TI Designs: TIDM-1019
Ultrasonic Sensing Subsystem Reference Design for Water Flow Measurement

TEXAS INSTRUMENTS

Description

This reference design helps designers develop an ultrasonic water-metering subsystem using an integrated, ultrasonic sensing solution (USS) module, which provides superior metrology performance, with low-power consumption and maximum integration. The design is based on the 256KB MSP430FR6047 microcontroller (MCU), with integrated high-speed, ADC-based, signal acquisition and an integrated low-energy accelerator (LEA) to optimize digital signal processing.

Resources

|	
TIDM-1019	Design Folder
MSP430FR6047	Product Folder
EVM430-FR6047	Tool Folder

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Features

- Best-In-Class Metrology Performance: 25-ps Zero-Flow Drift (ZFD) and 32-ps Single-Shot Standard Deviation
- Low-Power Consumption: Approximately 2.5 µA With 1-MHz Transducer at 1 Measurement per Second For Metrology
- Flexibility to Test Different Pipes and Transducers; Direct Interface to Pair of Transducers
- Easy to Test and Customize Using Ultrasonic Sensing Design Center Graphical User Interface (GUI)
- Ultrasonic Sensing Software Library Includes Time of Flight (ToF) Algorithms
- Stand-Alone Demo Using Liquid-Crystal Display (LCD)

Applications

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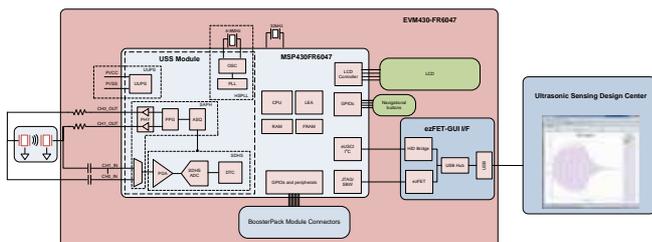
An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.

1 System Description

The TIDM-1019 device was built using the MSP430FR6047 MCU from TI and other discrete components. The implementation is based on the calculation of differential time of flight (ToF), involving two transducers for upstream and downstream paths. Transducer excitation and signal captures are implemented using the internal, ultrasonic sensing solution (USS) module of the MSP430FR6047 MCU. The signal is then passed through a series of algorithms using the LEA of the MSP430™ MCU, to calculate the necessary output data in a quick and power-effective manner.

The TIDM-1019 device uses the EVM430-FR6047 evaluation kit, targeted specifically for ultrasonic sensing applications like water-flow meters. The EVM includes a connector to interface with other BoosterPack™ plug-in modules. The reference design includes all the hardware files required.

The software is written in a modular and portable manner by using MSP430Ware™ software and MSP430's Ultrasonic Sensing Water Metering Library from TI.

The reference design also includes the Ultrasonic Design Center, which enables designers to modify and optimize different configuration parameters through an easy-to-use GUI. The USS Design Center lets users implement and customize different transceivers easily without modifying the application code in the example project.

The design files include source code for an application example and corresponding Code Composer Studio™ (CCS) and IAR Embedded Workbench™projects.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Zero-flow drift (ZFD)	25 ps (typ)	Section 3.2.2.2
Single-shot standard deviation (STD)	32 ps (typ)	Section 3.2.2.1
Minimum detectable flow (MDF)	1 LPH	Section 3.2.2.4
Average current consumption at one measurement per second (P_{AVG})	2.5 µA (typ)	Section 3.2.2.5

2   System Overview
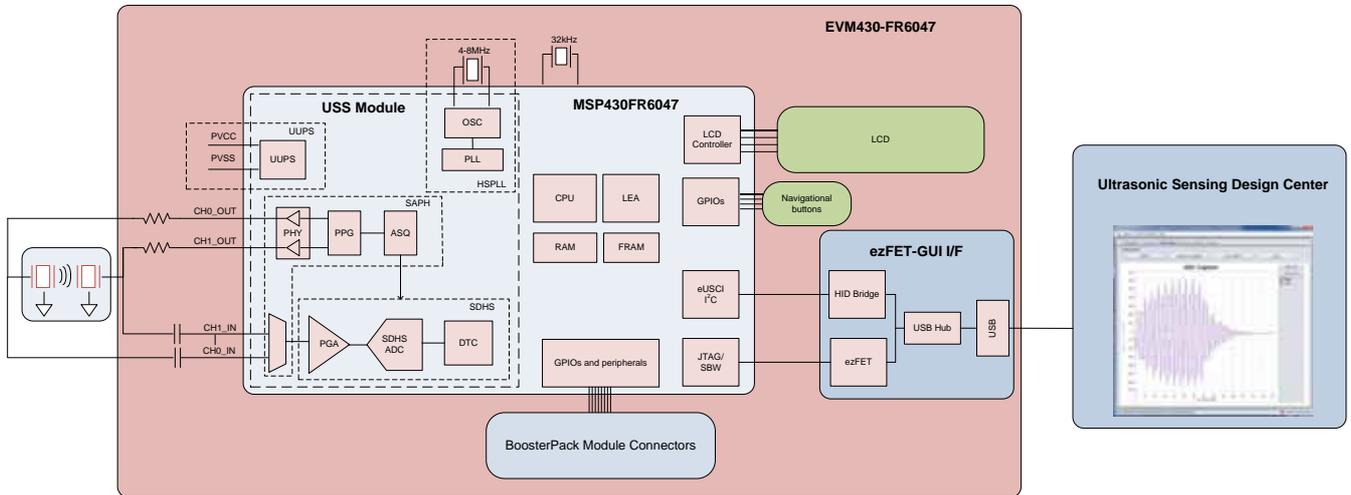
2.1   Block Diagram

Figure 1. TIDM-1019 Block Diagram

2.2 Design Considerations

2.2.1 Flow Measurement

The ultrasonic water-flow meter design is based on the principle of ToF measurement. This measurement refers to the time it takes a signal to travel from a transmitting transducer to a receiving transducer.
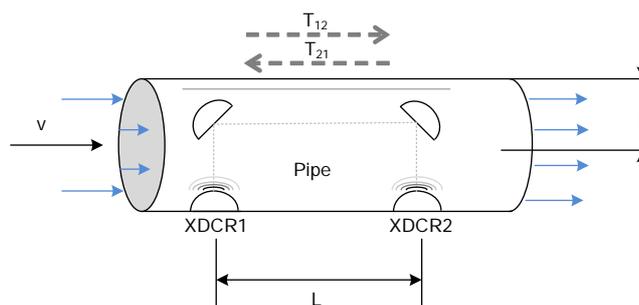
Figure 2 shows a flow pipe.

Figure 2. ToF in Flow Meter

The propagation time of a signal traveling from the first transducer, XDR_1, to the second transducer, XDR_2, is given by T_{12}. In the same way, T_{21} represents the propagation time in the opposite direction. Calculate these timings, according to the following equations, as a function of the velocity of the ultrasound in water and the velocity of water flow. Because this length is much larger than the radius of the pipe, *r*, the propagation length of the wave that is perpendicular to the flow is considered to be negligible in the following analysis.

$$T_{12} = \frac{L}{c + v} \tag{1}$$

$$T_{21} = \frac{L}{c - v} \tag{2}$$

$$\Delta t = T_{21} - T_{12} \tag{3}$$

where:
- c is the velocity of the ultrasound in the medium.
- v is the velocity of water flow.
- L is the propagation length of the pipe along the flow of water.

Use Equation 1 through Equation 3 to derive the velocity of water flow (v), which is possible even without knowing the velocity of the ultrasound in the medium (c).

This reference design calculates water flow assuming that the velocity of the ultrasound is unknown. In this case, derive Equation 4 from Equation 1 and Equation 2 by eliminating *c* .

$$v = \frac{L}{2} \times \left(\frac{1}{T_{12}} - \frac{1}{T_{21}} \right) = \frac{L}{2} \times \frac{T_{21} - T_{12}}{T_{21} T_{12}} = \frac{L}{2} \times \frac{\Delta T}{T_{21} T_{12}} \tag{4}$$

Using Equation 4, calculate the actual propagation times, T_{12} and T_{21}, in the two directions along the cross section of the pipe.

2.2.2 ToF Measurement

In the implementation discussed in this reference design, the MSP430FR6047 device performs the complete acquisition process using the USS module in the device for signal conditioning. Figure 3 shows this acquisition process.

At the beginning of the sequence, the MSP430FR6047 device sends a train of pulses to the first transducer, $XDCR_1$. The signal is then received by the second transceiver, $XDCR_2$, after a propagation time, T_{12}. The difference in time between transmission and reception determines the upstream (UPS) ToF, or ToF_{UPS} .

The MSP430FR6047 device repeats the same process in the opposite direction during the downstream stage, resulting in the propagation time, T_{21}, which represents the downstream (DNS) ToF, or ToF_{DNS}.

The DToF, Δt, can then be calculated as the difference between T_{12} and T_{21}, as described in Equation 3.

The DToF is typically measured using two techniques: Zero-crossing using a time-to-digital converter (TDC) or through Correlation using the ADC captured signal

The TIDM-1019 device uses the ADC-based technique instead of the TDC technique due to the following advantages.

1. Improved performance: the correlation acts as a digital filter to suppress noise, which results in a benefit of approximately three to four times lower-noise standard deviation. Similarly, the correlation approach also acts as a low-pass filter that suppresses other interference like line noise.

2. Improved robustness for signal amplitude variations: because the algorithm is insensitive to the received signal amplitude, transducer-to-transducer variation, and temperature variation.

3. The envelope of the signal is obtained naturally; this signal enables tuning to the transducer frequencies, as well as slow variations in the envelope across time, which can be used to maintain performance even with aging transducers or meters.

2.2.2.1 *ADC-Based Acquisition Process*

The ADC-based acquisition process implemented in this reference design heavily uses the hardware capabilities of the USS module in the MSP430FR6047 device, including pulse generation and the high-speed sigma-delta ADC, to completely automate the sampling process. This process not only provides tighter control of the sampling process without dependencies on CPU latencies and compilers, but it also reduces the power consumption, because the CPU is in low-power mode (LPM3) during the measurement.

Figure 4 shows a timing diagram of the signal acquisition process. The signal acquisition steps follow:

1. At the start of the process (t_0), the device initializes the USS module that is running off the internal clock derived from USSXT and triggers the start of pulse generation.

2. The CPU goes into LPM0 low-power mode after starting the USS module, waiting for the measurement sequence to complete. This sequence also includes signal acquisition by the high-speed sigma-delta ADC, and the captured data is stored in the RAM shared between the CPU and LEA module.

3. After the last sample, the USS module automatically wakes up the CPU through an interrupt mechanism.

4. The CPU prepares to go into LPM3 mode at the end of conversion time (tEoC).

5. After a specified UPS-DNS gap ($t_{UPS-DNS-GAP}$), the CPU starts the USS module to process the other (DNS) channels. The CPU goes into LPM0 mode waiting for the DNS samples and measurement.

6. After the last sample is received for the DNS, the USS module automatically wakes up the CPU through an interrupt mechanism.

7. The CPU processes the data and obtains the delta time of flight (DTOF) and absolute time of flight (AbsToF) for both the DNS and UPS channels, and the volume flow rate (VFR). After processing is complete, the CPU goes into LPM3 mode for the duration of $t_{DNS-UPS-GAP}$, which is the gap between the end of the current measurement and the start of the next measurement.

2.2.2.2 *Ultrasonic Sensing Flow-Metering Library*

This reference design is intended to explain some of the key concepts of implementing an ultrasonic, flow-metering, metrology solution, so it is important to note that the proposed solution makes use of the Ultrasonic Sensing Flow Metering Library, which implements several proprietary algorithms from TI, to capture and process the signal as well as calculates the ToF and water flow rate.

The Ultrasonic Sensing Flow Metering Library and documentation are available for download from the USSSWLibrary.

2.2.3   Low-Power Design

The USS module in the MSP430FR6047 device used in this design is intended to meet the low-power requirements of water meter applications. While the current consumption of the system depends on the meter, transducers, and configuration of the application, the solution was designed to consume approximately 2.5 μA, using 1-MHz transducers taking one measurement per second. This includes one UPS and one DNS measurement per second and the associated signal processing. This is only for the metrology portion and does not include any current consumption in between the measurements that can be used for other unrelated application-level processing or when the device can be put in a low-power mode like LPM3. For more details on power consumption measurements, see Section 3.2.2.5.

The low-power features implemented by this application include:

- Energy-efficient software
- Optimized hardware design internal to the MSP430FR6047 device
- Efficient use of FRAM
- Uses the low-energy signal-processing capabilities of LEA

2.2.3.1   Energy-Efficient Software

The application software and Ultrasonic Sensing Water Flow Metering Library used by the TIDM-1019 device maximize the use of low-power modes. The MCU enters the lowest-power mode available when possible.

2.2.3.2   Optimized Hardware Design

The TIDM-1019 device uses not only the MSP430 platform, which combines high performance with industry leading ultra-low-power consumption, but all external components were selected for their energy efficiency.

2.2.3.3   Efficient Use of FRAM

The MSP430FR6047 device uses FRAM technology, which combines the best of Flash and RAM. FRAM offers the nonvolatile nature of Flash together with fast and low-power writes, a write endurance of 10^{15} cycles, resistance to radiation and electromagnetic fields, and unmatched flexibility.

This use of this technology results in an application that writes and logs data more efficiently than its Flash-based counterparts.

The application provided in this software package uses FRAM to store several nonvolatile variables, such as the configuration received from the GUI. This storage lets users reconfigure the device on-the-fly and keeps the configuration after subsequent power cycles.

Developers of metering applications can use FRAM to implement many additional features including:

- Logging historical statistical data, such as differential ToF, absolute time of flight (absToF), or volume flow rate
- Logging errors and faults in nonvolatile memory
- Saving and restoring the state of the device before a power failure (see TIDM-FRAM-CTPL)

2.2.3.4 The LEA Advantage

The TIDM-1019 device also makes efficient use of the LEA available in the MSP430FR6047 device.

LEA is a 16-bit, hardware engine designed to perform signal processing, matrix multiplications, and other operations that involve vector-based signal processing, such as FIR, IIR, and FFT, without CPU intervention. Efficient use of this module can result in improvements of up to 36.4 times for typical math intensive operations.

LEA is heavily used by the Ultrasonic Sensing Flow Metering Library to accelerate all vector operations in its proprietary algorithms. LEA not only reduces the processing time of many operations, but LEA also allows the CPU to go into a low-power state.

For more information about LEA, see *Low-Energy Accelerator (LEA) Frequently Asked Questions* and *Benchmarking the Signal Processing Capabilities of the Low-Energy Accelerator on MSP430 MCUs*.

2.3 Highlighted Products

2.3.1 MSP430FR6047

The MSP430FR604x family of ultrasonic sensing and measurement system on chips (SoCs) from TI are powerful, highly-integrated MCUs that are optimized for water and heat meters. The MSP430FR6047 MCU offers an integrated USS module, which provides high accuracy for a wide range of flow rates. The USS module helps achieve ultra-low-power metering, combined with lower system costs, due to maximum integration requiring few external components. The MSP430FR6047 MCU implements a high-speed, ADC-based, signal acquisition followed by optimized digital signal processing using the integrated LEA module, to deliver a high-accuracy metering solution with ultra-low power optimum for battery-powered metering applications.

The USS module includes a programmable pulse generator (PPG) and a physical interface (PHY) with a low-impedance output driver for optimum sensor excitation and accurate impedance matching, to deliver the best results for ZFD. The module also includes a programmable gain amplifier (PGA) and a high-speed, 12-bit, 8-msps, sigma-delta ($\Sigma\Delta$) ADC (SDHS) for accurate signal acquisition from industry standard ultrasonic transducers.

Additionally, the MSP430FR6047 MCU uses other peripherals to improve system integration for metering. The device has a metering test interface (MTIF) module, which implements pulse generation to indicate the flow measured by the meter. The MSP430FR6047 MCU also has the following:

- On-chip, 8-MUX, LCD driver
- RTC
- 12-bit, SAR ADC with up to 16 external channels
- Analog comparator with up to 16 channels
- Four eUSCI_A to implement universal asynchronous receiver/transmitter (UART)
- IrDA or serial peripheral interface (SPI)
- Two eUSCI_B to implement I^{2}C or SPI
- Six, 16-bit timers
- Advanced encryption accelerator (AES256)
- Cyclic redundancy check (CRC) module

The MSP430, ultra-low-power, FRAM, MCU platform combines uniquely embedded FRAM and a holistic, ultra-low-power, system architecture, letting system designers increase performance while lowering energy consumption. FRAM technology combines the low-energy fast writes, flexibility, and endurance of RAM with the nonvolatile nature of flash.

The TIDM-1019 device uses the MSP430FR6047 device to not only act as a host processor communicating with a PC GUI, but also to perform measurements in an automated process. The powerful peripherals of the MSP430FR6047 device, particularly the USS module, together with FRAM technology and the LEA, allow for an accurate and efficient implementation of an ultrasonic water flow meter.

2.4   System Design Theory

The ADC-based approach to estimate the differential ToF and AbsToF is based on correlation techniques.

2.4.1   Signal Processing for ToF

Equation 5 gives the signal processing for time of flight.

$$r_{2i} = r_2 i f_s \tag{5}$$

where:

- f_s is the sampling rate of the ADC.
- i is the index of the sample.
- $r_2(t)$ indicates the received ultrasonic signal at the output of the transducer 2 (downstream capture).

Similarly, let the received signal at transducer 1 (upstream capture), $r_1(t)$, be represented by the data vector, see Equation 6.

$$r_1 - = r_{11}, r_{12}, r_{13}, \ldots, r_{1N} \tag{6}$$

As an example, for the sampling frequency of f_s = 4000 kHz and capture duration of 40 μs, the size of the received data vectors N = 160.

Based on r_1 and r_2, a correlation value, *corr(k)*, is calculated as Equation 7.

$$corr(k) = \sum_{i=1}^{N} r_{1i+k} r_{2k}; \quad for \; k = -m, -(m-1), \ldots, -1, 0, 1, \ldots, (m-1), m \tag{7}$$

where:

- values for $r_1{}^i$, $r_2{}^i$ = 0 for $i < 1$
- $i > N$

The maximum of the correlation is calculated as Equation 8.

$$k^{\wedge} = \max_k corr(k) \tag{8}$$

where:

- Z_{-1} = *corr(k–1)*
- Z_0 = *corr(k)*
- Z_{+1} = *corr(k+1)*

These variables are the correlation values at and around the maximum. The real maximum of the correlation is now given by an interpolation (see Equation 9).

$$\delta = interpmax Z_{-1}, Z_0, Z_{+1} \tag{9}$$

The DToF is now given by Equation 10.

$$T_{12corr} = k^{\wedge} - m + \delta \tag{10}$$

For efficient implementation, *m* is chosen as +1, implying that only three correlations (Z_{-1}, Z_0, and Z_{+1}) are computed most of the time. Figure 3 shows the previous relationships.
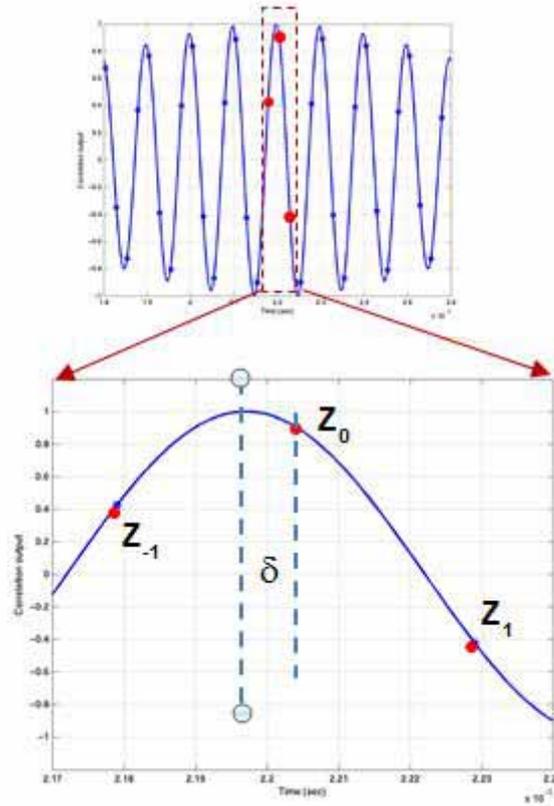
Figure 3. Interpolation Step for Differential ToF

The correlator-based ToF calculation has been reported in the literature previously, as given in the *MSP430FR58xx, MSP430FR59xx, and MSP430FR6xx Family User's Guide*. Efficient interpolation techniques are given in the *EVM430-FR6047 Hardware Guide*. As previously mentioned, for efficiency of implementation, the correlation is only computed over a few points, leading to a low-power implementation.

Estimating an accurate absToF in water means that a temperature sensor is not needed to compute the velocity of sound in water. In the USS SW Library used in this reference design, the absToF is determined by computing the envelope of the received signal. A maximum of the signal for each capture is first computed. The envelope crossing as a given ratio of this maximum is then determined. The absToF is then calculated by a constant offset from this threshold crossing of the envelope, as shown in Figure 4 and Equation 11.
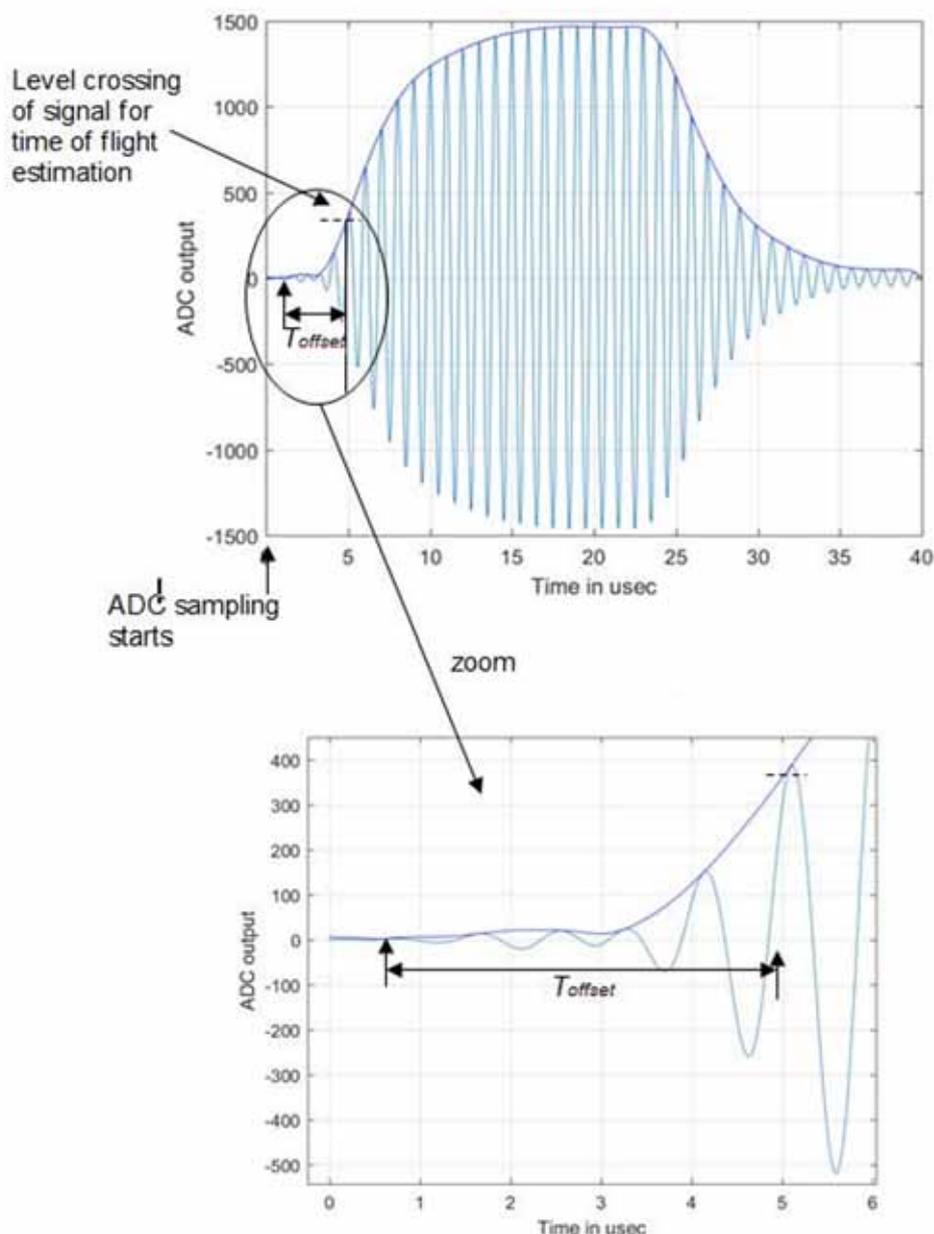
Figure 4. ADC Captured Waveform and Envelope for AbsToF Calculation

The UPS and DNS absToF are therefore given by Equation 11.

$$T_{ups}^{abs} = T_{prop} + T_{thresh}^{ups} - T_{offset} \qquad T_{dns}^{abs} = T_{prop} + T_{thresh}^{dns} - T_{offset} \tag{11}$$

where:

- T_{prop} is the propagation time which is pre-programmed from USS Design Center GUI or application configuration and corresponds to approximate propagation time for the ultrasound signal in the given meter.

Typically, this value can range from 35 to 70 µs. The threshold parameters, T_{thresh}^{ups} and T_{thresh}^{dns}, correspond to the time from the ADC trigger to the envelope crossing a certain ratio (typically chosen to be 20%) of the signal maximum.

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

3.1.1 Hardware

The hardware used for this reference design consists of the EVM430-FR6047 ultrasonic sensing evaluation module.

3.1.1.1 EVM430-FR6047

The EVM430-FR6047 evaluation kit is a development platform which can be used to evaluate the performance of the MSP430FR6047 device for ultrasonic sensing applications (for example, smart water meters). The kit provides a flexible solution to let engineers quickly evaluate and develop with the MSP430FR6047 device, with a variety of transducers ranging from 130 kHz to 2.5 MHz. The EVM can display the measurement parameters using the onboard LCD and connectors for the RF communication modules.

The EVM430-FR6047 kit can be USB-powered, but a provision is also provided for external power. The EVM also has BoosterPack headers to interface with external boards through various interfaces like I^{2}C, SPI, UART, or GPIO, as well as RF communication modules. The EVM has an onboard, segmented LCD and an onboard, eZ-FET emulation circuit to enable programming and debug.

When using a USB as the power source, users must set the POW_SEL switch to the middle position (*ezFET*). When using an external power source, users must set the POW_SEL switch to the top position (*External*), as shown in Figure 5.
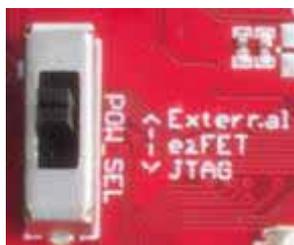
Figure 5. eZ-FET Power Selection

Figure 6 shows J1 and J3 set for the USB power source (ezFET).

Figure 6. USB (eZ-FET) Power Jumper Configuration

NOTE: All the tests whose results are presented in this TI Design are done using an external power supply (EXT_POW).

3.1.2 Software

Figure 7 shows the software architecture implemented in this reference design. The software is implemented in a modular and portable manner. The main components include the MSP430 Driver library (DriverLib), Ultrasonic Sensing Flow Metering Library (USS SW LIB), Application, and Ultrasonic Sensing Design Center GUI.
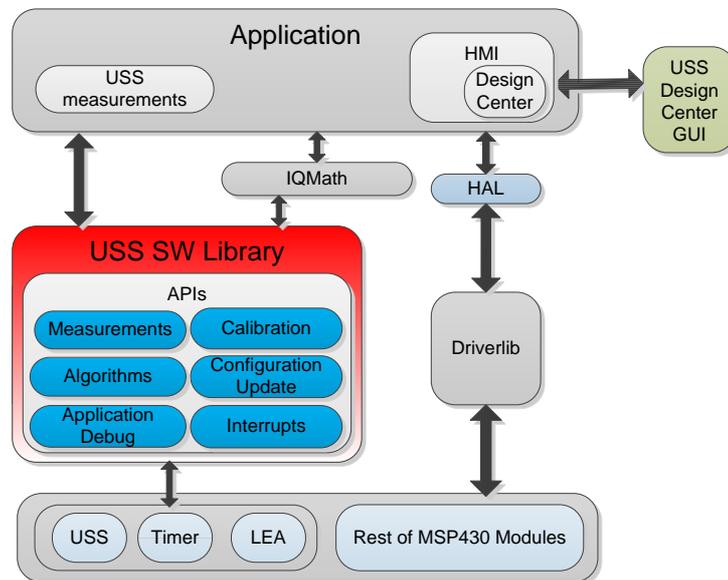
Figure 7. Software Architecture

This TI Design only includes examples tested on the MSP430FR6047 device using the EVM430-FR6047 evaluation kit. The software package includes source code for the application, the Ultrasonic Sensing Flow Metering Library in binary format, and corresponding IAR and CCS projects. The main software components are discussed in the following sections.

3.1.2.1 *MSP Driver Library (MSP DriverLib)*

The driver library (DriverLib) includes APIs for selected MSP430 device families, providing easy-to-use function calls. Each API is thoroughly documented through a user's guide, API Guide, and code examples.

The TIDM-1019 device uses the MSP Driver Library to interface with all hardware modules used by the application from eUSCI_A, which is used for asynchronous communication with the PC to the USS module, which is then used to sample the incoming signal. This feature not only allows for an easier migration to other MSP430FR604x MCUs, but it also makes the code easier to read and understand by using common language APIs.

The source code in the software package includes all DriverLib files used by this application. The MSP DriverLib and documentation are also available at MSPDRIVERLIB.

3.1.2.2 *Ultrasonic Sensing Flow Metering Library*

The Ultrasonic Sensing Flow Metering Library includes proprietary algorithms to capture and process the signal received from the transceivers as well as to calculate the ToF and water flow rate. The library includes an easy-to-implement set of fully-documented APIs that hide the complexity behind ultrasonic measurement calculations and allow for a faster implementation of the application. A comprehensive list of parameters lets developers configure the system according to different hardware and transceiver requirements.

The Ultrasonic Sensing Flow Metering Library used by the application is included in CCS and IAR library format. This library and its documentation are available at USSFlowLibrary.

3.1.2.3 *Application*

Figure 8 shows the flow diagram of the application.
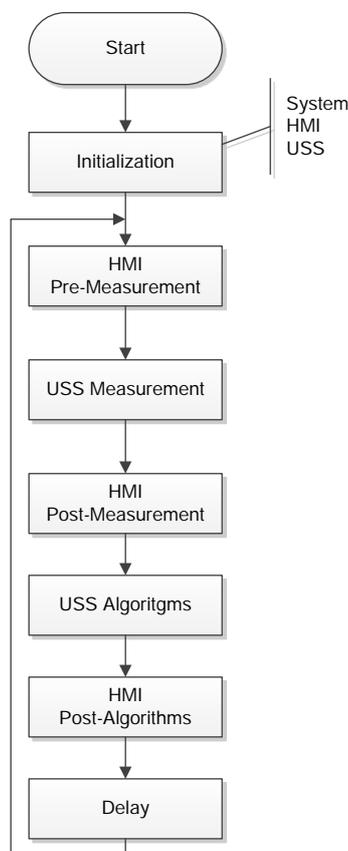
Figure 8. Application Flow Diagram

The application starts by initializing the basic functionality of the system including peripherals, clocks, and IOs, followed by initializing the HMI peripherals including LCD, GUI communication, buttons, and LEDs. Finally, the system performs the initial configuration of the ultrasonic subsystem and its algorithms.

After initialization, the application stays in a continuous loop performing the following tasks:

- HMI pre-measurement: Performs user interaction functions before an ultrasonic measurement, such as checking if the GUI has a new configuration to send or if the user pressed a button.
- USS measurement: Performs an ultrasonic measurement. The result of this function is an ADC-sampled waveform.
- HMI post-measurement: Performs user interaction functions after a measurement such as sending the ADC waveform to the GUI.
- USS algorithms: Runs ultrasonic algorithms on the ADC-sampled waveform to calculate data such as the ToF and volume flow rate.
- HMI post-algorithms: Performs user interaction functions after the algorithms are executed. This includes sending the results to the GUI or displaying them on the LCD.
- Delay: The device goes to a low-power state waiting for the next iteration.

The Application Software (SW) for MSP430FR6047-Based Ultrasonic Water Flow Meter user's guide describes the architecture and implementation of the application in more detail.

3.1.2.3.1 Application Customization

The ultrasonic water-flow meter application included in this TI Design is provided in the source code, letting developers customize it according to their needs. Although developers can customize the functionality and behavior of the application as needed, the most common customizations follow.

- Changing the default USS configuration – Although the Design Center GUI lets developers modify different ultrasonic configuration parameters, as described in Section 3.1.2.4, the application includes source code of configuration files, which can be modified to customize the default configuration of the system.
- Customizing the hardware – The application was designed in a modular way, including a hardware abstraction layer (HAL) to encapsulate hardware interactions. This feature allows for easier customization of different hardware requirements from developers and an easier migration between TI platforms.
- Customizing data processing – The library includes proprietary algorithms, which are used to process captured ADC waveforms and obtain flow rate information. However, it is possible for developers to implement custom algorithms to add a proprietary IP or attempt to optimize the performance of the system.
- Changing the default application configuration – The application supports several features that can be enabled, disabled, or customized by developers. Table 2 lists the features.

Table 2. Configuration of Application Features

FEATURE	DESCRIPTION	DEFINITIONS
Resonator calibration	The application periodically calibrates the resonator using the 32-kHz crystal as a reference. The resulting value is used as a correction term for ToF calculations.	USS_APP_RESONATOR_CALIBRATE
		USS_APP_RESONATOR_CALIBRATE_INTERVAL
Automatic gain control	The application periodically calculates the optimal gain setting.	USS_APP_AGC_CALIBRATE
		USS_APP_AGC_CALIBRATE_INTERVAL
DC offset cancellation	The application calculates and cancels the DC offset of the captured ADC signals.	USS_APP_DC_OFFSET_ESTIMATE
		USS_APP_DC_OFFSET_ESTIMATE_INTERVAL

The Application Software (SW) for MSP430FR6047-Based Ultrasonic Water Flow Meter user's guide describes application customization in more detail.

3.1.2.3.2   LCD Stand-Alone Mode

The application supports a stand-alone mode that can be used to show different flow measurement results using the LCD and buttons. This mode is entered by pressing the UP navigational button. The LCD turns on to show the first of the measurements (instantaneous flow rate). The navigational buttons LEFT and RIGHT can be used to scroll through the different measurement results, as follows.

- Instantaneous flow rate
- Average flow rate
- Volume
- Battery voltage
- Instantaneous differential ToF
- Average differential ToF
- Standard deviation of differential ToF

Pressing the UP navigational button again turns off the LCD and exits this mode.
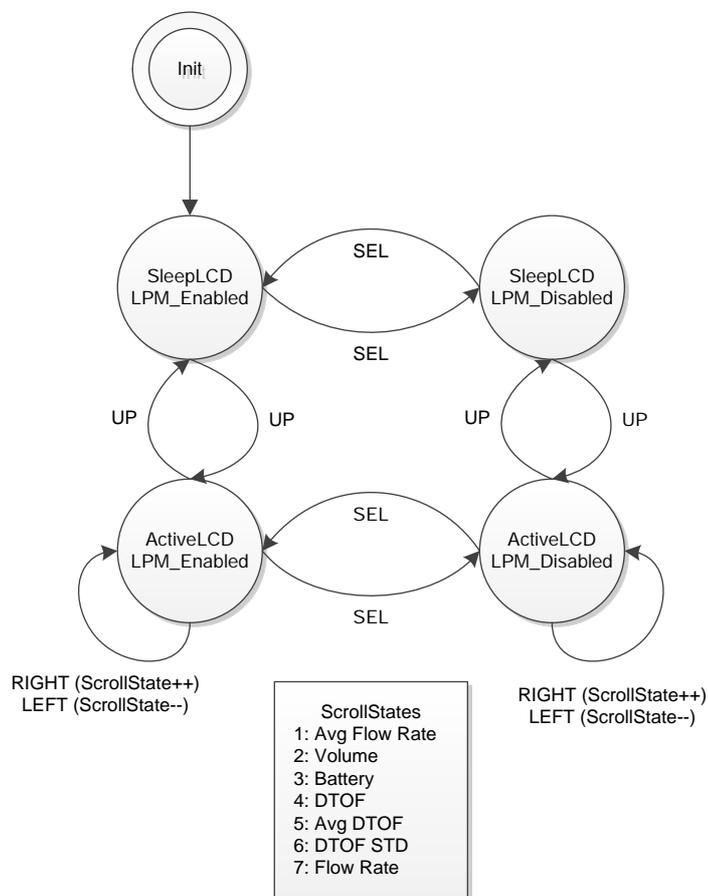
Figure 9 shows the stand-alone flow chart.

Figure 9. LCD and Buttons State Machine

3.1.2.4   USS Design Center (PC GUI)

The MSP430 Ultrasonic Sensor Design Center Tool GUI included in this reference design lets developers modify some configuration parameters required to test different transducers, as well as observe the behavior of the system in real time.

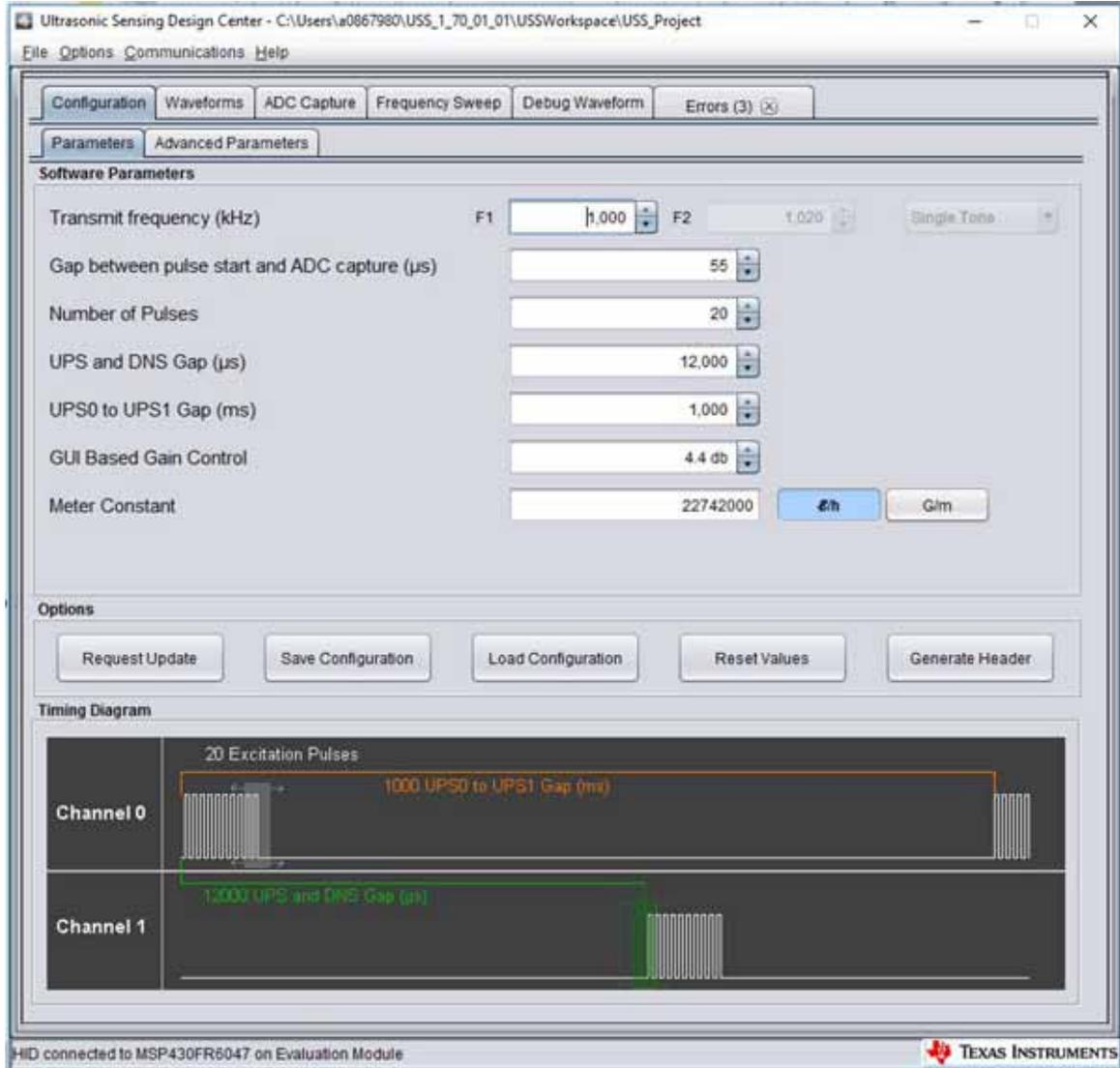The configuration window is shown by default when opening the application, see Figure 10.

Figure 10. GUI Configuration Parameters Window

The configuration window lets developers configure the parameters detailed in Table 3.

Table 3. GUI Configuration Parameters Description

TRANSMIT FREQUENCY (kHz)	PULSE OUTPUT FREQUENCY (kHz) USED TO EXCITE TRANSDUCERS
Gap between pulse start and ADC capture (μs)	Gap in microseconds between the generation of a pulse output and sampling of a received signal using SDHS
Number of pulses	Number of pulses sent during pulse generation
UPS and DNS gap (μs)	Gap in microseconds between upstream and downstream captures
UPS0 to UPS1 gap (ms)	Gap in milliseconds between captures. This is measured from the end of the downstream capture to the start of the next upstream.
GUI-based gain control	PGA gain setting in dB. This only takes specific values that are supported by the MSP430FR6047 device.
Meter constant	Constant used to calculate the volume flow rate. This static constant is related to the cross section area of the meter that the vendor should provide as a one-time input. This also needs to vary depending on whether LPH or GPM is used for the display.

Figure 11 shows the Advanced Parameters configuration panel.
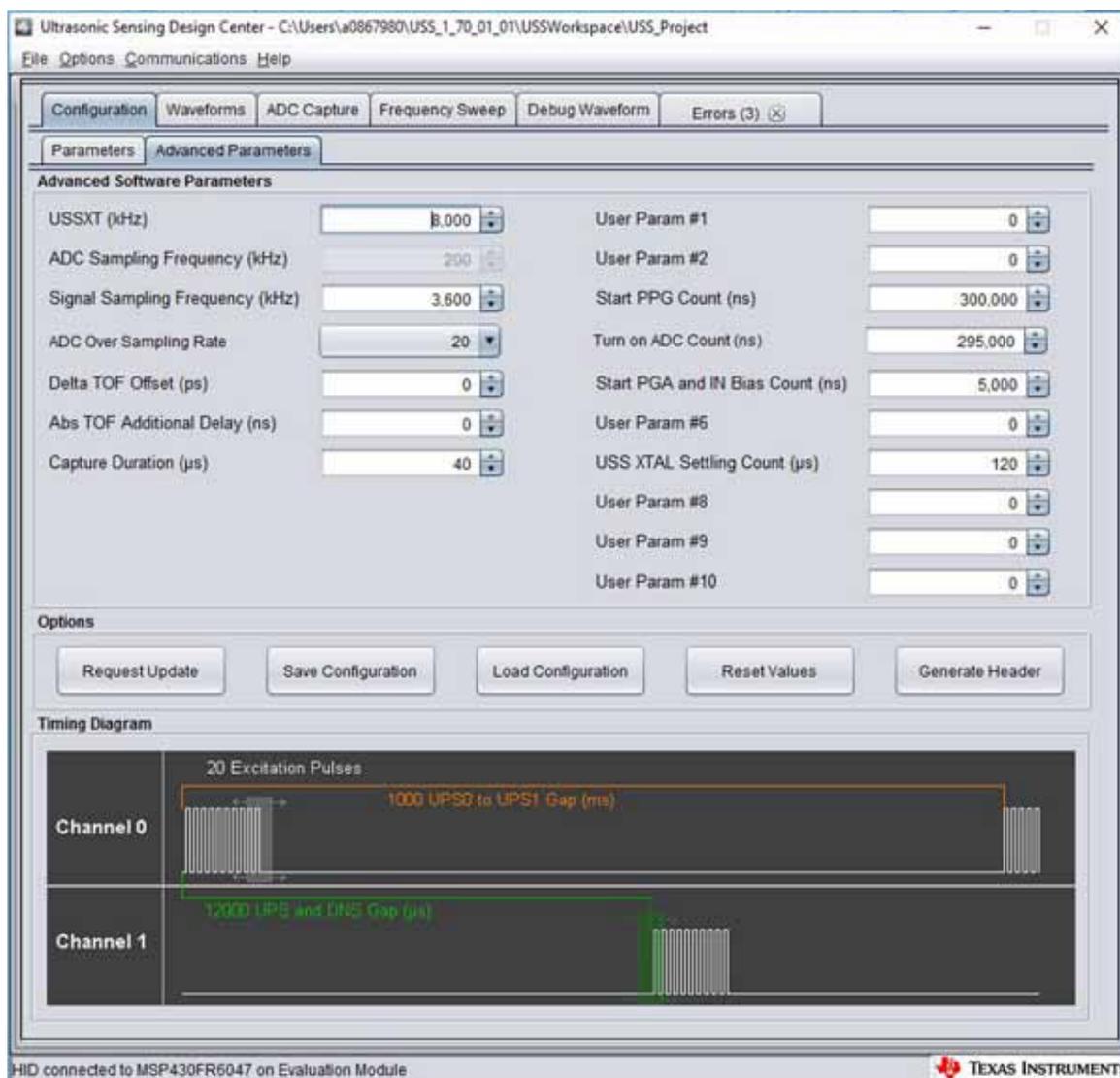
Figure 11. GUI Advanced Parameters Configuration Window

The Advanced Parameters Configuration panel lists the parameters in Table 4.

Table 4. GUI Configuration Advanced Parameters Description

USSXT (kHz)	FREQUENCY OF X1 RESONATOR IN kHz CONNECTED TO MSP430FR6047 ON EVM430-FR6047
ADC Sampling Frequency (kHz)	RESERVED
Signal Sampling Frequency (kHz)	Sampling frequency of the received signal in kHz
ADC Oversampling Rate	Oversampling ratio (OSR) of the SDHS. This is 10 for signal sampling frequency in the range of [6.8 to 8.0] MHz, and 20 for sampling frequency in the range of [3.4 to 4.0] MHz.
Delta ToF offset (ps)	Offset to compensate the delta ToF in picoseconds for any non-zero bias
Absolute ToF additional delay (ns)	Time in nanoseconds to compensate for unaccounted additional delays in absolute ToF
Capture duration (µs)	Duration of the ADC capture in microseconds
User Param 1	RESERVED
User Param 2	(ULPBiasDelay) selects the delay in applying the bias after the initialization of the USS module. TI recommends setting this to 3 (representing 300 µs) and should not be modified.
Start PPG Count (ns)	Time to start PPG Pulse trigger in *nanoseconds*.
Turnon ADC count (ns)	Time to turn ON the ADC in *nanoseconds*.
Start PGA and IN Bias Count (ns)	Time to turn the PGA and Input biasing in *nanoseconds*.
User Param 6	RESERVED
USS XTAL Settling Count (µs)	Time allocated for USS crystal settling after initialization.
User Param 8	RESERVED
User Param 9	RESERVED
User Param 10	RESERVED

The MSP430 Ultrasonic Sensor Design Center Tool lets developers observe the behavior of the system in real time by using the Waveforms window, shown in Figure 12. This tool plots the delta time of flight (DToF) in the upper panel, the upstream absolute time of flight (AbsToFUPS) and downstream absolute time of flight (AbsToFDNS), and the volume flow rate (VFR). The plots include both the instantaneous measurement as well as the mean value of the measurements.
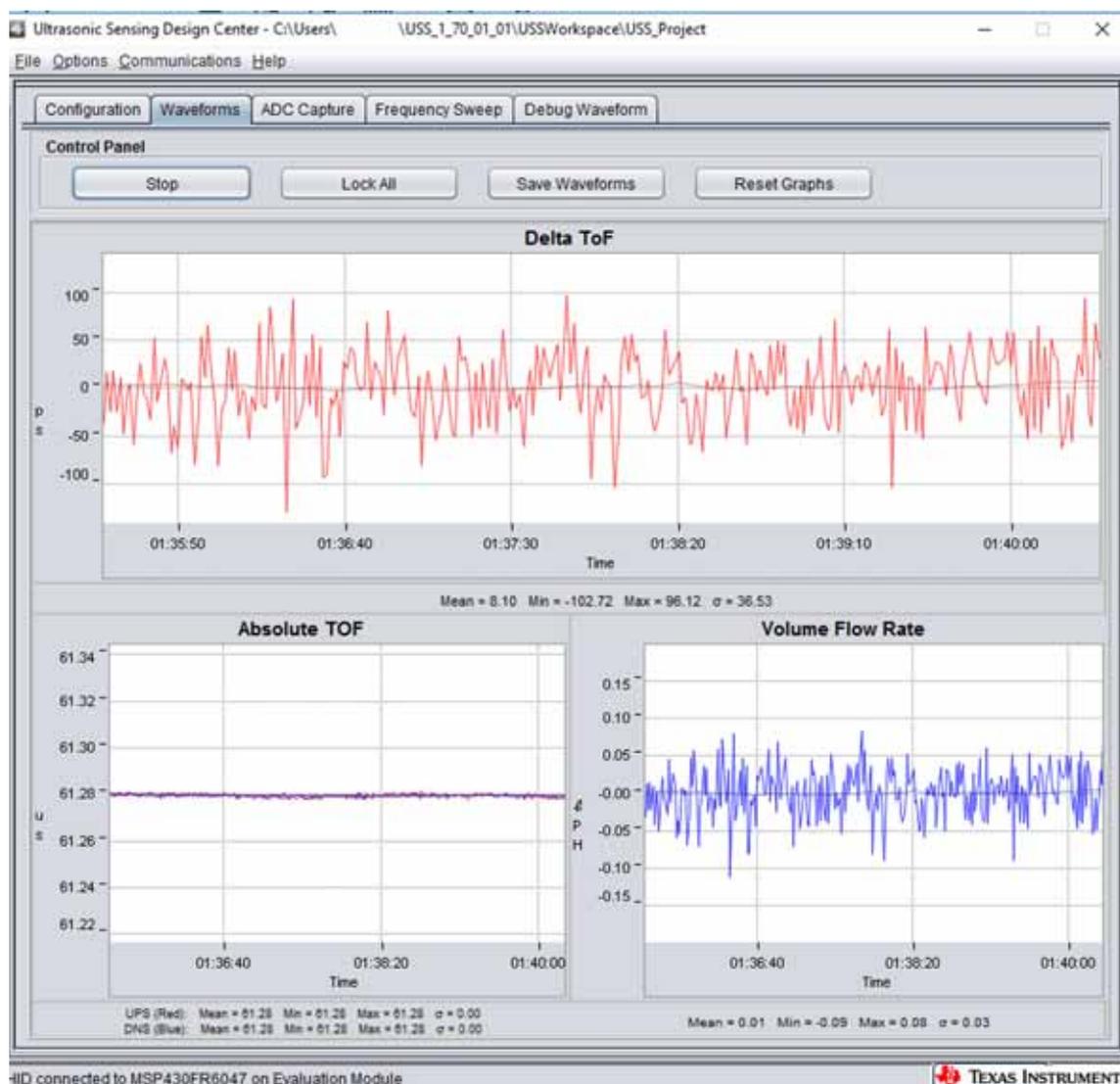
Figure 12. USS Design Center GUI Waveforms Window

Additionally, it is also possible to obtain and plot a single capture to validate the integrity of the signal by using the ADC Capture panel (see Figure 13). The panel lets users obtain continuous captures of the ADC waveform of contiguous measurements and allows the user to do additional debugging if required.
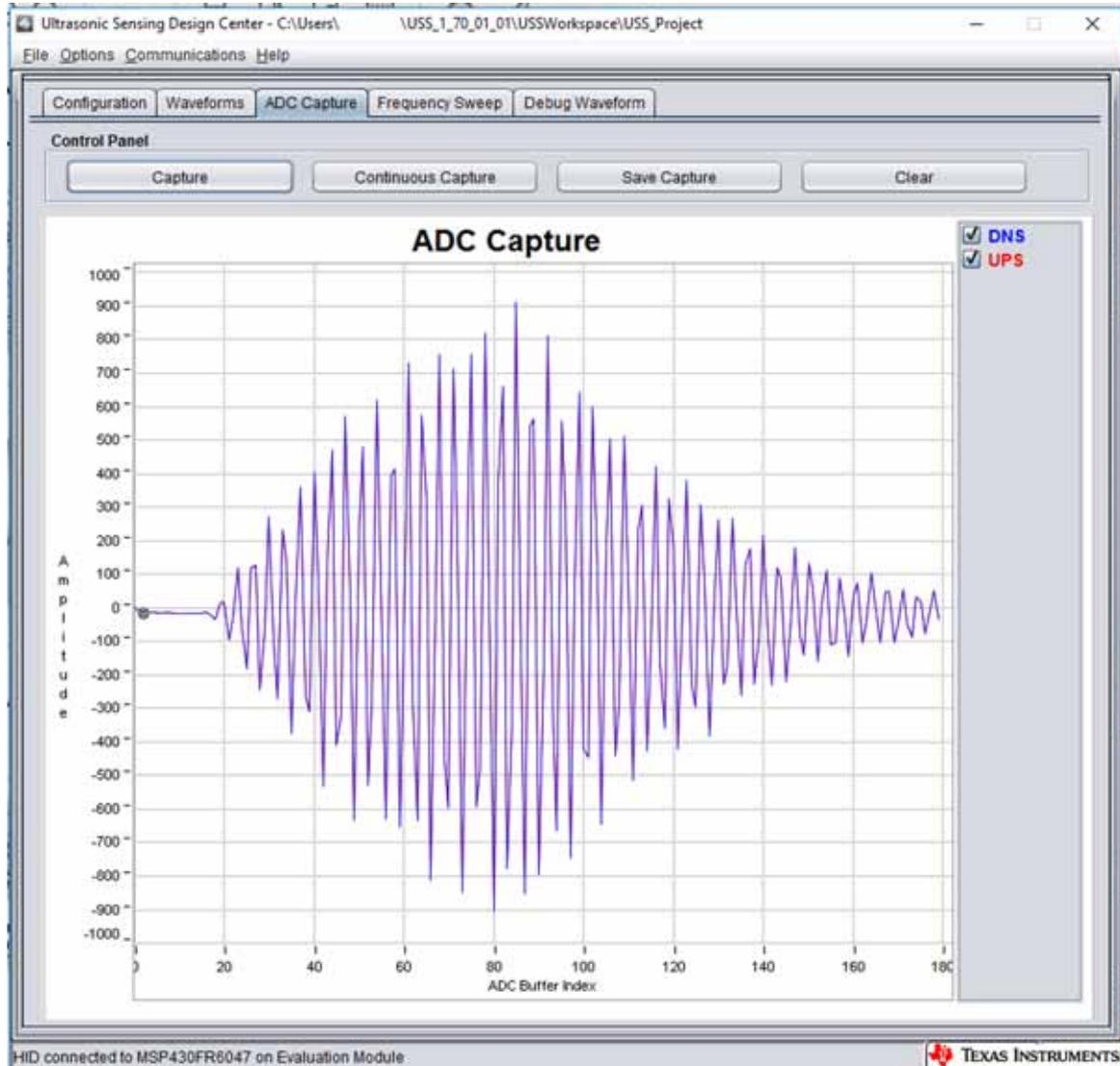
Figure 13. USS Design Center ADC Waveform Capture Window

3.1.3 Transducer and Meter

The purpose of this TI Design is to show the implementation of an ultrasonic front end for a flow-meter application, not the design of a transducer or meter. The test meters are based on a combination of off-the-shelf meters available from third party vendors like Audiowell or Jiakang, as well as other meter vendors. Figure 14 shows the transducer connections between the meter and the EVM430-FR6047 device, with the meter in stationary (zero flow) conditions. The connections do not change even during the flow tests.
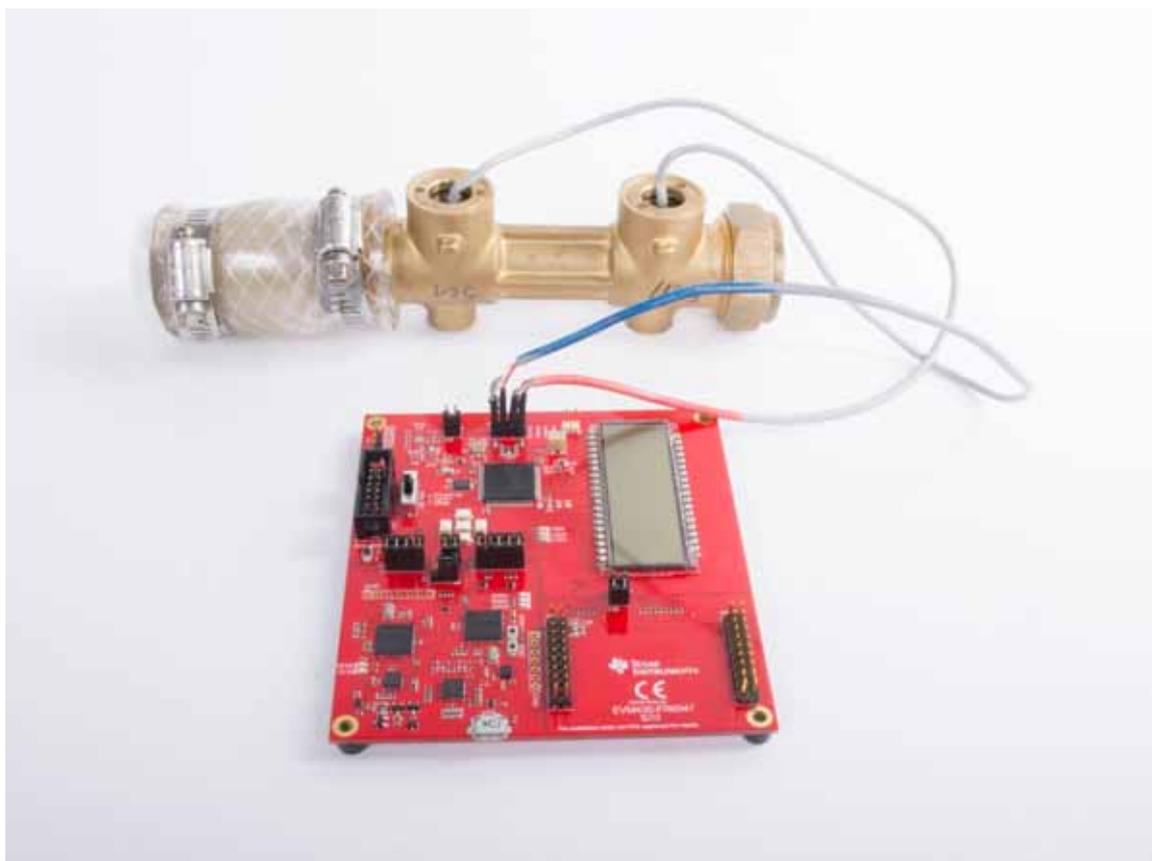
Figure 14. EVM430-FR6047 Connected to Water-Flow Meter in Stationary Setup

As explained in Section 2.2.1, an ultrasonic transmission is first generated by the first transducer and received by the second transducer after propagation through the liquid medium. The second transducer then emits an ultrasonic signal that is subsequently received by the first transducer. In both cases, the ultrasonic signal generated by the transducers is a result of the excitation (pulses generated) at the transducer frequency by the USS module on the MSP430FR6047 device.

3.1.3.1 Frequency Characterization of Transducer and Meter

Different meters and transducers have different responses; consequently, it is important to characterize the frequency response of the meter to obtain an optimal performance.

The MSP430 Ultrasonic Sensor Design Center Tool GUI provided in this TI Design can be used for this purpose. The GUI includes a Frequency Sweep panel. Ultrasonic Sensing Design Center User's Guide describes the detailed operation, but a brief description is provided here for completeness.

To start a sweep, do the following:

1. Set the F1 Parameter on the Configuration tab, and then set the Number of Captures parameter in the Frequency Sweep tab to determine the range in which to sweep.
2. Click on the Frequency Sweep button and navigate to the desired location in the file system where the Frequency Sweep data is saved, and then click the Save button.

The Frequency Sweep tool helps to determine at which transducer excitation frequency the ADC capture achieves the maximum amplitude. The frequency at which the peak amplitude is reached should be used as the new F1 parameter to achieve the strongest signal for the meter configuration. For the example, in Figure 15 a value of 2220 to 2300 should be placed into the F1 parameter.
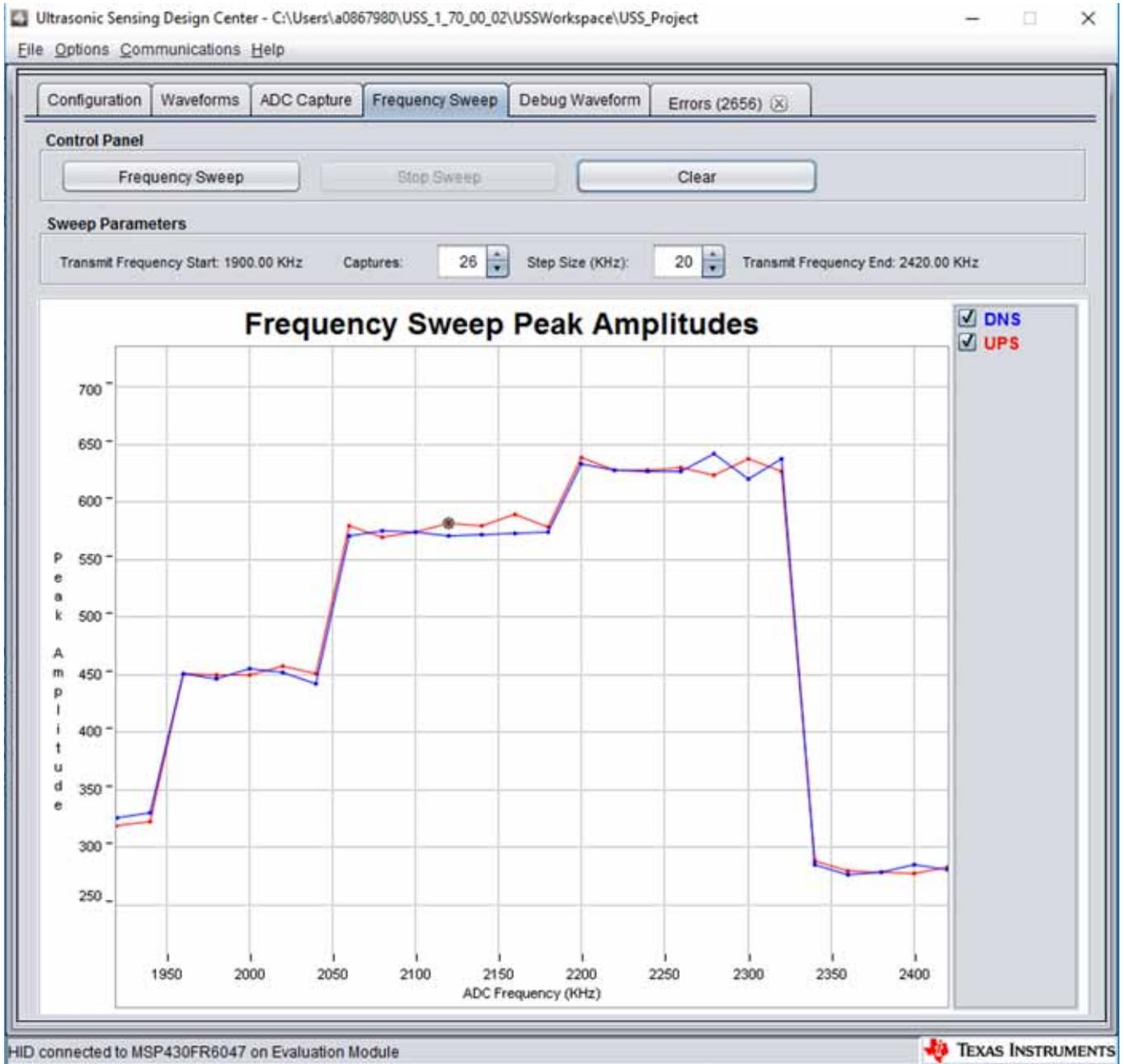
Figure 15. Frequency Response Test Results

3.2 Testing and Results

3.2.1 Test Setup

This section describes how to run and demonstrate the ultrasonic flow-meter reference design.

3.2.1.1 Connecting Hardware

The following connections must be in place for the demo:

1. Configure the EVM430-FR6047 device according to the Programming configuration shown in Section 3.1.1.1.

2. Connect the transducers to J5 on the EVM. The ground connections are the two inside pins of J5. Additional ground connections are available on this header, to accommodate transducers which use three pins (one signal pin and two ground pins). The transducers signal pins should be connected to CH0 and CH1 and the ground pins to GND, see Table 5 (transducer header).

Table 5. Transducers J5 Connections

OUTER ROW →	GND	GND	GND	GND
INNER ROW →	CH0	GND	GND	CH1

3. Connect the USB of the EVM to the PC. The ultrasonic portion of the EVM430-FR6047 device is powered using an external power source for these tests and the results are presented later. When using external power, the POW_SEL switch must be set to the top position (External), see Figure 16.
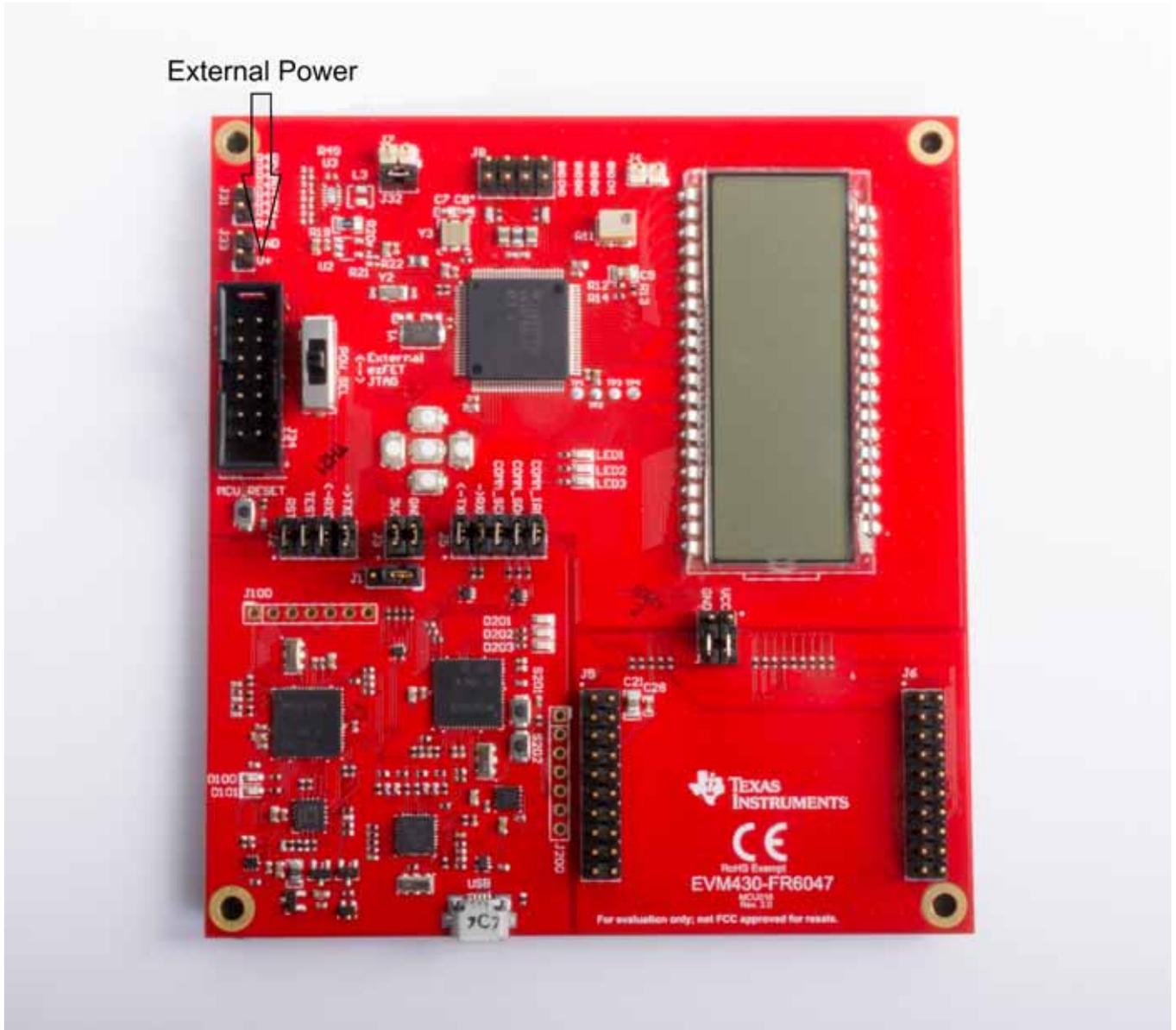
Figure 16. External Power to EVM

The external supply voltage must be applied to the EXT_POW header. GND on J1 and J3 must be connected. The TEST and RST jumpers on J2 must be connected to download code from the PC. Communication jumpers on J4 – COMM_IRQ, COMM_SDA, and COMM_SCL – are required, because the tests require communicating through USB over I^{2}C, to collect the measurement data by the PC.

EVM430-FR6047 Hardware Guide describes the different capabilities of the EVM and the different configurations in more detail.

3.2.1.2 Building and Loading Software

The software package included in this reference design includes projects for CCS and IAR. The following sections explain how to build and load the software to the device.

3.2.1.2.1 Using Code Composer Studio

1. Open or create a workspace.
2. Import the application project by selecting Menu → Project → Import CCS Projects, and then select the following path: <USS Flow Meter Library folder>\examples\USSLib_GUI_Demo\CCS\ (see Figure 17).
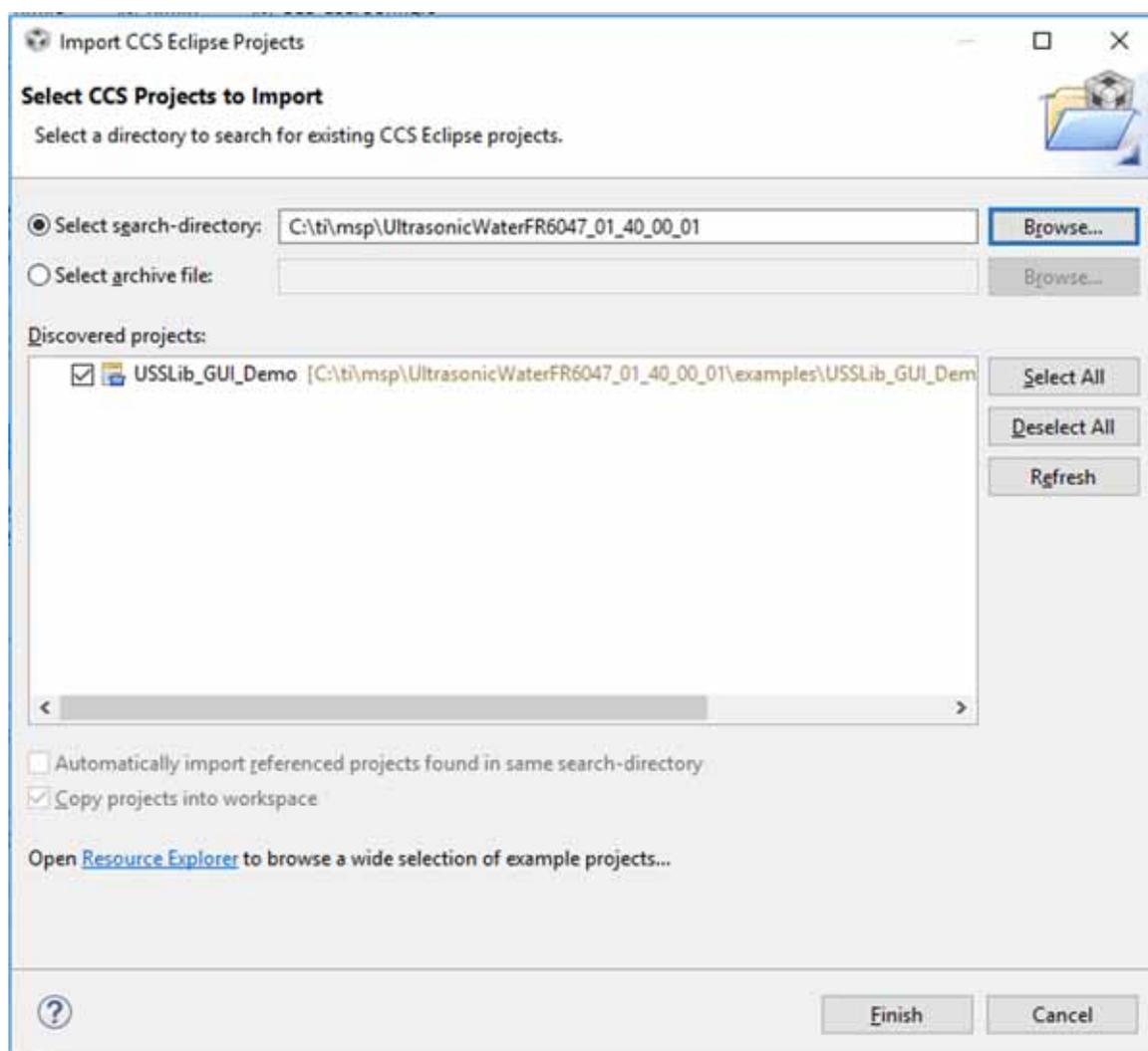
Figure 17. Importing Project to CCS

3. Build the project (Ctrl+B).
4. Download the code to the device (F11).
5. Close the debugger. It is also possible to execute or debug the application, but this design guide only shows the standalone execution.

3.2.1.2.2 Using IAR

1. Open the project workspace from:
   <USS Flow Meter Library folder>\examples\USSLib_GUI_Demo\IAR\USSLib_Workspace.eww.
2. Build the project (F7).

3. Download the code to the device (Ctrl+D).

4. Close the debugger. It is possible to execute or debug the application, but this design guide only shows the standalone execution.

3.2.1.3 Executing Application

1. To execute the application without debugger interaction, configure the EVM jumpers as shown in Section 3.1.1.1.

2. Press the EVM430-FR6047 reset button (MCU_RESET) to reset the device and execute the application. The device is programmed at this point, and the application always executes when pressing the reset button or after a power-on-reset.

3.2.1.4 Configure Device and Observe Results Using GUI

1. Launch the GUI application located in: <USS_GUI root>\USS.exe. The GUI application automatically detects the HID device corresponding to the EVM430-FR6047 EVM.

2. Click the *Communications→ Connect* option in the GUI application menu.

3. Click the *Load Configuration* button to load one of the default configurations.

4. Select one of the configurations at: <Flow Library folder>\examples\gui_config\.

5. Click the *Request Update* button to send the configuration to the device.

The GUI shows the message in Figure 18 when the configuration is loaded to the device.
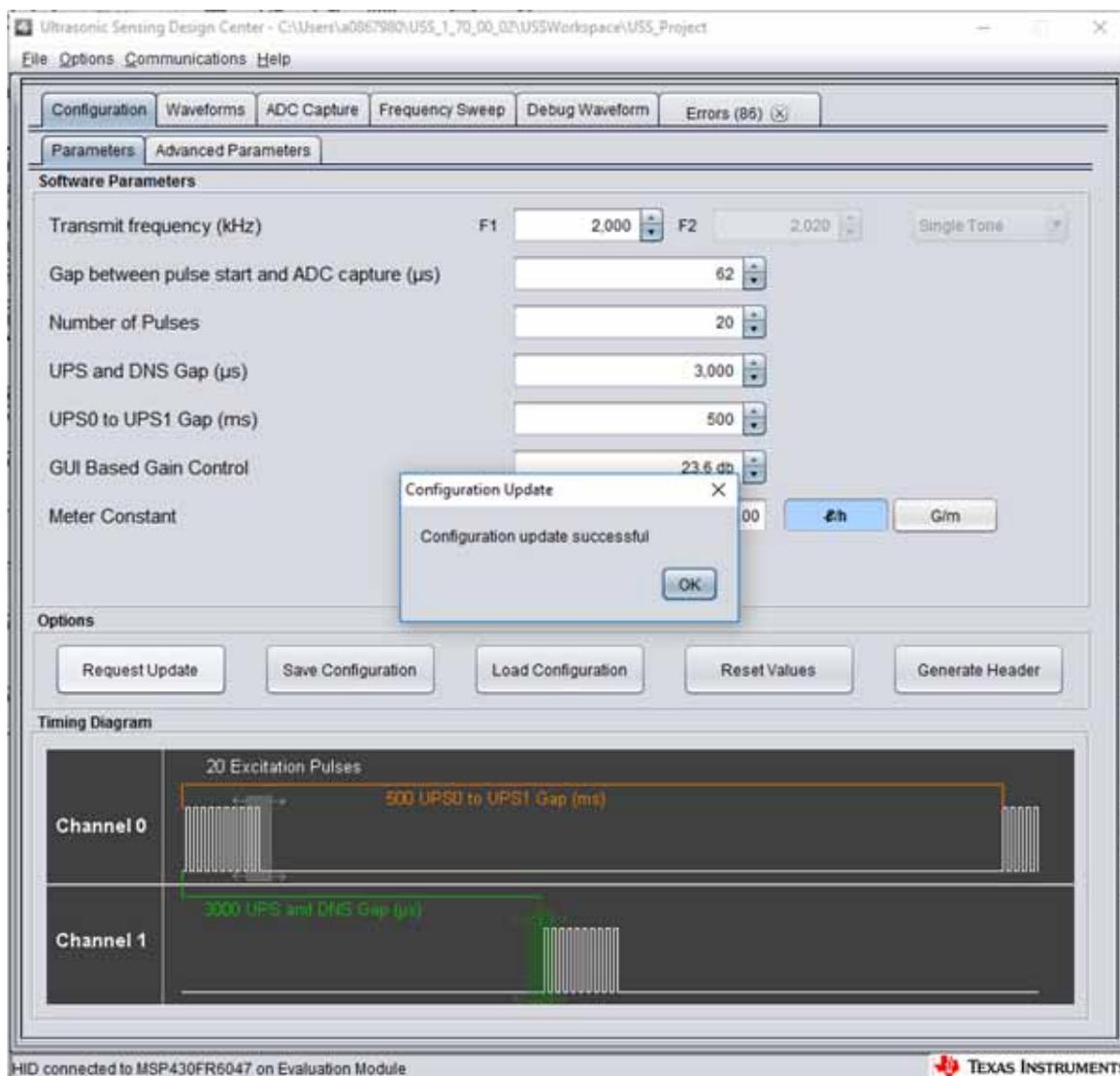
Figure 18. Loading Configuration to Device From GUI

6. Check the integrity of the signal by using the *ADC Capture* window, as explained in Section 3.1.2.4.
7. Check the calculated ToF and volume in the *Waveforms* window, as explained in Section 3.1.2.4.
8. If desired, adjust the parameters and observe the impact on the captured waveform and calculations.

3.2.1.5 Customization and Optimization

The TIDM-1019 device was tested using third party meters and other proprietary meters described in Section 3.1.3. However, the system allows for easy customization and optimization using other transducers and meter designs.

Developers are encouraged to use the MSP430 Ultrasonic Design Center Tool GUI to adjust the different configuration parameters, to achieve the required balance between performance and power consumption.

For example, developers can select a signal sampling frequency (SIG_SAMPLING_FREQ) of 8 MHz to achieve higher resolution at the expense of higher current consumption; however, this would be unnecessary for transducers in the 1-MHz region. In such case, developers can select a sampling frequency of 3.4, 3.6, 3.8, or 4 MHz, which results in lower power consumption.

The following GUI parameters should be adjusted based on the characteristics of the meter and transducers:

- *Transmit Frequency (kHz)*: depends on the excitation frequency of the transducer. For example, selecting f1 = 1000 kHz generates an excitation signal at 1 MHz for a 1000-kHz transducer.

- *Gap between pulse start and ADC capture (µs)*: depends on the dimensions of the meter and should be characterized to allow for an appropriate signal capture at different flow rates and temperature variations.

- *Number of Pulses*: affects the peak amplitude and, in turn, the energy received by the receiving transducer. This affects the SNR and the single-shot STD achieved by the meter; however, this parameter is also directly proportional to current consumption. Developers must adjust this value to generate an appropriate signal amplitude and standard deviation while meeting current consumption targets.

- *UPS and DNS gap (µs)*: developers must select an appropriate delay, ensuring a idle channel, before the start of the next excitation.

- *UPS0 to UPS1 gap (ms)*: the gap between the end of a measurement and the start of the next measurement and it controls the measurement rate. A setting of 1000 ms gives an approximately 1-Hz measurement rate.

- *GUI based gain control*: selects the gain setting of the PGA in the USS module on the MSP430FR6047 device.

- *Meter constant*: constant used to calculate volume flow rate as a function of the ToF and the area of a given meter, as described in Equation 4. A typical procedure to calculate this constant is to provide a constant flow (for example, 200 LPH or 1 GPM) and adjust the meter constant to provide the corresponding volume flow rate using the GUI.

- *USSXT (kHz)*: selectable between 4 MHz and 8 MHz, depending on the frequency of the USSXT on the EVM430-FR6047 EVM. The EVM is usually shipped with an 8-MHz resonator and should use with this parameter set to 8 MHz. Users must set this value appropriately if using a different USSXT on the EVM.

- *SIG_SAMPLING_FREQ (kHz)*: selectable between 6800, 7200, 7600, or 8000 kHz and must be high enough to meet the Nyquist criterion for reduced error during interpolation. The recommended sampling rate is > 3.4 times of the transducer frequency. Developers can modify it for a tradeoff between resolution and power consumption.

- *ADC Over Sampling Rate*: selectable between 10 or 20. Here, 20 is used for an ADC sampling frequency of ≤ 4 MHz and 10 is used for an ADC sampling frequency > 6 MHz. The MSP430FR6047 device only supports ADC sampling frequencies between [3.4 MHz to 4 MHz] or between [6.8 MHz to 8 MHz]. Sampling frequencies between 4 MHz to 6.8 MHz are not supported by the device.

- *Delta ToF offset (ps)*: adjustment is made to the differential ToF during the calculation of volume flow rate inside the ultrasonic flow meter library. Developers can optionally make their custom calculation of the volume flow rate based on the ToF values provided by the library.

- *Absolute ToF additional delay (ns)*: adjustment is made to the absolute ToF to account for any additional delays. The value depends on the shape of the signal and the envelope threshold discussed following. Developers can optionally set this value to zero and make their own adjustments of the absolute ToF in the application layer.

- *Capture duration (µs)*: depends on the shape of the signal received from the transducer. Must be characterized to allow for an appropriate signal capture at different flow rates and temperature variations.

- *Param 2 (ULPBiasDelay)*: selects the delay in applying the bias after the initialization of the USS module. TI recommends setting this to 3 (representing 300 µs) and should not be modified.

- *Start PPG Count (ns)*: sets the delay between the start of the internal timer in the USS module in FR6047 and the start of the excitation pulses (PPG pulse trigger). TI recommends setting this to 10,000 (for 10 µs).

- *Turn on ADC Count (ns)*: sets the delay between the start of the internal timer in the USS module in FR6047 and enables the sigma-delta high-speed ADC. TI recommends setting this to 5,000 (for 5 µs).

- *Start PGA and IN Bias Count (ns)*: sets the delay between the start of the internal timer in the USS module in FR6047 and the start of the bias application. TI recommends setting this to 0 (for 0 µs).

- *USS XTAL Settling Count (µs)*: sets the settling time for USSXT. TI recommends setting this to 120 µs for the resonator (USSXT) on the EVM.

3.2.2 Test Results

This section details experimental results aggregated over multiple meters using 1-MHz transducers.

3.2.2.1 Single-Shot Standard Deviation

The single-shot standard deviation of the differential ToF is a measure used to express the expected variance of the output at zero-flow and ambient temperature (see Figure 19). The STD is calculated by executing the application at an ambient temperature and in a zero-flow condition.
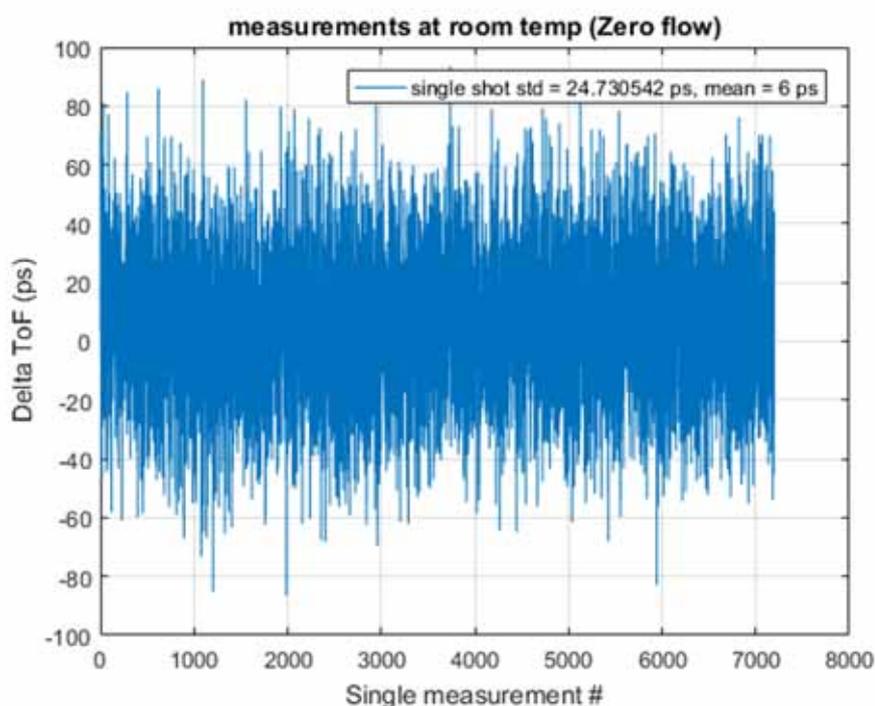
Figure 19. Delta ToF Over Time

The MSP430 Ultrasonic Design Center GUI can then be used to capture the DToF for 5 to 30 minutes, and the STD can be calculated using a tool like MATLAB® or Excel®.

The single-shot STD of blocks of 200 measurements are computed and plotted in Figure 20. Each plot represents single-shot STD of 200 measurements. The plot clearly shows the variation of single-shot STD is just ± 2 ps, and the average is < 25 ps.
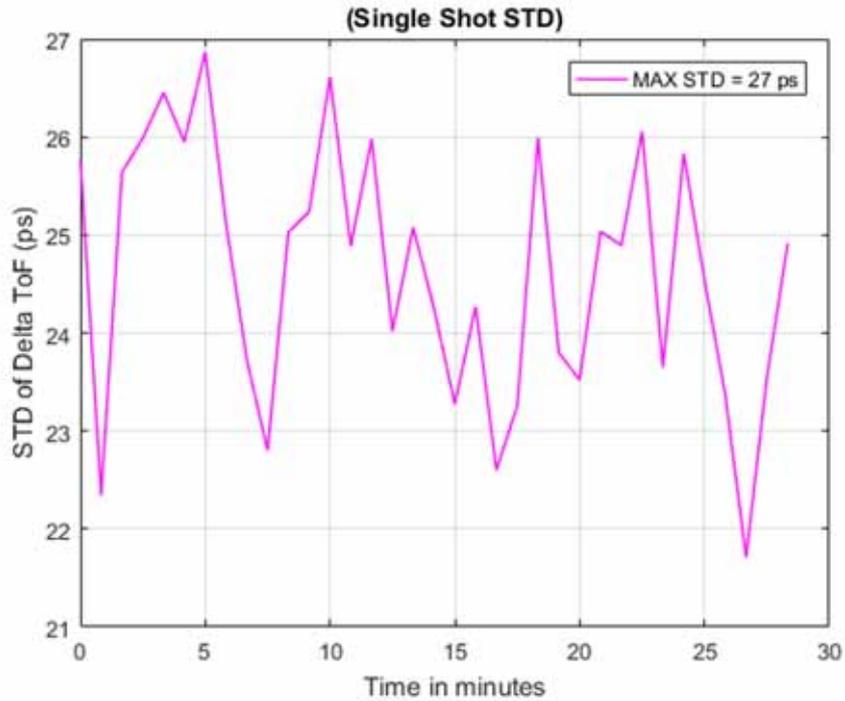
Figure 20. Single-Shot Standard Deviation at Room Temperature

3.2.2.2   *Zero-Flow Drift*

Zero-flow drift (ZFD) is a measure used to express the expected drift of the DToF at zero-flow across temperature. This measure also impacts the minimal detectable flow of the meter overtemperature.

With both the meter and the EVM430-FR6047 device at room temperature, the ZFD over a long duration of about 36 hours is only around 11 ps. This test is conducted where there can be small variations in ambient temperature within the test lab. The drift is within a small band of just about 6 ps.
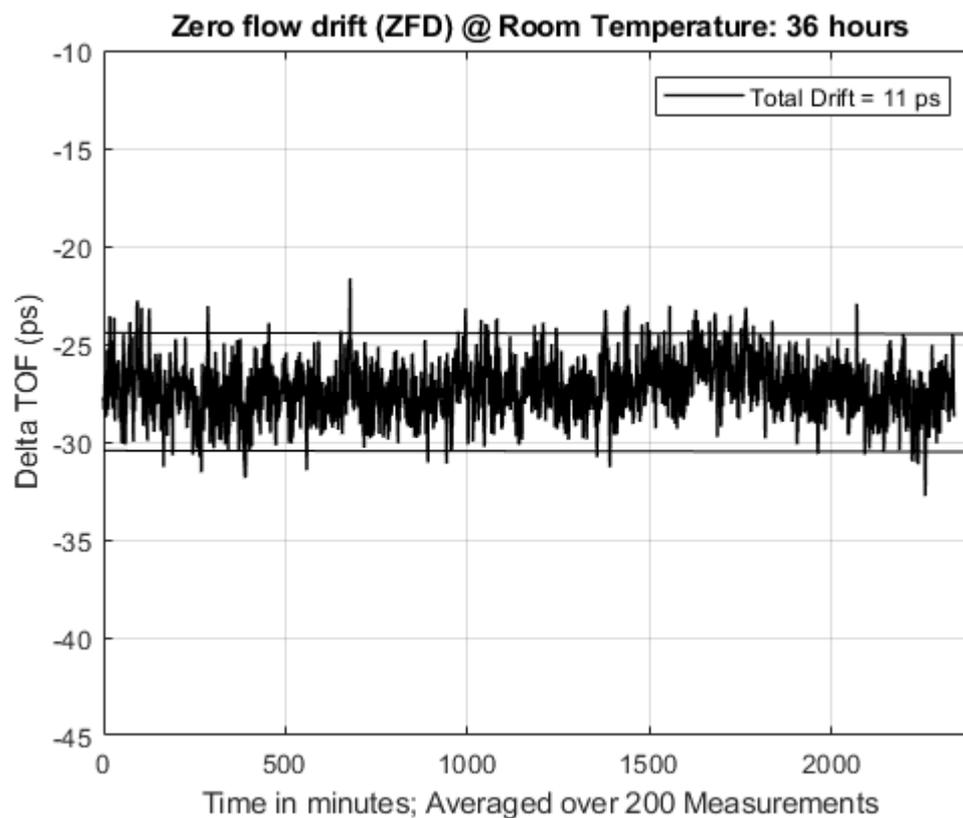
Figure 21. Zero-Flow Drift of DToF at Room Temperature

Two separate ZFD tests are conducted with variable temperature, both of which are at zero flow. A meter in-oven test varies the temperature of the water/meter over a 5ºC to 85ºC range, while the electronics (EVM430-FR6047 EVM) are at room temperature. The device in-oven test varies the temperature of the electronics over –40ºC to +85ºC, while the meter/water are placed at room temperature. The oven profile used to calculate ZFD is shown in Figure 22, together with the expected change in absToF. As observed, the absToF is expected to vary over the temperature range.

Figure 22. Zero Flow Drift of DToF With Meter In-Oven

ZFD is calculated by obtaining the range of the differential ToF averaged over 200 samples. The MSP430 Ultrasonic Design Center GUI can be used to capture the differential ToF, while tools like MATLAB or Excel can be used to calculate the average over 200 samples and the total drift.

Figure 23 shows the resulting differential ToF across temperatures, averaged over 200 samples.
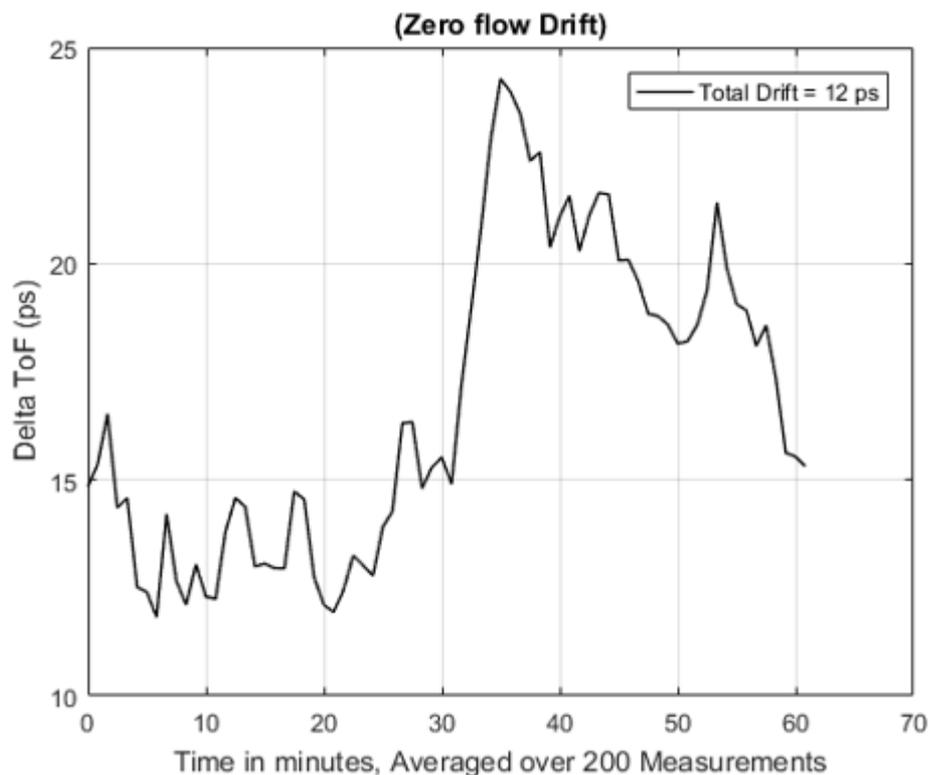
Figure 23. Zero Flow Drift of DToF With EVM430-FR6047 In-Oven

3.2.2.3 *Absolute Time of Flight Measurements*

Variation of the absolute time of flight (AbsToF) measurements is also an important metric in both flow meter applications as well as other applications like mixture analysis. The important metric in the case of AbsToF is also the drift over time as well as the standard deviation of the measurements.
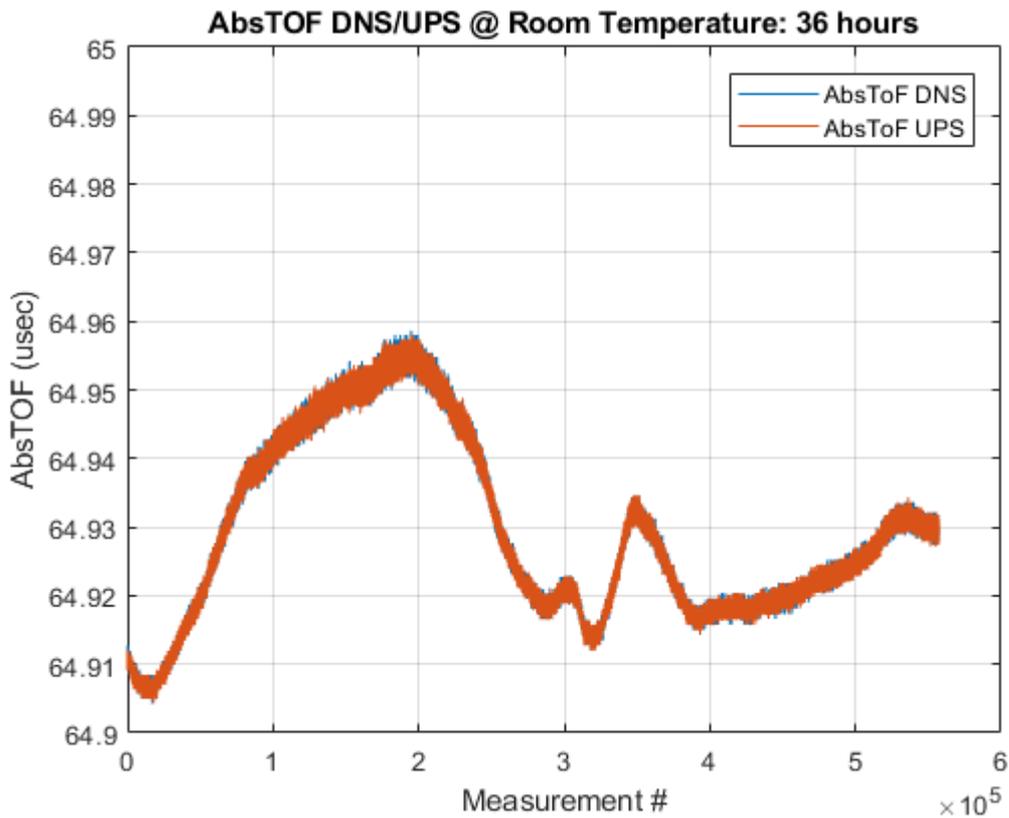
Figure 24. AbsToF Measurement Over 36 Hours

3.2.2.4   *Flow Measurements*

The flow measurements were performed on a third party brass pipe (Audiowell) and transducer that is easily available and can be obtained independently of Texas Instruments. The Audiowell pipe housed transducers that have a nominal excitation frequency of 1 MHz.

The MSP430FR6047 and Ultrasonic Software Based Water Flow Meter Measurement Results application note contains more details of the flow test bench used for the flow measurements.

A fixed-flow test is conducted at 1 gallon per minute (GPM), which is approximately 220 liters per hour (LPH). A measurement rate of 1 Hz (1 measurement per second) was used to obtain the flow rates on water that was at room temperature. The sampling rate of the SDHS is varied over a few of the possible frequencies of 3.4, 3.6, 4.0, 7.2 and 8.0 MHz. Figure 25 shows the results of the differential ToF (DToF) at different sampling rates.
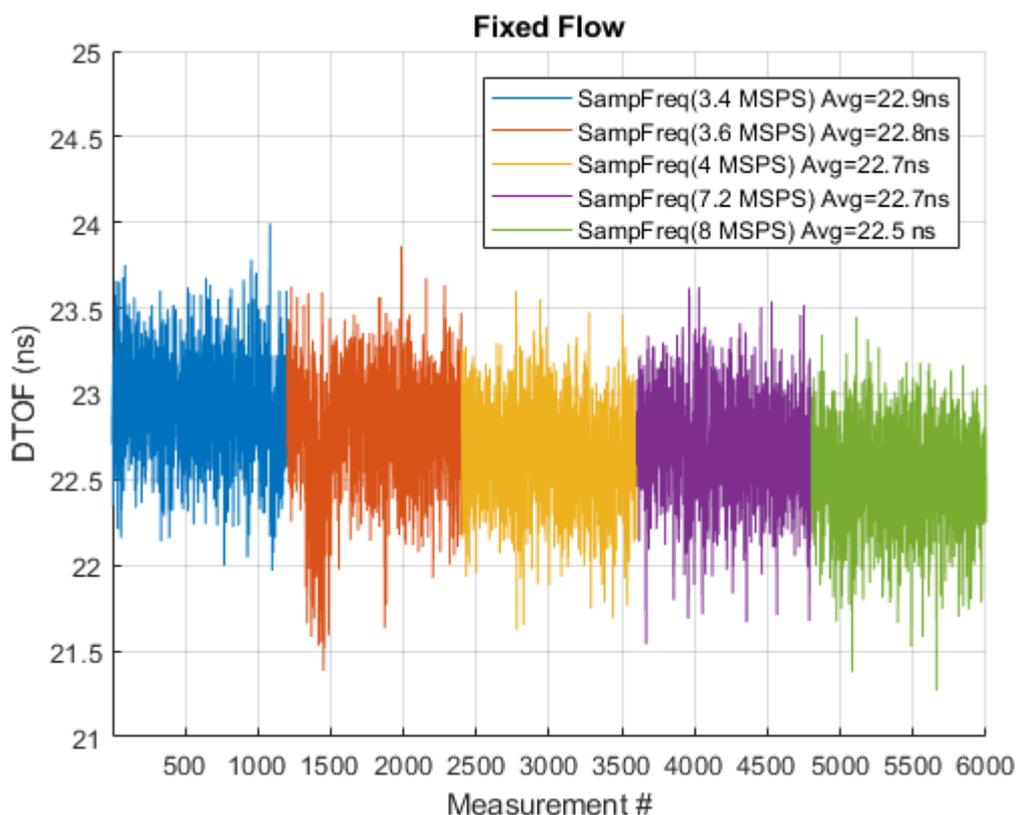
Figure 25. DToF of 1 GPM at Different Sampling Rates

3.2.2.5   *Average Power Consumption*

The average power consumption is an important consideration for power-restricted systems, such as battery-operated water-flow meters.

The power consumption of the device depends on several different parameters, which can be configured using the MSP430 Ultrasonic Design Center GUI. These parameters include the transducer frequency, number of pulses, gap between UPS and DNS, measurement rate (DNS-UPS gap), signal sampling frequency, and capture duration.

The optimal configuration of these parameters depends on the meter and a trade-off between performance and power consumption exists (see Figure 26).
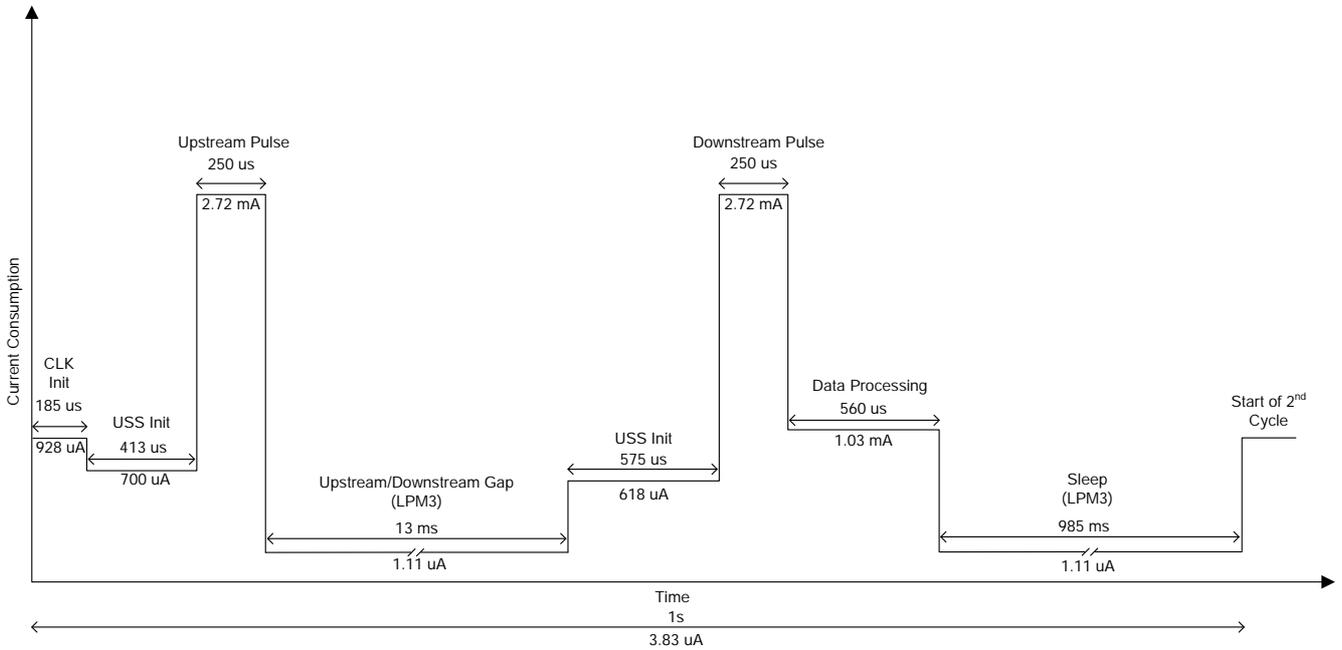
Figure 26. Profile of Current Consumption During Duration of Measurement

The current profile in Figure 26 is based on a water meter pipe and the MSP430FR6047 device, with parameters configured as listed in Table 6. For brevity, it does not include configuration parameters that have no impact on current consumption.

Table 6. Configuration for Current Measurements

TRANSMIT FREQUENCY (kHz)	1000 kHz
Gap between pulse start and ADC capture (μs)	62 μs
Number of pulses	20
UPS and DNS gap (μs)	13,000 (for 13 ms)
UPS0 to UPS1 gap (ms)	990 ms
Signal Sampling Frequency (kHz)	3600 kHz
ADC Over Sampling Rate	20
Delta ToF offset (ps)	0
Absolute ToF additional delay (ns)	0
Capture duration (μs)	40 μs
User Param 2	3 (for 300 μs)
Start PPG Count (ns)	10,000 (for 10 μs)
Turn on ADC count (ns)	5,000 (for 5 μs)
Start PGA and IN Bias Count (ns)	0
USS XTAL Settling Count (μs)	120 μs

As shown in Figure 26, the instantaneous current consumption varies depending on the state of the software. The different states and the functionality of each state is enumerated in Table 7.

Table 7. States in Each Measurement for Current Consumption

STATE	DURATION	CURRENT CONSUMPTION (INSTANTANEOUS, CONTRIBUTION)	DESCRIPTION OF STATE
CLK INIT	185 μs	928 μA (0.172 μA)	Initialization of USSXT. The USS module is powered OFF.
USS INIT (UPS)	413 μs	700 μA (0.289 μA)	The USS module is powered ON and registers of all submodules are initialized.
UPSTREAM PULSE	250 μs	2.72 mA (0.68 μA)	Upstream pulse firing and signal capture
UPSTREAM/DOWNSTREAM GAP	13 ms	1.11 μA (0.014 μA)	Gap between UPS and DNS. CPU is in LPM3 mode.
USS INIT (DNS)	575 μs	618 μA (0.355 μA)	Prior to DNS firing, the USS module is powered ON and registers of all submodules are initialized.
DOWNSTREAM PULSE	250 μs	2.72 mA (0.68 μA)	DNS pulse firing and signal capture
DATA PROCESSING	560 μs	1.03 mA (0.577 μA)	DToF, AbsToF, and VFR computation; The USS module is powered DOWN.
SLEEP	985 ms	1.11 μA (1.093 μA)	Gap between the end of a measurement and start of the next measurement. CPU is in LPM3 mode. USS is OFF.

3.2.2.6   Memory Footprint

The memory footprint provides an estimate of the memory requirements for implementing an ultrasonic water flow meter application. Table 8 lists the memory use across FRAM, RAM, and LEARAM, as well as between the USSSW Library and the demonstration application that encapsulates the Library API calls and interfaces to the USS Design Center GUI. The memory size is listed in KB (Kilobytes). The memory footprint tabulates the memory used with the CCS IDE. The memory use is similar with the IAR IDE.

Table 8. Memory Footprint

PARAMETER	BUILD CONDITIONS	TYPICAL MEMORY (KB)
Total FRAM used by demonstration application (MEM_{APP_FRAM})	Includes code and constants	69.2
Total RAM used by demonstration application (MEM_{APP_RAM})	Includes variables placed in RAM and FRAM	5.3
FRAM used by library (MEM_{LIB_FRAM})	Includes all library code and constants used by the application	21.9
RAM used by library (MEM_{LIB_RAM})	Includes all library variables used by the application	4.4
LEARAM used by library (MEM_{LIB_LEARAM})	Includes all library variables and data structures used by the application and library	2.6

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDM-1019.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDM-1019.

4.3 PCB Layout Recommendations

General PCB guidelines should be followed to ensure accurate measurements and proper operation.

- Decoupling capacitors must be placed close to the supply pins.
- Oscillators must be placed close to the chip and use a separated ground plane from the main ground plane. These components be tied to the main ground plane with a small connection, see Figure 27.
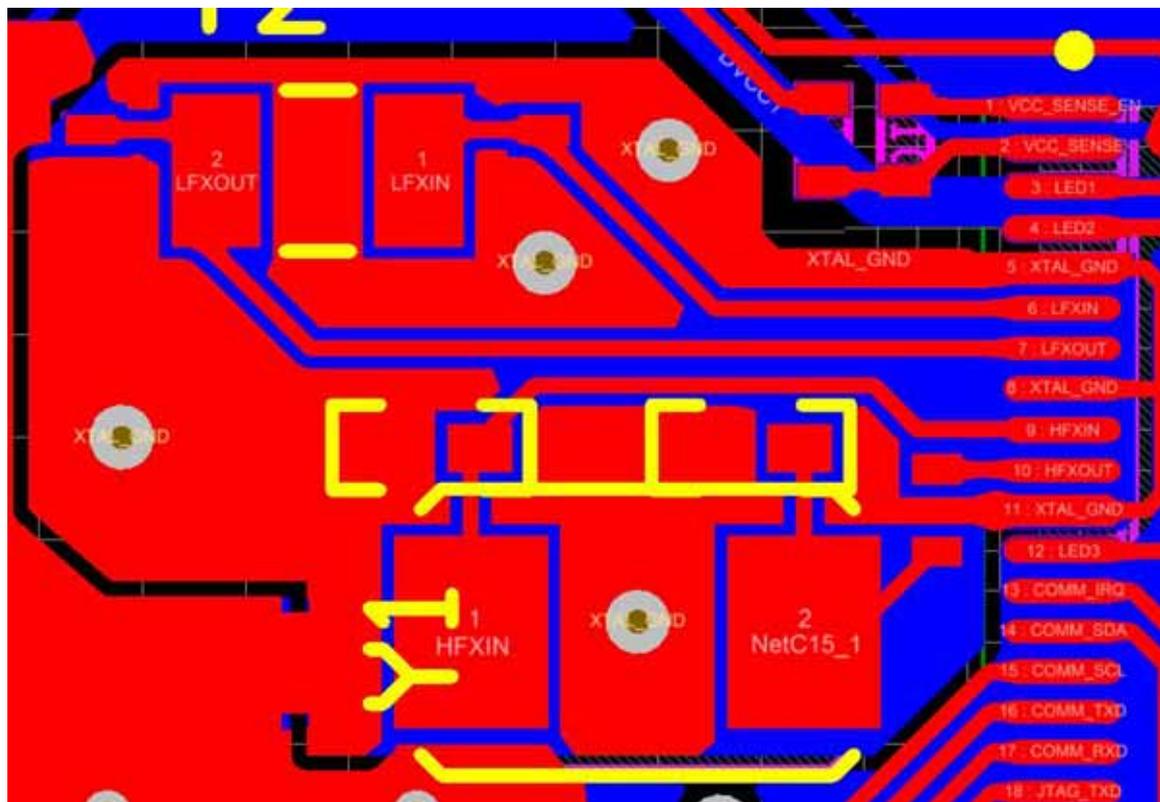
Figure 27. Layout Guidelines: Oscillator

- Traces for USS CH0_IN, CH0_OUT, CH1_IN, and CH1_OUT must be matched in length to ensure proper timing of signals, because these are in the picosecond range, as shown in Figure 28.
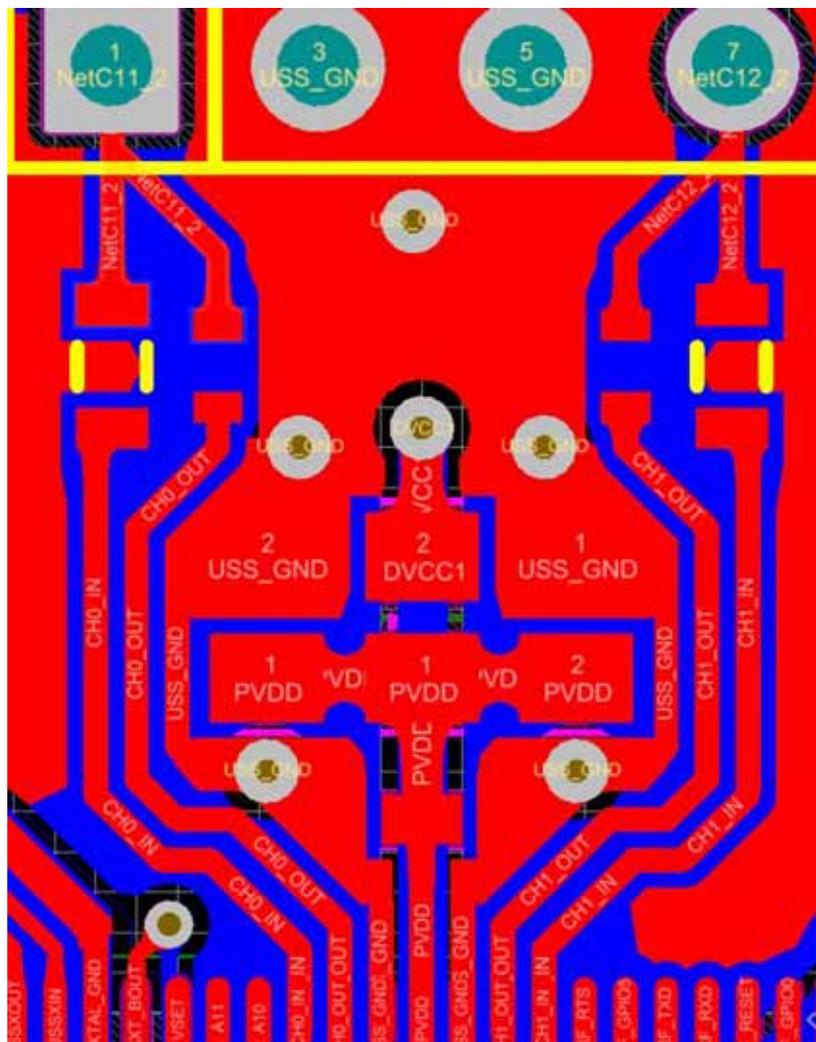
Figure 28. Layout Guidelines: Transducer Symmetric Traces

- 1% component tolerance must be used for all USS signal components for the highest accuracy.
- Ensure that no traces are crossing the USS signal traces on other layers.
- LCD connections must follow the guidelines in the *Designing With MSP430 and Segment LCD* application report.

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDM-1019.

4.4 Altium Project

To download the Altium project files, see the design files at TIDM-1019.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDM-1019.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDM-1019.

5 Software Files

To download the software files, see the design files at TIDM-1019.

6 Related Documentation

1. Texas Instruments, MSP430FR6047 Ultrasonic Sensing MSP430 Microcontollers for Water-Metering Applications, data sheet
2. Texas Instruments, MSP430FR58xx, MSP430FR59xx, and MSP430FR6xx Family User's Guide
3. Texas Instruments, Quick Start Guide for MSP430FR6047-Based Ultrasonic Water Flow Meter
4. Texas Instruments, EVM430-FR6047 Hardware Guide
5. Texas Instruments, Application Software (SW) for MSP430FR6047-Based Ultrasonic Water Flow Meter, user's guide
6. Texas Instruments, Ultrasonic Design Center User's Guide
7. Texas Instruments, Low-Energy Accelerator (LEA) Frequently Asked Questions (FAQ), application report
8. Texas Instruments, Benchmarking the Signal Processing Capabilities of the Low-Energy Accelerator on MSP430 MCUs, application report
9. Texas Instruments, MSP430FR6047 and Ultrasonic Software Based Water Flow Meter Measurement Results, application report
10. Texas Instruments, Designing with MSP430 MCUs and Segment LCDs, application report

6.1 Trademarks

MSP430, BoosterPack, Code Composer Studio are trademarks of Texas Instruments.
IAR Embedded Workbench is a trademark of IAR Systems.
MATLAB is a registered trademark of MathWorks, Inc.
Excel is a registered trademark of Microsoft Corporation.
All other trademarks are the property of their respective owners.

7 Terminology

ADC— analog-to-digital converter

DNS— Downstream acquisition

DToF— Delta (differential) time of flight

GPM— Gallons per minute

GUI— Graphical user interface

LCD— Liquid crystal display

LEA— Low energy accelerator

LPH— Litres per hour

MCU— Microcontroller

MTIF— Metering test interface

SDHS— Sigma-delta high-speed ADC

ToF— Time of flight

UPS— Upstream acquisition

USS— Ultrasonic Sensing Solution module

8   About the Authors

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