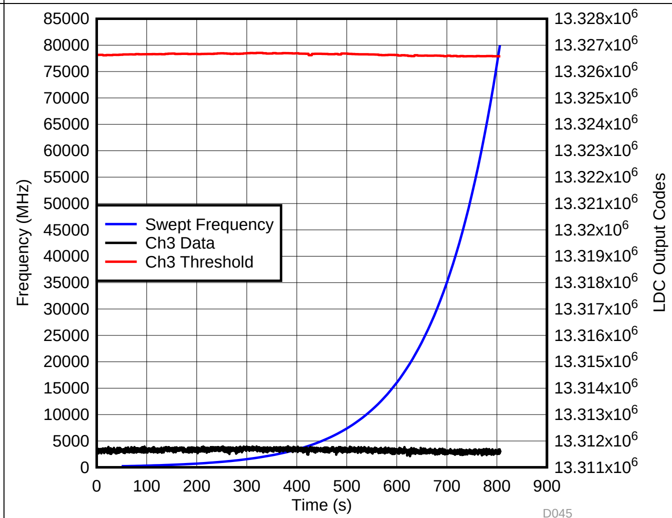


Figure 87. LDC Ch3 Data During Conducted Immunity Test—*Little* Button Channel

7 Design Files

7.1 Schematics

To download the schematics, see the design files at TIDA-00314 Schematics.

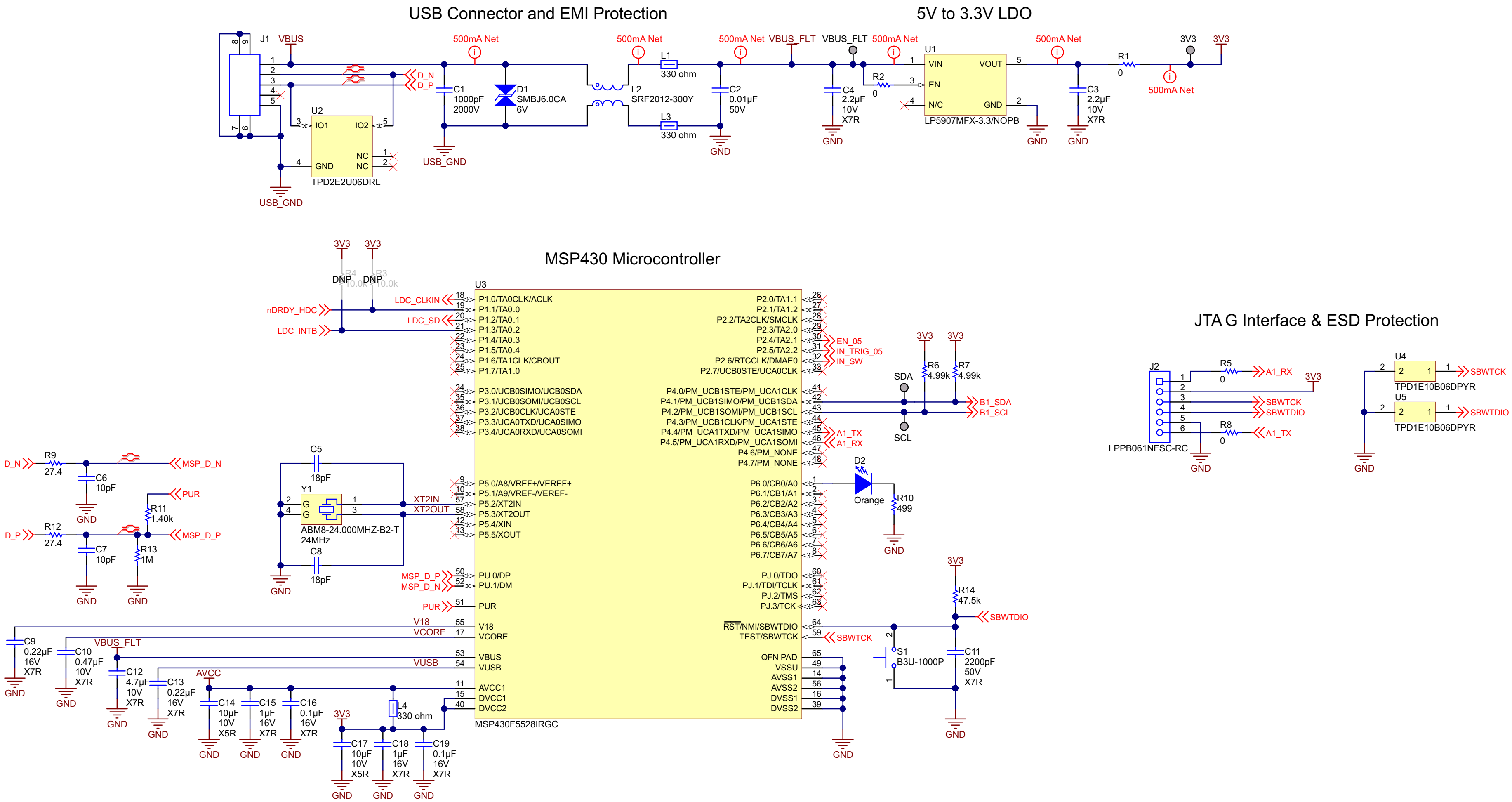


Figure 88. Touch on Metal Buttons With Integrated Haptic Feedback Schematic—Page 1

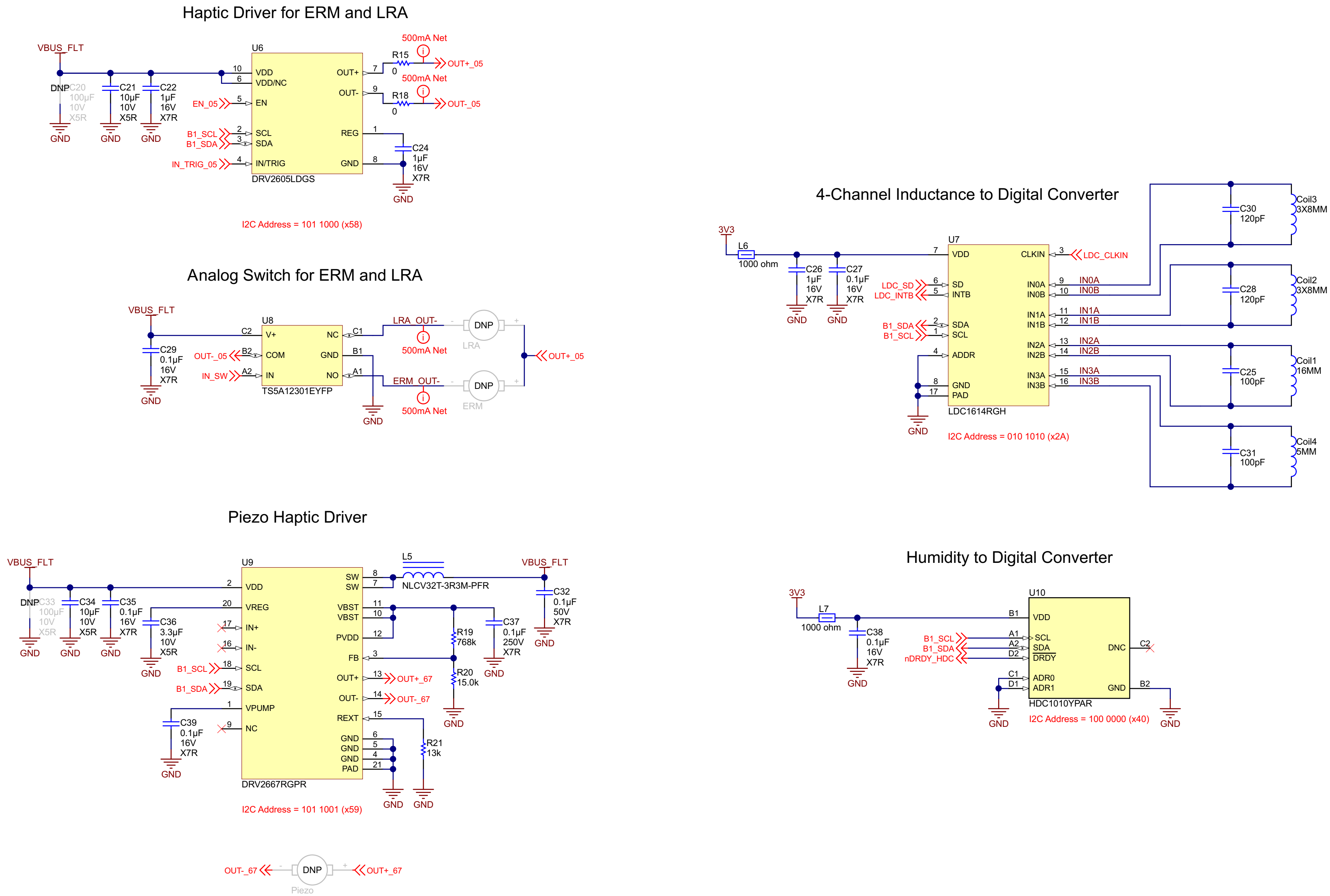


Figure 89. Touch on Metal Buttons With Integrated Haptic Feedback Schematic—Page 2

7.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00314 BOM.

7.3 Layer Plots

To download the layer plots, see the design files at TIDA-00314 Layer Plots.

7.4 Altium Project

To download the Altium project files, see the design files at TIDA-00314 Altium.

7.5 Layout Guidelines

To ensure high performance, the *Touch on Metal Buttons With Integrated Haptic Feedback* TI Design was laid out using a four-layer PCB. The second layer is a solid GND pour, and the third layer is used for power rail routing, with a GND fill in the unused areas. The top and bottom layers are used for general signal routing and also have GND fills in the unused areas.

The sensor coils for all four buttons are required to have the GND fill pulled out on all four layers by at least one radius length. For the rectangular sensing coils, the shortest side dominates. If possible, pulling the GND out by a full diameter is optimal. The traces leading from each sensor coil back to the LDC1614 device are placed on the third layer, buried between the GND pours. No other traces or nets cross the sensor coil traces. Via stitching was implemented to create low-impedance paths to GND in a “fence” around each trace between the LDC1614 device and sensor coils. Burying the traces in this manner reduces EMI susceptibility.

Any haptic actuators used in an end-equipment design must be placed such that the optimal displacement occurs during operation. Typically, this location is in the corners of the PCB, but an accelerometer (such as http://www.ti.com/tool/drv-acc16-evm) can be used to determine the optimal position of the actuators.

There is a ring of exposed GND around the outer edge of the PCB on the bottom side. The intent is to ensure that the PCB GND is shorted to the aluminum enclosure and to ensure that the enclosure is at the same potential as GND. All vias were tented or covered over by solder mask on the bottom of the PCB. This application of solder mask is intended to prevent any signal shorts where the PCB is mounted to the top part of the aluminum enclosure.

For all of the TI products used in this design, ensure that care is taken to adhere to the layout guidelines given in the respective datasheets.

7.6 Gerber Files

To download the Gerber files, see the design files at TIDA-00314 Gerber.

7.7 Assembly Drawings

To download the Assembly files, see the design files at TIDA-00314 Assembly Drawings.

7.8 Software Files

To download the software files, see the design files at TIDA-00314 Firmware.

8 References

For additional references, see the following:

1. Texas Instruments, "*LDC1612, LDC1614 Multi-Channel 28-Bit Inductance to Digital Converter (LDC) for Inductive Sensing*", LDC1614 Datasheet, (SNOSCY9).
2. Texas Instruments, "*DRV2605L 2 to 5.2 V Haptic Driver for LRA and ERM With Effect Library and Smart-Loop Architecture*", DRV2605L Datasheet, (SLOS854).
3. Texas Instruments, "*Piezo Haptic Driver With Boost, Digital Front End, and Internal Waveform Memory*", DRV2667 Datasheet, (SLOS751).
4. Texas Instruments, "*HDC1010 Low Power, High Accuracy Digital Humidity Sensor with Temperature Sensor*", HDC1010 Datasheet, (SNAS685).
5. Texas Instruments, "*Mixed Signal Microcontroller*", MSP430F5528 Datasheet, (SLAS590).
6. Texas Instruments, "*LP5907 Ultra Low-Noise, 250-mA Linear Regulator for RF and Analog Circuit – Requires No Bypass Capacitor*", LP5907 Datasheet, (SNVS798).
7. Texas Instruments, "*IEC Level 4 ESD-Protected 0.75-Ω SPDT Analog Switch With 1.8-V Compatible Input Logic*", TS5A12301E Datasheet, (SCES707).
8. Texas Instruments, "*Dual-Channel High-Speed ESD Protection Device*" TPD2E2U06 Datasheet, (SLLSEG9).
9. Texas Instruments, "*Single Channel ESD Protection Device in 0402 Package*" TPD1E10B06 Datasheet, (SLLSEB1).
10. Texas Instruments, "*Haptic Energy Consumption*", Application Report, (SLOA194).
11. Texas Instruments, "*Haptic Implementation Considerations for Mobile and Wearable Devices*" Application Report, (SLOA207).

9 About the Author

EVAN D. CORNELL is a Systems Architect at Texas Instruments where he is responsible for developing reference design solutions for the industrial segment. Evan brings to this role experience in system-level analog, mixed-signal, and power management design. Evan earned his Master of Electrical and Computer Engineering (M.Eng.) and Bachelor of Science (BS) in Electrical Engineering from the Rose-Hulman Institute of Technology in Terre Haute, IN. Evan is a member of the Institute of Electrical and Electronics Engineers (IEEE).

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Revision D History

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

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Revision C History

Changes from Original (January 2015) to C Revision **Page**

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