White Paper
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Ultrasonic sensing of gas flow

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This white paper describes the implementation of a high-performance ultrasonic gas meter with the Texas Instruments MSP430FR6043 microcontroller (MCU) and the advantages of a waveform capture method over the alternative zero-crossing method.

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1 Introduction

Ultrasonic sensing of gas flow uses the time of flight (ToF) of an ultrasonic wave and its dependency and behavior in the medium. Volume flow is the measure and calculation of the difference in propagation time between ultrasonic signals in the upstream and downstream directions. This technology is outstanding at measuring volume flow rates.

2 Gas Meter Configuration

ToF-based ultrasonic gas meters are often constructed in a trans-axial or reflective-tube configuration (see Figure 1). While the trans-axial configuration provides a stronger ultrasonic signal (and an improved signal-to-noise ratio [SNR]), this tube configuration provides lower sensitivity due to the reduced amount of ultrasonic contact with the flowing gas. The reflective configuration has the added advantage of enabling the mounting of electronics with transducers on the same side of the pipe.

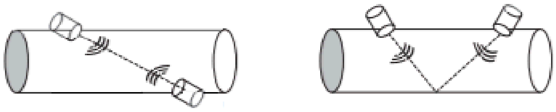


Figure 1. Trans-Axial and Reflective-Tube Configurations

3 Ultrasonic Transmit Signal Configuration

In gas metering applications, the frequency of transducers is typically between 160 kHz and 600 kHz. Because higher-frequency ultrasonic waves attenuate more quickly, higher-frequency transducers are better for space-constrained designs with smaller pipe geometries.

The integrated ultrasonic subsystem in the MSP430FR6043 MCU provides three different excitation modes: single tone, dual tone, and multitone. While single- and dual-tone excitation work well for transducers operating with a higher SNR, multitone provides improved performance for transducers operating with a lower SNR.

The SNR of the ultrasonic signal is determined by a number of different factors, including transducer sensitivity, spacing and gas attenuation. Figure 2 shows single tone, dual tone, and multitone patterns. During temperature changes, the gas meter’s frequency response changes. Both transmit and receive sensitivity can decrease in extreme temperatures. The resulting decrease in SNR can result in decreased accuracy for single- and dual-tone applications.

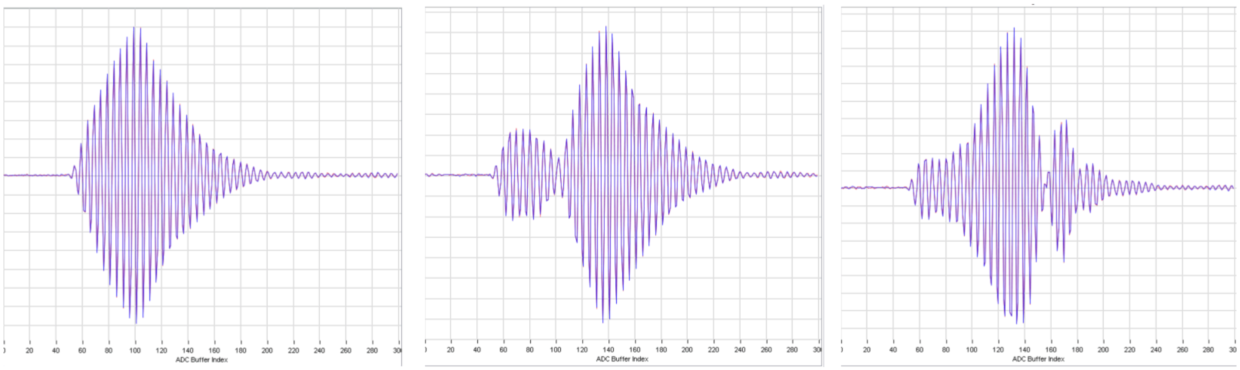


Figure 2. Single Tone, Dual Tone, and Multitone Transducer Response

Multitone excitation preserves accuracy under these low SNR conditions by encoding both frequency and amplitude information for subsequent correlation with the received signal. Multitone excitation also addresses shifts in the frequency response of the transducer, because it is possible to configure the excitation band to address these variations.

To determine an appropriate excitation band, the Ultrasonic Design Center graphical user interface (GUI) provides a frequency response tool that produces a real-time graphical representation of the frequency response at a given operating temperature. To determine an appropriate excitation band, it’s best to characterize several representative meters for their frequency response at temperature extremes, thus ensuring variability in transducer manufacturing. Figure 3 shows a frequency response for a transducer pair at –35°C, 25°C, and 65°C.

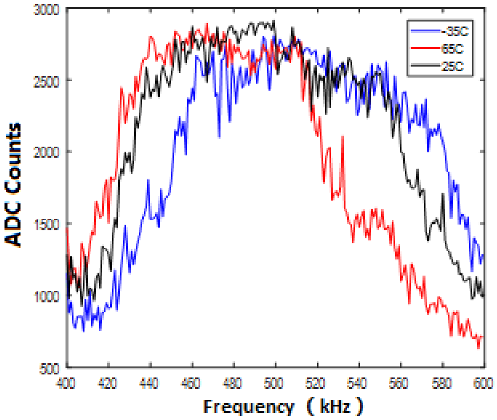


Figure 3. Frequency Sweep Response Over Temperature

After determining an appropriate excitation band, an incremental increase in the number of pulses can obtain robust results under flow.

4 Ultrasonic Receive Signal Configuration

To get a quality, stable and robust receive signal, the capture window and gain of the received signal should be adjusted to accommodate anticipated shifts and amplitude variations caused by flow and temperature. Figure 4 shows a waveform capture from the GUI. Adjust the GUI settings as follows to ensure a good receive signal:

- Adjust the programmable gain amplifier (PGA) setting to make the amplitude of the received signal ±800 analog-to-digital converter (ADC) counts.
- Adjust the gap between pulse start and waveform capture to give at least 50 µs of delay between the start of the waveform capture and the start of the received ultrasonic signal.
- Adjust the capture duration to give at least 50 µs of delay between the tail of the received ultrasonic signal and the end of the waveform capture.

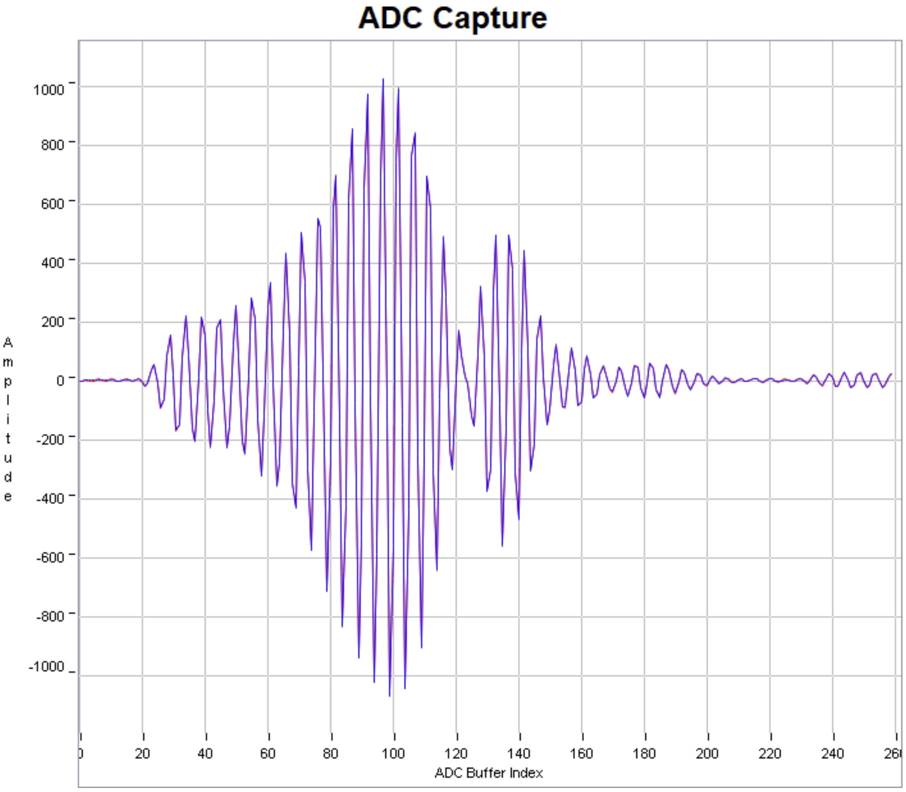


Figure 4. Waveform Capture Result

5 Signal Flow and ToF Measurement

The MSP430FR6043 MCU performs the complete excitation and acquisition process using an ultrasonic sensing (USS) module. At the beginning of the sequence, the MSP430FR6043 device sends a train of excitation pulses to the first transducer. A second transceiver then receives and captures the signal after a propagation time, T_{12}. The difference in time between transmission and reception determines the upstream ToF (ToF_{UPS}).

The MSP430FR6043 device repeats the same process in the opposite direction during downstream excitation and capture resulting in propagation time T_{21}, which represents the downstream ToF (ToF_{DNS}).

The delta time of flight (DToF) is calculated as the difference between T_{12} and T_{21}.

DToF is typically measured using two different techniques: zero crossing with a time-to-digital converter or correlation with a waveform capture of the signal using an ADC and the associated excitation signal.

The MSP430FR6043 MCU uses the ADC-based correlation technique to calculate ToF with all required functions included in the USS library.

6 TI Technology

TI's ultrasonic flow sensing solution comprises an MCU with an operational amplifier that connects to two ultrasonic transducers. Figure 5 shows the system block diagram for this solution. Unlike other solutions, this system and associated transducers can be powered from a 3-V battery without additional voltage boosting.

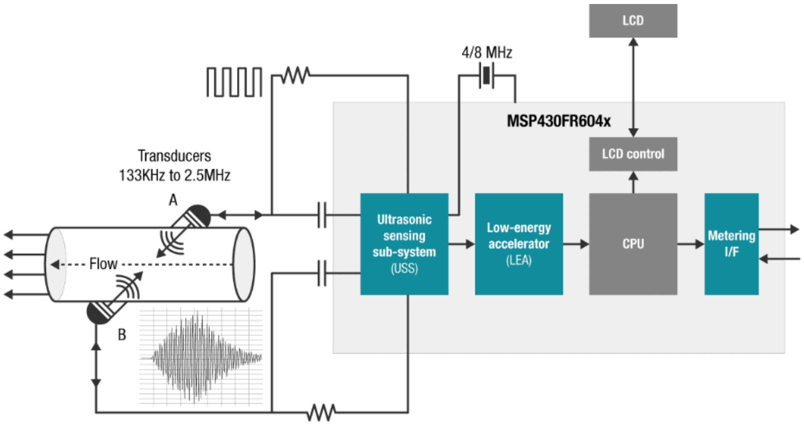


Figure 5. System Block Diagram for a Gas Meter Application Using the MSP430FR6043

6.1 MSP430FR6043 MCU USS Module

The MSP430FR6043 MCU comprises an USS intellectual property block that enables ultra-low-power metering with low-cost integration. Figure 6 shows a block diagram of the USS. The USS module includes a universal power supply, a power sequencer, a programmable pulse generator, a physical driver and impedance matching network, a PGA, a high-speed phase-locked loop, a sigma-delta high-speed ADC, and an acquisition sequencer. Each of these blocks is configurable through the MCU to enable the independent excitation and capture of upstream and downstream ultrasonic signals.

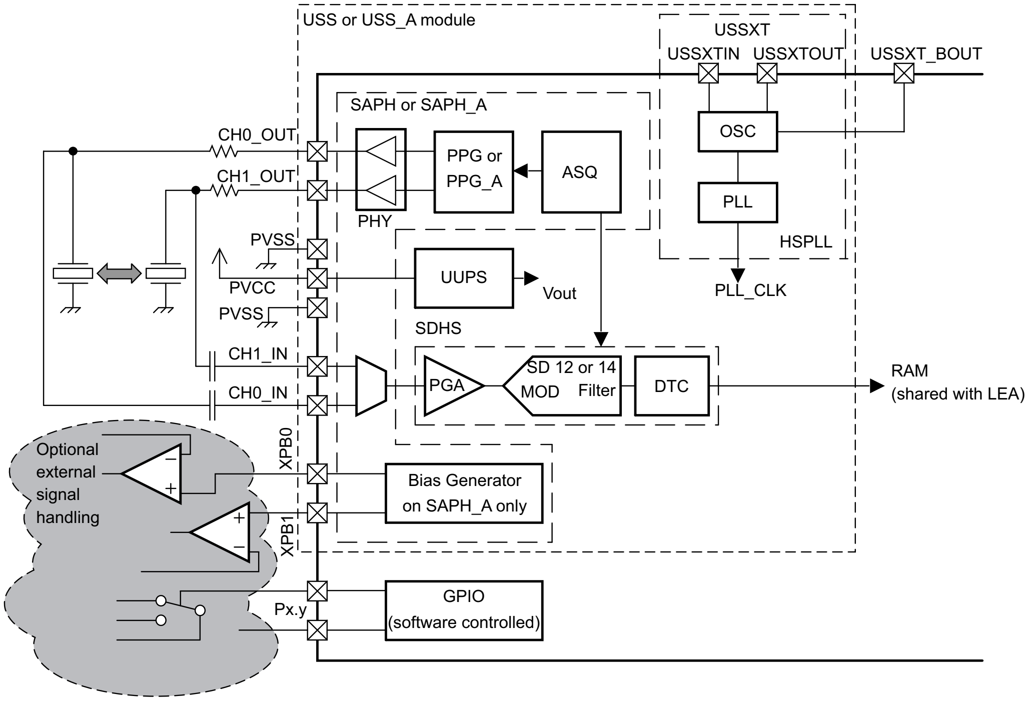


Figure 6. USS Functional Block Diagram

6.2 External Amplifier

Although the USS can provide up to 30 dB of gain, an external amplifier is required to provide enough gain to get at least 1600 ADC counts of a received signal under gas-attenuating conditions. The OPA838 operational amplifier operates over a power-supply range of 2.7 V to 5.4 V with a single supply. For solutions requiring a lower operating voltage (2.5 V), the OPA836 is a pin-compatible drop-in alternative.

6.3 Advantages

The waveform capture-based technique provides these advantages over the zero-crossing technique:

- **Improved accuracy**. 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.
- **Improved robustness against amplitude variations**. The correlation between the excitation and received signal is insensitive to the received signal amplitude, transducer-to-transducer variation and temperature variations.
- **Improved zero-flow drift**. It is possible to minimize variations in zero-flow DToF due to the shifting transducer frequency response over temperature by exciting the transducers across a frequency band that accommodates these shifts. This reduced drift often enables simplified and cost-effective meter calibration.
- **Low power**. TI's solution provides a complete set of measurement results, with less than 20 µA of current consumed per measurement per second.

7 Results

Single-shot standard deviation of the DToF is a measure used to express the expected variance of the output at zero flow and ambient temperature. The standard deviation is calculated at a zero-flow condition. Figure 7 shows that the standard deviation using the MSP430FR6043 MCU for gas metering is less than 500 ps. These results were obtained using the OPA838 external amplifier.

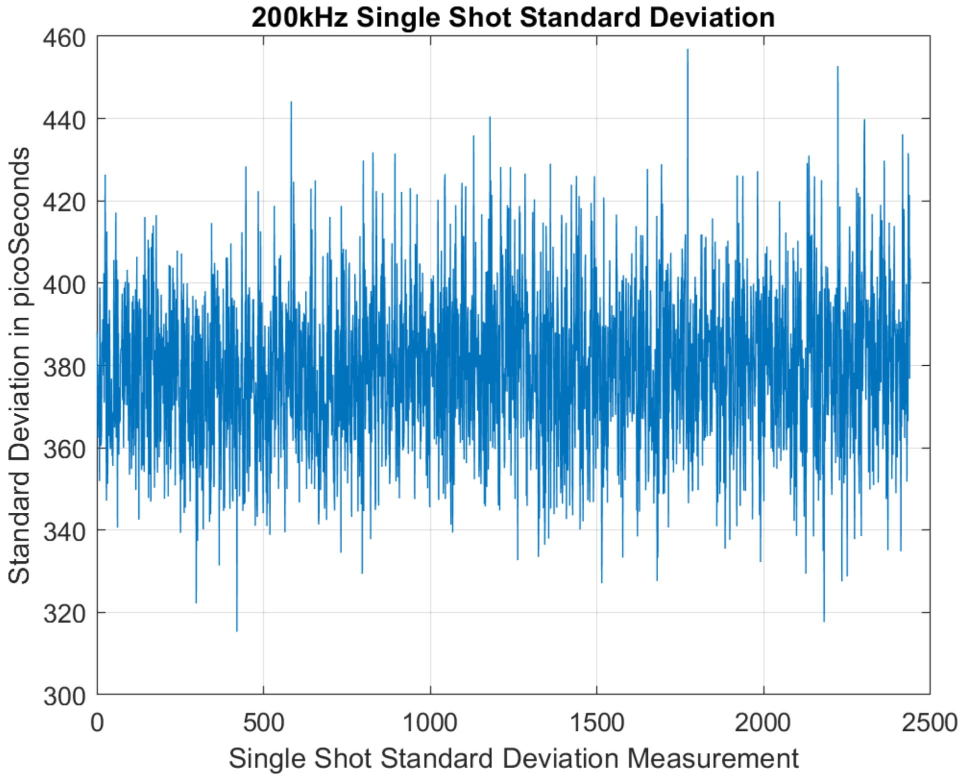


Figure 7. Results of Standard Deviation Using the MSP430FR6043 MCU for Gas Metering

Zero-flow drift 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 over temperature. Figure 8 shows a standard deviation using the MSP430FR6043 MCU for gas metering that is less than 500 ps.

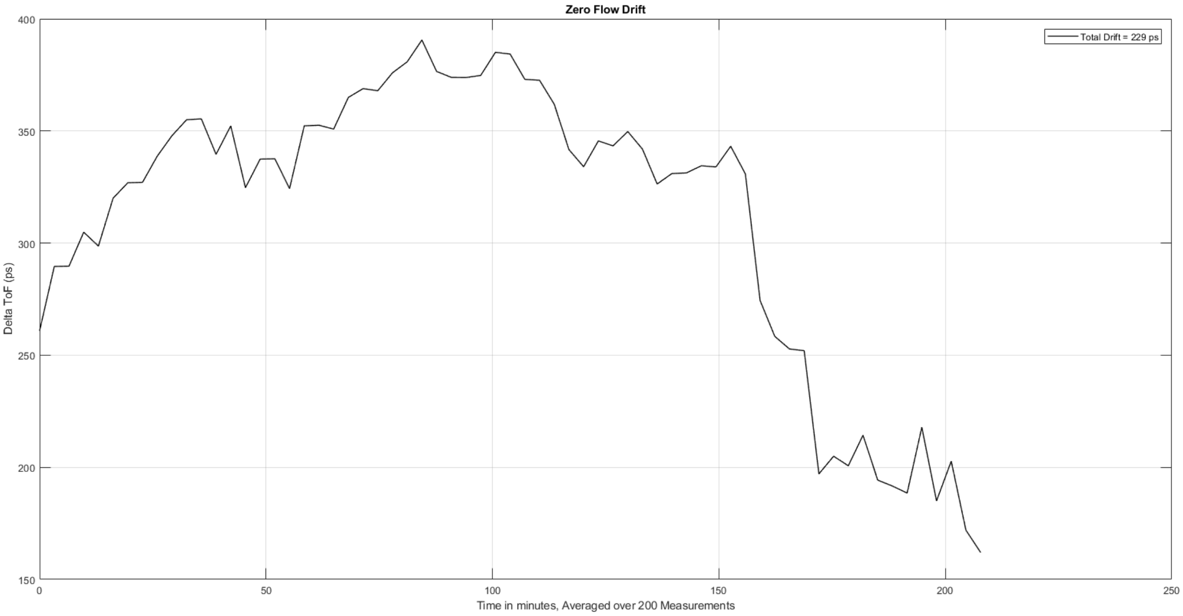
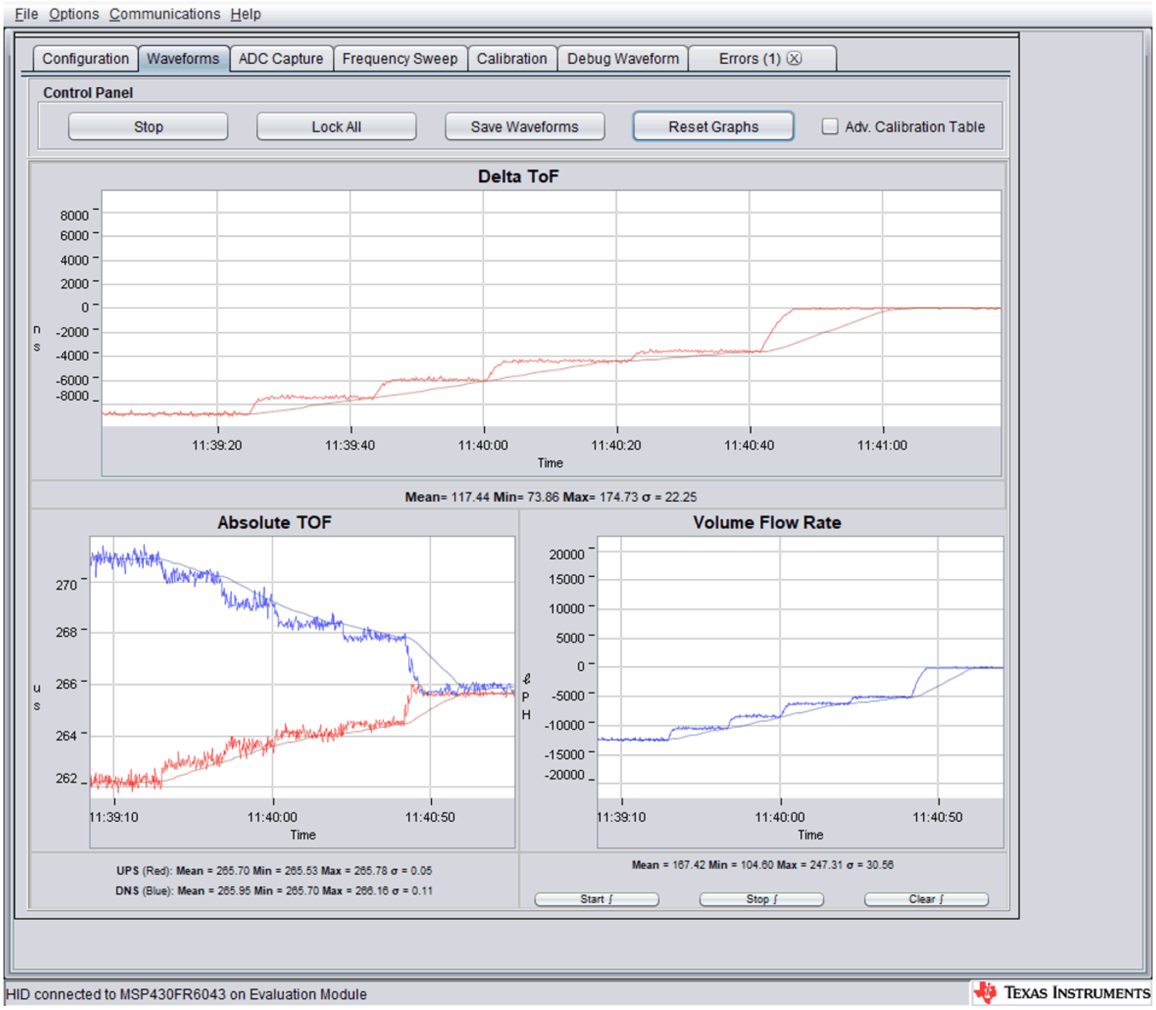


Figure 8. Results of Zero-Flow Drift Using the MSP430FR6043 MCU for Gas Metering

Conducting variable flow-rate testing ensures linearity in the calibrated operation of a flow meter. This test is typically conducted with a reference meter to determine the error over the dynamic range of the meter. Figure 9 shows the results of flow-rate testing using the MSP430FR6043 MCU for gas metering using a 3D-printable tube.



Mean= 117.44 **Min=** 73.86 **Max=** 174.73 σ = 22.25

UPS (Red): **Mean** = 265.70 **Min** = 265.53 **Max** = 265.78 σ = 0.05
DNS (Blue): **Mean** = 265.95 **Min** = 265.70 **Max** = 266.16 σ = 0.11

Mean = 167.42 **Min** = 104.60 **Max** = 247.31 σ = 30.56

HID connected to MSP430FR6043 on Evaluation Module

Figure 9. Results of Variable Gas Flow-Rate Testing Using the MSP430FR6043 MCU

8 Conclusion

The USS subsystem integrated with the MSP430FR6043 MCU contains a number of advanced peripherals that enable robust gas meter products. The waveform capture-based technique implemented in this solution enables improved accuracy, robustness, and zero-flow drift over competing zero crossing-based solutions. The combination of the MSP430FR6043 MCU and the OPA838 offers enhanced system level performance with ultra-low power consumption.

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