

TI Designs: TIDA-01469

采用无线振动传感器并支持预防性维护的电机监控参考设计



说明

此参考设计是一种低功耗无线子系统，它使用振动传感器来监控电机，确定是否需要预防性维护。可通过低功耗 Bluetooth®或低于 1GHz 的无线协议将振动数据的 FFT 发送到另一个器件。通过低功耗和无线功能，此子系统能够在单节纽扣电池上运行，这使得器件的体积得以缩小、成本得以降低，并可置于难以接触到的位置。借助这些特性，该设计可帮助消除本来可通过预防来避免的昂贵维护，而且它还可以作为更大、更昂贵且需要有线连接的监控器的理想替代方案。

资源

TIDA-01469	设计文件夹
CC1350	产品文件夹
ADS8866	产品文件夹
OPA2325	产品文件夹
TPS61291	产品文件夹
REF5030	产品文件夹
TPS22860	产品文件夹
LMT01	产品文件夹
LAUNCHXL-CC1350	工具文件夹

特性

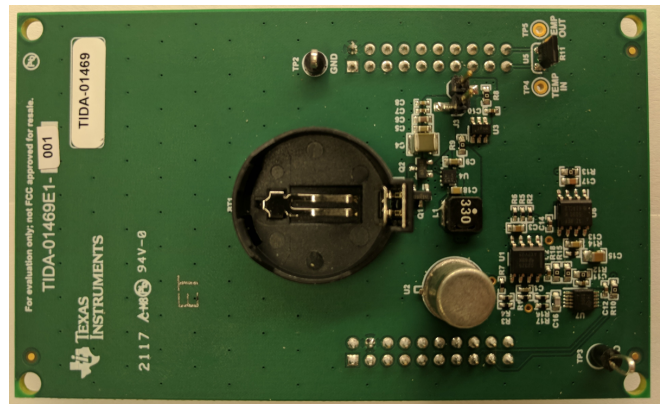
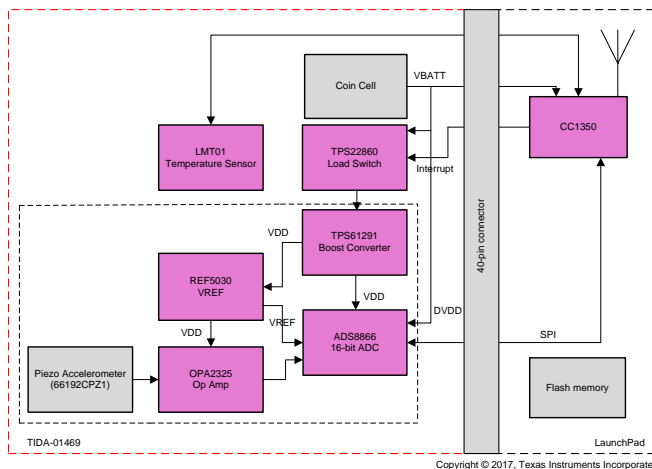
- 超低功耗设计能够使单个 CR2032 纽扣电池拥有长达 10 年的电池寿命
- 提供机械振动 (20kSPS) 和温度传感
- 2K FFT 局部计算，用于进行振动频谱分析
- 用于电机诊断的可编程唤醒时间间隔
- 设计用于 SimpleLink™ 低于 1GHz 和低功耗蓝牙无线连接 LaunchPad™ (LAUNCHXL-CC1350)

应用

- 远程电机运行状态监控
- 无线机器监控
- 结构监控



咨询我们的 E2E 专家



该 TI 参考设计末尾的重要声明表述了授权使用、知识产权问题和其他重要的免责声明和信息。

1 System Description

Many industrial settings include motors that require maintenance as they age and stop working correctly. This maintenance is expensive, and significant downtime can occur if the need for maintenance is not predicted and accounted for. Wireless monitors that can run on a single coin cell battery can be placed almost anywhere and do not need to be accessed often, which is ideal for industrial settings.

The Motor Monitoring Using Wireless Vibration Sensor Reference Design provides a wireless motor monitoring subsystem that can run on a single CR2032 coin cell battery with 10+ year battery life. This allows for a small motor monitor that can be placed in difficult-to-reach locations and does not need to be reached often to change the battery or access the data with a wired connection.

This reference design uses Texas Instruments' CC1350 SimpleLink Ultra-Low Power Dual Band Wireless Microcontroller to read the sensor data, process this data by computing a 2K FFT, and send the data out over an ultra-low-power 2.4-GHz Bluetooth low energy or Sub-1 GHz network. The firmware provided in this design guide uses Texas Instruments' Bluetooth low energy software stack to send the FFT data out in notifications in a connection with another device.

At a high level, this reference design consists of a CR2032 coin cell battery, an ultra-low-power wireless MCU, a piezoelectric accelerometer to acquire the vibration data, an analog-to-digital converter (ADC) to sample this data, and a load switch and boost convertor to gate power to the system. The real-time clock on the CC1350 MCU is used to only wake the system at configurable time intervals. When the system is powered up, the accelerometer acquires the vibration data, the ADC converts the data and sends it to the MCU over SPI, the MCU computes the FFT of the data, and the data is sent to another device over Bluetooth low energy. The device that receives the data can then indicate that the motor monitor can power back down until it is time to take vibration measurements again. A temperature sensor is also provided to monitor the ambient temperature and further help to predict the need for motor maintenance.

This design guide addresses component selection, design theory, and the testing results of this reference design system. The scope of this design allows designers to develop motor monitoring applications that use TI's components for the analog front end (AFE) and TI's SimpleLink ultra-low-power wireless MCU platform.

The following subsections describe the key blocks within the reference design system and what characteristics are most critical to best implement the corresponding functions.

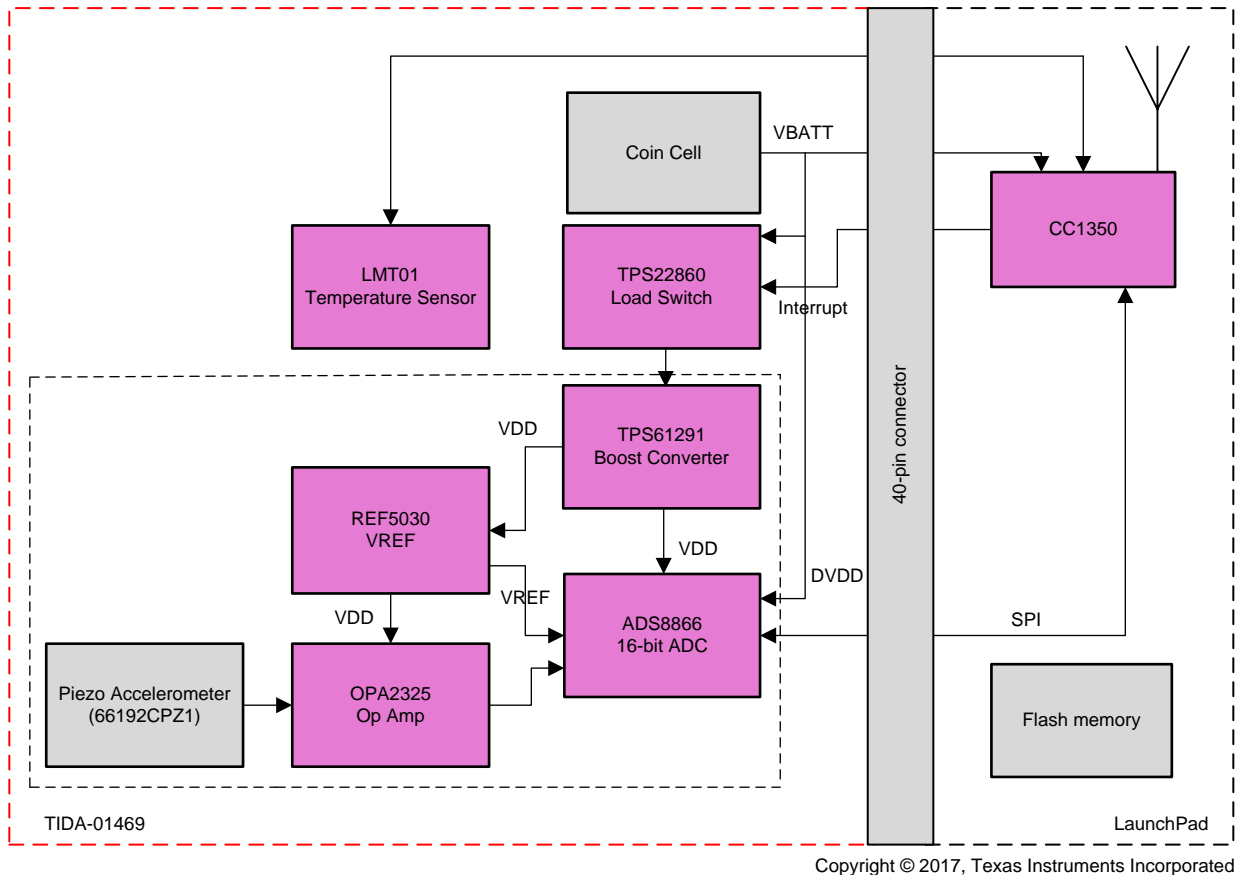
1.1 Key System Specifications

表 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Input power source	CR2032 Lithium-ion coin cell battery (3.0-V nominal voltage)	节 2.2.6
Sensor type	Accelerometer	节 2.2.2
Average standby-state current	879.5 nA	节 3.2.2.1
Estimated battery life	> 10 years	节 3.2.2.2
Fourier transform	2048 points at 20 kSPS	节 3.2.2.3
Frequency monitoring range	50 Hz to 10 kHz	节 3.2.2.3
Operating temperature	-30°C to 85°C	2.3 节
Wireless protocol	Bluetooth low energy	节 2.4.3
Radio transmission range	72 meters	节 3.2.2.5
Default reporting interval	8 hours (Can be dynamically selected)	节 2.4.4
Form factor (sensor board)	58.50-mm x 95.30-mm rectangular PCB	节 3.1.1

2 System Overview

2.1 Block Diagram



Copyright © 2017, Texas Instruments Incorporated

图 1. Block Diagram

2.2 Design Considerations

2.2.1 Ultra-Low-Power Wireless MCU

In this reference design, the acquired vibration data and the FFT of the data need to be sent to another device so that it can be used to determine if maintenance is or will soon be necessary. To allow for a small device with a long enough battery life to justify putting the monitor in difficult-to-reach locations, however, the radio and processor must also be low power. The CC1350 has two antennas to allow data to be transmitted over either Bluetooth low energy or Sub-1 GHz networks, depending on what device will receive the data and how it will be stored and accessed. TI's SimpleLink ultra-low-power wireless MCU platform, with a combined radio and MCU, enables an extremely long battery life for wireless motor monitors.

2.2.2 Piezoelectric Accelerometer

Piezoelectric accelerometers can accurately measure vibrations, which allows for the health of the motor to be quantified. This reference design uses the 66192CPZ1 from IMI Sensors®. This device has a good sensitivity for the design, and its 10-kHz frequency range allows for a stable input signal to the ADC after filtering. It also has a high linearity, which allows for more accurate data.

2.2.3 Analog-to-Digital Conversion

This reference design uses an ADC with external voltage reference to digitize the output of the op-amp stage. The ADS8866 is a 16-bit SAR ADC that provides the necessary resolution and sampling for the wireless motor monitor design. The device communicates with the MCU over SPI, and the high resolution allows for an accurate FFT to be calculated and observed. The digital power supply of the ADC is connected directly to the output of the battery to match the digital input/output pin voltage levels of the wireless MCU.

An external voltage reference source is used for the ADC to provide an output voltage that is stable across ambient temperature, loading, input supply, and time. The REF5030 device provides a low-noise, low-drift, very high-precision voltage reference. The standard grade device has an initial output voltage accuracy of $\pm 0.1\%$ (max), a temperature drift of 8 ppm/ $^{\circ}\text{C}$ (max), a long-term stability of 45 ppm/1000 hr after 1000 hours (typ), and an output voltage noise of $3 \mu\text{V}_{\text{pp}}/\text{V}$ (typ).

At a 100-kHz sampling rate, the ADC consumes 230 μA when operated at 3 V while the voltage reference has a quiescent current of 800 μA . To meet the battery life target for this reference design, it is necessary to completely power off the ADC and voltage reference when the system is in standby mode. The ADC and voltage reference are powered on when a vibration measurement is needed.

2.2.4 Low-Leakage Boost Converter

Some sensor end-nodes require a regulated voltage rail to operate at their highest levels of sensing performance. To provide a well-regulated voltage rail over the entire lifetime of the battery, a boost converter is necessary. However, to reduce the battery life loss due to converter inefficiency, an extremely high-efficiency boost converter is required.

In this reference design, the TPS61291 device regulates the battery voltage to 3.3 V. With a battery voltage of 3.0 V, the TPS61291 maintains an efficiency level greater than 95% at the load currents typical of a sensor end-node: 1 to 100 mA. Even at the depleted coin cell voltage of 2.0 V, the TPS61291 device maintains an efficiency level greater than 90% over the typical load current range of 1 to 100 mA.

The boost converter provides the operating voltage for the sensor subsystem of the design, which includes the operational amplifiers, ADC, and voltage reference.

2.2.5 Low-Leakage Load Switch

This reference design uses a low-leakage load switch to shut off power to the sensor subsystem of the design leaving only the CC1350 wireless MCU and temperature sensor with power. The sensor subsystem includes the boost converter, operational amplifiers, ADC, and voltage reference. The most important characteristic of this switch is the off-state leakage, because that leakage affects the overall battery life of the system significantly.

In this reference design, the TPS22860 device is the switch used to disconnect the sensor subsystem from the battery. The TPS22860 has a typical leakage current of 2 nA at the VIN pin and 10 nA at the VBIAS pin, which enables extremely long battery life in this system.

2.2.6 Coin Cell Battery

The power source for this reference design is a CR2032 lithium-ion coin cell. The CR2032 coin cell battery is the power source because of the ubiquity of that battery type.

The voltage characteristics of a lithium-ion CR2032 coin cell battery are also ideal. The output voltage remains relatively flat throughout the discharge life until the cell is nearly depleted. When the cell is depleted, the output voltage drops off relatively quickly.

Immediately following the battery are two low R_{DS_ON} P-channel MOSFETs and a bulk capacitor. The P-channel MOSFETs prevent damage to the hardware if the coin cell battery is inserted backwards while minimizing the forward voltage drop in normal operation. The bulk capacitor is sized to prevent too much voltage drop, particularly during the transitions into the MCU on-state for radio transmissions.

2.3 Highlighted Products

This motor monitoring reference design features the following devices:

- OPA2325 (节 2.3.1): Dual, precision, low-voltage CMOS operational amplifier
- ADS8866 (节 2.3.2): 16-bit, 100-kSPS, single-ended input, SAR analog-to-digital converter
- REF5030 (节 2.3.3): Low-noise, low-drift, very high precision voltage reference
- TPS61291 (节 2.3.4): Low- I_Q boost converter
- TPS22860 (节 2.3.5): Ultra-low leakage current, single-channel load switch
- LMT01 (节 2.3.6): High-accuracy, 2-pin temperature sensor
- CC1350 (节 2.3.7): Ultra-low-power wireless SimpleLink MCU capable of handling both Sub-1 GHz and 2.4-GHz RF frequencies

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

2.3.1 OPA2325

The OPA2325 device is a dual, precision, low-voltage complementary metal oxide semiconductor (CMOS) operational amplifier optimized for very low noise and wide bandwidth when operating on a low quiescent current of only 650 μ A.

The OPA2325 features a linear input stage with zero-crossover distortion that delivers excellent common-mode rejection ratio (CMRR) of typically 114 dB over the entire input range. The input common-mode range extends 100 mV beyond the negative and positive supply rails. The output voltage typically swings within 10 mV of the rails.

The zero-crossover distortion combined with wide bandwidth (10 MHz), high slew rate (5 V/ μ s), and low noise (9 nV/ $\sqrt{\text{Hz}}$) make the OPA2325 a very good successive-approximation register (SAR) ADC input driver amplifier. The low offset, and 0.2-pA input bias current make this device ideal for a wide range of precision applications with high-impedance sensors. The unique feature of interfacing to high-impedance sensors on the input and being able to drive ADC inputs with very little distortion make the OPA2325 suitable for various data acquisition and process control applications.

In addition, the OPA2325 has a wide supply voltage range from 2.2 to 5.5 V with excellent power-supply rejection ratio (PSRR) over the entire supply range, making the device suitable for precision, low-power applications that run directly from batteries without regulation.

Key features of this device include:

- Precision with zero-crossover distortion:
 - Low offset voltage: 150 μ V (max)
 - High CMRR: 114 dB
 - Rail-to-rail I/O
- Wide bandwidth: 10 MHz
- Quiescent current: 650 μ A/ch
- Single-supply voltage range: 2.2 to 5.5 V
- Low input bias current: 0.2 pA
- Low noise: 9 nV/ $\sqrt{\text{Hz}}$ at 10 kHz
- Slew rate: 5 V/ μ s

- Unity-gain stable

2.3.2 ADS8866

The ADS8866 is a 16-bit, 100-kSPS, single-ended input ADC. The device operates with a 2.5- to 5-V external reference, offering a wide selection of signal ranges without additional input signal scaling. The reference voltage setting is independent of, and can exceed, the analog supply voltage (AVDD).

The device offers an SPI-compatible serial interface that also supports daisy-chain operation for cascading multiple devices.

The device supports unipolar single-ended analog inputs in the range of -0.1 V to $V_{\text{REF}} + 0.1\text{ V}$.

Device operation is optimized for very low-power operation. Power consumption directly scales with speed. This feature makes the ADS8866 excellent for lower-speed applications.

Key features of this device include:

- Sample rate: 100 kHz
- No latency output
- Unipolar, single-ended input range: 0 to +VREF
- SPI-compatible serial interface with daisy-chain option
- Excellent AC and DC performance:
 - SNR: 93 dB, THD: -108 dB
 - INL: $\pm 1.0\text{ LSB}$ (typ), $\pm 2.0\text{ LSB}$ (max)
 - DNL: $\pm 1.0\text{ LSB}$ (max), 16-bit NMC
- Wide operating range:
 - AVDD: 2.7 to 3.6 V
 - DVDD: 1.65 to 3.6 V (independent of AVDD)
 - Operating temperature: -40°C to 85°C
- Low-power dissipation:
 - 0.7 mW at 100 kSPS
 - 70 μW at 10 kSPS
- Power-down current (AVDD): 50 nA
- Full-scale step settling to 16 bits: 1200 ns
- Packages: MSOP-10 and SON-10

2.3.3 REF5030

The REF5030 is a low-noise, low-drift, very high-precision voltage references. These references are capable of both sinking and sourcing current and have excellent line and load regulation.

Excellent temperature drift (3 ppm/ $^{\circ}\text{C}$) and high accuracy (0.05%) are achieved using proprietary design techniques. Combined with very low noise, these features make the REF5030 device ideal for use in high-precision data acquisition systems.

Each reference voltage is available in both high grade (REF50xxIDGK and REF50xxID) and standard grade (REF50xxAIDGK and REF50xxAID). The reference voltages are offered in 8-pin VSSOP and SOIC packages and are specified from -40°C to 125°C .

Key features of this device include:

- Low temperature drift:
 - High-grade: 3 ppm/ $^{\circ}\text{C}$ (Max)
 - Standard-grade: 8 ppm/ $^{\circ}\text{C}$ (Max)
- High accuracy:
 - High-grade: 0.05% (Max)
 - Standard-grade: 0.1% (Max)
- Low noise: $3\ \mu\text{V}_{\text{pp}}/\text{V}$
- Excellent long-term stability:
 - 45 ppm/1000 hr (typ) after 1000 hours
- High-output current: $\pm 10\ \text{mA}$
- Temperature range: -40°C to 125°C

2.3.4 TPS61291

The TPS61291 is a boost converter with pin mode. In bypass operation, the device provides a direct path from the input to the system and allows a low-power MCU such as the MSP430™ to operate directly from a single 3-V Li-MnO₂ battery or dual alkaline battery cells. In bypass mode, the integrated feedback divider network for boost mode operation is disconnected from the output and the quiescent current consumption drops down to only 15 nA (typical).

In boost mode, the device provides a minimum output current of 200 mA at 3.3-V V_{OUT} from 1.8-V V_{IN} . The boost mode is used for system components that require a regulated supply voltage and cannot directly operate from the input source. The boost converter is based on a current-mode controller using synchronous rectification to obtain maximum efficiency and consumes typically 5.7 μA from the output. During startup of the boost converter, the VSEL pin is read out and the integrated feedback network sets the output voltage to 2.5 V, 3 V, or 3.3 V.

Bypass mode or boost mode operation is controlled by the system through the EN/BYP pin.

The device integrates an enhanced bypass mode control to prevent charge, stored in the output capacitor during boost mode operation, from flowing back to the input and charging the battery.

The device is packaged in a small 6-pin SON package (DRV) measuring 2.0 mm x 2.0 mm x 0.75 mm.

Key features of this device include:

- Input voltage range: 0.9 to 5 V
- Startup voltage: 1.5 V at 20-mA load
- Pin selectable output voltages: 3.3 V, 3 V, 2.5 V
- 15-nA typical quiescent current in bypass mode
- 5.7- μA typical quiescent current in boost mode
- Bypass switch from V_{IN} to V_{OUT}
- $I_{\text{OUT}} > 200\ \text{mA}$ at 3.3-V V_{OUT} , $V_{\text{IN}} = 1.8\ \text{V}$

- Internal feedback divider disconnect (bypass mode)
- Controlled bypass transition prevents reverse current into battery
- Power-save mode at light loads
- Overtemperature protection
- Redundant overvoltage protection
- Small 2-mm×2-mm SON 6-pin package

2.3.5 TPS22860

The TPS22860 is a small, ultra-low leakage current, single-channel load switch. The device requires a V_{BIAS} voltage and can operate over an input voltage range of 0 V to V_{BIAS} . The device can support a maximum continuous current of 200 mA. The switch is controlled by an on/off input (ON), which is capable of interfacing directly with low-voltage control signals. The TPS22860 is available in two small, space-saving 6-pin SOT-23 and SC70 packages. The device is characterized for operation over the free-air temperature range of -40°C to 85°C .

- Integrated single-channel load switch
- Bias voltage range (V single channel load switch. The device requires a BIAS): 1.65 to 5.5 V
- Input voltage range: 0 V to V_{BIAS}
- ON-resistance (R_{ON})
 - $R_{ON} = 0.73 \Omega$ at $V_{IN} = 5 \text{ V}$ ($V_{BIAS} = 5 \text{ V}$)
 - $R_{ON} = 0.68 \Omega$ at $V_{IN} = 3.3 \text{ V}$ ($V_{BIAS} = 5 \text{ V}$)
 - $R_{ON} = 0.63 \Omega$ at $V_{IN} = 1.8 \text{ V}$ ($V_{BIAS} = 5 \text{ V}$)
- 200-mA maximum continuous switch current
- Ultra-low leakage current
 - V_{IN} leakage current = 2 nA
 - V_{BIAS} leakage current at 5.5 V = 10 nA
- 6-pin SOT-23 or SC70 package
- ESD performance tested per JESD 22
 - 2-kV HBM and 1-kV CDM

2.3.6 LMT01

The LMT01 device is a high-accuracy, 2-pin temperature sensor with an easy-to-use pulse count current loop interface, which makes it suitable for onboard and off-board applications in automotive, industrial, and consumer markets. The LMT01 digital pulse count output and high accuracy over a wide temperature range allow pairing with any MCU without concern for integrated ADC quality or availability, while minimizing software overhead. TI's LMT01 device achieves a maximum $\pm 0.5^{\circ}\text{C}$ accuracy with very fine resolution (0.0625°C) over a temperature range of -20°C to 90°C without system calibration or hardware and software compensation.

The LMT01's pulse count interface is designed to directly interface with a GPIO or comparator input, thereby simplifying hardware implementation. Similarly, the LMT01's integrated EMI suppression and simple 2-pin architecture makes it suitable for onboard and off-board temperature sensing in a noisy environment. The LMT01 device can be easily converted into a two-wire temperature probe with a wire length up to two meters. See LMT01-Q1 for the automotive qualified version.

Key features of this device include:

- High accuracy over -50°C to 150°C wide temperature range:
 - -20°C to 90°C : $\pm 0.5^{\circ}\text{C}$ (maximum)
 - 90°C to 150°C : $\pm 0.625^{\circ}\text{C}$ (maximum)
 - -50°C to -20°C : $\pm 0.7^{\circ}\text{C}$ (maximum)
- Precision digital temperature measurement simplified in a 2-pin package
- Pulse count current loop easily read by processor
 - Number of output pulses is proportional to temperature with 0.0625°C resolution
- Communication frequency: 88 kHz
- Conversion current: 34 μA
- Continuous conversion plus data-transmission period: 100 ms
- Floating 2- to 5.5-V (VP–VN) supply operation with integrated EMI immunity
- Multiple 2-pin package offerings: TO-92/LPG (3.1 mm \times 4 mm \times 1.5 mm)
 - $\frac{1}{2}$ the size of traditional TO-92 and WSON with wettable flanks

2.3.7 CC1350

The CC1350 is a member of the CC26xx and CC13xx family of cost-effective, ultra-low-power, 2.4-GHz and Sub-1 GHz RF devices from Texas Instruments. Very low active RF and MCU current consumption, in addition to flexible low-power modes, provide excellent battery lifetime and allow long-range operation on small coin cell batteries and in energy-harvesting applications.

The CC1350 is the first device in the CC13xx and CC26xx family of cost-effective, ultra-low-power wireless MCUs capable of handling both Sub-1 GHz and 2.4-GHz RF frequencies. The CC1350 device combines a flexible, very low-power RF transceiver with a powerful 48-MHz ARM® Cortex® M3 MCU in a platform supporting multiple physical layers and RF standards. A dedicated radio controller (Cortex-M0) handles low-level RF protocol commands that are stored in ROM or RAM, thus ensuring ultra-low power and flexibility to handle both Sub-1 GHz protocols and 2.4-GHz protocols (for example, Bluetooth low energy). This enables the combination of a Sub-1 GHz communication solution that offers the best possible RF range together with a Bluetooth low energy smartphone connection that enables great user experience through a phone application. The Sub-1 GHz only device in this family is the CC1310.

The CC1350 device is a highly integrated, true single-chip solution incorporating a complete RF system and an on-chip DC-DC converter.

Sensors can be handled in a very low-power manner by a dedicated autonomous ultra-low-power MCU that can be configured to handle analog and digital sensors; thus the main MCU (Cortex-M3) can maximize sleep time.

The CC1350 power and clock management and radio systems require specific configuration and handling by software to operate correctly, which has been implemented in the [TI-RTOS](#). TI recommends using this software framework for all application development on the device. The complete TI-RTOS and device drivers are offered in source code free of charge.

Key features of this device include:

- Microcontroller:
 - Powerful ARM Cortex-M3 processor
 - EEMBC CoreMark® Score: 142
 - EEMBC ULPBench™ Score: 158
 - Clock speed up to 48 MHz
 - 128kB of in-system programmable flash
 - 8kB of SRAM for cache (or as general-purpose RAM)
 - 20kB of ultra-low-leakage SRAM
 - 2-pin cJTAG and JTAG debugging
 - Supports over-the-air (OTA) update
- Ultra-low-power sensor controller
 - Can run autonomously from the rest of the system
 - 16-bit architecture
 - 2kB of ultra-low-leakage SRAM for code and data
- Efficient code-size architecture, placing parts of TI-RTOS, drivers, Bluetooth low energy controller, and bootloader in ROM
- RoHS-compliant package
 - 7-mm×7-mm RGZ VQFN48 (30 GPIOs)
 - 5-mm×5-mm RHB VQFN32 (15 GPIOs)
 - 4-mm×4-mm RSM VQFN32 (10 GPIOs)
- Peripherals
 - All digital peripheral pins can be routed to any GPIO
 - Four general-purpose timer modules (eight 16-bit or four 32-bit timers, PWM each)
 - 12-bit ADC, 200 kSPS, 8-channel analog MUX
 - Continuous time comparator
 - Ultra-low-power clocked comparator
 - Programmable current source
 - UART
 - 2× SSI (SPI, MICROWIRE, TI)
 - I²C, I2S
 - Real-time clock (RTC)
 - AES-128 security module
 - True random number generator (TRNG)

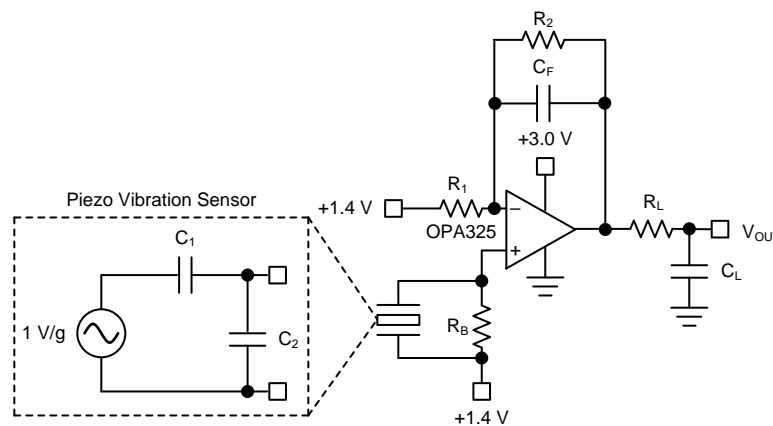
- Support for eight capacitive sensing buttons
- Integrated temperature sensor
- External system
 - On-chip internal DC-DC converter
 - Seamless integration with the SimpleLink CC1190 and CC2592 range extenders
- Low power
 - Wide supply voltage range: 1.8 to 3.8 V
 - RX: 5.4 mA (Sub-1 GHz), 6.4 mA (Bluetooth low energy, 2.4 GHz)
 - TX at 10 dBm: 13.4 mA (Sub-1 GHz)
 - TX at 9 dBm: 22.3 mA (Bluetooth low energy, 2.4 GHz)
 - TX at 0 dBm: 10.5 mA (Bluetooth low energy, 2.4 GHz)
 - Active-mode MCU: 48 MHz running Coremark: 2.5 mA (51 μ A/MHz)
 - Active-mode MCU: 48.5 CoreMark/mA
 - Active-mode sensor controller at 24 MHz: 0.4 mA + 8.2 μ A/MHz
 - Sensor controller, one wakeup every second performing one 12-bit ADC sampling: 0.95 μ A
 - Standby: 0.7 μ A (RTC running and RAM and CPU retention)
 - Shutdown: 185 nA (wakeup on external events)
- RF section
 - 2.4-GHz RF transceiver compatible with Bluetooth low energy 4.2 specification
 - Excellent receiver sensitivity: -124 dBm using long-range mode, -110 dBm at 50 kbps (Sub-1 GHz), -87 dBm at Bluetooth low energy
 - Excellent selectivity (± 100 kHz): 56 dB
 - Excellent blocking performance (± 10 MHz): 90 dB
 - Programmable output power up to 15 dBm (Sub-1 GHz) and 9 dBm at 2.4 GHz (Bluetooth low energy)
 - Single-ended or differential RF interface
 - Suitable for systems targeting compliance with worldwide radio frequency regulations
 - ETSI EN 300 220, EN 303 204 (Europe)
 - EN 300 440 Class 2 (Europe)
 - EN 300 328 (Europe)
 - FCC CFR47 Part 15 (US)
 - ARIB STD-T66 (Japan)
 - ARIB STD-T108 (Japan)
 - Wireless M-Bus and selected IEEE[®] 802.15.4g PHY
- Tools and development environment
 - Full-feature and low-cost development kits
 - Multiple reference designs for different RF configurations
 - Packet sniffer PC software

- Sensor Controller Studio
- SmartRF™ Studio
- SmartRF Flash Programmer 2
- IAR Embedded Workbench® for ARM
- Code Composer Studio™

2.4 System Design Theory

2.4.1 Analog Front End

To monitor machine vibrations, this design uses a piezo vibration sensor. Because piezo sensors have high-impedance output nodes, the AFE circuitry was carefully designed to reduce the noise and increase the sensitivity of the system. For the AFE circuitry with piezo sensor, see 图 2. The amplifier and the sensor affect the noise and sensitivity values of the AFE. Because of this effect, proper modeling of the sensor helps to analyze the noise and sensitivity of the AFE. Piezoelectric vibration sensors are typically used in much lower-frequency domains than resonant frequency. These sensors can be electrically modeled as a voltage source that converts force to voltage through two capacitors, C_1 and C_2 . For these capacitors, see 图 2. This model disregards the noise of the sensor because it is typically much less than the noise of the interface circuitry.



Copyright © 2017, Texas Instruments Incorporated

图 2. AFE Schematic With Piezo Vibration Sensor

The sensitivity at the sensor output, S_S , is defined by 公式 1.

$$S_S = \frac{C_1}{C_1 + C_2 + C_{IN}} \quad (1)$$

where:

- C_{IN} is the input common-mode capacitor of the amplifier

Because a large C_{IN} reduces the S_S , it is desirable to make C_{IN} small in comparison to C_2 . However, because the piezo sensors are high-impedance output sensors, CMOS or JFET input amplifiers are desirable but typically have large C_{IN} for low flicker noise. The OPA325 and the PCB Piezotronics sensor result in good performance when these constraints are taken into consideration because the C_{IN} of the OPA325 is 4 pF, which is very small compared to the 350 pF of the PCB Piezotronics sensor capacitance, and the OPA325 has low-input referred voltage noise, V_n , and low-input referred current noise, I_n .

The sensitivity of the amplifier output, S_{AMP} , is defined by 公式 2.

$$S_{AMP} = \frac{C_1}{C_1 + C_2 + C_{IN}} \times \left(1 + \frac{R_2}{R_1} \right) \quad (2)$$

The resistor, R_B , is necessary for the DC bias at the amplifier input, and it sets a high-pass filter with the sensor output capacitance.

The cut-off frequency of the high-pass filter $\approx \frac{1}{2\pi R_B C_2}$.

The capacitors, C_F and C_L , set low-pass filters with R_2 and R_L , respectively.

The cutoff frequency of low-pass filter 1 is shown in 公式 3.

$$\frac{1}{2\pi R_L C_L} \tag{3}$$

The cutoff frequency of low-pass filter 2 is shown in 公式 4.

$$\frac{1}{2\pi R_2 C_F} \tag{4}$$

A TINA-TI™ simulation is run to determine the upper and lower cutoff frequencies. The upper cutoff frequency is shown to be 11.3 kHz, as shown in 图 3.

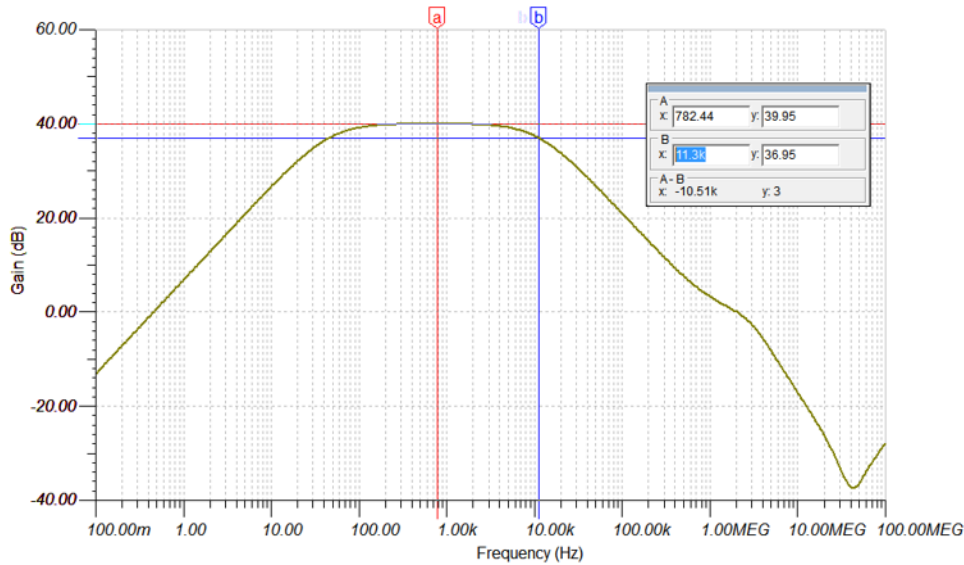


图 3. Upper Cutoff Frequency TINA-TI Simulation

The lower cutoff frequency is shown to be 45 Hz, as shown in 图 4.

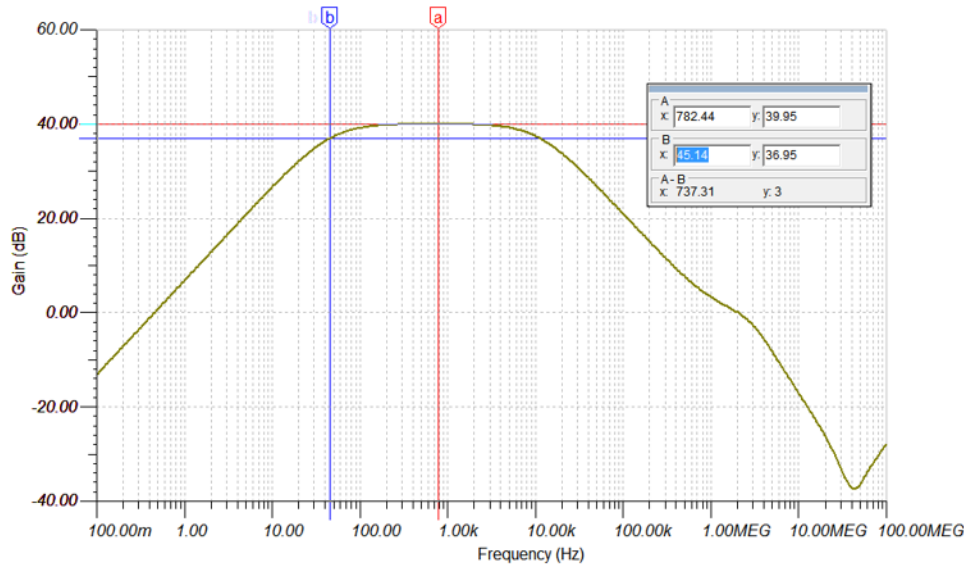


图 4. Lower Cutoff Frequency TINA-TI Simulation

These cutoff frequencies are verified by varying the input signal generated by the function generator given to the reference design and viewing the amplified signal that was provided as an input to the ADC.

The noise at the amplifier input can be calculated as shown in 公式 5.

$$\sqrt{4kT \times R_1 / R_2 + V_n^2 + I_n^2 \times (R_1 / R_2)^2 + \left(I_n^2 + \frac{4kT}{R_B} \right) \times \left(\frac{1}{2\pi f \times (C_2 + C_{IN})} \right)^2} \quad (5)$$

Here the assumption is that $C_1 \ll C_{IN}$ and C_2 , and $R_B \gg \frac{1}{2\pi f (C_2 + C_{IN})}$.

Finally, the input referred noise of the AFE including the sensor can be calculated as shown in 公式 6.

Noise at the amplifier input

$$S_S \quad (6)$$

The design parameters are shown in 表 2.

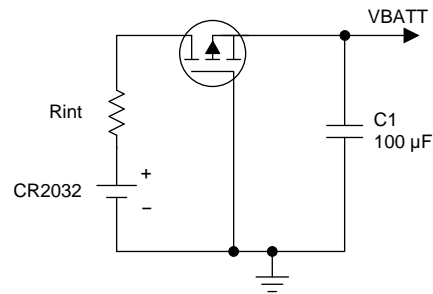
表 2. Design Parameter Examples

DESIGN PARAMETER	VALUE
C_1	5 pF
C_2	350 pF
C_{IN}	4 pF
R_B	10 MΩ
R_1	100 Ω
R_2	10 kΩ
Gain	101
The sensitivity at the sensor output, S_S	14 mV/g
The sensitivity at the amplifier output, S_{AMP}	1.4 V/g
Noise at the amplifier input at 1 kHz	19.2 nV/√Hz
Input referred noise of the AFE at 1 kHz	1.4 μg/√Hz
Low cutoff frequency	45 Hz
High cutoff frequency	11.3 kHz

2.4.2 Power Supply Design

Because of the increasing battery impedance over the life of the battery supply, it is important to design the power supply network to prevent current spikes generated by the MCU from causing false triggers. While a software algorithm can help to filter such problems, this unwanted power supply feedback loop can become an issue. Ideally, the sensor supply would be regulated to break this loop; however, in this design, the extra quiescent current of a regulator reduces battery life, so other methods were explored.

图 5 shows a simplified schematic of the power supply network. The PMOS transistor is used in place of the traditional Schottky diode for reversed battery protection. Because the peak currents are in the 10-mA range when the radio transmits, using a low R_{DS_ON} PMOS provides a much lower voltage drop compared to a Schottky diode, which helps to maximize battery life by allowing the battery to decay to a lower voltage before the circuit is no longer able to function (for more on this technique, see the application report *Reverse Current/Battery Protection Circuits*[®] (SLVA139).



Copyright © 2017, Texas Instruments Incorporated

图 5. Simplified Power Supply Network Schematic

Capacitor C1 supplies the circuit during periods of high and fast peak current demand, which helps to maximize the battery capacity and minimize voltage droop on the power supply rail, especially as the battery approaches its end of life and its internal impedance increases (represented by R_{int} in 图 5). The calculation for C1 is provided in 公式 7. For more details on this calculation and the effects of high current peaks on battery life and capacity, see the white paper *Coin cells and peak current draw*[®] (SWRA349).

$$C2 = \frac{\Delta Q}{V_{MAX}} - V_{MIN} \quad (7)$$

where:

- $\Delta Q = Q_{dis} - \frac{V_{MIN}}{R_{int}} \times t_{tot}$
- $Q_{dis} = \sum i_n \times t_n$

V_{MAX} is the voltage across the capacitor at the start of the current pulse at the end of the battery's life, and V_{MIN} is the circuit operating minimum. V_{MAX} is taken to be 2.698 V assuming an unloaded end of life battery voltage of 2.7 V (V_p).

Based on the power consumption characterization presented in 节 3.2.2.1, this reference design experiences the period of highest current consumption when it is advertising. The load profiles based on this event is shown in 图 16.

Based on this profile, C1 can be calculated using 公式 8:

$$C1 = \frac{10 \text{ mA} \times 8.32 \text{ ms} - \frac{2.0 \text{ V}}{1 \text{ k}\Omega} \times 8.32 \text{ ms}}{2.698 \text{ V} - 2.0 \text{ V}} = 95.35 \mu\text{F} \quad (8)$$

This design uses $C1 = 100 \mu\text{F}$ and additional decades of capacitors in parallel for improved impedance at higher frequencies.

2.4.3 Wireless Network Design

This design leverages TI's Bluetooth low energy stack to implement a Bluetooth connection over which data is sent.

The wireless subsystem (CC1350) is configured for 100-ms advertisement and connection intervals. These intervals may be configured to longer periods through software. Each connection interval enables communication of 20 bytes of data.

The firmware for this reference design connects to a central device to transmit sample and FFT data over Bluetooth low energy. The central device can then be used to tell the reference design to return to its low-power standby mode.

The antenna on this reference design is the inverted F printed circuit board (PCB) antenna for 2.4-GHz transceivers and transmitters. See the [2.4-GHz Inverted F Antenna application note \(SWRU120\)](#) for more details about layout and performance.

2.4.4 Firmware Control

图 6 describes the firmware operation in this reference design.

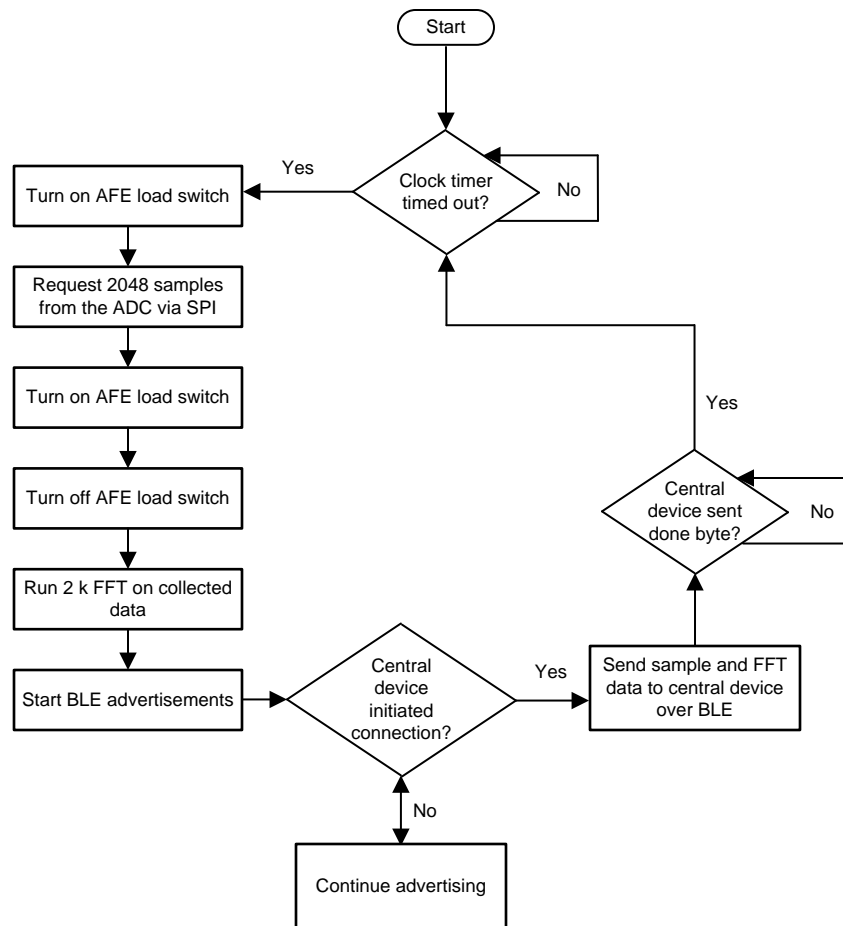


图 6. Firmware Flow Chart

For this design, a wakeup interval of 8 hours was used. The RTC on the CC1350 was used to keep track of the wakeup interval. By powering on the load switch only when data was being sampled by the ADC and sent to the MCU, power was conserved. Data was sent out in a connection (as opposed to just using advertising packets) due to the large amount of data that is being transmitted.

The task priority for the task containing the code for sampling from the ADC is currently set to a priority of 2. A higher number represents a high priority task. This is to prevent it from interfering with any tasks that are essential to the Bluetooth low energy operation, but it may need to be raised if any other tasks are added that could possibly preempt the sampling from the ADC. The highest priority task that is ready to run at any point will be run.

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

The motor monitoring reference design uses the following hardware:

- TIDA-01469 PCB (sensor board)
- CC1350 LaunchPad (LAUNCHXL-CC1350)
- CR2032 Coin cell battery
- CC13xx or CC26xx (CC1350, CC2650, CC2640, CC2640R2) device that can be used with the BTool PC tool (a LaunchPad or SmartRF06 board must be used)

This reference design includes the pre-built images needed for evaluation. For modifying, debugging, and rebuilding custom images the following software is needed:

- [TI's Code Composer Studio \(CCS\) version 7.1.0](#)
- [BLE stack v 2.2.1](#)
- [Flash Programmer 2](#)
- BTool (available with BLE-stack SDK)

3.1.1 Hardware

图 7 shows the hardware for the motor monitoring reference design. The PCB is in a 58.50x95.30-mm rectangular form factor. All the integrated circuits, sensor, test points, jumpers, and battery holder are located on the top side of the PCB. The bottom side of the PCB contains the connectors for the CC1350 LaunchPad.

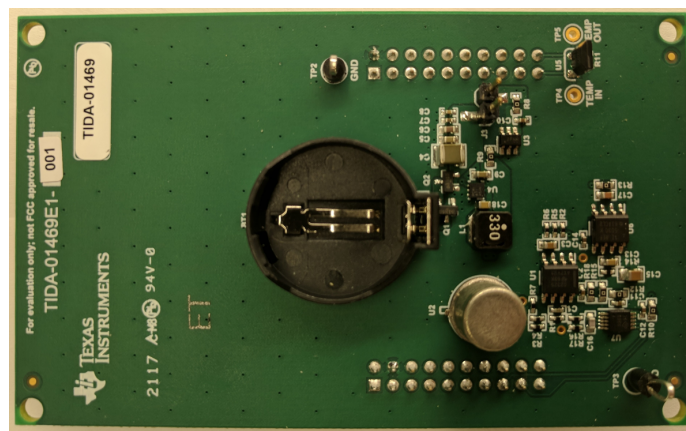


图 7. Wireless Vibration Sensor Reference Design Hardware Description

As shown in 图 8, the reference design PCB is designed to attach directly to the CC1350 LaunchPad (LAUNCHXL-CC1350). The reference design PCB and the CC1350 LaunchPad together make up the sensor node. The assembled system can be powered from the USB port on the CC1350 LaunchPad or from the battery on the PCB. See 节 3.1.1.1 for more details on the jumper configuration for each of these two options.

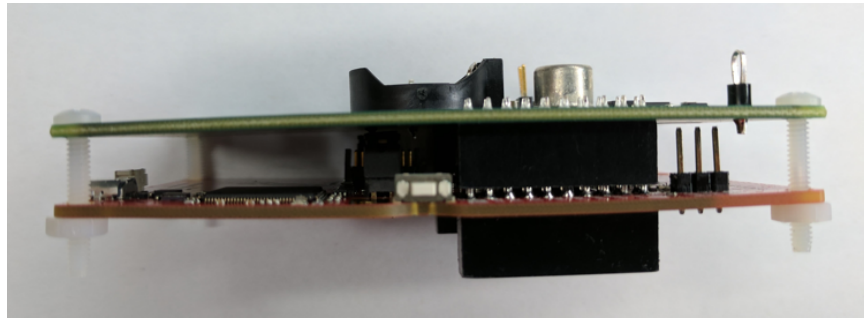


图 8. Fully Assembled System

表 3 lists the assignments of different signals in the reference design PCB to the input/output pins of the CC1350 LaunchPad.

表 3. Pin Assignments When Used with CC1350 LaunchPad

SIGNAL	PIN ASSIGNMENT
SPI_CLK	DIO10
SPI_CS	DIO21
SPI_SDI	DIO22
LS_INT	DIO19
TEMP_IN	DIO15
TEMP_OUT	DIO8

3.1.1.1 Jumper Configuration

To properly operate the reference design, the jumpers on the design PCB and the CC1350 LaunchPad must be installed correctly.

To power the entire system from the CC1350 LaunchPad and enable the onboard emulator configure the jumpers as follows:

- TIDA-01469 Board J3 = Opened (disconnects battery from system)
- CC1350 LaunchPad P4 = All jumpers on (XDS110 powers CC1350 and TIDA-01469 board, all JTAG signals connected to CC1350)
- CC1350 LaunchPad P10: Set to XDS110 Power (full debug supported)
- (Optional) CC1350 LaunchPad P6: Both jumpers on (enables LEDs)

To power the entire system from the coin cell battery and disable the onboard emulator configure the jumpers as follows:

- TIDA-01469 Board J3 = Jumper on (connects battery to system)
- CC1350 LaunchPad P4 = All jumpers removed (removes XDS power from CC1350 and TIDA-01469 board, disconnects all JTAG signals)
- CC1350 LaunchPad P10: Off (removes power from level shifters, disables debug)
- (Optional) CC1350 LaunchPad P6: Both jumpers removed (disables LEDs)

3.1.1.2 Test Point Description

This reference design includes several test points to monitor critical signals. The following is a brief description of these test points:

- TP2, TP3: Ground points for probes or common points for voltage measurements
- TP4: Temperature sensor input
- TP5: Temperature sensor output

3.1.1.3 Battery Requirements

Only insert an Energizer™ CR2032VP lithium battery or battery with equivalent specifications:

- CR2032 UL certified battery
- Voltage: 3.0 V
- Minimum capacity: 240 mAh
- Minimum discharge rate: 0.19 mA

注: The battery must be replaced by a trained professional.

3.1.2 Software

3.1.2.1 Compiling Firmware

The firmware for this reference design is developed using TI's CCS software (version 7.1.0), BLE SDK 2.02.01.18, TI-RTOS 2.20.01.08, and ARM Compiler Tools 5.2.6. The instructions in this document detailing how to build the firmware assume that CCS and the software packages have been set up and configured correctly. For more information on how to set up the development environment, consult the [CC2640 BLE Software Developer's Guide](#) provided in the docs folder of the BLE SDK.

To import the project into CCS:

1. Open CCS.
2. Click on the *Project* toolbar.
3. Select *Import CCS Projects...*
4. Select the radio option *Select archive file*.
5. Navigate to where the TIDA01469_BLE_Peripheral_App.zip file is installed. If using the default location, the firmware is at the location, C:\ti\TIDA01469-Firmware.
6. Verify that the option TIDA01469_BLE_Peripheral_Stack is checked.
7. Click the *Finish* button.
8. Click on the *Project* toolbar.
9. Select *Import CCS Projects...*
10. Select the radio option *Select search-directory*.
11. Navigate to where the simple_peripheral_stack project is located. If using the default location, the firmware is at the location, C:\ti\simplelink\ble_sdk_2_02_01_18\examples\cc1350p\simple_peripheral\ccs\stack.
12. Verify that the option *simple_peripheral_cc1350p_stack* is checked.
13. Click the *Finish* button.

At this point, the CCS workspace must have both *simple_peripheral_cc1350p_app* and *simple_peripheral_cc1350p_stack* projects.

To build the firmware:

1. Set the `simple_peripheral_cc1350lp_stack` project as the active project, and build the project using Project → Build Project. The generated binary file, `simple_peripheral_cc1350lp_stack.hex`, is in the `simple_peripheral_cc1350lp_stack/FlashROM` folder.
2. Set the `simple_peripheral_cc1350lp_app` project as the active project, and build the project using Project → Build Project. The generated binary file, `simple_peripheral_cc1350lp_app.hex`, is in the `simple_peripheral_cc1350lp_app/FlashROM` folder.

3.1.2.2 Loading Firmware on Wireless MCU Using Binaries

Included in the reference design firmware is a set of pre-built binary images for the application and stack, which can be loaded through the onboard emulator on the CC1350 LaunchPad. Both can be loaded at the same time. Simply configure the jumpers on the CC1350 LaunchPad to enable the onboard emulator (see 节 3.1.1.1) and connect a USB cable to the CC1350 LaunchPad. After setting up all the hardware, follow these steps to load the firmware on the sensor and collector using the SmartRF Flash Programmer 2:

1. Download and install SmartRF Flash Programmer 2 (<http://www.ti.com/tool/flash-programmer>).
2. Open SmartRF Flash Programmer 2.
3. In the "Connected devices" window, CC1350 must be listed under XDS110. If it is not listed, check the USB connection to the CC1350 LaunchPad and click "Refresh" button to rescan for devices. Highlight the CC1350 device.
4. In the "Main" tab, click the "Multiple" radio button.
5. **IMPORTANT:** In the "Main" tab, under "Actions", click the "All unprotected pages" radio button. This button erases previous network association information.
6. Click on the "Browse" button and navigate to the location of the binary files as described in 节 3.1.2.1 (see 图 9).

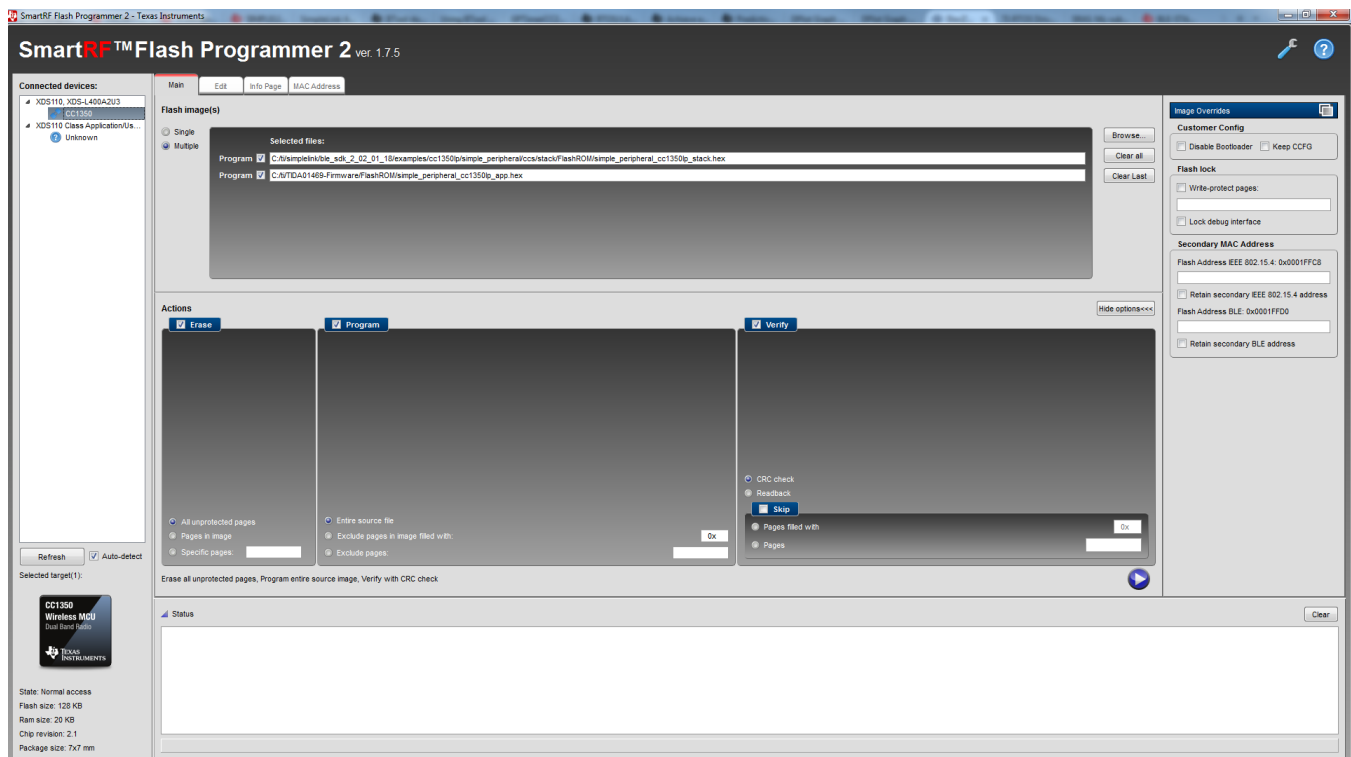


图 9. SmartRF Flash Programmer 2 Configuration

7. Click on the blue circle play button to flash the firmware image onto the sensor. The status bar on the bottom of SmartRF Flash Programmer 2 will show if flashing the image was successful.

3.1.2.3 Loading Firmware Using CCS

Follow these steps to program with CCS:

1. Download `simple_peripheral_cc1350lp_stack` by selecting the `simple_peripheral_cc1350lp_stack` project as the active project, and choosing Run → Debug.
2. Choose Run → Terminate to stop the debug.
3. Download `simple_peripheral_cc1350lp_app` by selecting the `simple_peripheral_cc1350lp_app` project as the active project, and choosing Run → Debug.

注: The preceding steps are needed only for the initial download, and whenever the stack project is modified. As long as the stack project is not modified, the only required steps are:

1. Build the application.
 2. Download the application.
-

3.1.2.4 Configuring BTool

Follow these steps to set up BTool to act as a central device and communicate with the reference design:

1. Obtain a CC13xx or CC26xx device that can connect to a computer using a USB cable (either a LaunchPad or a SmartRF board) and can run TI's BLE SDK.
2. Plug the device into a computer using the provided USB cable.
3. Flash the device with the `host_test` project, found in the `Examples` folder of the SDK.
4. Run BTool, which can be found in the `Tools` folder of the SDK.
5. In BTool, connect to the correct port corresponding to the device that is connected through USB.

A more detailed description of using BTool can be found in the [BTool User's Guide](#)

注: This design guide is written specifically for the CC2640R2 LaunchPad, but very similar steps are required to use other platforms.

3.1.2.5 Running the Firmware

To gather motor data, process it, and send it out over a Bluetooth low energy connection, follow these steps:

1. Disconnect all jumpers from the CC1350 LaunchPad. This prevents the debugging and power interface of the board from unnecessarily drawing high current when the reference design is running on a coin cell battery. See [节 3.1.1.1](#) for details.
2. Attach the CC1350 LaunchPad to the TIDA-01469 board using four screws and four hex nuts and the mounting holes in each corner of both boards. The following parts are used to test this design:
 - NY PMS 440 0075 PH
 - NY HN 440

Before using the screws, make sure that the boards are correctly connected using the pin connectors.

3. Make sure that a coin cell battery has been inserted into the battery holder. Do not connect the J3 jumper on the design board until the program is ready to start.
4. Attach a small magnet to the battery. This magnet couples the reference design to the motor to accurately detect the vibrations in the motor.
5. Connect the J3 jumper on the design board, and use the magnet to attach the reference design to the motor.
6. The program will now begin. For demo purposes, the reference design wakes up after 5 seconds to take measurements, process the data, and begin sending out Bluetooth low energy advertisements. Every time the reference design goes back into standby, this wake-up interval is the amount of time

after which the design will wake up to sample data and take the FFT. The code also has an option for a wake-up interval of 8 hours, and any other value can be chosen.

7. Once the device is advertising, the device running BTool can be used to connect to the reference design. Follow the BTool User's Guide described in [节 3.1.2.4](#) for detailed instructions on how to do this.
8. Once connected, BTool can be used to request the desired data from the reference design. [表 4](#) shows what values to write to characteristic 1 to request each block of sample and FFT data.

表 4. Values for Requesting Data

CHARACTERISTIC 1 VALUE	DATA TO REQUEST
5D	200 sampled data points
5E	First 200 FFT points
5C	Second 200 FFT points
5B	Third 200 FFT points
5A	Fourth 200 FFT points
59	Fifth 200 FFT points

9. Once notifications have been enabled for characteristic 5 (by writing a value of 1 to characteristic 5's Client Characteristic Configuration Descriptor), each group of 200 points will be sent to the device running BTool in groups of 20 notifications. The BTool User's Guide describes this process.
10. To tell the design board to go back to standby and wait for the next time to sample data, use BTool to write any non-zero value to characteristic 3.

3.2 Testing and Results

3.2.1 Test Setup

The Motor Monitoring Using Wireless Vibration Sensor Reference Design has been characterized to support all of the critical specifications for this subsystem. The following sections describe the test setup for these measurements, including the equipment used and the test conditions unless otherwise noted.

3.2.1.1 Power Consumption

The power consumption measurements for this reference design are critical in estimating battery life. Measurements of supply current are performed on the reference design hardware.

The majority of the time, the system operates in a very low-power consumption state, often only consuming microamps of current. The test setup for measuring these small currents is illustrated in [图 10](#).

The resolution setting of the Agilent 34410A 6½ digit multimeter can place a limit on the amount of instantaneous current flowing to the device under test (DUT). This limit can become a problem because at different points during normal operation the current jumps from the microamp range to the milliamp range. For example, when powering on the board, there is an initial inrush of current to the board. Generally, a resolution of 10 mA is enough to prevent any issues with current limits.

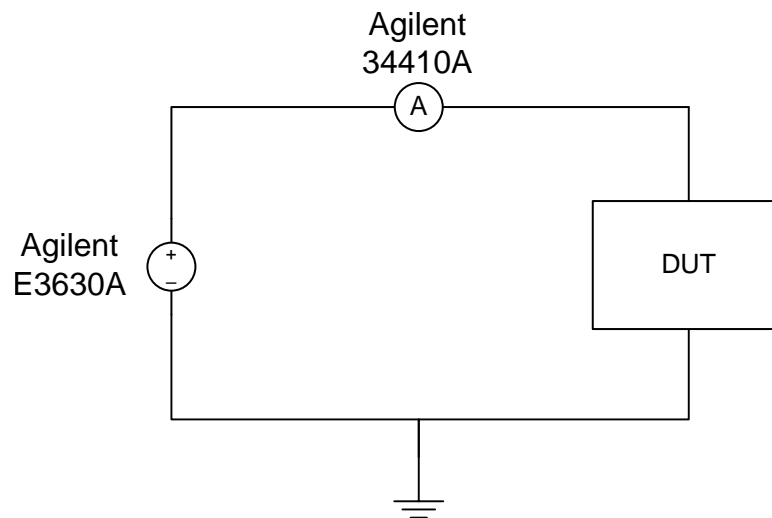


图 10. Test Circuit Used for Measuring Small Currents

The system also experiences peaks of high current such as those generated during radio transmission. Measuring these intervals involves using a voltage probe that interfaces to an oscilloscope, which can then be used to trigger on the high current events. The voltage is measured across a small sense resistor, which allows the current to be calculated. This setup is illustrated in [图 11](#).

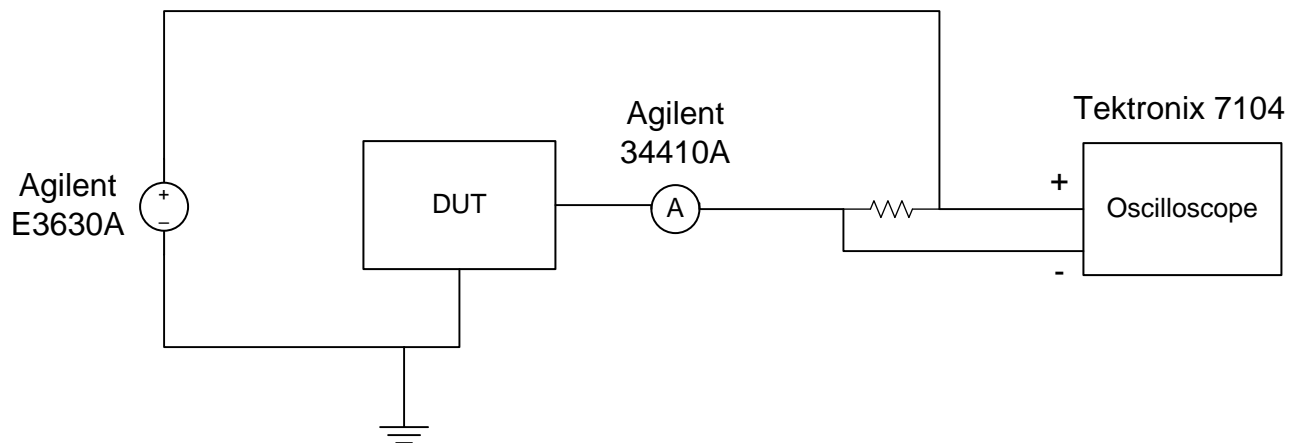


图 11. Test Circuit Used for Measuring Supply Current During High-Peak Currents

3.2.1.2 Signal Chain Testing

The accelerometer is taken off of this design board so that a function generator could be used to give a known sine wave input to the AFE. This setup is shown in 图 12. This test shows that the AFE provides the correct amplified signal to the ADC, and that the ADC and MCU properly samples the signal and take the FFT. An offset of 1.7 V is used with the function generator to match the reference voltage that was provided to the accelerometer. An amplitude of 20 mV is used, and the frequency is varied throughout the range of the reference design (50 Hz to 10 kHz). Because of the output limitations of the function generator, a voltage divider is used to get a signal amplitude that is low enough to prevent attenuation of the amplified signal.

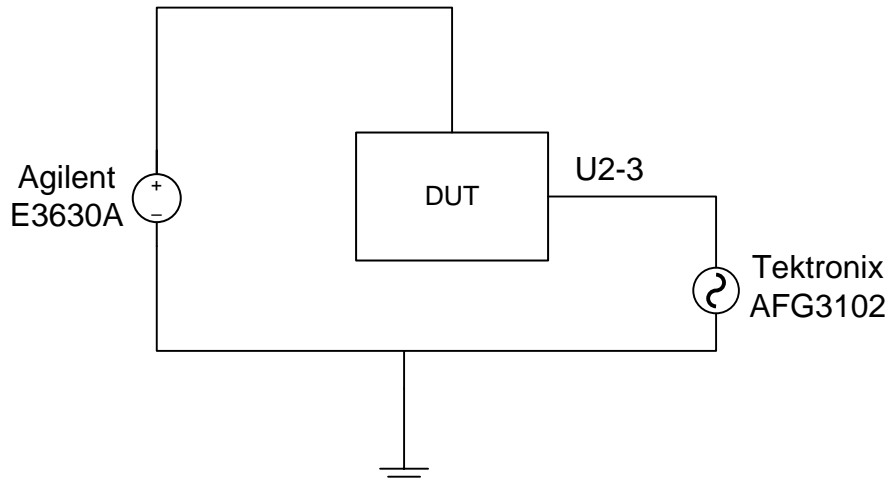


图 12. Setup With Accelerometer Replaced by Function Generator

3.2.1.3 Motor Vibration Sensing

An actual industrial motor is used to get motor vibration test data. As described in 节 3.1.2.5, a magnet attached to the battery on the design board couples the reference design to the motor. 图 13 shows the motor, and 图 14 shows how the reference design is attached to it. Sample and FFT data are then obtained as described in 节 3.1.2.5.

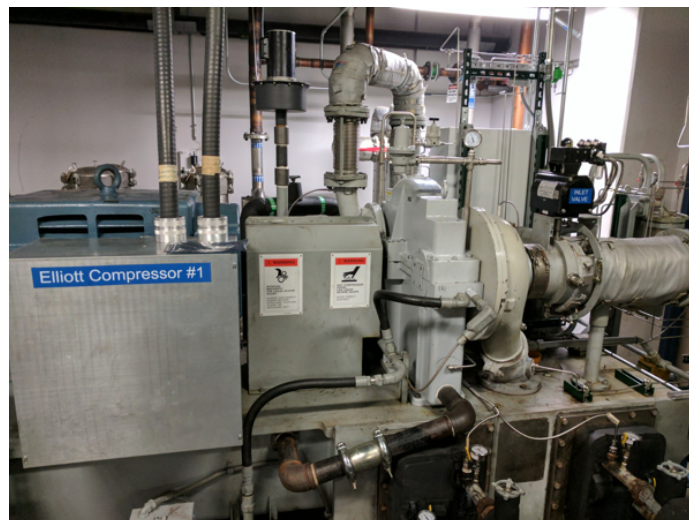


图 13. Motor Setup



图 14. Reference Design Coupled to Motor

3.2.1.4 Wireless Range

The range of the wireless 2.4-GHz Bluetooth low energy transmission is measured using one CC1350 LaunchPad (as part of the reference design) and a Google Pixel with the BLE Scanner app. The reference design is set to send out advertisement packets with 100-ms advertising intervals. The phone is then moved further away from the reference design and checked to see if the reference design could still be seen advertising. The phone is always in direct sight of the reference design. The distance at which packets are no longer received are then measured.

3.2.2 Test Results

注: Unless otherwise noted, the test data in the following sections are measured with the system at room temperature. All of the measurements in this section are measured with calibrated lab equipment.

3.2.2.1 Power Characterization

Because the primary purpose of this reference design is to showcase a battery-powered wireless sensor, characterization of the power consumption of the system is critical.

This reference design remains primarily in the standby state, which is the default state. It is critical that the power consumption of this state remain as low as possible such that the battery life of the system can be maximized. In this state, the CC1350 receives power, but will go into its standby mode to minimize power consumption. The TPS22860 load switch is turned off to cut off power completely to the op amp, ADC, VREF, and boost converter in the analog input stage.

表 5 shows the average current consumption of the entire system when it is operating in the standby mode. The current consumption is characterized across different battery voltages. As expected, the current consumption increases at the lower voltage ranges because the internal DC-DC of the CC1350 must recharge the bypass capacitors more often to maintain a constant supply voltage. For battery life calculations, the average current is calculated over the range of battery voltages from 2.4 to 3.6 V. The average current for standby mode in these voltage ranges is 879.5 nA.

表 5. Average Current Consumption Across Battery Voltage in Standby Mode

VBATT (V)	AVERAGE SYSTEM CURRENT (nA)
3.6	801
3.3	832
3.0	853
2.8	885
2.6	932
2.4	974

In addition to the standby state, this reference design consumes varying amounts of power when it is acquiring samples from the ADC, applying the FFT to these samples, sending out Bluetooth low energy advertisements, and sending out data over a Bluetooth low energy connection. A small sense resistor is used to measure the small amount of current being drawn by the system during each of these periods, and this was confirmed using a digital multimeter. This process is described in 节 3.2.1.1.

The first state of this reference design after it exits standby mode is sampling data from the ADC through SPI and performing an FFT on this data. 图 15 shows the power characterization of the design during this state.

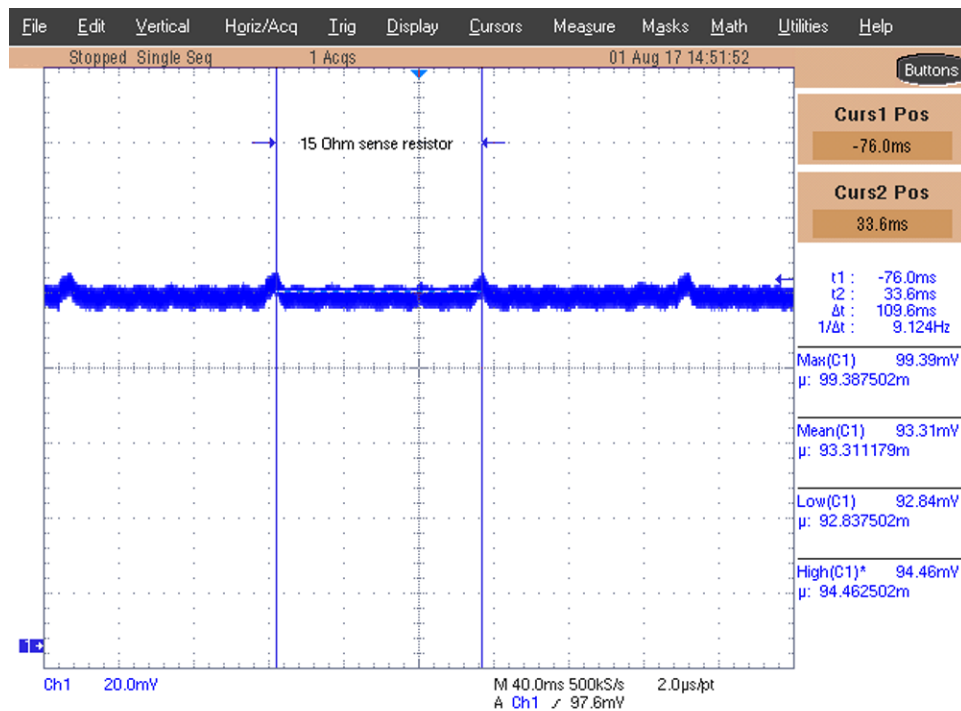


图 15. ADC Sampling and FFT Power Characterization

The average voltage is 93.31 mV, so dividing by the resistance of the sense resistor gives an average current of 6.221 mA. This average current is over a period of approximately 109.6 ms. The larger pulses correspond to the FFT, and the smaller pulses in between correspond to the ADC sampling through SPI. Only one period is actually performed by this design each time that it wakes up to take data. A loop is used around the ADC sampling and FFT to make it easier to visualize.

图 16 shows the equivalent current waveform for a Bluetooth low energy advertisement. The voltage readings are averaged over the time of the packet pulse time and a 15-Ω sense resistor is used.

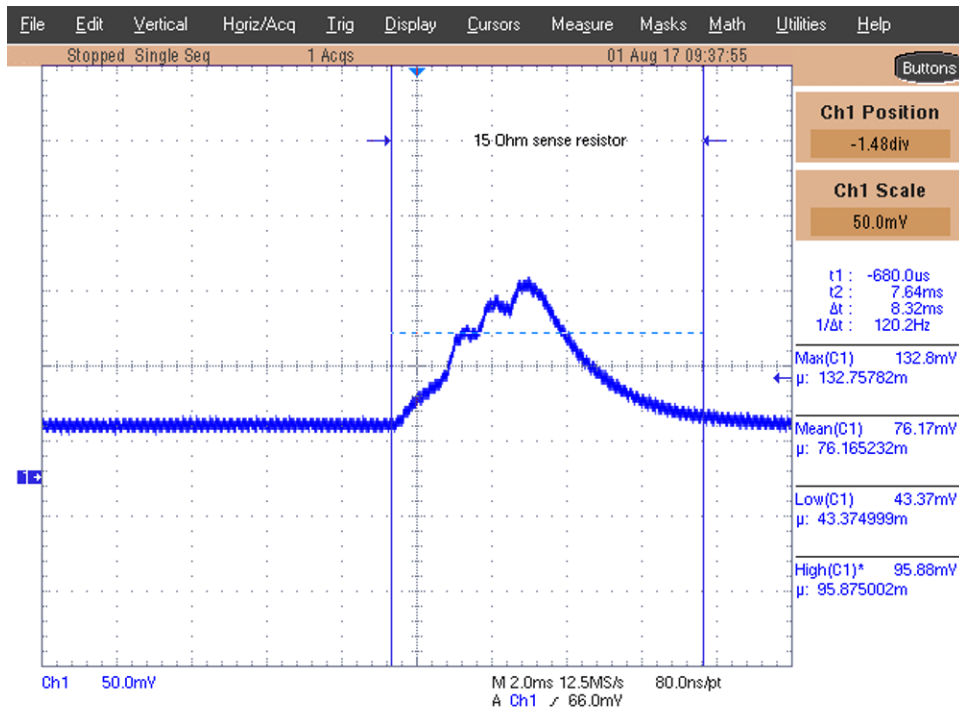


图 16. Advertising Packet Power Characterization

The average voltage is 76.17 mV, so dividing by the resistance of the sense resistor gives an average current of 5.078 mA. This average current is over a pulse width of approximately 8.32 ms.

This reference design sends out advertisement packets every 100 ms, as shown in 图 17. The tiny pulses seen between the advertising packet transmissions are the internal DC-DC converter of the CC1350 charging up for the next transmission.

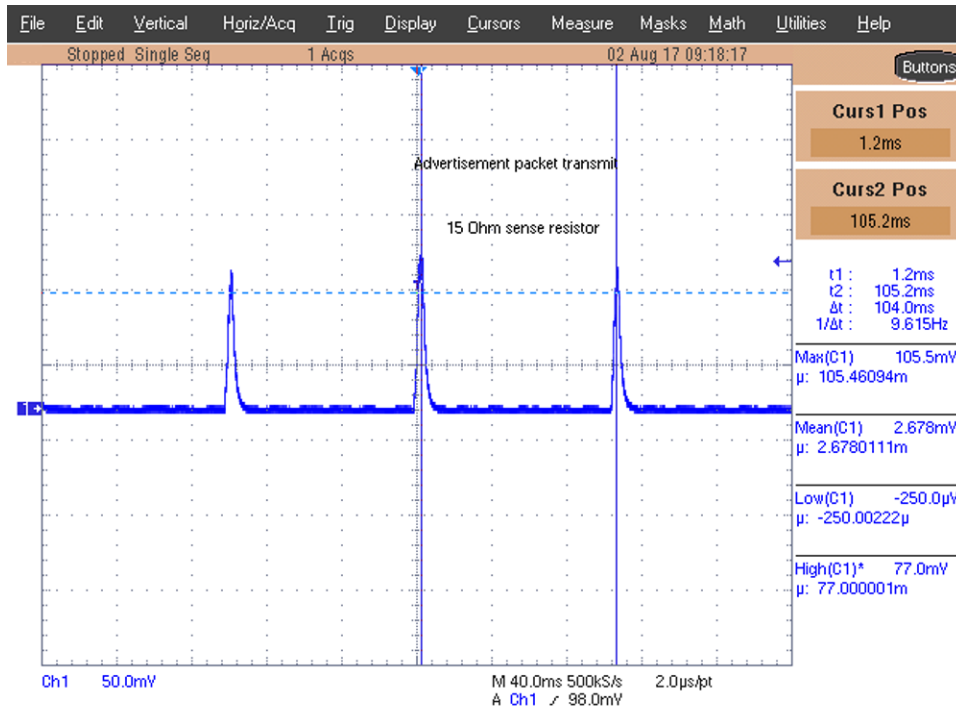


图 17. Advertisement Transmit Period

Once the device connects to another Bluetooth low energy device, the current consumption looks slightly different. 图 18 shows what the waveform looks like for each connected pulse. These connection events are sent to maintain the connection. The maximum voltage is slightly lower than that of the advertisement packets, and the pulse length is shorter.

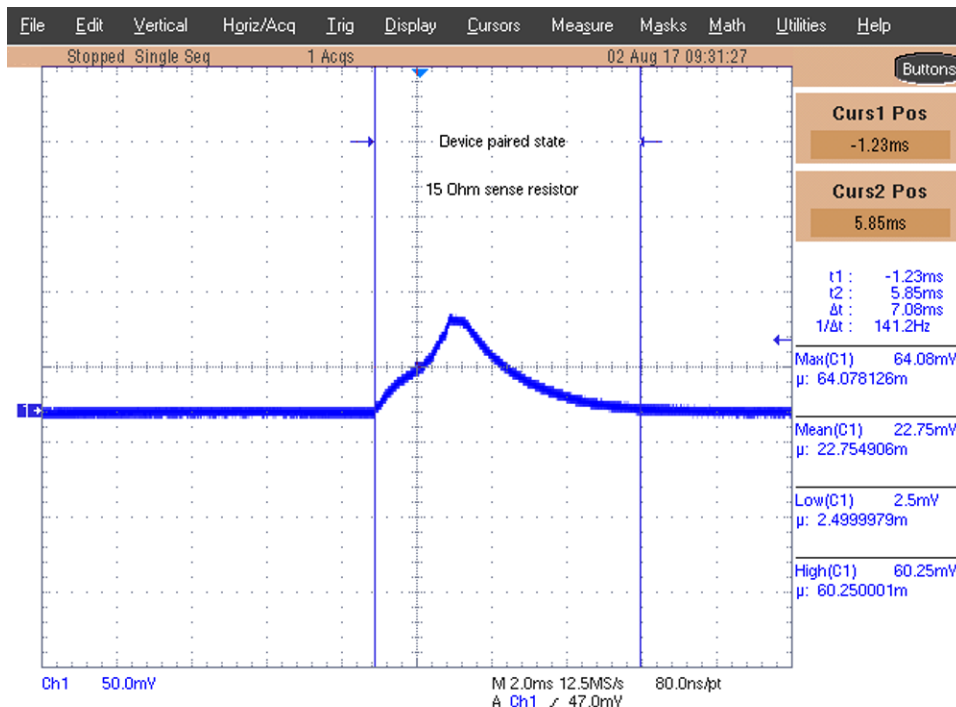


图 18. Connection Packet Power Characterization

The average voltage is 22.755 mV, so dividing by the resistance of the sense resistor gives an average current of 1.517 mA. This average current is over a pulse width of approximately 7.08 ms. 图 19 shows the period of the device when it is in a connection. The connection interval is 100 ms.

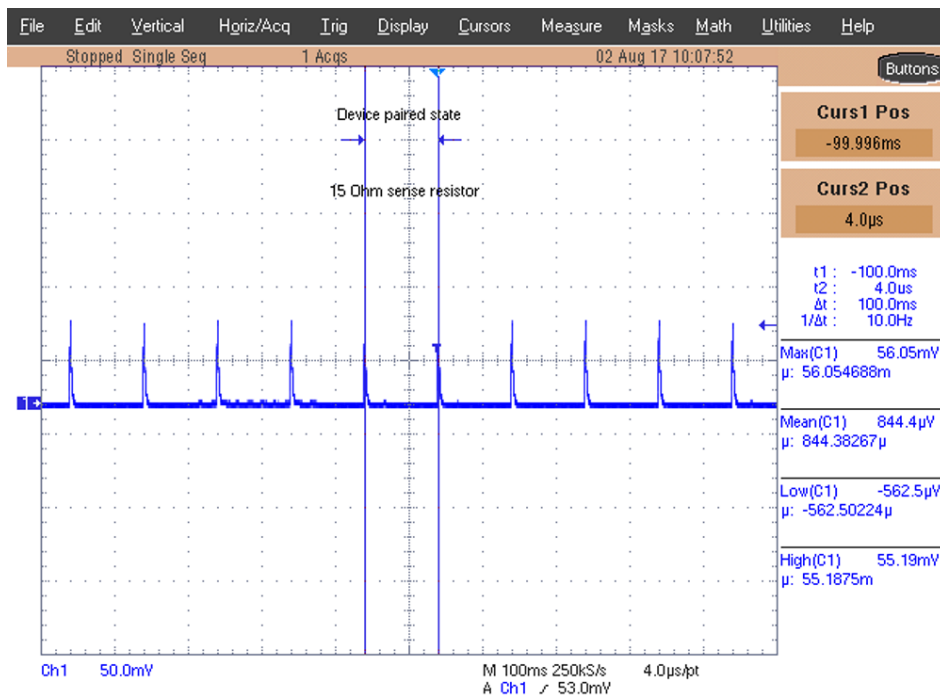


图 19. Connection Packet Transmit Period

图 20 shows the power characterization of notification pulse. Each pulse corresponds to the transmission of 20 bytes of data in a single notification.

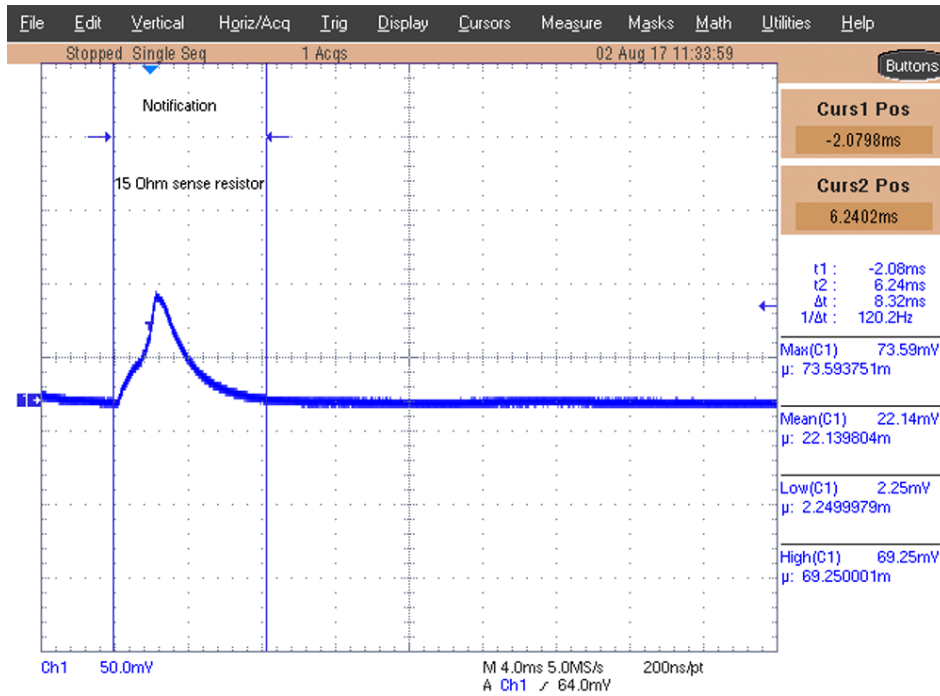


图 20. Notification Power Characterization

For BTool to be able to process the notifications before filling its buffer, a delay is required between each notifications. A 20-ms delay is used, so one of these pulses are seen every 20 ms, meaning there are five pulses for each connection period.

3.2.2.2 Battery Life Calculations

The main parameters that affect the estimated battery life of the entire system are:

- Capacity rating of the battery
- Average standby-state current consumption
- Standby-state duration
- Average sampling and FFT current consumption
- Sampling and FFT duration
- Average advertising packet current consumption
- Advertising duration
- Average connection and data transmission current consumption
- Connection and data transmission duration

公式 9 describes the estimated battery life of the system.

$$\text{Battery Lifetime (yr)} = \frac{\text{Battery Capacity (mAh)}}{\left(\frac{I_{\text{Standby}}^{(\text{mA})} \times t_{\text{Standby}}^{(\text{s})} + I_{\text{Sampling + FFT}}^{(\text{mA})} \times t_{\text{Sampling + FFT}}^{(\text{s})} + I_{\text{Advertising}}^{(\text{mA})} \times t_{\text{Advertising}}^{(\text{s})} + I_{\text{Data}}^{(\text{mA})} \times t_{\text{Data}}^{(\text{s})}}{t_{\text{Total}}^{(\text{s})}} \right)} \times \frac{1 \text{ year}}{8760 \text{ hours}} \times \text{Derating Factor} \tag{9}$$

Because this design involves a connection being established between two devices and data being sent over that connection, the exact timing with which the connection is established and data is requested affects exactly how long the reference design operates in each power consumption state. For the battery calculations of the device, the following assumptions are made:

- An 8-hour interval is used between wakeup events. This interval is the amount of time that the reference design is in standby mode before waking up to sample data.
- A connection is established after one advertisement packet is received by the central device.
- 1000 points of FFT data are sent in five groups that each consisted of 20 10-sample notifications.
- After receiving all of the data, the central device immediately sends a byte to the reference design, indicating that the design must go back into standby mode and wait for the next wakeup event.

With these assumptions considered, 公式 9 can be used to calculate the battery life as 25.112 years.

表 6 and 图 21 show the battery life estimates for wakeup intervals ranging from 8 hours down to 10 minutes. This is important because, although larger intervals are more useful for low-power periodic monitoring, a smaller interval may be desired when a motor is showing minor signs of damage so that more frequent monitoring can detect when the damage warrants maintenance.

表 6. Battery Lifetime versus Wakeup Period

WAKEUP PERIOD (MIN)	BATTERY LIFE (YEARS)
480	25.112064790
240	23.248417910
120	20.244317780
60	16.088422360
30	11.408638870
20	8.840325148
10	5.281879421

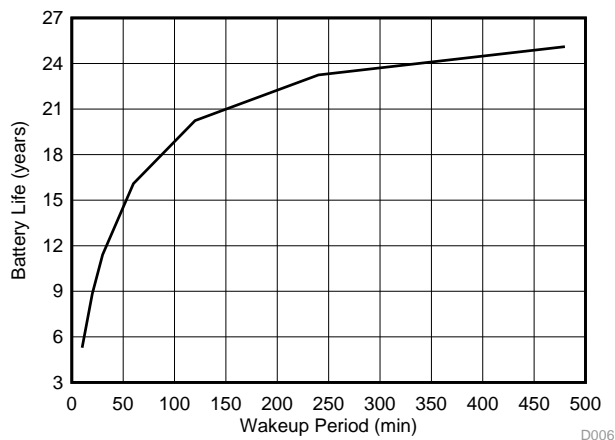


图 21. Battery Lifetime versus Wakeup Period

3.2.2.3 Signal Chain Testing

As described in 节 3.2.1.2, a function generator is used to give a know signal to the reference design to sample and take the FFT of. 图 22 shows the data that was sampled and sent out over Bluetooth low energy for a 1-kHz sine wave.

图 23 显示了从 1-kHz 正弦波中采样的数据的 FFT。

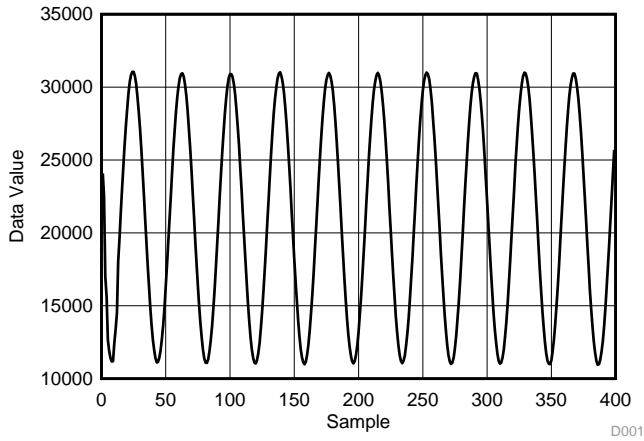


图 22. 1-kHz 正弦波的采样数据

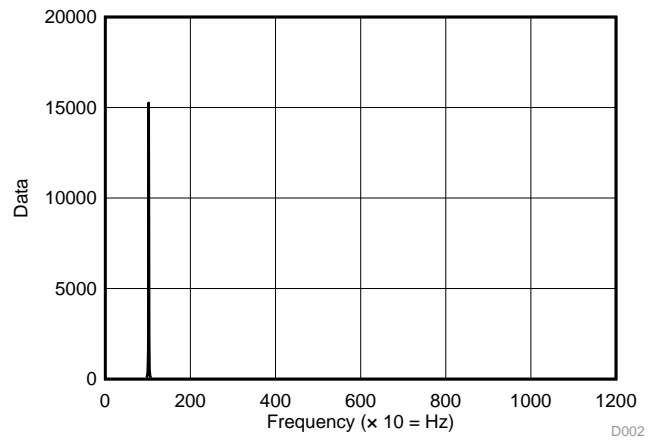


图 23. 从 1-kHz 正弦波中采样的数据的 FFT

因为进行了 2K FFT，所以有 1000 个唯一点。对于 20-kHz 采样频率，x 轴上的每个点都对应于 10 Hz。因此，对于 1-kHz 正弦波，预期在 100 处看到一个 FFT 峰值。图 23 显示这是实际情况，从而证实了 FFT 计算的准确性以及数据采样的准确性。

This process is repeated for a 5-kHz sine wave. The results are shown in 图 24 and 图 25.

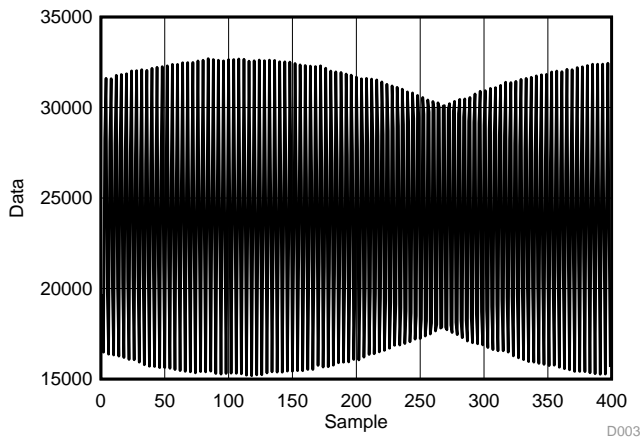


图 24. Sampled Data for 5-kHz Sine Wave

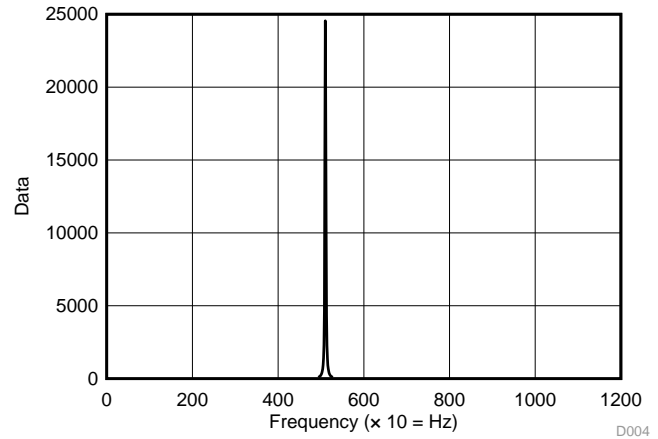


图 25. FFT of Data Sampled From 5-kHz Sine Wave

As described for the 1-kHz sine wave, each point on the x-axis for the FFT corresponds to 10 Hz, so expect to see a peak at 500. This is the case here, again confirming the accuracy of the sampling and FFT calculation. The sampled data plot shows less resolution than it did for the 1-kHz sine wave because the signal frequency is closer to the sampling frequency, but the FFT is still able to identify the frequency correctly.

3.2.2.4 Motor Vibration Sensing

The sampled data from the motor setup is shown in 图 26.

The periodicity of the data can be seen. Because of the multiple present frequencies, only 400 points are shown to increase readability. The FFT generated from this data is shown in 图 27.

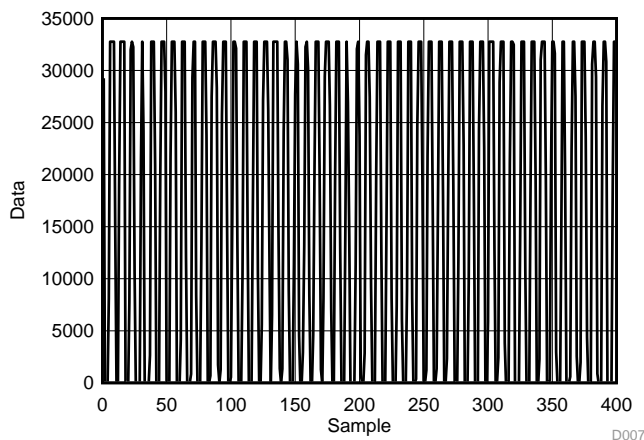


图 26. Motor Setup Sampled Data

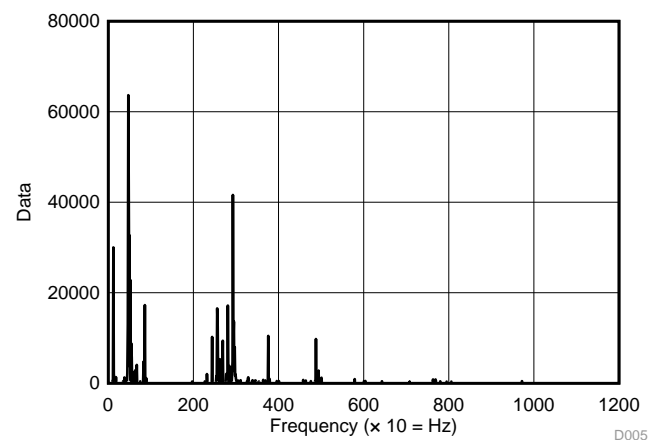


图 27. FFT From Motor Setup Sampled Data

Multiple FFT peaks can be seen, which correspond to the multiple harmonics that are present in an actual motor setup. Spectral data generated by the software that is driving the motor is compared to this FFT data to confirm the accuracy of the reference design's sampling and FFT calculation.

3.2.2.5 Wireless RF Range

The wireless RF range is measured to be about 72 meters in a typical office environment with a direct line of sight. The transmit power is set to 0 dBm, which is the default used by the Bluetooth low energy SDK. Radio performance varies in the end-equipment environment because of the number of obstructions in the RF transmit path reduces range. For full verification of the hardware transmitting characteristics of this reference design, further testing with end-equipment context is required.

4 Design Files

4.1 Schematics

To download the schematics, see the design files at [TIDA-01469](#).

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-01469](#).

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-01469](#).

4.4 Altium Project

To download the Altium project files, see the design files at [TIDA-01469](#).

4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-01469](#).

4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-01469](#).

5 Software Files

To download the software files, see the design files at [TIDA-01469](#).

6 Related Documentation

1. Texas Instruments, [Reverse Current/Battery Protection Circuits](#), Application Report (SLVA139)
2. Texas Instruments, [Coin cells and peak current draw](#), White Paper (SWRA349)

6.1 商标

SimpleLink, LaunchPad, MSP430, SmartRF, Code Composer Studio, TINA-TI are trademarks of Texas Instruments.

ARM, Cortex are registered trademarks of ARM Ltd.

Bluetooth is a registered trademark of Bluetooth SIG.

ULPBench is a trademark of Embedded Microprocessor Benchmark Consortium.

CoreMark is a registered trademark of Embedded Microprocessor Benchmark Consortium.

Energizer is a trademark of Energizer Brands, LLC.

IAR Embedded Workbench is a registered trademark of IAR Systems AB.

IEEE is a registered trademark of IEEE.

IMI Sensors is a registered trademark of PCB Group, Inc.

All other trademarks are the property of their respective owners.

7 About the Authors

NATHAN SIEGEL is a systems designer at Texas Instruments, where he is responsible for developing reference design solutions for the industrial segment. Nathan earned his bachelor of science (BS) in electrical engineering from the University of California, Los Angeles (UCLA).

GUSTAVO MARTINEZ is a senior systems architect at Texas Instruments where he is responsible for developing reference designs for industrial applications. Gustavo has ample experience developing system reference designs for the Smart Grid and home automation segments, which include high performance application processors, floating-point digital signal processors, and RF technology. Gustavo obtained his master of electrical engineering degree from the University of Houston and his bachelor of science in electrical engineering degree from the University of Texas at El Paso.

有关 TI 设计信息和资源的重要通知

德州仪器 (TI) 公司提供的技术、应用或其他设计建议、服务或信息，包括但不限于与评估模块有关的参考设计和材料（总称“TI 资源”），旨在帮助设计人员开发整合了 TI 产品的应用；如果您（个人，或如果是代表贵公司，则为贵公司）以任何方式下载、访问或使用了任何特定的 TI 资源，即表示贵方同意仅为该等目标，按照本通知的条款进行使用。

TI 所提供的 TI 资源，并未扩大或以其他方式修改 TI 对 TI 产品的公开适用的质保及质保免责声明；也未导致 TI 承担任何额外的义务或责任。TI 有权对其 TI 资源进行纠正、增强、改进和其他修改。

您理解并同意，在设计应用时应自行实施独立的分析、评价和判断，且应全权负责并确保应用的安全性，以及您的应用（包括应用中使用的 TI 产品）应符合所有适用的法律法规及其他相关要求。您就您的应用声明，您具备制订和实施下列保障措施所需的一切必要专业知识，能够 (1) 预见故障的危险后果，(2) 监视故障及其后果，以及 (3) 降低可能导致危险的故障几率并采取适当措施。您同意，在使用或分发包含 TI 产品的任何应用前，您将彻底测试该等应用和该等应用所用 TI 产品的功能。除特定 TI 资源的公开文档中明确列出的测试外，TI 未进行任何其他测试。

您只有在为开发包含该等 TI 资源所列 TI 产品的应用时，才被授权使用、复制和修改任何相关单项 TI 资源。但并未依据禁止反言原则或其他法律授予您任何 TI 知识产权的任何其他明示或默示的许可，也未授予您 TI 或第三方的任何技术或知识产权的许可，该等产权包括但不限于任何专利权、版权、屏蔽作品权或与使用 TI 产品或服务的任何整合、机器制作、流程相关的其他知识产权。涉及或参考了第三方产品或服务的信息不构成使用此类产品或服务的许可或与其相关的保证或认可。使用 TI 资源可能需要您向第三方获得对该等第三方专利或其他知识产权的许可。

TI 资源系“按原样”提供。TI 兹免除对 TI 资源及其使用作出所有其他明确或默示的保证或陈述，包括但不限于对准确性或完整性、产权保证、无屡发故障保证，以及适销性、适合特定用途和不侵犯任何第三方知识产权的任何默认保证。

TI 不负责任何申索，包括但不限于因组合产品所致或与之有关的申索，也不为您辩护或赔偿，即使该等产品组合已列于 TI 资源或其他地方。对因 TI 资源或其使用引起或与之有关的任何实际的、直接的、特殊的、附带的、间接的、惩罚性的、偶发的、从属或惩戒性损害赔偿，不管 TI 是否获悉可能会产生上述损害赔偿，TI 概不负责。

您同意向 TI 及其代表全额赔偿因您不遵守本通知条款和条件而引起的任何损害、费用、损失和/或责任。

本通知适用于 TI 资源。另有其他条款适用于某些类型的材料、TI 产品和服务的使用和采购。这些条款包括但不限于适用于 TI 的半导体产品 (<http://www.ti.com/sc/docs/stdterms.htm>)、[评估模块](http://www.ti.com/sc/docs/sampters.htm)和样品 (<http://www.ti.com/sc/docs/sampters.htm>) 的标准条款。

邮寄地址：上海市浦东新区世纪大道 1568 号中建大厦 32 楼，邮政编码：200122
Copyright © 2017 德州仪器半导体技术（上海）有限公司