

TI Designs: TIDA-01575

Reference Design for Wireless Condition Monitor for Motors and Pumps Using Multi-Axis Vibration



Description

This reference design provides a non-invasive and non-disruptive method to monitor and assess motor health and includes both the analog front end (AFE) as well as the embedded application. The embedded application software configures the internal analog-to-digital converter (ADC) to sample the data as well as perform frequency analysis of the data. Additionally, the SimpleLink™ Software Development Kit (SDK) is used in this embedded application to enable both wired and wireless connectivity (*Bluetooth® low energy*). With the SimpleLink SDK, the user can easily migrate the design to Wi-Fi® and sub-1G connectivity. This solution of AFE, embedded processing, and wireless connectivity addresses the costly challenge of motor maintenance and is a foundation to implement predictive maintenance systems. By predicting the life of a motor, an operator can optimize maintenance schedules of often costly and large motors and pumps while improving the operational lifetime of the production lines using these motors.

Resources

TIDA-01575		Design Folder
MSP-EXP432P401R	BOOSTXL-CC2650MA	Tool Folder
TPS22860	LMP7702	Product Folder



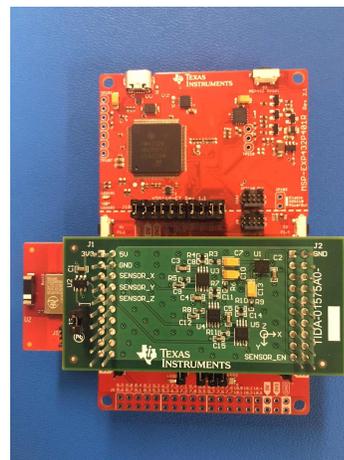
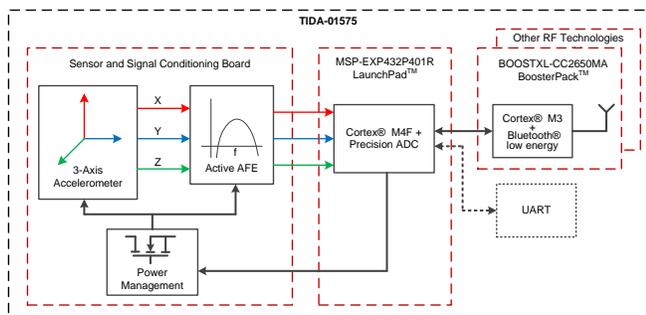
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Features

- Single Solution Provides Vibration Measurement in Three Axes With MEMS Analog Accelerometer
- Most Precise Integrated ADCs Capable of Capturing Vibration With Resolution of 0.01 g
- Simple Software Migration Between Wired Serial, Wi-Fi, Bluetooth 5, Sub 1 GHz With SimpleLink Platform and With Pre-Certified RF Modules From TI
- Extended Multiyear Battery Life With Lowest-Power Integrated ADC and Efficient Scalable FFT Processing
- Edge Processing to Reduce System Power and Lower Network Bandwidth
- Modular BoosterPack™ Plug-in Module Design for Easy Integration and Development With LaunchPad™ Development Kit Ecosystem for Prototyping

Applications

- [Motor Diagnostics and Monitoring](#)
- [Vibration Monitor Sensor](#)
- [HVAC Motor Condition Monitoring](#)





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1 System Description

Motor maintenance has traditionally been a tedious, inefficient and costly process which requires manufacturers to periodically shut down the motors on their production line to perform maintenance checks. These maintenance checks are often a time-intensive process which can affect production capability and are absolutely detrimental to processes that must run continuously.

This reference design provides a non-invasive and non-disruptive method to monitor and assess motor health and includes both the analog front end (AFE) as well as the embedded application. The embedded application software configures the internal analog-to-digital converter (ADC) to sample the data as well as perform frequency analysis of the data. Additionally, the SimpleLink™ Software Development Kit (SDK) is used in this embedded application to enable both wired and wireless connectivity (*Bluetooth® low energy*). With the SimpleLink SDK, the user can easily migrate the design to Wi-Fi® and sub-1 GHz connectivity. This solution of AFE, embedded processing, and wireless connectivity addresses the costly challenge of motor maintenance and is a foundation to implement predictive maintenance systems. By predicting the life of a motor, an operator can optimize maintenance schedules of often costly and large motors and pumps while improving the operational lifetime of the production lines using these motors.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Sensor type	Three-axis accelerometer	—
Resolution of sensor	220 mV/g	—
Sampling frequency per channel	24 kHz	Adjustable in software
Number of FFT points	512 per axis	Adjustable in software
Signal conditioning 3-dB bandwidth	424 Hz	—
Signal conditioning full bandwidth	6.4 kHz	—
Maximum signal conditioning gain	38 dB at 100 Hz	—
Sampling interval	1 min to 24 hours in increments of 1 min	Adjustable in software
Power consumption with serial COM port	31.7 μ A	Sampling every 1 hr
Power consumption with <i>Bluetooth® low energy</i>	303.347 μ A	Sampling every 1 hr with 100-ms auto-advertisement
Power consumption with <i>Bluetooth® low energy</i>	56.597 μ A	Sampling every 1 hr with 1-s auto-advertisement
Battery life	15.904 years	Default configuration of measurement once every 4 hrs and reporting over serial link

2 System Overview

2.1 Block Diagram

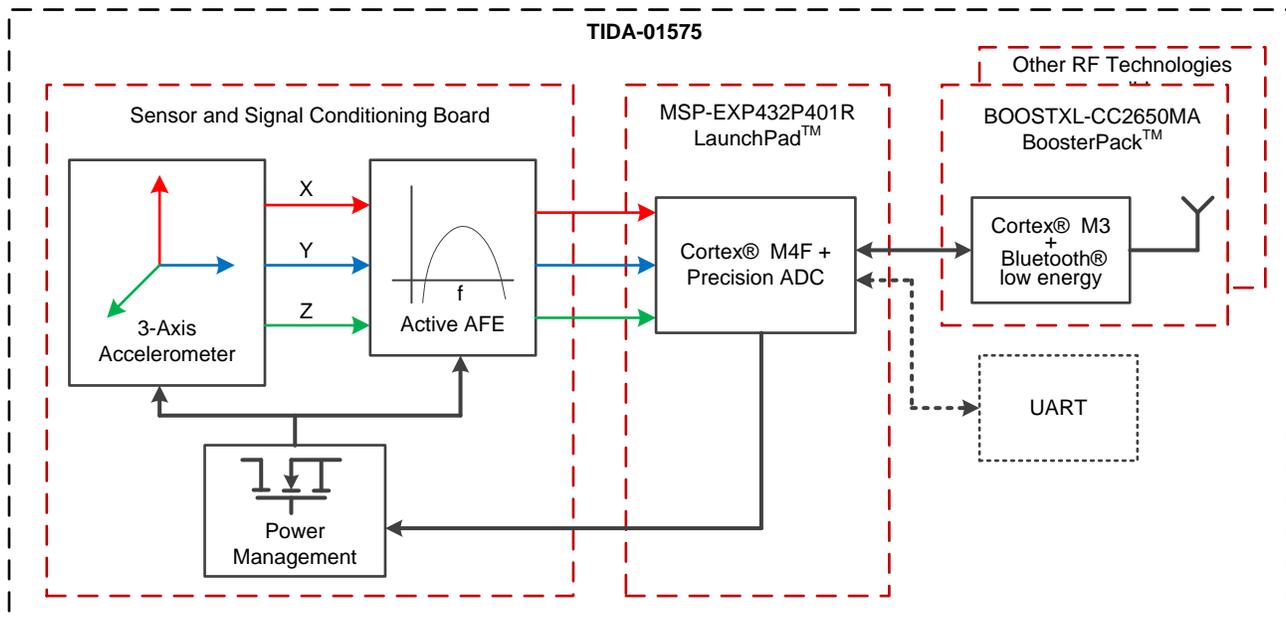


Figure 1. TIDA-01575 Block Diagram

2.2 Highlighted Products

2.2.1 SimpleLink™ MSP432P401R MCU

The SimpleLink MSP432P401R device is an ultra-low-power, 32-bit, ARM®Cortex®-M4F-based microcontroller (MCU). The MSP432P401R MCU features a precision analog-to-digital converter (ADC) and a wide range of analog, timing, and communication peripherals. The MSP432P401R device is optimized to be the wireless host MCU for a wide range of connected applications. The device includes 256KB of flash main memory and 64KB of SRAM. With a clock system of up to 48 MHz, the large amount of memory available makes the MSP432P401R MCU ideal for applications that require efficient data processing with enhanced low-power operation. [Figure 2](#) shows the functional block diagram of the MSP432P401R MCU.

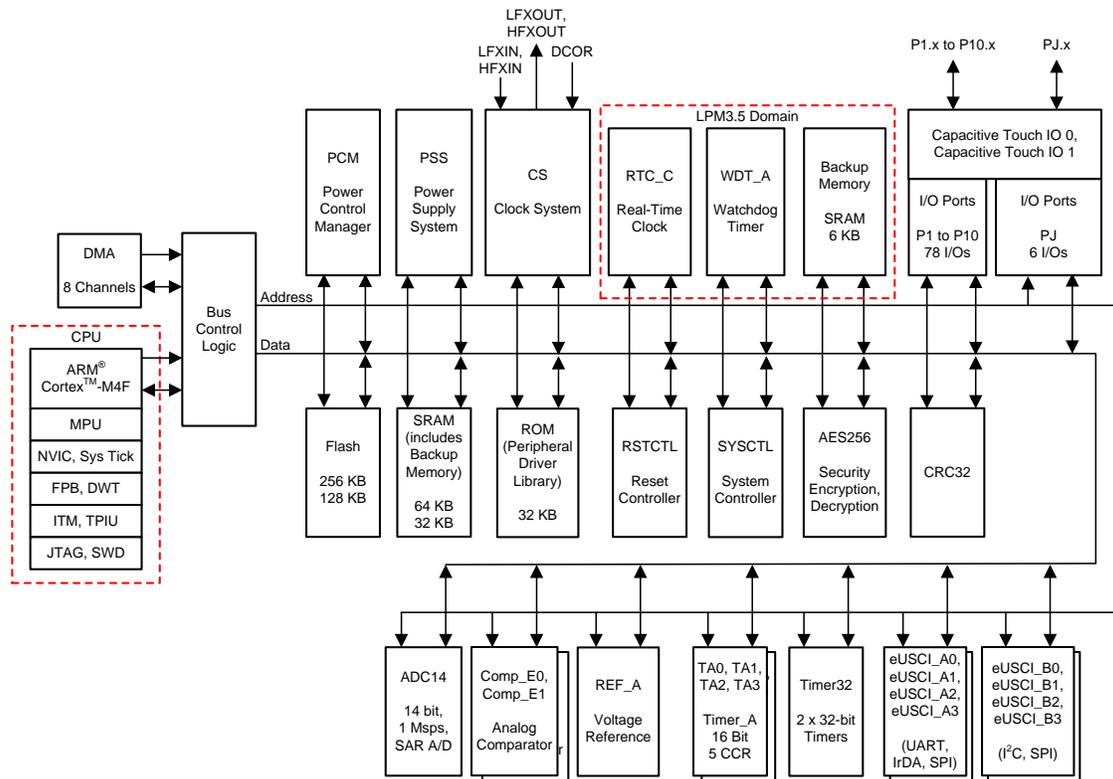


Figure 2. SimpleLink™ MSP432P401R MCU Block Diagram

Features:

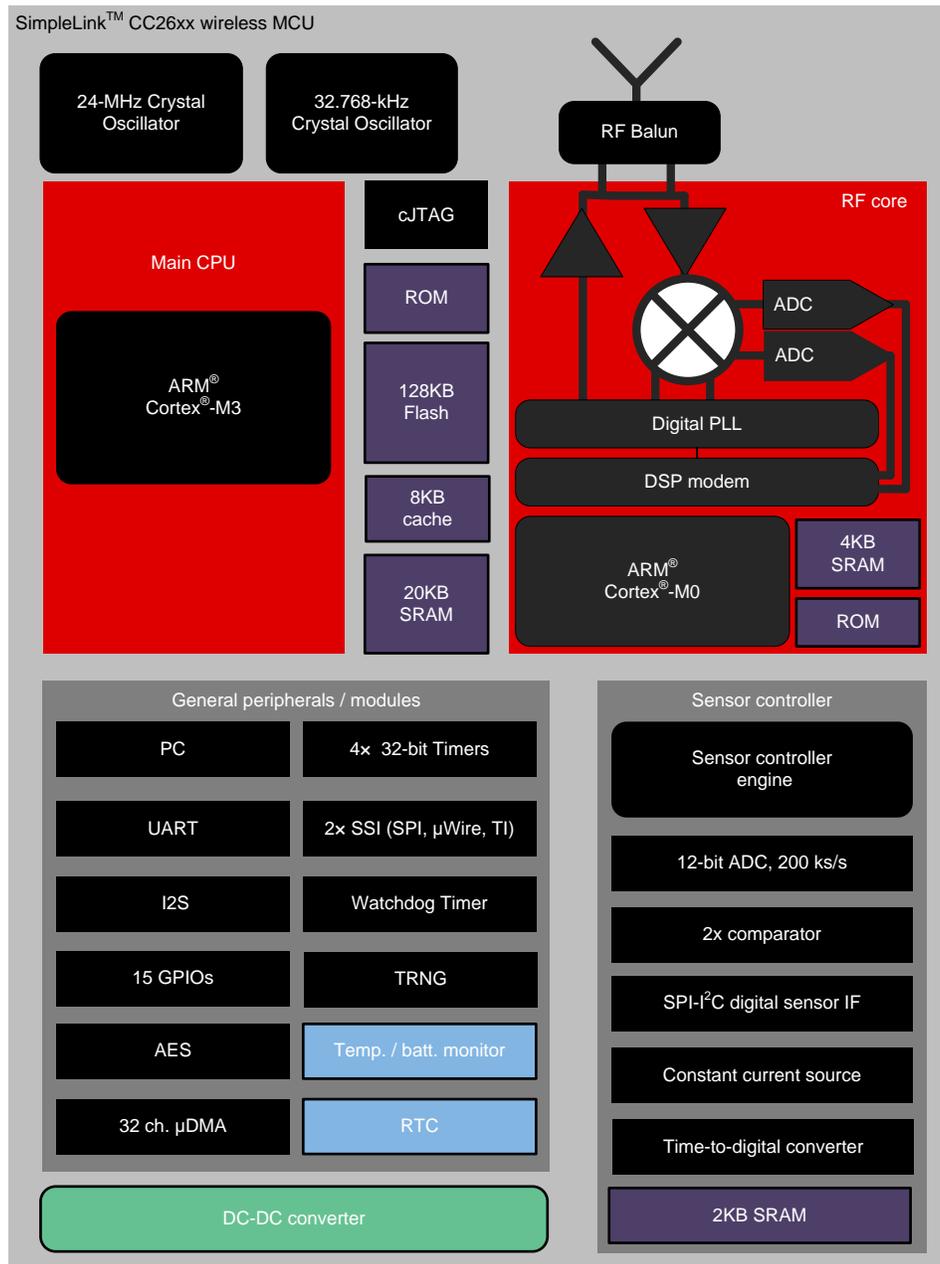
- 32-bit ARM Cortex-M4F CPU with a floating point unit and a memory protection unit
- Flexible clocking with frequency up to 48 MHz
- 256KB of flash main memory, 16KB of flash information memory, 64KB of SRAM, and 32KB of ROM programmed with SimpleLink MSP432 SDK driver libraries
- Eight-channel direct memory access (DMA)
- Four 16-bit timers, two 32-bit timers, and a real time clock (RTC) with calendar and alarm functions
- Four eUSCI-A modules for universal asynchronous receiver/transmitter (UART), Infrared Data Association (IrDA), or serial peripheral interface (SPI)
- 48 I/Os with interrupt and wake-up capability
- 1-MSPS precision 14-bit successive approximation (SAR) ADC
- 128-, 192- and 256-bit Advanced Encryption Standard (AES) encryption and decryption accelerator with a 32-bit hardware cyclic redundancy check (CRC) engine

2.2.2 SimpleLink™ CC2650 2.4-GHz Multi-Standard Wireless MCU

The SimpleLink CC2650 2.4-GHz multi-standard MCU is an ARM Cortex-M3 MCU with wireless communication peripherals targeting 2.4-GHz ultra-low-power applications. The device includes 128KB of system flash memory, an 8KB SRAM cache, and 20KB of ultra-low-leakage SRAM. The architecture features very-low current draw when the radio frequency (RF) and MCU domains are active, and a low-power mode that reduces current consumption further to enable long battery life, particularly within applications powered by coin-cell batteries. The memory capacity and the low current draw are designed for battery-powered Internet-of-Things (IoT) applications.

The SimpleLink *Bluetooth® low energy* CC2650 BoosterPack plug-in module offers an expedited way to provide an integrated hardware solution without having to develop a new hardware board, integrate an antenna, and obtain approval from regulatory agencies.

Figure 3 shows the functional block diagram of the CC2650 MCU. The CC2650 MCU functions as a simple network interface to the entire system. The CC2650 MCU has an ARM Cortex-M3 core, which is a sensor core for running peripherals while the CPU is in a low-power mode, and a fully integrated RF front-end radio with an additional Cortex-M0 to control the RF front end. The CC2650MODA device used in the hardware stack has a larger architecture because it supports multiple wireless standards, integrates an antenna, and is pre-certified for following radio standards: Federal Communications Commission/Industry Canada (FCC/IC), Conformité Européenne (CE), and Association of Radio Industries and Businesses (ARIB).



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Figure 3. SimpleLink™ CC2650 MCU Block Diagram

2.2.3 LMP7702

The LMP7702 comprises dual, low-offset-voltage, rail-to-rail input and output precision amplifiers, each with a CMOS input stage and a wide supply voltage range. The LMP7702 is part of the precision amplifier family of LMP™ integrated circuits and is ideal for sensor interface and other instrumentation applications.

The specified low-offset voltage of less than $\pm 220 \mu\text{V}$, along with the specified low input bias current of less than $\pm 1 \text{ pA}$, make the LMP7702 ideal for precision applications. The LMP7702 are built using VIP50 technology, which allows the combination of a CMOS input stage and a 12-V common-mode and supply voltage range. This makes the LMP7702 ideal for applications where conventional CMOS parts cannot operate under the desired voltage conditions.

The LMP7702 has a rail-to-rail input stage that significantly reduces the common-mode rejection ratio (CMRR) glitch commonly associated with rail-to-rail input amplifiers. This reduction is achieved by trimming both sides of the complimentary input stage, thereby reducing the difference between the NMOS and PMOS offsets. The output of the LMP7702 swings within 40 mV of either rail to maximize the signal dynamic range in applications that require low supply voltage.

2.2.4 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 TPS22860 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 six-pin SOT-23 and SC70 packages. The device is characterized for operation over the free-air temperature range of -40°C to 85°C .

2.3 System Design Theory

This section details the individual software components developed for the vibration analysis and data transmission from the host MCU through either the serial communication port or the wireless MCU over *Bluetooth low energy*. The application creates individual tasks for sampling the data and transmitting the data.

2.3.1 Vibration Capture

The application creates a task (*vibrationTask*) for vibration capture. The task handles the initialization of the ADC channels for a timer-triggered sampling with 14-bit resolution. The timer A1 is configured for generating the trigger to the ADC module. The trigger rate for the timer is set as 72 kHz because there are three channels to sample, each with a sampling rate of 24 kHz. [Table 2](#) shows the channel mapping used in the ADC for sampling the three-axis accelerometer

Table 2. Vibration Capture Channel Mapping

DEVICE PORT	ADC CHANNEL	ADC MCTL MAPPING	ACCELEROMETER AXIS
P6.1	A14	MCTL0	X-axis
P4.0	A13	MCTL1	Y-axis
P4.2	A11	MCTL2	Z-axis

The define *ADCBUFFERSIZE* in the *vibrationCapture.h* file is used to define the number of samples of ADC channel data to be captured. On acquiring the *ADCBUFFERSIZE* samples for each axes, the RTOS stops the timer to prevent any further data sampling and calls the callback function *adcBufCallback* for processing the data.

2.3.2 Vibration Analysis

The vibration analysis section of the application is invoked after the task completes the vibration capture phase. An understanding of certain concepts is necessary before going into the sequence of operations.

The fast Fourier transform (FFT) of a signal involves transforming a time domain signal into frequency domain components. This transformation is characterized by FFT bins, with each bin being a discrete frequency component. The number of FFT bins and frequency step between each bin is a function of the sampling frequency and the number of samples. If the sampling frequency is F_{SAMPLING} , then, according to the Nyquist theory, the maximum frequency of a signal that can be captured is defined in Equation 1 as:

$$F_{\text{NYQUIST}} = F_{\text{SAMPLING}} / 2 \quad (1)$$

The Fourier transformation of N samples results in N/2 frequency bins; hence, the user can obtain the frequency resolution of each bin using Equation 2:

$$F_{\text{NYQUIST}} / (N / 2) \quad (2)$$

In the context of this reference design, where $N = 1024$ and $F_{\text{SAMPLING}} = 24$ kHz, the result is a frequency resolution of 23.4375 Hz per bin.

The software allows the user to change the sampling frequency and the number of samples captured, which can be used to further improve the frequency resolution. The define `ADC_CH_SAMPLING_FREQ` in the file `vibrationCapture.h` is used to define the sampling frequency of each channel. Such adjustments require a specific understanding of the motor, its operation parameters and the bandwidth of the accelerometer sensor, which are not within the scope of this design. However, by providing the required hooks in software, the user may be able to adjust the parameters as per the requirement of the application.

The predefine symbol `AVG_LOOP_COUNT` is provided as a mechanism to perform multiple sample acquisition and FFT conversions and then averaging the result to improve the quality of sample acquisition.

The first operation done in the analysis is to take the raw 14-bit data from the ADC and convert it to microvolts using the `ADCBuf` application programming interface (API) `ADCBuf_adjustRawValues`. The next operation is to convert the output in microvolts to floating point representation so that the user can utilize the FFT functions of the Cortex Microcontroller Software Interface Standard (CMSIS) digital signal processing (DSP) library to transform the time domain data to frequency domain representation. The last stage of the operation is to adjust the FFT output for frequency domain wrapping of the negative and positive frequency and then calculating the energy index of the maximum energy bin other than DC. Because the values computed for the frequency domain representation must be transmitted, a structure `Energy_Bin` has been defined for this application as outlined in Table 3.

Table 3. Energy_Bin Structure

NAME OF ELEMENT	DESCRIPTION OF ELEMENT	TYPE OF ELEMENT	NUMBER OF ENTRIES
iteration	Number of FFT computations performed when averaging	8-bit unsigned integer	1
energyValue	Magnitude of energy detected at the corresponding frequency bin	32-bit floating point	N/2
maxValue	Maximum magnitude of energy between bin-1 and bin-N/2	32-bit floating point	1
maxValueBin	Index of the bin where maximum energy has been detected	16-bit unsigned integer	1
dataReady	Variable to indicate that the FFT data has been updated since the last transmission	boolean	1

2.3.3 Serial Communication Port

When using the MSP432P401R device as a stand-alone MCU, the application is required to transfer the data to a host machine, such as a personal computer (PC). For this case, the application creates a task called *commsTask*. The task opens a UART serial communication port in 8-N-1 format at a 460.8-kbps baud rate. The user may update the serial baud rate per the application requirement. A serial console application like TeraTerm can be used to retrieve the data from the application. On its part, the application transmits the FFT energy value at every bin in a comma separated vector (.csv) file format. The user can log the output and open it with any spreadsheet PC application to look at the frequency domain representation of the sensor output.

2.3.4 Bluetooth low energy Communication Port

When using the MSP432P401R device as a host MCU for *Bluetooth low energy* communication, the application creates a task called *AP_createTask*. The task calls the SimpleLink SDK Bluetooth plugin stack that runs on the host MCU to establish UART communication with a *Bluetooth low energy* wireless MCU, the CC2650. shows the interaction between the *vibrationTask* and *AP_createTask* which the host MCU runs for collecting and transmitting the data.

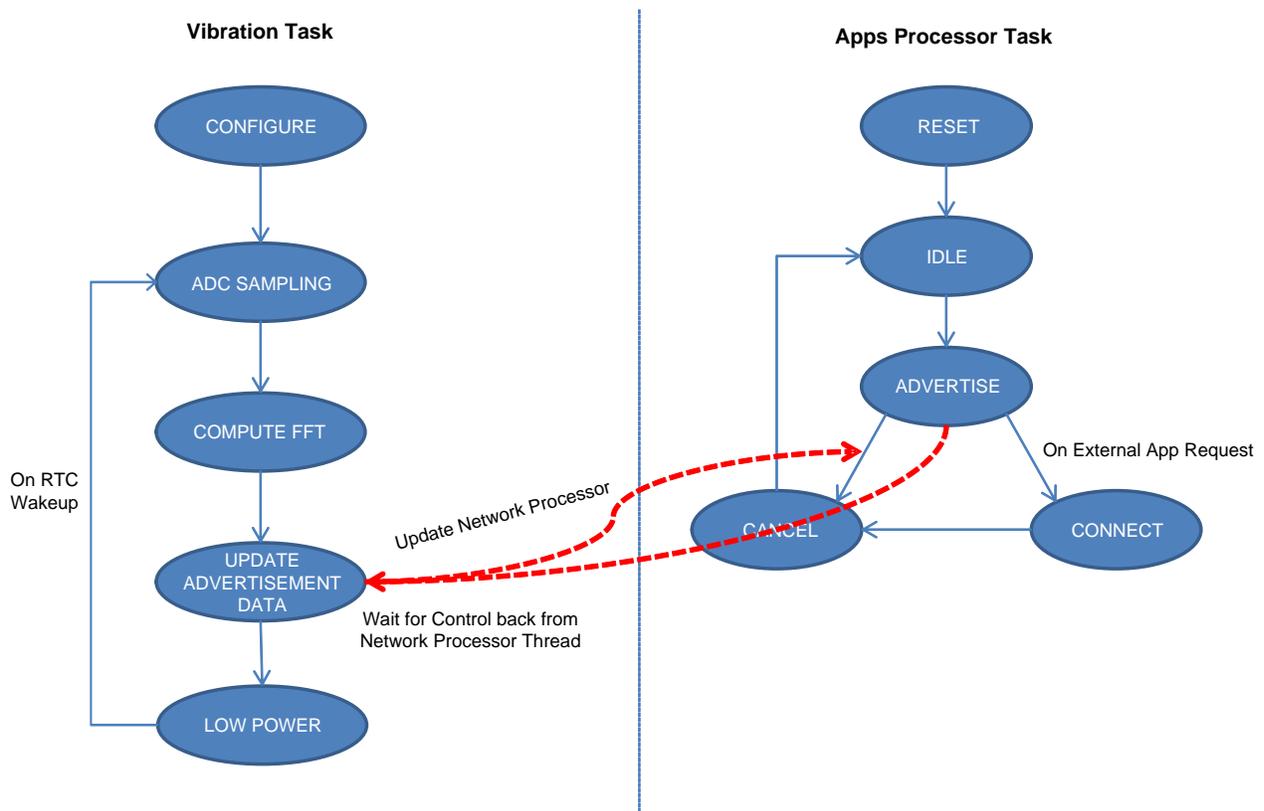


Figure 4. Software Flow Chart

A profile has been created for motor condition monitoring for the purposes of this application. The *Bluetooth low energy* communication consists of two parts with respect to data transmission.

The first part of the *Bluetooth low energy* communication is when the operator is not connected to the motor condition monitoring unit. During this time, the *Bluetooth low energy* is in auto-advertisement phase. The application sends 27 bytes of data during the auto-advertisement to a central device like a smartphone, tablet, or gateway with key information regarding the health of the motor. Table 4 shows the data sent in the auto-advertisement.

NOTE: The predefine symbol *BLE_COMMS* may be removed from the *Bluetooth low energy* example to print the FFT data on serial COM port

Table 4. Auto Advertisement Data

AUTO ADVERTISEMENT BYTE	DATA
0	0x1B
1	0xFF
2	ASCII character 'T'
3	ASCII character 'I'
4	FFT length and upper 5 bits of index of the maximum energy on x-axis
5	Lower bits of index of the maximum energy on x-axis
6	Upper 8 bits of sampling frequency on x-axis
7	Lower 8 bits of sampling frequency on x-axis
8	Bits 7-0 of the floating point value for the maximum energy on x-axis
9	Bits 15-8 of the floating point value for the maximum energy on x-axis
10	Bits 23-16 of the floating point value for the maximum energy on x-axis
11	Bits 31-24 of the floating point value for the maximum energy on x-axis
12	FFT length and upper 5 bits of index of the maximum energy on y-axis
13	Lower bits of index of the maximum energy on y-axis
14	Upper 8 bits of sampling frequency on y-axis
15	Lower 8 bits of sampling frequency on y-axis
16	Bits 7-0 of the floating point value for the maximum energy on y-axis
17	Bits 15-8 of the floating point value for the maximum energy on y-axis
18	Bits 23-16 of the floating point value for the maximum energy on y-axis
19	Bits 31-24 of the floating point value for the maximum energy on y-axis
20	FFT length and upper 5 bits of index of the maximum energy on z-axis
21	Lower bits of index of the maximum energy on z-axis
22	Upper 8 bits of sampling frequency on z-axis
23	Lower 8 bits of sampling frequency on z-axis
24	Bits 7-0 of the floating point value for the maximum energy on z-axis
25	Bits 15-8 of the floating point value for the maximum energy on z-axis
26	Bits 23-16 of the floating point value for the maximum energy on z-axis
27	Bits 31-24 of the floating point value for the maximum energy on z-axis

The central device can then make a more informed decision of connecting to the motor condition monitoring unit and downloading the FFT data.

The second part of the *Bluetooth low energy* communication is when the operator connects to the motor condition monitoring unit. When the central device connects to the motor condition monitoring unit, it can download the energy value for each of the three axes across from DC to $F_{NYQUIST}$ and use the data to perform predictive maintenance calculations regarding failure time, shock pulse, and specific direction of vibration that may result in motor failure.

2.3.5 Power Management

Because the unit may be placed or located in hard to reach locations, which may not have access to a power supply, utilizing the low-power features of the MSP432P401R is necessary to ensure a long battery life. The application manages the power of the system by correctly power sequencing the hardware components and software components.

The sensor and the signal conditioning circuit consume high current during the state when the system actively samples the sensor. therefore, shutting down the power is necessary when the sensor is not in use. For this purpose, the TPS22860 load switch is used to provide power to the sensor and signal conditioning circuit. When the MCU wakes up from a low-power state to sample the sensor output, a general-purpose input/output (GPIO) is used to power up the supply through the TPS22860 load switch. Similarly, another GPIO is used to keep the accelerometer in a low-power state while the power to the sensor and signal conditioning circuit is ramping up. When the sampling is completed, the load switch is turned off to reduce the current consumption. Table 5 shows the GPIOs that have been used in the design to control the power-up and power-down sequencing.

Table 5. Power Sequencing GPIO Mapping

DEVICE PORT	GPIO FUNCTION	DESCRIPTION
P4.1	Accelerometer power enable	Active high signal that enables the output of the accelerometer
P3.7	Load switch enable	Active high signal that enables the output of the load switch

Power management partitioning in software is done at two levels. The first level of power partitioning is achieved by allowing an LPM3 transition during the idle period between sensing intervals. The function *predictive_maintenance_setWakeTime(uint8_t Hours, uint8_t Minutes)* in vibrationCapture.c provides the sensing interval. The first argument specifies the hours between sensing events and the second argument specifies the minutes between sensing events. So, if the user wants to specify the application to wake up once every 3 hours and 25 minutes for sensing, the application must call the function *predictive_maintenance_setWakeTime(3,25)*. This function is loaded into the RTC for generating the match time for the sensing event.

At the second level of power partitioning is using the LPM0 transition when the device is idle. As an example, when powering up the sensor and signal conditioning circuit, the wait time requires 30 ms for the supply to stabilize. To ensure the MCU does not consume active mode current during this time, the value is loaded into the 32-bit timer-0 and the device is put into the LPM0 state. When the timer elapses, it wakes up the device, at which point the sensing can begin. This safeguard helps to reduce the current consumption from the device during an active period of the system. Figure 5 shows the sequencing of power partitioning in software.

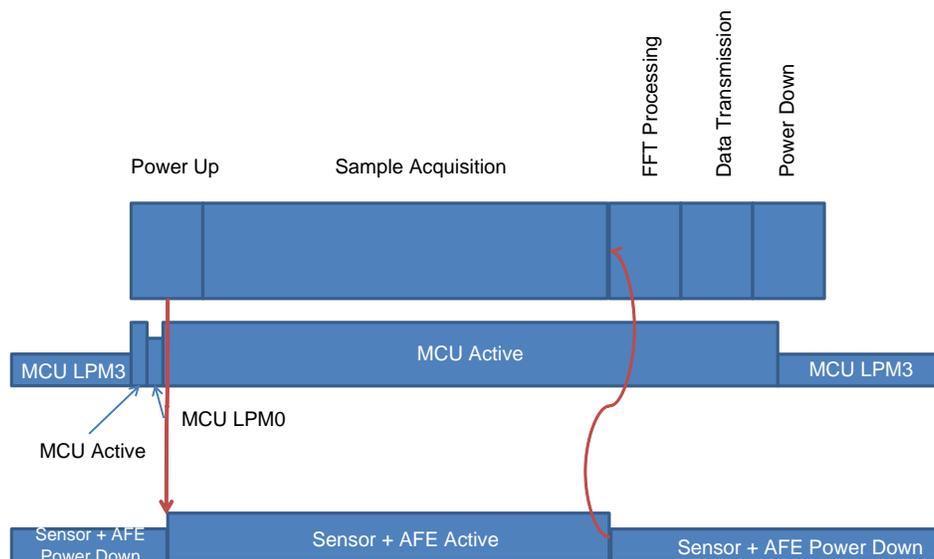


Figure 5. Software Power Partitioning

2.3.6 Sensor and Signal Conditioning Board

The sensor and signal conditioning board has been designed to simplify system integration by allowing the user to change components to meet system requirements for the actual end application. The board serves the following purposes from an ease-of-use perspective:

- Sensitivity improvement
- DC amplification and offset compensation

The micro-electro-mechanical sensor (MEMS) accelerometer selected for this application is the KXTC9-3672 from Kionix. The output sensitivity of the sensor is typically 220 mV/g with a full range of ± 6 g. Depending on the application requirement, the pulse shock generated by the motor may be of the order of 0.01 g to 0.1 g depending on early failure detection. For motors that run at a lower rotation per minute (RPM), the pulse shock is 0.01g. Hence the output of the sensor would be of the order of $220 \text{ mV/g} \times 0.01 \text{ g} = 2.2 \text{ mV}$.

The integration precision ADC on the MSP432P401R device with a 2.5-V reference yields a resolution per bit of $152.587 \mu\text{V}$; therefore, the effective vibration detected would be of the order of a 14 LSB change. This difference in LSB is insufficient for resolving the vibration, which means a low noise amplification stage is required to improve the sensitivity of the vibration.

Similarly, the MEMS accelerometer has a zero-g offset variation of 1.622 V (min) to 1.678V (max). Based on the position of the sensor, the acceleration of earth's gravity may add up or subtract 1 g from the zero-g offset. Hence for a typical value of 1.65 V, the lowest offset is 1.402 V when the zero-g offset is at its minimum characterized value and the sensor is mounted so that it registers -1 g of acceleration or 1.898 V when the zero-g offset is at its maximum characterized value and the sensor is mounted so that it registers $+1$ g of acceleration. At the same time, if the signal is passed as is to the low-noise pre-amplification stage, the DC is also amplified, which causes the output of the amplification to saturate and results in a constant DC for the ADC input.

To compensate the offset and block the DC, place an input capacitor so that only the signal variation resulting from dynamic shock pulses is coupled to the input of the operational amplifier (op amp) OP1. At the same time, a constant 1.25-V reference is added to the non-inverting stage so that both positive and negative acceleration shock pulses can be detected without clipping the signal. The amplification stage is provided with the help of a second-order low-pass filter that helps manage the bandwidth of the output signal, which enables the software to decrease the frequency of sampling to improve the resolution of the frequency bin without increasing the number of samples for data capture. Figure 6 shows the TINA netlist for the amplification stage.

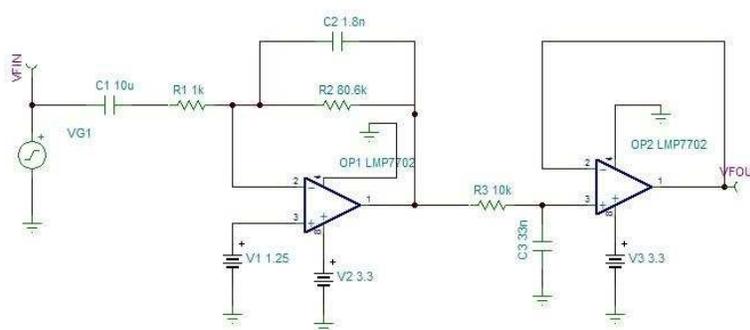


Figure 6. TINA Netlist

The resistor R2 and R1 provide the gain amplification by a factor of 80.6 or +38 dB in the first stage of amplification. The first-stage low-pass filter is formed by R2 and C2, with R3 and C3 providing the second stage of the low-pass filtering. The second op amp, OP2, helps reduce the impedance of the signal conditioning circuit to match the integrated precision ADC.

Figure 7 shows the AC transfer response for both amplitude and phase response of the circuit. Note that the 0-dB cutoff at the lower frequency is approximately 0.2 Hz and the 0-dB cutoff at the higher frequency is approximately 6.45 kHz. The bandwidth requirement of 6.45 kHz helps the application set a sampling frequency of 24 kHz, to avoid aliasing of signals. The 3-dB bandwidth has a lower frequency of 14.9 Hz and upper frequency of 439 Hz, which effectively covers bearing faults for most motor speeds. Although the sampling frequency must be at least twice that of the maximum signal frequency, per the Nyquist sampling theory, the current application may reduce the sampling frequency to as low as 13 kHz, thereby improving the frequency resolution per bin.

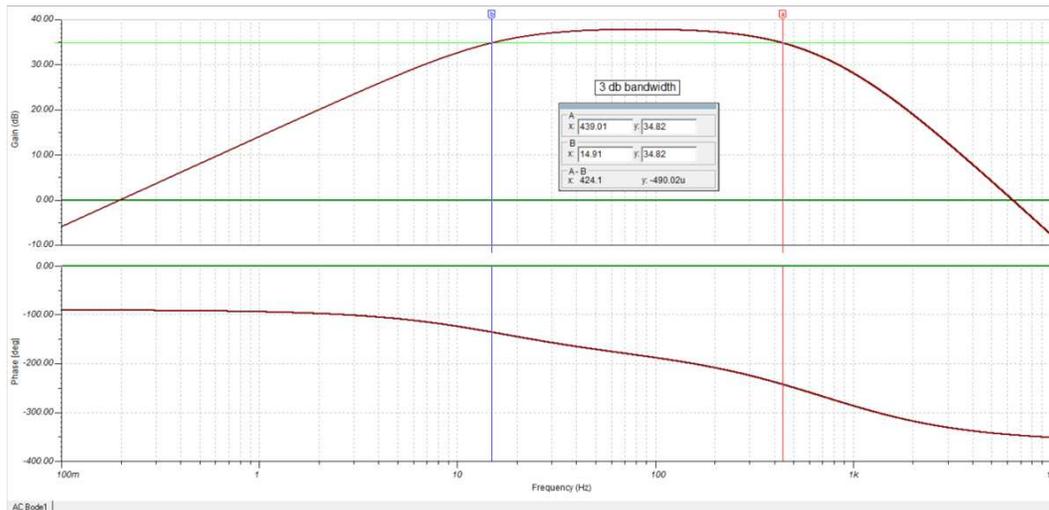


Figure 7. Amplitude and Phase Response

Table 6 lists the value of the gain at different frequency bins. Because each frequency bin is 23.4375 Hz apart, the gain has been tabulated for the first ten frequency bins. The gain has been tabulated as such because the test setup and results in Section 3 specify a 190-Hz sine wave as the main test input. The designer can easily generate additional values of gain using the TINA-TI™ software to simulate the AC transfer characteristics.

Table 6. Gain Table

FREQUENCY BIN	FREQUENCY POINT	G _{AFEDB}	G _{AFEV}
1	23.4375 Hz	36.5 dB	66.835
2	46.875 Hz	37.6 dB	75.858
3	70.3125 Hz	37.8 dB	77.625
4	93.75 Hz	37.8 dB	77.625
5	117.1875 Hz	37.7 dB	76.736
6	140.625 Hz	37.6 dB	75.858
7	164.0625 Hz	37.5 dB	74.989
8	187.5 Hz	37.3 dB	77.282
9	210.9375 Hz	37.2 dB	72.443
10	234.375 Hz	36.9 dB	69.984

The user may change the value of R1, R2, R3, C2, and C3 to change the gain and the AC response of the filter to meet the requirements in terms of resolution of the vibration pulse (acceleration) and improve the frequency resolution of the bin to meet the requirements of the application.

Similarly, the user can change the Kionix KXTC9-3672 sensor with the pin-compatible KX220-1071 or KX220-1072 to increase the range of vibration up to ±40 g, increase the frequency range of vibration to 9.6 kHz, and easily update the gain and AC response to monitor high vibration machines where low shock pulses may not require monitoring.

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

The software for this design contains two application examples. The first example uses the MSP432P401R with a serial communication port, which requires the following boards:

- MSP-EXP432P401R LaunchPad™ development kit
- TIDA-01575 vibration sensor board

The second example uses the MSP432P401R with *Bluetooth low energy* communication, which requires the following additional boards and hardware:

- BOOSTXL-CC2650MA for *Bluetooth low energy* communication
- A smartphone or tablet running iOS® 11.0 or higher with the SimpleLink SDK Explorer application

To simulate a vibration bench, use a resonator with a function generator to send a sinusoidal signal.

3.1.1 Hardware

The first step in constructing the setup is mounting the EXP-MSP432P401R LaunchPad to the resonator. A 3-D printed base is used for this purpose and is firmly attached to the resonator. The designer can then screw the LaunchPad device into the base, as [Figure 8](#) shows, so that most of the energy from the resonator is coupled to the sensor.



Figure 8. Mounting LaunchPad™ to Resonator

Now mount the TIDA-01575 sensor and signal conditioning board on top of the BoosterPack header of the LaunchPad, as [Figure 9](#) shows.



Figure 9. Mounting Sensor Board

The last step is to mount the BOOSTXL-CC2650MA BoosterPack on top of the TIDA-01575 sensor and signal conditioning board (see [Figure 10](#)). This step is required only when using the *Bluetooth low energy* for data communication between the MSP-EXP432P401R LaunchPad and the SimpleLink SDK Explorer application running on the smartphone.



Figure 10. Mounting BOOSTXL-CC2650MA BoosterPack™

3.1.2 Software

The example code for the application requires the SimpleLink MSP432 SDK version 2.10.00.14 and the Bluetooth plug-in for the SimpleLink MCU SDK version 1.40.00.42 to be installed on the PC.

- `motor_condition_monitor_tida_01575_ble` example in the Bluetooth plug-in contains the project for TIDA-01575 with *Bluetooth low energy* communication for TI-RTOS and FreeRTOS that may be used with CCS, GCC, or IAR compilers.
- `tida_01575_serial` example in the SimpleLink MSP432 SDK contains the project for TIDA-01575 with Serial COM port communication for TI-RTOS and FreeRTOS that may be used with CCS, GCC, or IAR compilers.

If using the *Bluetooth low energy* project, then the CC2650 Module BoosterPack requires a firmware. The user must download the firmware binary image `simple_np_cc2650bp_uart_pm_sbl_2_02_01_18a_merge.hex` from the `C:\ti\simplelink_sdk_ble_plugin_1_40_00_42\source\ti\snpl\cc2650` path to the CC2650 module. For more details on how to download the image, see [SimpleLink MSP432 SDK Bluetooth Plugin User Guide](#).

For the next step, import the projects `motor_condition_monitor_tida_01575_ble` and `tida_01575_serial` in the CCS or IAR and compile the project.

3.2 Testing and Results

To test the setup, a 190-Hz sine wave was provided to the resonator and then the amplitude of the output was varied to show the varying effect of acceleration.

3.2.1 Test Setup With Serial COM Port

To create a vibration bench, use the following steps.

1. Power up the setup with the MSP-EXP432P401R LaunchPad and the TIDA-01575 sensor and signal conditioning board mounted on top of the resonator.
2. Download the application firmware for tida_01575_serial.
3. Open a serial COM port application like TeraTerm on the PC and configure the COM port for 460800 bps. Configure the TeraTerm to log the output to a .csv file.
4. Now use a tone or function generator to output a 190-Hz sine wave. Using a tone generator is more useful because it allows the user to output a sine wave tone and enables control of the output in terms of percentage amplitude.

3.2.2 Test Results With Serial COM Port

The test setup was run with the amplitude set to 80%, 90%, and 100% for the sine wave. The user can open the output .csv file in a spreadsheet application like Microsoft® Excel and plot a line graph to see the distribution of the energy in the frequency domain. The x-axis corresponds to the frequency bin of the energy and the y-axis corresponds to the magnitude of the energy at the corresponding frequency bin. Use the previous [Equation 2](#) to easily convert the bin to frequency in Hz.

Figure 11 shows the amplitude of the sine wave on the z-axis output with an 80% amplitude.

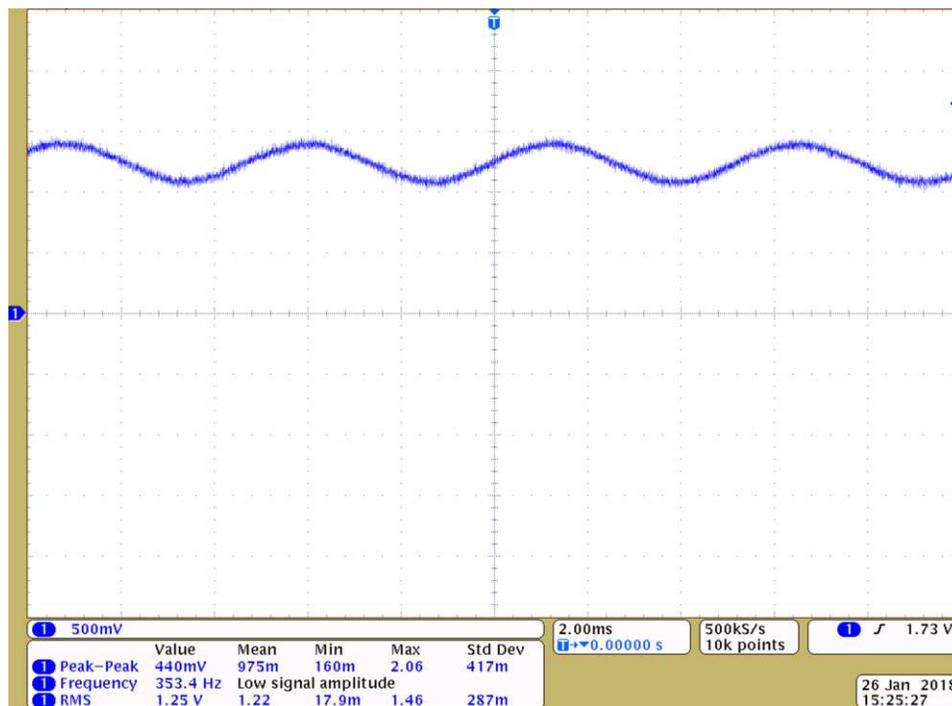


Figure 11. Z-axis Output for 190-Hz 80% Amplitude Sine Wave

Figure 12 shows the resulting FFT output from the .csv file.

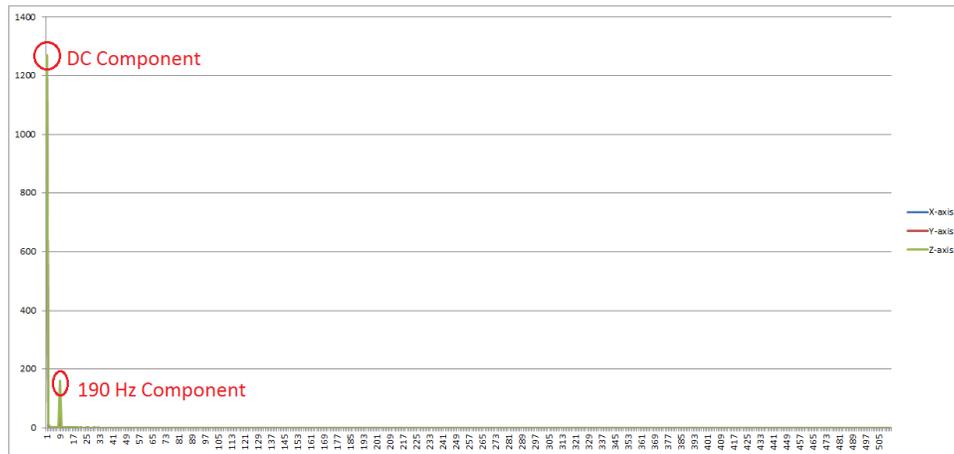


Figure 12. Z-axis FFT Output for 190-Hz 80% Amplitude Sine Wave

Figure 13 shows the amplitude of the sine wave on the Z-axis output with a 90% amplitude.

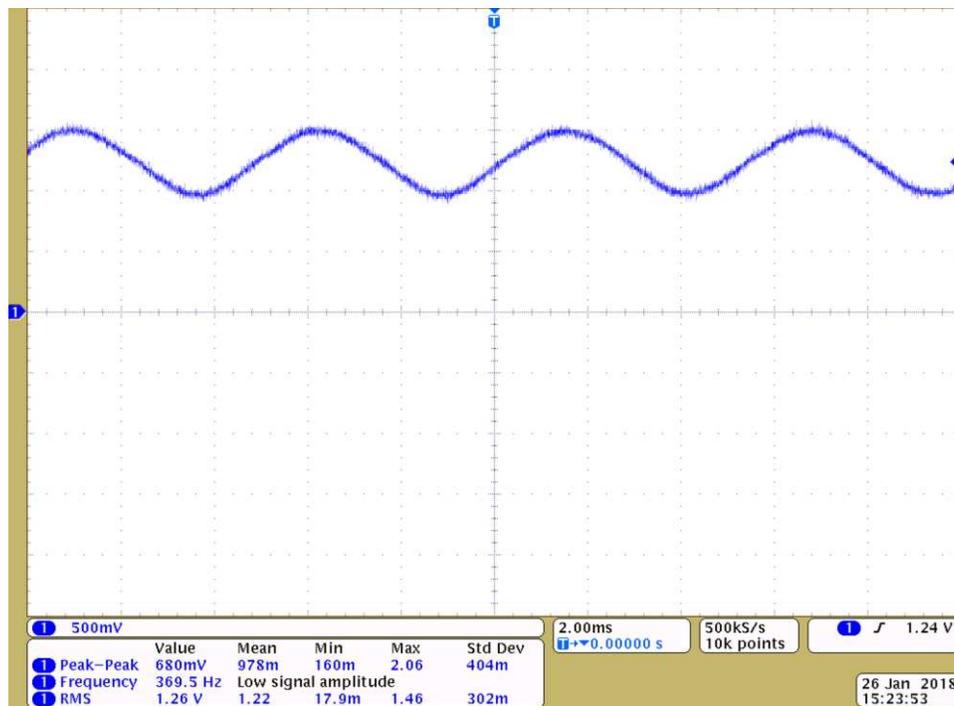


Figure 13. Z-axis Output for 190-Hz 90% Amplitude Sine Wave

Figure 14 shows the resulting FFT output from the .csv file.

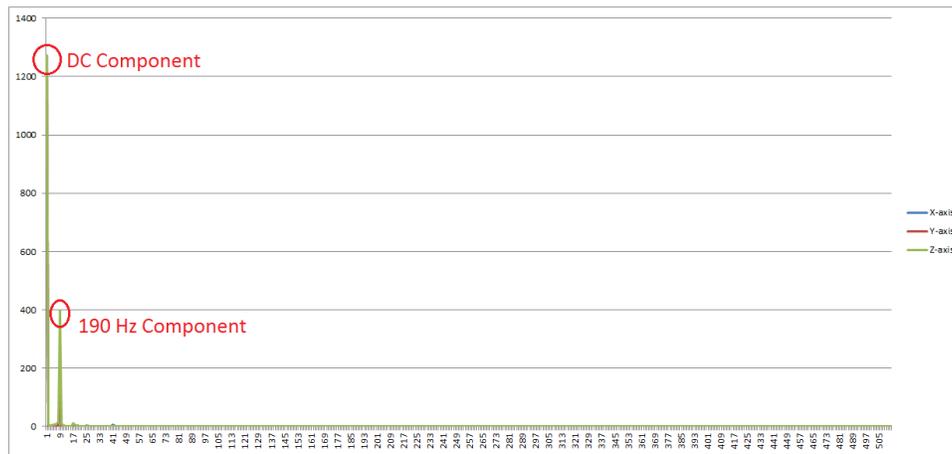


Figure 14. Z-axis FFT Output for 190-Hz 90% Amplitude Sine Wave

Figure 15 shows the amplitude of the sine wave on the Z-axis output with a 100% amplitude.

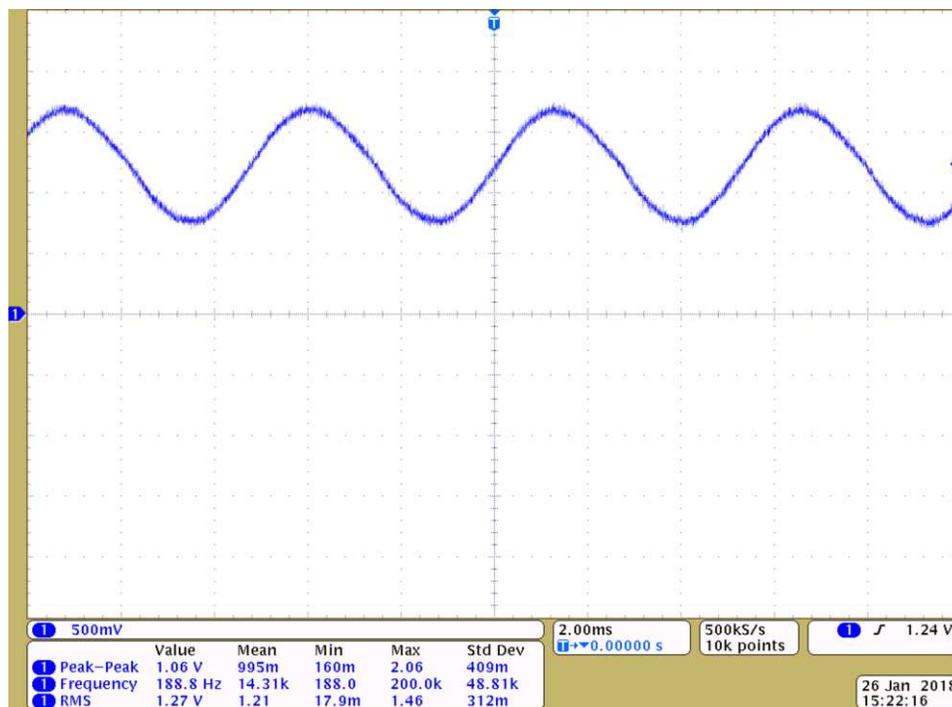


Figure 15. Z-axis Output for 190-Hz 100% Amplitude Sine Wave

Figure 16 shows the resulting FFT output from the .csv file.

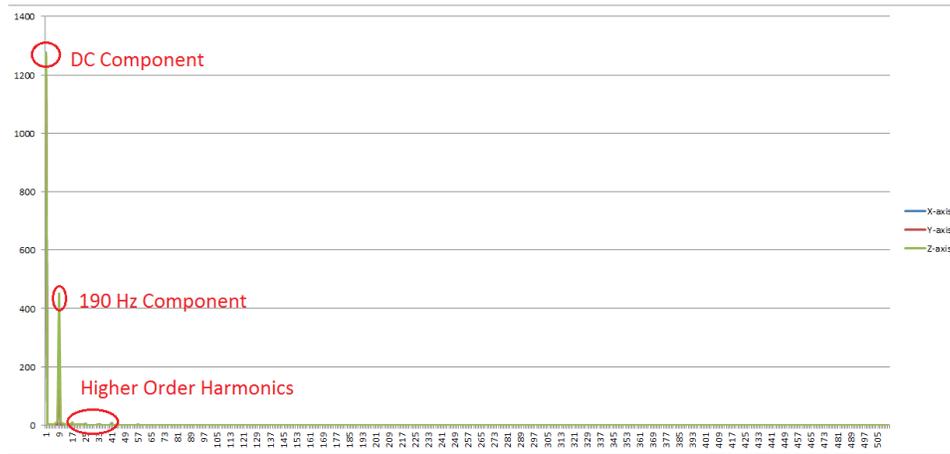


Figure 16. Z-axis FFT Output for 190-Hz 100% Amplitude Sine Wave

3.2.3 Test Setup With *Bluetooth low energy*

The test setup with *Bluetooth low energy* was run with the amplitude set to 100% for the sine wave and an audio file collected for an actual motor. The SimpleLink SDK Explorer was used to visualize the data being captured.

1. Power up the setup with the MSP-EXP432P401R LaunchPad, BOOSTXL-CC2650MOD, and the TIDA-01575 sensor and signal conditioning board mounted on top of the resonator.
2. Download the application firmware for motor_condition_monitor_tida_01575_ble and run the application.
3. Now use a tone or function generator to output a 190-Hz sine wave. Using a tone generator is more useful because it allows the user to output a sine wave tone and enables control of the output in terms of percentage amplitude.
4. On the smartphone or tablet, launch the SimpleLink SDK Explorer application. [Figure 17](#) shows the launch page of the application.

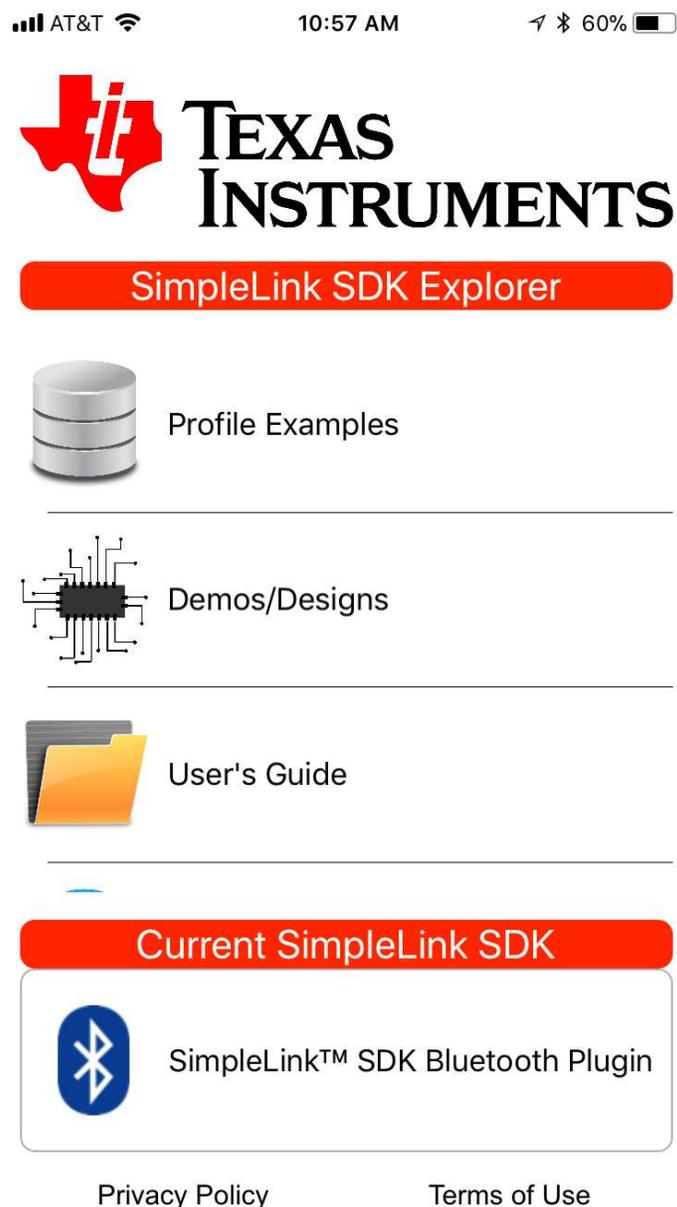


Figure 17. SimpleLink™ SDK Explorer Launch Page

5. To Launch the TIDA-01575 application, click the *Demos/Design* section. This action launches the application page for the *Motor Condition Monitor* (see [Figure 18](#)).

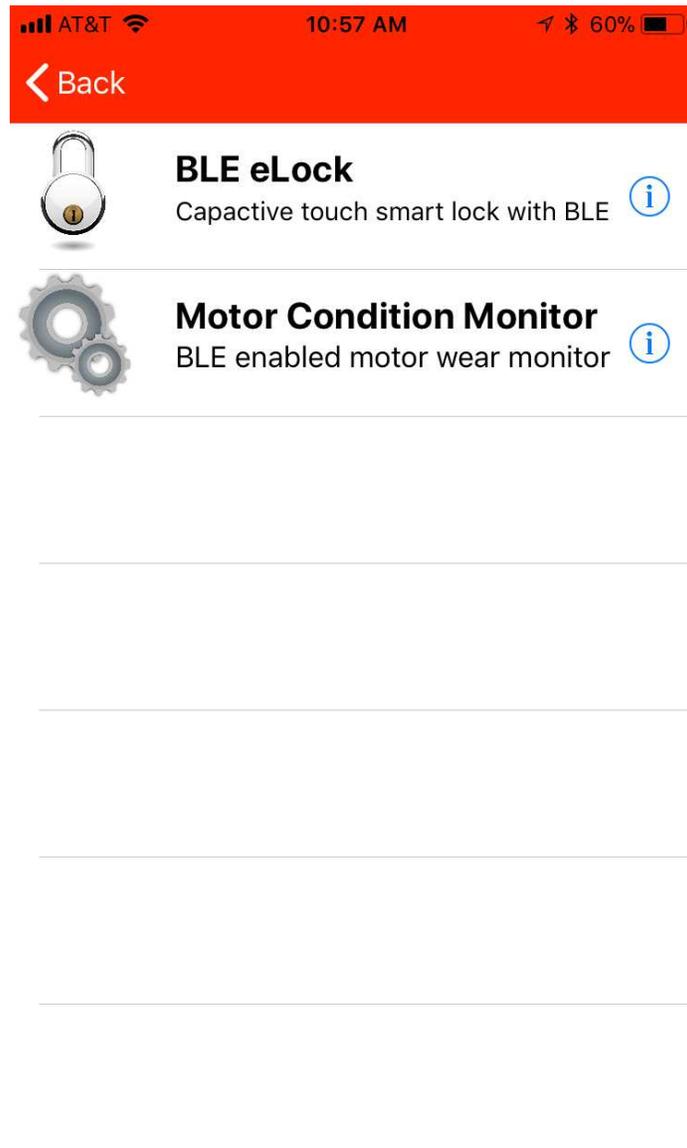


Figure 18. Motor Condition Monitor Launch Page

- Now click on the *Motor Condition Monitor* section to see if the *Bluetooth low energy* target device is scannable. The device must come up as *TIDA-01575*, as [Figure 19](#) shows.

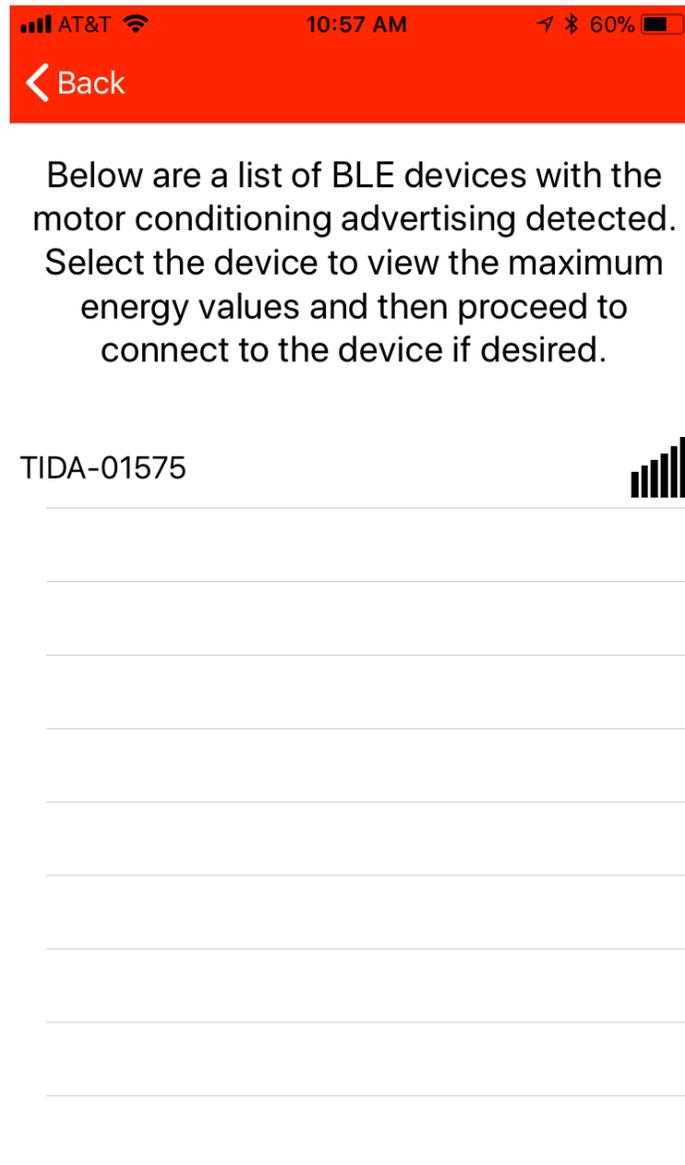


Figure 19. TIDA-01575 Scan Page

- When the user clicks on *TIDA-01575*, the application uses the data provided during the auto-advertisement to provide a visual of the summary for the last data sample, and FFT analysis done by the design (see [Figure 20](#)).

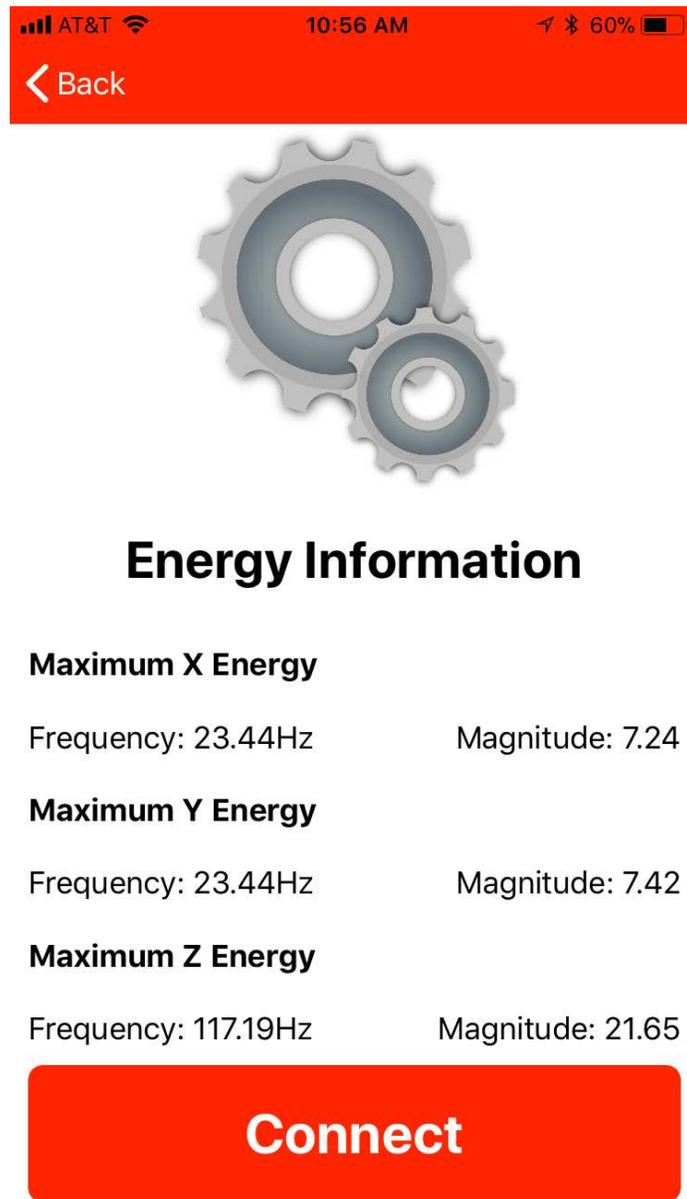


Figure 20. Auto-Advertisement Data From Design

- At this point, the user can connect to the design by clicking on the *Connect* button. This action causes the application to connect (through *Bluetooth low energy*) to the motor condition monitor unit and download the 6KB of FFT data and plot the frequency spectrum for the x-, y-, and z-axes (see [Figure 21](#)).

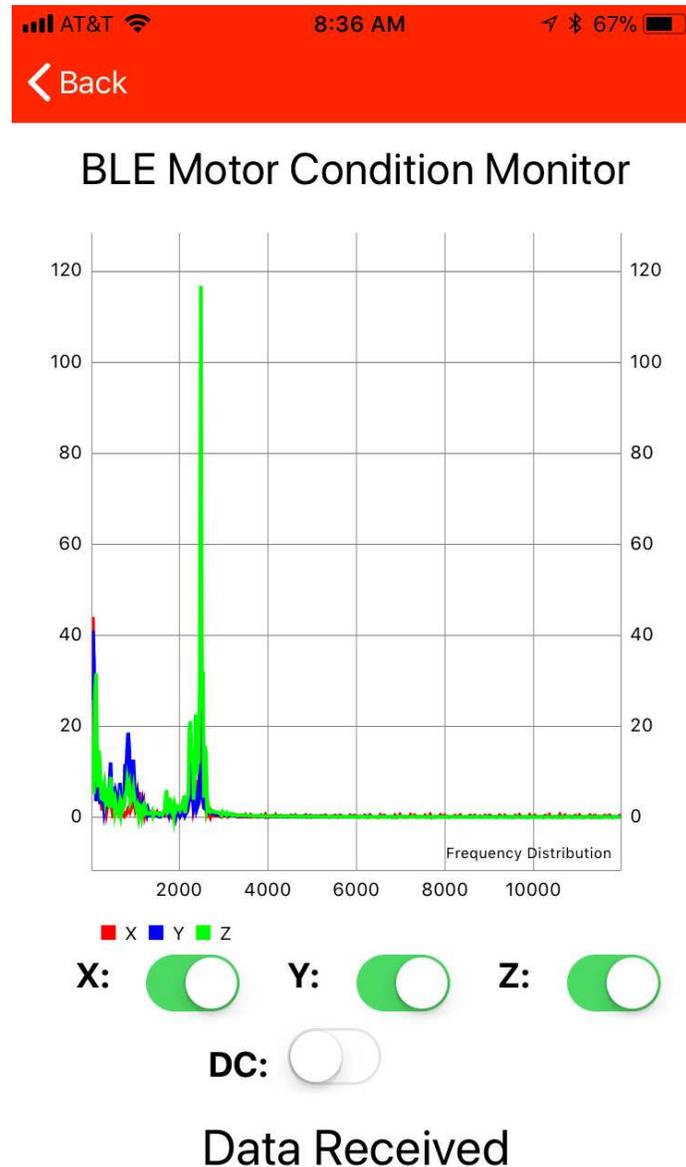


Figure 21. FFT Data for Sine Wave

3.2.4 Test Results With *Bluetooth low energy*

The audio data collected from an actual motor was run with the setup. [Figure 22](#) shows the FFT spectrum as computed by a PC-based application. The light blue line shown in the image is the maximum energy detected at the frequency for the entire audio stream. The dark blue line shown in the image indicates the average energy at the same frequency for the entire audio stream.

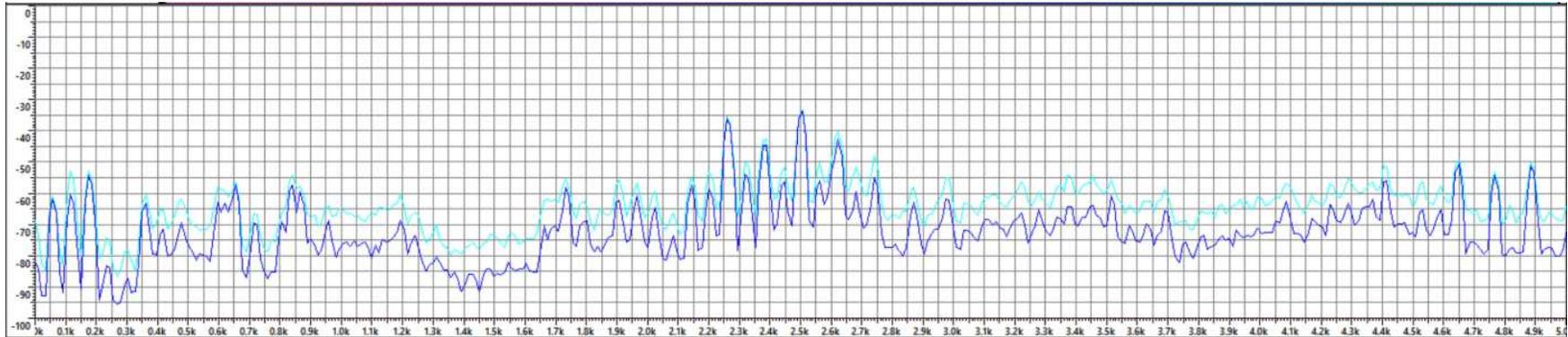


Figure 22. PC-Based FFT for Motor Audio File

Figure 23 shows the result of the same data collected on the motor condition monitor unit and as plotted on the application. Note how, in both Figure 21 and Figure 23, the peaks of the data captured show a high degree of correlation.

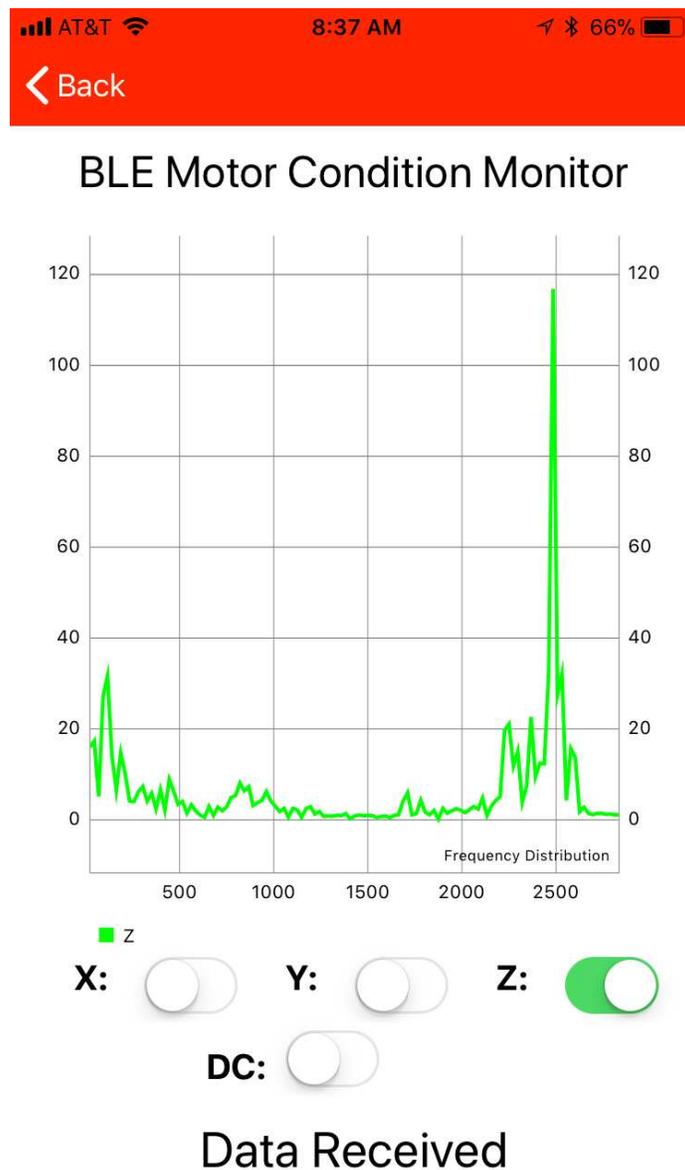


Figure 23. Motor Condition Monitor FFT for Motor Audio File

3.2.5 Test Results With Motor Setup

In the next step, the *Bluetooth low energy* code was run on an actual motor, as [Figure 24](#) shows. The setup consists of the drive brushless DC (BLDC) motor on the left side of the image and a load consisting of another BLDC motor without any active driver. The shaft (shown in white) is aligned between the two motors. The drive motor is operated at 3600 RPM or 60 cycles per second.

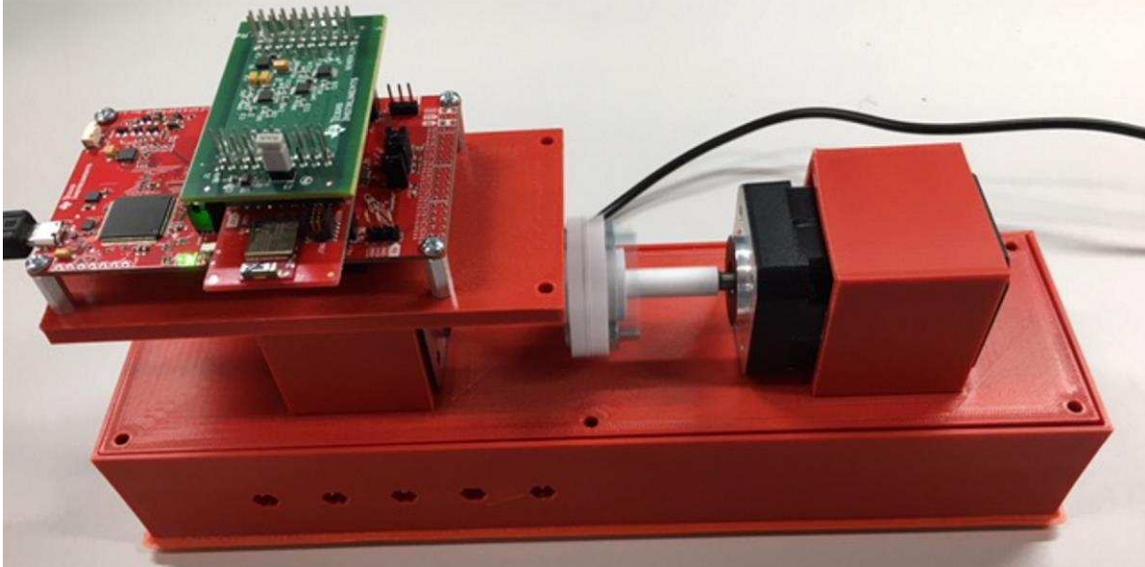


Figure 24. Motor Setup

The data collection phase consists of two parts. In the first part, the motor is firmly mounted to the housing, and in the second part, the motor has been loosened by half a screw turn to emulate a weakened foundation. The data was collected using the SimpleLink SDK Explorer application on a smartphone. The collected data is shown with the *PASS* condition on the left side of the image and *FAIL* condition on the right side of the image.

- Figure 25 shows the data collected for the x-axis. In the passing case (left side), note the maximum amplitude at approximately 60 Hz with a progressively decreasing amplitude for the harmonics. However, in the failing case (right side), the amplitude of the fundamental component has decreased and the energy in the fifth harmonic has increased, which indicates a potential fault.

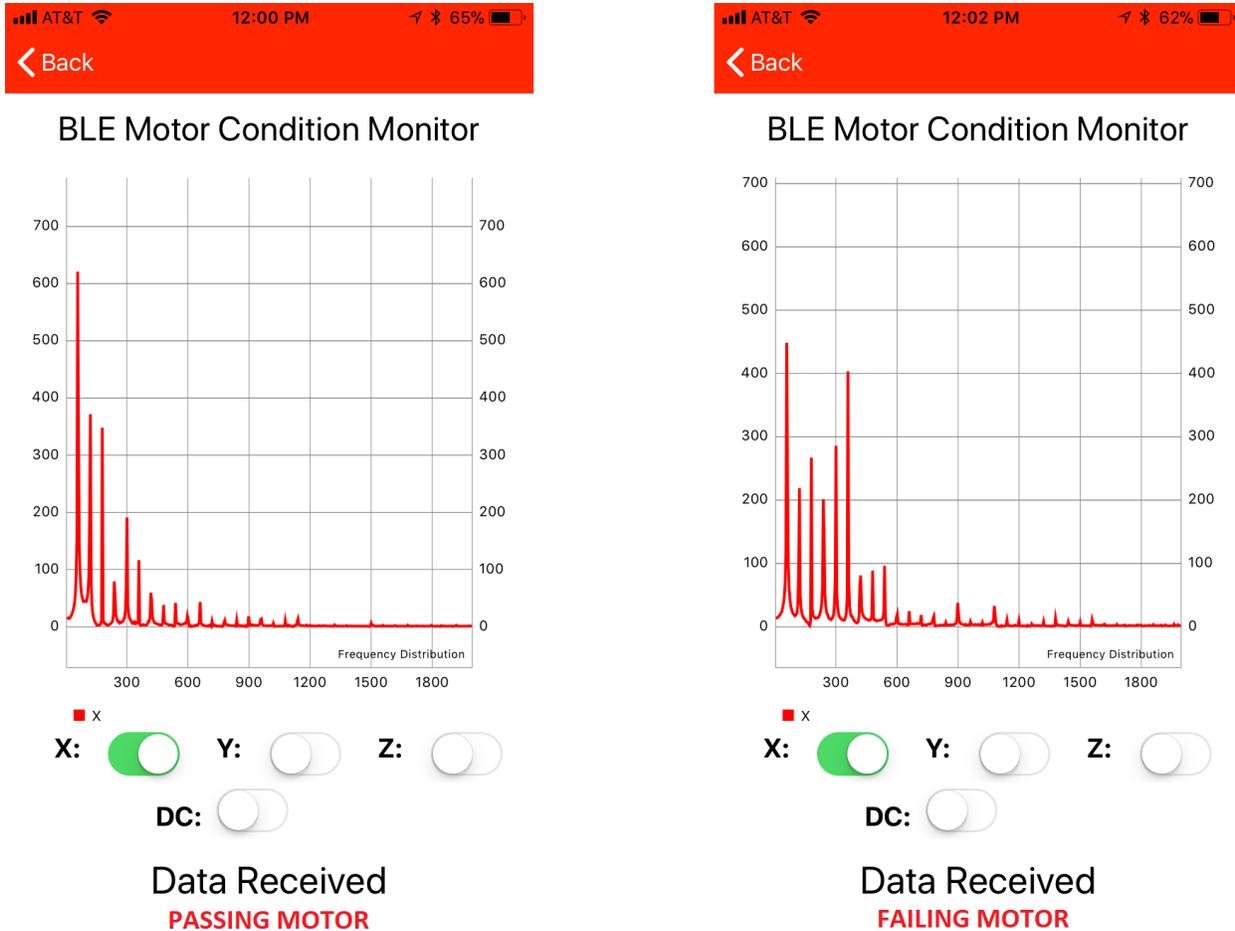


Figure 25. X-Axis Data

- Figure 26 shows the data collected for the y-axis. In the passing case (left side), note the maximum amplitude at approximately 60 Hz with a progressively decreasing amplitude for the harmonics. However, in the failing case (right side), the amplitude of the fundamental component has decreased and the energy in the third harmonic has increased, which indicates a potential fault.

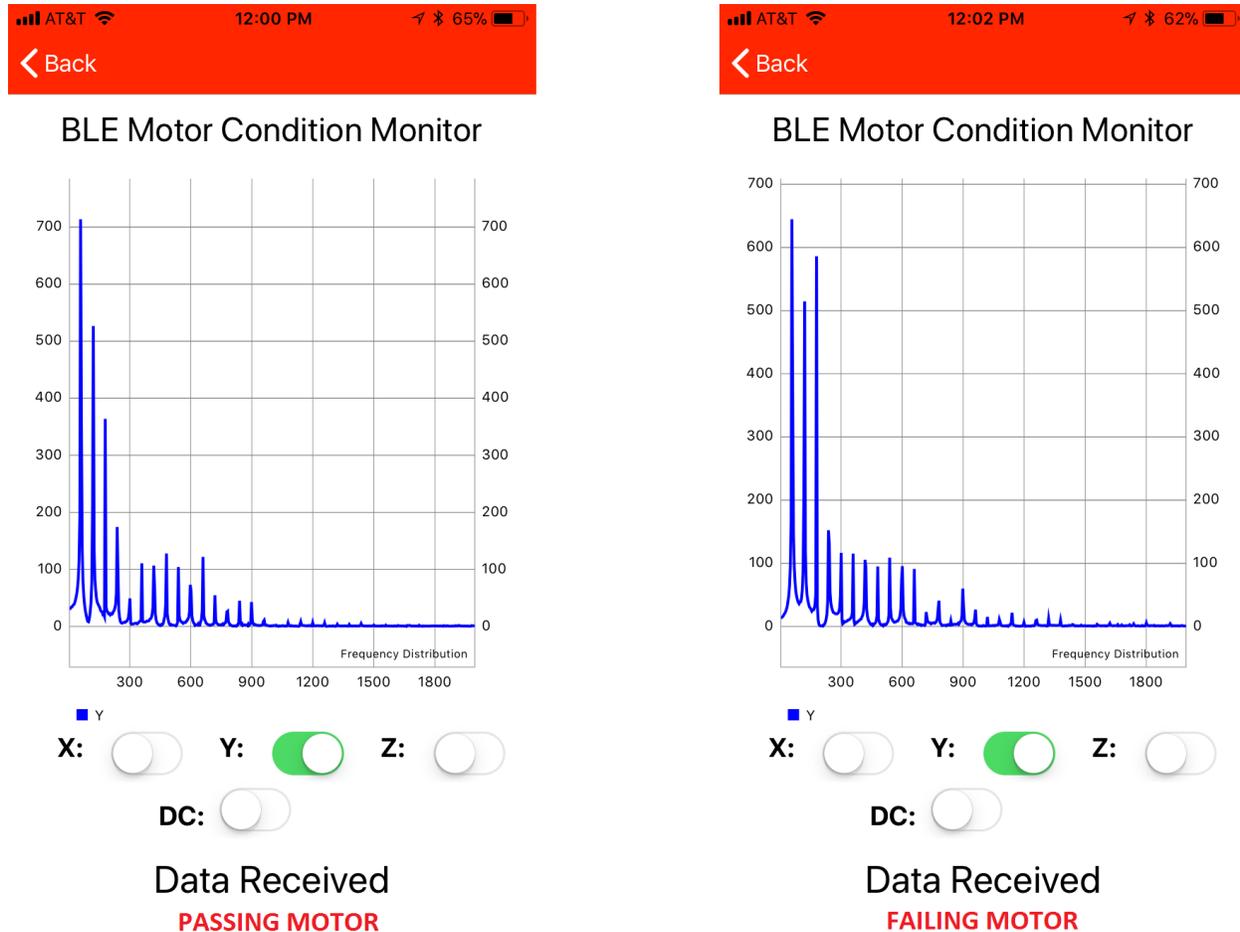


Figure 26. Y-Axis Data

- Figure 27 shows the data collected for the y-axis. In the passing case (left side), note the maximum amplitude at approximately 60 Hz with a progressively decreasing amplitude for the harmonics. However, in the failing case (right side) the amplitude of the fifth harmonic has increased, surpassing the energy for the fundamental component. This data indicates a movement along the z-axis, which is expected because the motor is loose along the z-axis.

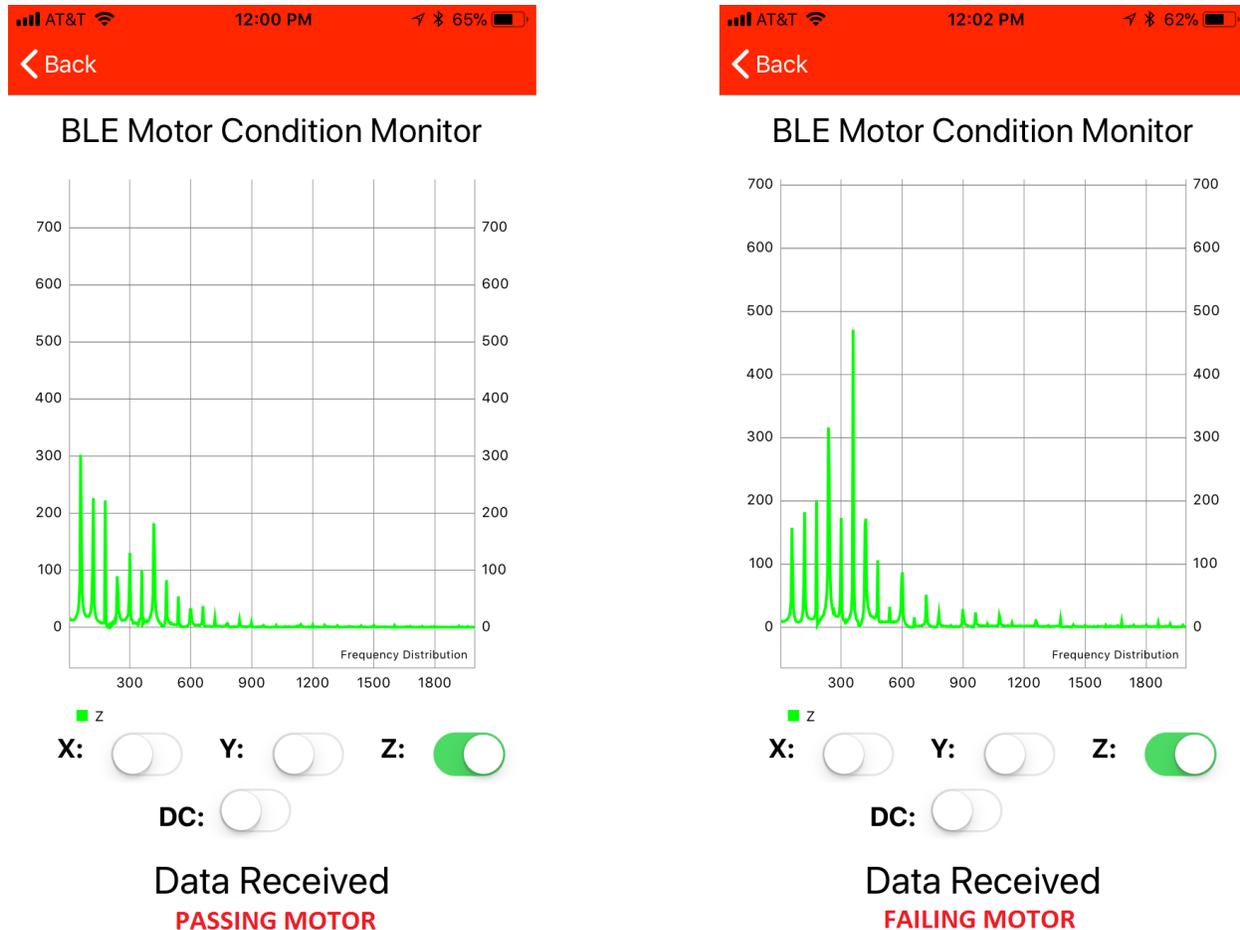


Figure 27. Z-Axis Data

3.2.6 Interpreting FFT results

After obtaining the frequency domain representation of the vibration data, the user can calculate the vibration component in terms of g. To make a visual representation of the computation, take the 190-Hz, 100% amplitude sine wave response. The graph plotted from the .csv shows the maximum energy for a 190-Hz component as approximately (V_{ENERGY}) 1.06-V peak-to-peak. The previous spice simulations have established that the gain (G_{AFEDB}) provided by the signal conditioning circuit is 37.3 dB or, in voltage, the gain (G_{AFEV}) is 73.282.

$$G_{\text{AFEV}} = 10^{\frac{G_{\text{AFEDB}}}{20}} \quad (3)$$

Hence, calculate the output of the sensor (V_{SENSOR}) as shown in [Equation 4](#).

$$V_{\text{SENSOR}} = \frac{V_{\text{ENERGY}}}{G_{\text{AFEV}}}$$

$$V_{\text{SENSOR}} = \frac{1.06 \text{ V}}{73.282 \text{ mV}}$$

$$V_{\text{SENSOR}} = 14.4647 \text{ mV} \quad (4)$$

The sensor used in this design is the KXTC9-3672, which has an output sensitivity of 220 mV/g. Because the output voltage is peak-to-peak, this implies both a positive and negative acceleration; therefore, the acceleration generated due to the vibration can now be computed as follows in [Equation 5](#).

$$\text{ACCEL} = \frac{V_{\text{SENSOR}}}{(\text{SENSITIVITY} \times 2)}$$

$$\text{ACCEL} = \frac{14.3981 \text{ mV}}{(220 \times 2)}$$

$$\text{ACCEL} = 0.0329 \text{ g} \quad (5)$$

The actual acceleration being generated by the vibration on the resonator for a 190-Hz, 100% amplitude is ± 0.0329 g. The user can apply this same [Equation 5](#) to each of the frequency points to generate the plot in terms of acceleration of the monitor unit.

Because the signal conditioning circuit may be different from the device that this design implements, the user must compute the G_{AFEDB} for all of the frequency points and feed it as a look-up table to the firmware to compute the actual sensor output and resulting acceleration.

3.2.7 Power Consumption

Unlimited power may not be available because the motor condition monitoring unit may have been placed after the motor assembly was commissioned. Therefore, the design must be able to work on a battery for an extended period of time. For this application, TI highly recommends selecting the CR123A battery, which has a current capacity of 1470 mAh. A derating of 5% has been applied to account for the self discharge of the battery. The derating of 5% results in an effective current capacity of 1396 mAh.

[Table 7](#) shows the current consumption data collected when using the serial communication port for data transmission over a 24-hr time frame. Different interval periods for sampling the sensor and computing the FFT were used for the design.

Table 7. Current Consumption for Serial Communication Port

INTERVAL FOR SAMPLING	AVERAGE CURRENT CONSUMPTION	OPERATIONAL LIFETIME
1 hr	31.7 μ A	44037 hr or 5 years
2 hr	16.5 μ A	84606 hr or 9.65 years
4 hr	8.8 μ A	158636 hr or 18.1 years
6 hr	6.2 μ A	225161 hr or 25.7 years

Table 8 shows the current consumption data collected when using the *Bluetooth low energy* for data transmission. The most important factor when using *Bluetooth low energy*, which impacts the current consumption, is the use of the auto-advertisement and the interval for auto-advertisement pulses. In this design, a 1-min sampling interval was used to effectively measure the current consumption due to auto-advertisement, for which different auto-advertisement intervals were used. The auto-advertisement interval impacts the interval at which the design unit can be discovered and connected to the smartphone or tablet app.

Table 8. Current Consumption for Bluetooth low energy

AUTO-ADVERTISEMENT INTERVAL	AVERAGE CURRENT CONSUMPTION FOR AUTO-ADVERTISEMENT	OPERATION LIFETIME
100 ms	303.347 μ A	4601 hr or 0.5 year
1 sec	56.597 μ A	24665 hr or 2.8 years
2 sec	41.663 μ A	33506 hr or 3.82 years
5 sec	31.168 μ A	44789 hr or 5.1 years

Figure 28 shows the current consumption profile for the MSP432P401R during the different phases of power-up, sampling, FFT processing, and subsequent data transmission using *Bluetooth low energy*.

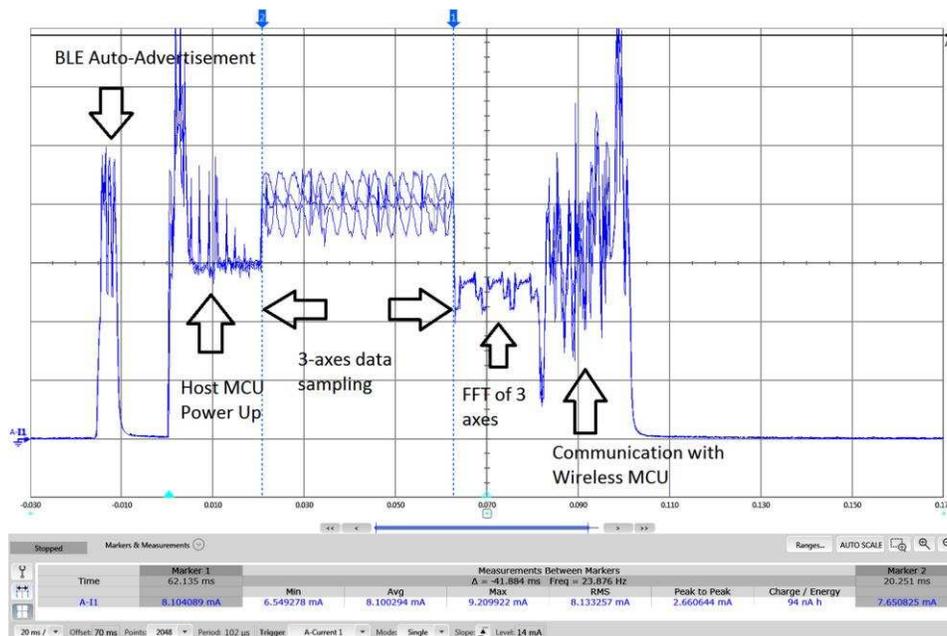


Figure 28. Host MCU Current Consumption Profile

3.3 Optimizations for the Design

The current reference design may potentially be optimized further by means of hardware and software changes which are not in the scope of the reference design. Few of the possible optimizations possible are listed below

- A Nano-timer may be used to wakeup the device from LPM3.0 state instead of using the RTC. This will help reduce power as the RTC is not being used.
- The software may use the auto-advertisement pulses to send the data to a gateway so that it does not need to be connected to a central device for downloading the data. When the data is sent the auto-advertisement may be stopped and conserve power on the RF.

4 Design Files

4.1 Schematics

To download the schematics, see the design files at [TIDA-01575](#).

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-01575](#).

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-01575](#).

4.4 Altium Project

To download the Altium project files, see the design files at [TIDA-01575](#).

4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-01575](#).

4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-01575](#).

5 Software Files

To download the software files, see the design files at [TIDA-01575](#).

6 Related Documentation

The following related documents, software and URL have been used in this application report.

1. Texas Instruments, [Leveraging Precision ADC on SimpleLink™ MSP432™ Microcontrollers for Predictive Maintenance](#)
2. Texas Instruments, [MSP432P401R, MSP432P401M SimpleLink™ Mixed Signal Microcontrollers](#)
3. Texas Instruments, [SimpleLink MSP432 SDK Bluetooth Plugin User Guide](#)
4. Texas Instruments, [High-precision ADC for motor condition monitoring](#)
5. Kionix, [KXTC9-3672 Product Specification](#)

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7 About the Author

AMIT ASHARA is an application engineer and Member Group technical staff member at Texas Instruments. He works on developing applications for the SimpleLink MSP432 MCU. Amit brings his extensive experience in high-speed digital and MCU system-level design to this role. Amit earned his bachelor of engineering (BE) from the University of Pune, India.

Revision History

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

Changes from February 24, 2018 to May 4, 2018	Page
• Changed Figure 1 , <i>TIDA-01575 Block Diagram</i>	3
• Added description of ADC_CH_SAMPLING_FREQ and AVG_LOOP_COUNT in Section 2.3.2 , <i>Vibration Analysis</i>	7
• Added Figure 4 , <i>Software Flow Chart</i>	8
• Added the note that begins "The predefine symbol <i>BLE_COMMS...</i> " in Section 2.3.4 , <i>Bluetooth low energy Communication Port</i>	9
• Updated the description of the FFT bytes (Auto Advertisement Byte 4, 12, 20) in Table 4 , <i>Auto Advertisement Data</i>	9
• Corrected part number of the MEMS accelerometer in Section 2.3.6 , <i>Sensor and Signal Conditioning Board</i>	11
• Updated description in Section 3.1.2 , <i>Software</i>	15
• Corrected application firmware name in step (2) in Section 3.2.3 , <i>Test Setup With Bluetooth low energy</i>	20
• Updated description of figure in Section 3.2.4 , <i>Test Results With Bluetooth low energy</i>	25
• Added Section 3.3 , <i>Optimizations for the Design</i>	33
• Added item (4) in Section 6 , <i>Related Documentation</i>	34

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