Application Report
Gas Meter Design Guide

![Texas Instruments]

ABSTRACT

This document describes a process for designing and testing a gas meter with TI's ultrasonic solutions. This process comprises transducer selection, iterative tube design and configuration, and calibrated flow testing with sensitivity and power optimizations.

Demo source code and schematics are provided to accelerate the development of a variety of ultrasonic applications. The source files can be downloaded from USSSW_Lib_Gas. An overview of MSP430™ MCUs and how to enable a variety of end equipment with them can be found at the MSP430™ ultra-low-power sensing & measurement MCUs overview.

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1 Introduction

Current gas meters often rely on mechanical diaphragms to measure flow rates. Because of the construction of these meters, small gas flows (or leaks) cannot be detected. In addition, these meters are often expensive to manufacture.

Ultrasonic technology is well suited for gas meters because differences in the speed of sound in a flow tube can give enough resolution to detect small flows that diaphragm based solutions cannot. There are two methods for ultrasonic gas metering commonly found in the market: time-to-digital conversion (TDC) and analog-to-digital conversion (ADC) based.

The ADC-based approach provides the following advantages over the TDC zero-crossing approach:

- Improved accuracy. The correlation acts as a digital filter to suppress noise, which results in a benefit of approximately three times lower standard deviation. Similarly, the correlation approach also acts as a low-pass filter that suppresses other interference like line noise.
- Improved zero-flow drift. Exciting the transducers over a range of transmit frequencies (instead of just one frequency) can account for resonance shifts over temperature and reduce the zero flow drift of the gas meter.

1.1 TI's Ultrasonic Sensing Solution

TI's ultrasonic sensing technology comprises an ADC based cross-correlation approach that uses frequency information to determine the ultrasonic time of flight with much higher accuracy than existing TDC-based techniques. More about how this unique algorithm works and TI's ultrasonic sensing subsystem (USS) can be found in TIDM-02003.

TI's ultrasonic sensing subsystem enables a single-chip solution that can be connected to ultrasonic transducers along with an op-amp and mux for high-resolution flow measurements. TI's USS is integrated with the low-energy accelerator (LEA) and the MSP CPU to enable autonomous low-power operation with an average current consumption of less than 20 µA (at one measurement per second).

TI's ultrasonic sensing subsystem (see Figure 1-1) comprises a programmable pulse generator (PPG) and a high-speed sigma-delta analog-to-digital converter with a programmable gain amplifier (PGA) that can autonomously excite and capture ultrasonic waveforms for subsequent processing via an integrated low-energy accelerator (LEA).
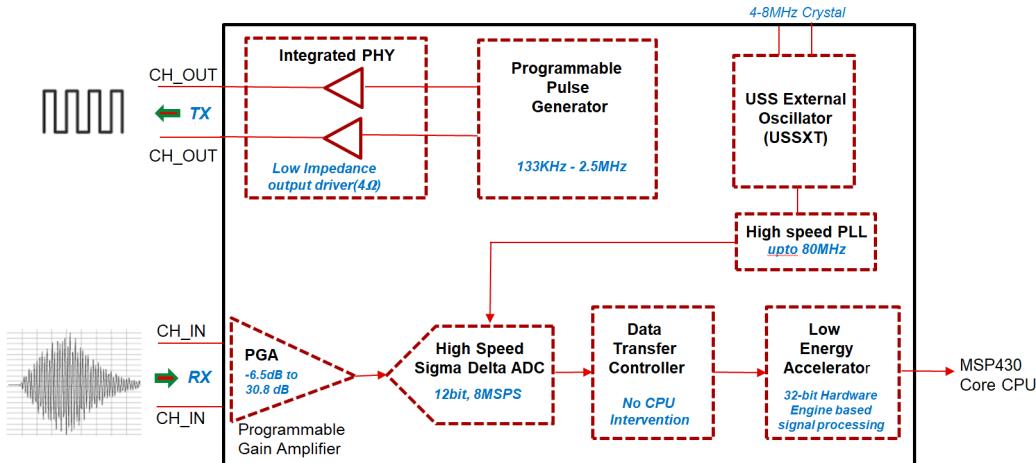

Figure 1-1. TI's Ultrasonic Subsystem

This ultrasonic subsystem first excites an "upstream" (UPS) transducer connected to CH0_OUT while capturing the waveform from a "downstream" (DNS) transducer connected to CH0_IN. The ultrasonic subsystem subsequently excites the "downstream" transducer connected to CH1_OUT while capturing the waveform from the "upstream" transducer connected to CH1_IN. These waveforms are then processed by the low-energy accelerator to determine the difference between the upstream and downstream time of flight.

2 Design Process

Figure 2-1 shows the overall design process for a 7000 l/h (liters per hour) gas meter system with TI's ultrasonic solutions. This process begins with transducer evaluation at low flow rates. This process continues with iterative tube optimization and configuration tuning at higher flow rates. The process is completed with calibrated oven testing with sensitivity and power optimizations.
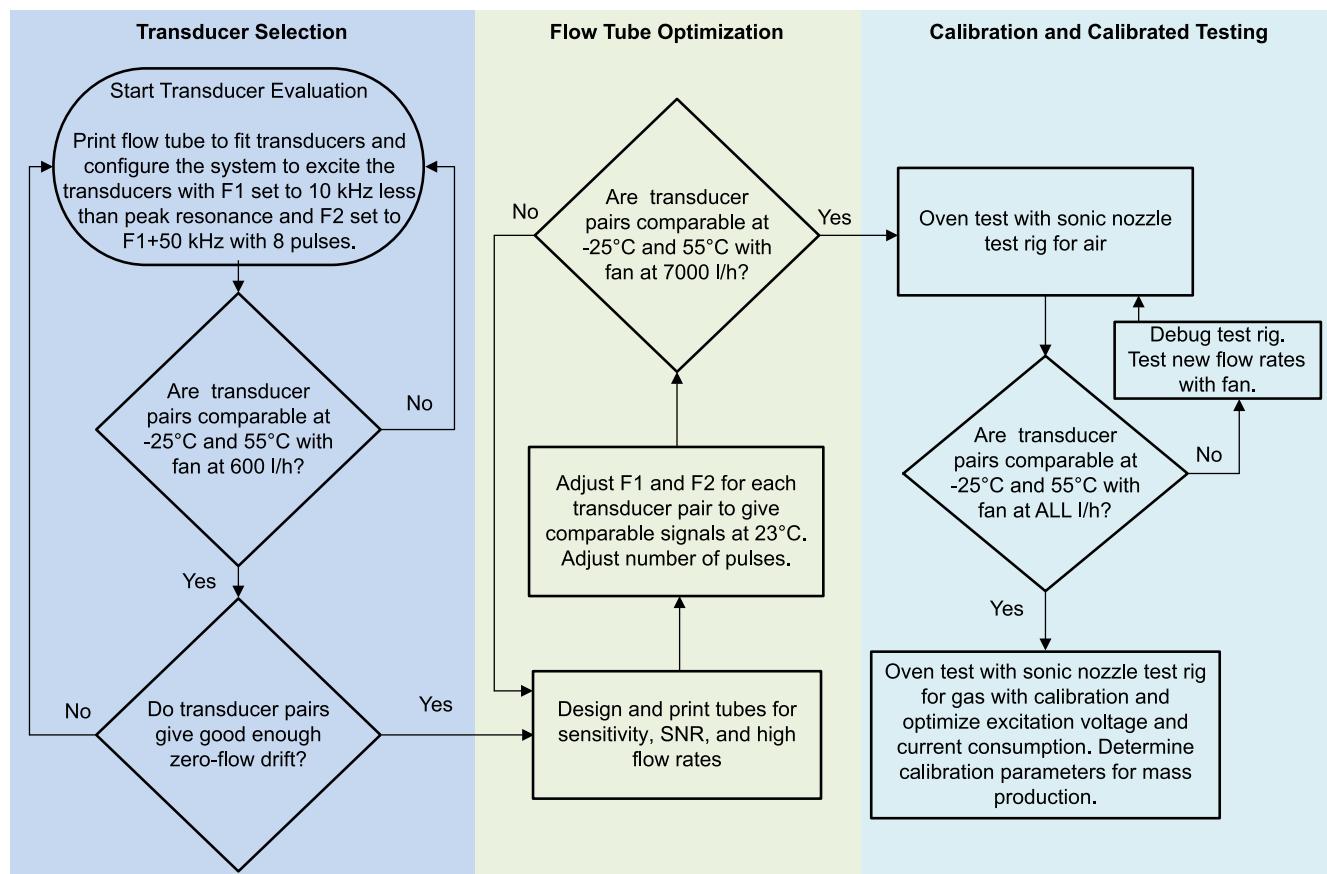

Figure 2-1. Design Process

2.1 Transducer Selection

Repeatability across transducer pairs is critical to being able to go to mass production. When selecting a transducer, the variation in frequency response over temperature is the most critical consideration because it is cost prohibitive to calibrate each individual meter over the full range of operating temperatures. Calibrated gas testing is expensive and should be conducted after transducer evaluation tests have been conducted. Transducers exhibiting more comparable frequency response over temperature are preferred for this reason. The sensitivity, bandwidth, and zero-flow drift of transducers within a given tube design are also key aspects which should be evaluated after variations in frequency response over temperature have been assessed. A simple comparative oven test for transducer frequency response variation can be found in the Transducer Selection Guide.

To select the best transducers, a suboptimal tube design can be used with low flow rate testing (such as 600 lph). When using TI's 3D printable designs, modify the TRANSDUCER_RADIUS parameter to accommodate the transducers being evaluated. Once good enough transducers have been identified, optimizations in the tube design for higher flow rates should be explored.

2.2 Flow Tube Design

There are two types of ultrasonic tube designs commonly found in the market: trans-axial and reflected. Trans-axial tube designs position transducers to face each other at an angle to a channel through which the gas flows. Reflected tube designs position transducers to reflect the ultrasonic energy off a surface inside the tube before reaching the other transducer.

While trans-axial tube designs can enable stronger ultrasonic signals over a shorter ultrasonic path, reflected tube designs can enable greater sensitivity over a longer ultrasonic path at the expense of ultrasonic signal strength. Figure 2-2 shows these two types of ultrasonic tube designs.
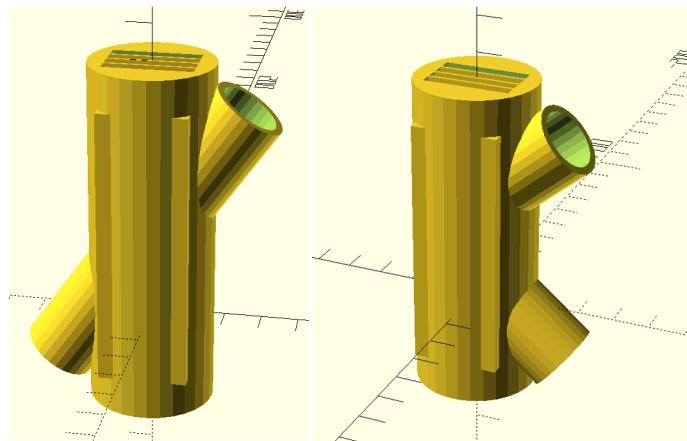

Figure 2-2. Trans-Axial and Reflected Flow Tube Designs

In both of these designs, there are four key design considerations that can significantly affect the characteristics of the design: flow channel dimensions, ultrasonic angle, collimating elements, and flow plates. Table 2-1 shows how these four elements relate to the accuracy, sensitivity, and signal strength of a given design.

Table 2-1. Tube Design Considerations

Property	Accuracy	Sensitivity	Signal Strength
Ultrasonic Angle	✓	✓	
Channel Dimensions		✓	✓
Flow Plates	✓		✓
Collimating Elements	✓		✓

The height and width of the flow channel can have a significant affect on the characteristics of a given tube design. While reducing the width of the channel can accelerate the flow of gas through the tube to give greater sensitivity, doing so also reduces the strength of the ultrasonic signal. Increasing the height of the channel can also increase the sensitivity of the tube at the expense of ultrasonic signal strength.

The angle at which the ultrasonic signal comes in contact with the gas can also have a significant affect on the sensitivity of the tube. An ultrasonic angle that is more closely aligned with the flow gives greater sensitivity at the expense of ultrasonic signal strength. The accuracy of measurements can also be compromised if the ultrasonic angle is too small.

Collimating elements are commonly introduced to attenuate ultrasonic reflections within a tube while giving a representative measurement of flow though the tube. Addition of these elements can improve the accuracy of a given design at the expense of signal strength.

Flow plates are commonly used to minimize flow interactions with the transducer face. While these can give more accurate measurements at higher flow rates, these also come with a reduction in ultrasonic signal strength.

2.3 Optimizing the Number of Pulses and Excitation Frequency

There are various configuration parameters that can be optimized for power consumption, flow performance, standard deviation, and zero flow drift. The relationship between these four aspects and the associated configuration parameters can be seen in Table 2-2. The transmit frequency and number of pulses are the most critical parameters because these can have the greatest impact on flow performance (and accuracy). More

details on how to configure these and other less critical parameters can be found in the Quick Start Guide for Gas Flow Meter.

The transmit frequency for a given transducer pair can significantly affect accuracy over temperature. This frequency may need to be shifted by a few kHz to ensure ultrasonic signals are comparable at 23°C. This is based on the assumption that the frequency response of each transducer could vary by a few kHz over the operating temperature range. Transducer pairs without significant variation in their impedance over temperature may not require this transmit frequency tuning.

Table 2-2. Configuration Tuning

Parameter	Change to Parameter Affects...			
	Power Consumption	Flow Performance	Standard Deviation	Zero Flow Drift
Number of Pulses	✓	✓	✓	✓
UPS0 to UPS1 Gap	✓			
GUI Based Gain Control			✓	✓
Transmit Frequency		✓	✓	✓
Envelope Crossing Threshold		✓		
Capture Duration	✓	✓		✓

After determining the best transmit frequency, the number of pulses can be increased to give a lower standard deviation in low-flow measurements. Because the additional ultrasonic energy can have negative effects on the accuracy of measurements at high flows, increases in the number of pulses should be tested at temperature extremes and higher flow rates before proceeding with more advanced testing.

3 Design Metrics and Calibrated Flow Testing

The key design metrics of a complete gas meter include repeatability, accuracy, sensitivity, and current consumption.

3.1 Repeatability

The repeatability of the meter pertains to cost effectively manufacture, calibration, and qualification of these meters on a mass production line. Because gas meters must operate over a wide range of temperatures (from -25°C to 55°C), the frequency response of transducers over this range of temperature is a critical aspect of repeatability. If the variations in frequency response are too high, a cost effective calibration method at room temperature is not possible. A simple method for determining the repeatability of a given transducer across a representative production lot is described in the Transducer Selection Guide.

3.2 Accuracy

The accuracy of a meter pertains to the percentage in error that can be measured at a given flow rate over temperature. Gas meters have three flow ranges over which accuracy requirements can vary. The zero-flow drift of a given transducer in a tube design determines the minimum flow (or leakage) a meter can detect with a common accuracy requirement of ±10%. Details on zero-flow drift testing can be found in the TIDM-02003 user's guide. For European markets, the low flow range of a gas meter is typically between 40 liters per hour (lph) and 600 lph with a ±3% accuracy requirement. The high flow range of a gas meter is typically between 600 lph and 7000 lph with an accuracy requirement of ±1.5%.

Accuracy testing of a given tube design is typically first conducted with air in an oven that is set to operating temperature extremes (in addition to room temperature) with a sonic nozzle test rig that has been calibrated to provide a deterministic flow through the gas meter. After representative testing over temperature has been conducted over enough meters, calibration for mass production is limited to flow testing at room temperature. Measurements at flow rates ranging from 40 lph to 7000 lph are taken for a few minutes at temperatures typically ranging from -25°C to 55°C to determine variations in reported flows across multiple meters. Figure 3-1 shows a sonic nozzle flow test system.

Because this system involves multiple pneumatic valves and a large oven that can test multiple meters at the same time, there is often noise from the test equipment that can adversly affect the ultrasonic measurement

results. It is recommended to conduct initial testing with a high-precision fan and the oven turned off after temperature stabilization to distinguish between gas meter and test fixture problems.

After enough testing has been conducted with air, a separate (more elaborate) test fixture that introduces a variety of compressed natural gas mixtures is used. Problems not seen in air testing often arise due to the increased attenuation of methane and the decrease in time of flight (which can move the received ultrasonic signal into the excitation "ring down" time zone of the transmitting transducer). Because the time of flight decreases in methane, secondary reflections like the one shown in Figure 3-2 can occur earlier and require some adjustment to the timing between upstream and downstream measurements.
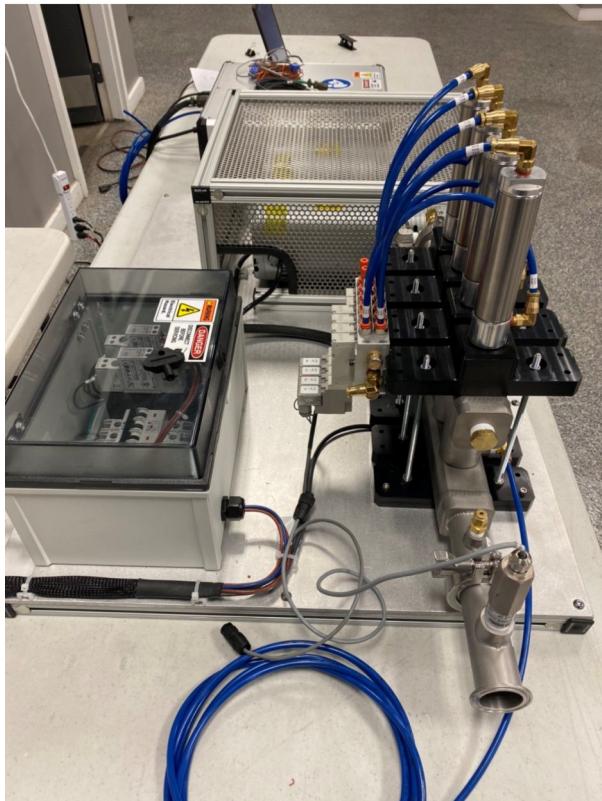
Figure 3-1. Sonic Nozzle Test and Calibration System
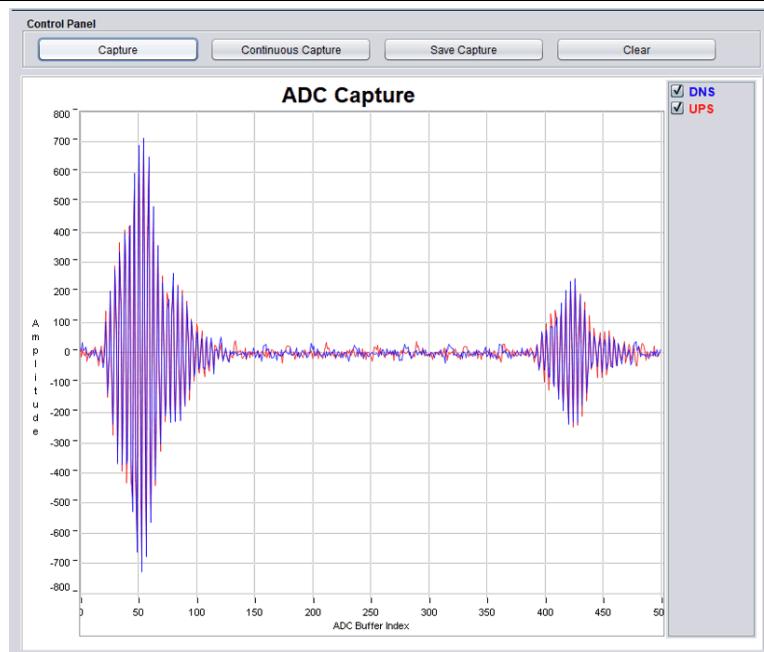
Figure 3-2. Secondary Reflection

3.3 Sensitivity and Power Optimizations

The sensitivity of a meter pertains to the standard deviation in measurements. As mentioned previously, the ADC-based approach provides a standard deviation that can be 3 times lower than the TDC approach. Tube designs with a longer ultrasonic path (or lower ultrasonic angle) can provide greater sensitivity provided the ultrasonic signal strength is strong enough to overcome ambient noise. The TIDM-02003 user's guide describes how to measure the standard deviation. The excitation voltage of the transducer can be increased to lower the standard deviation in measurements at lower flow rates and for high concentration methane applications.

The current consumption of a gas meter is typically measured with a power analyzer. The TIDM-02003 user's guide includes a typical current profile for a measurement that consumes less than 20 µA when averaged over a 1-second measurement period. This current consumption can be further reduced by reducing the frequency at which the absolute time of flight measurements are taken. Because a number of measurements need to be taken to get a mean value at low flow rates, a tube design with higher sensitivity (and lower standard deviation) can give a more accurate result with fewer measurements (and lower current consumption).

4 OpenSCAD Design Files

OpenSCAD (http://www.openscad.org/) is a freely available CAD tool that enables parametric generation of 3D models that can be exported for 3D printing. The parametric 3D flow tubes used in this paper are available from https://www.ti.com/lit/zip/slaa974.

5 References

1. USSSW_Lib_Gas
2. Ultrasonic sensing subsystem reference design for gas flow measurement (TIDM-02003)
3. Ultrasonic sensing subsystem reference design for gas flow measurement user's guide
4. Transducer Selection Guide
5. OpenSCAD
6. MSP430 MCUs Ultrasonic Sensing Design Center

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