Application Report

Oxygen Concentration Sensing

ABSTRACT

This document describes an oxygen concentration sensing solution based on TI's ultrasonic technology. This setup is capable of sensing oxygen concentrations to within 0.8% of reading value at a scale of 21% - 96%, with a response time of 78 ms and power consumption of 660 µW at 10 samples/sec. This setup uses a portable pulsed oxygen concentrator to generate high oxygen levels for testing.

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 equipments with them can be found at the MSP430 ultra-low-power sensing & measurement MCUs overview.

For more information on the example code and GUI used in this application report, see *Ultrasonic Sensing Subsystem Reference Design for Gas Flow Measurement*. The results presented in this application report are based on the standard example and GUI without modification.

200 kHz Jiakang transducers were found to give enough sensitivity to detect small changes in oxygen concentrations for a variety of flow rates.

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1 Introduction

Existing oxygen concentration sensors are typically based on electrochemical or Zirconium technologies. While being a mature technology, recent technological trends to increase integration, reduce size, and lower power consumption are making equipment manufacturers look into other implementations that better satisfy these new requirements. Ultrasonic sensors offer long lifespan and do not require replacement or re-calibration every 1-3 years like electrochemical or Zirconium sensors. This technology is not limited to just Oxygen sensing, it can also be used for other gases such as Nitrogen, Hydrogen, Nitrous Oxide, Carbon Dioxide, Argon, and Helium. These sensors are commonly found in ventilators, concentrators, and combustion monitors.

TI's ultrasonic sensing solution with the MSP430FR6043 brings high accuracy at flow rates ranging from less than 1LPM to greater than 190LPM, with measurement periods of less than 10 ms to bring precision to pulse oxygen applications.

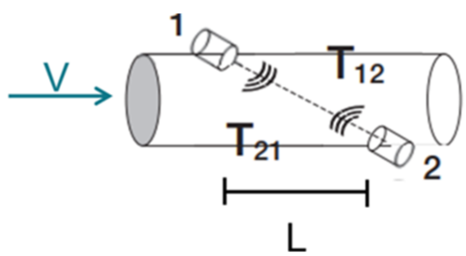
Ultrasonic concentration sensing relies on the relationship that exists between the sonic velocity of a gas medium and its molar weight (see Equation 3). This principle can be extrapolated to a binary gas composition. If the molar weights of the two gases present are known (simplified as oxygen and nitrogen in this application), the volume concentration of each gas can be extracted from the specific sonic speed of the sample mixture (see Equation 4).

$$T_{12} = \frac{L}{C + V} \quad T_{21} = \frac{L}{C - V} \tag{1}$$

$$V = \frac{L}{2}\left(\frac{1}{T_{12}} - \frac{1}{T_{21}}\right) \tag{2}$$

$$C = \sqrt{\frac{kRT}{M}} \tag{3}$$

$$\rho = \frac{\frac{kRT}{C^2} - M_N}{M_{O_2} - M_N} \tag{4}$$



C = Speed of sound in gas medium

k = Specific heat ratio ~ 1.4 for and air

R = Universal gas constant

T = Temperature ~ 295.85 K in this example

M = Molar weight of gas mixture

M_{O2} = Molar weight of ~ 32

M_N = Molar weight of ~ 28

p = Volume concentration

L = Sensor distance ~ 4.4 cm in this example

V = Velocity of gas flow

The speed of sound in a binary gas mixture is determined by using the TOF equations (1). For low flow rate applications, such as those in oxygen concentrators or CPAP machines with 1LPM – 15LPM of flow, the velocity of gas flow V can be ignored. In these cases, C >> V.

TI's ultrasonic sensing technology comprises an analog-to-digital converter (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. For more information about how this unique algorithm works and TI's Ultrasonic Sensing Subsystem (USS), see TIDM-02003.

TI's Ultrasonic Sensing Subsystem enables a single chip solution which can be connected to ultrasonic transducers along with an op-amp and mux for high resolution flow measurements. TI's USS is integrated with a Low Energy Accelerator (LEA) and 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 (depicted in 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).

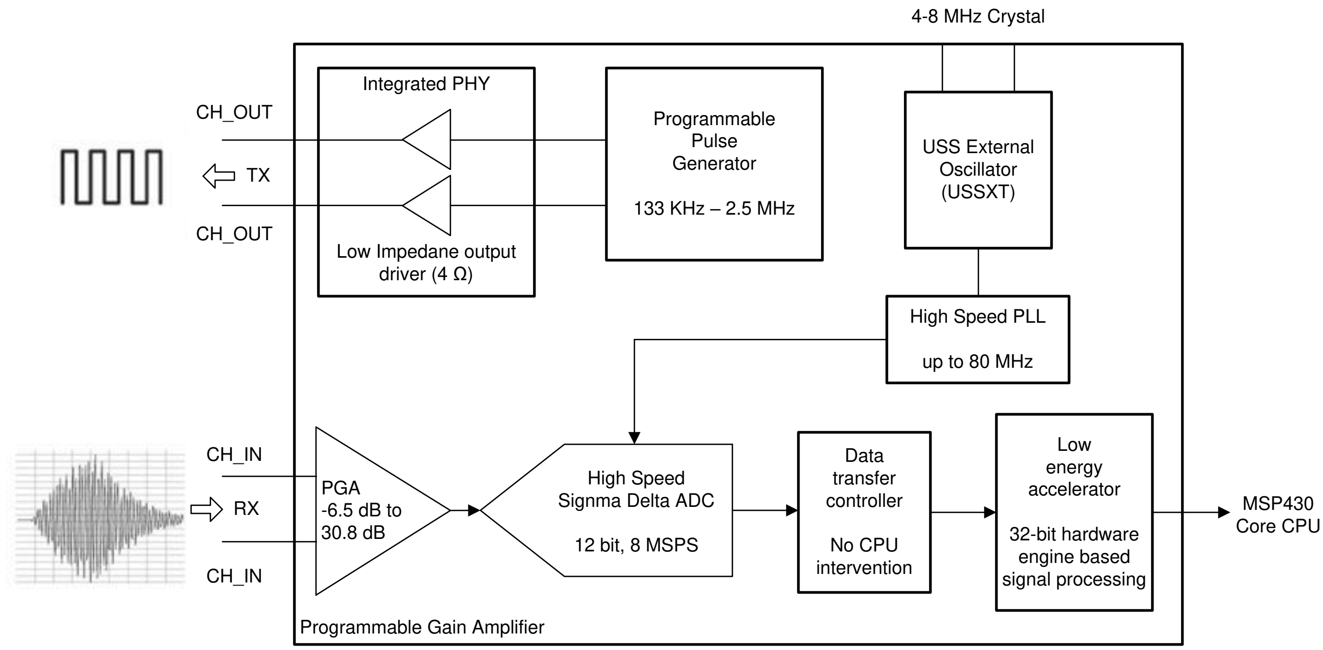


Figure 1-1. Ultrasonic Tube

This ultrasonic subsystem (depicted in Figure 1-1) first excites an "upstream" transducer connected to CH0_OUT while capturing the waveform from a "downstream" 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 Setup and Configuration

The EVM430-FR6043 is used with two Jiakang 200 kHz transducers. A 3D printed fixture is used to mount the transducers for experimentation.

The system diagram depicted in Figure 2-2 shows the use of the TMP117EVM to measure temperature. Based on Equation 3, you can see that concentration is dependent on temperature. In fact, for every 1°C measurement error in the system, we are introducing ~2.75% error in our oxygen concentration readings. Hence, a 0. 1°C accurate temperature sensor such as the TMP117 is recommended.

For simplicity purposes, because the temperature was constant in this experiment, temperature was only sampled once. The temperature in this experiment was found to be 22.7 °C (295.85 K). When calculating the concentration or speed of sound in a gas medium using the equations describe in this document, be sure to use degrees Kelvin as the unit of temperature.

Figure 2-1. Printed Fixture and EVM Implementation

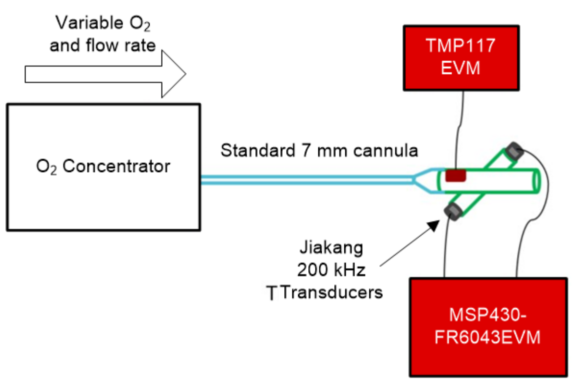


Figure 2-2. System Diagram

2.1 EVM430-FR6043 GUI Configuration

The ultrasonic GUI configuration used with this oxygen concentration set-up is depicted in Figure 2-3. In this configuration, the FR6043 is configured with a 200 kHz frequency sweep and with 1 MHz signal sampling frequency. for more information on properly setting up the GUI parameters as well as determining the excitation band of the transducers being used, see the *Quick Start Guide for Gas Flow Meter User's Guide*.

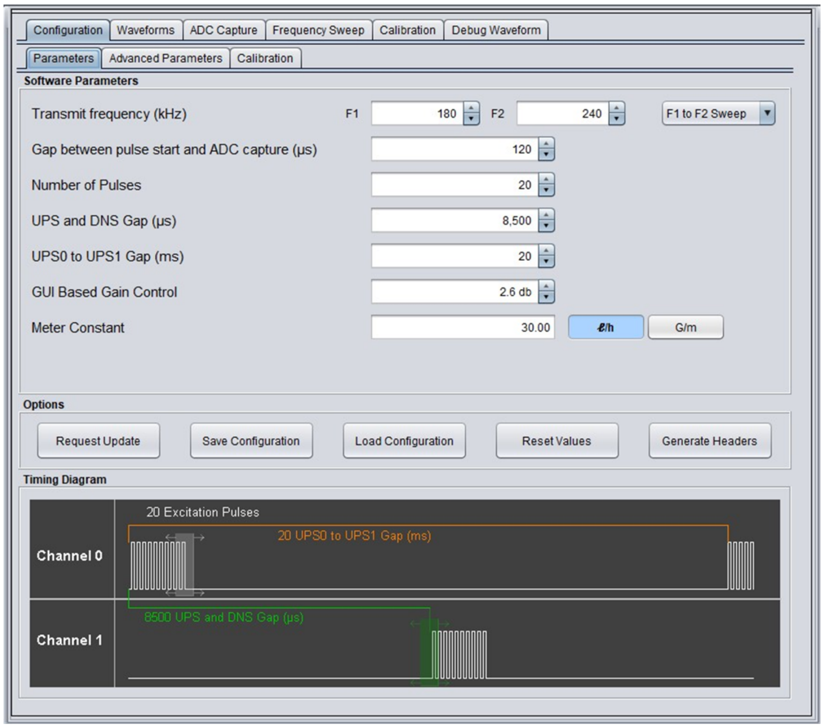


Figure 2-3. EVM430-FR6043 GUI Configuration

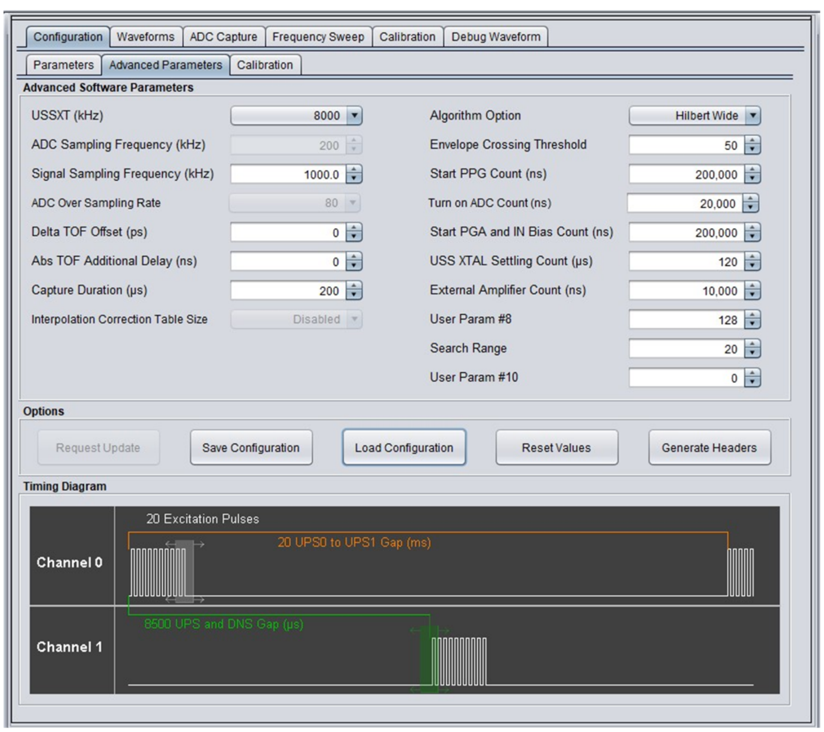


Figure 2-4. EVM-FR6043 GUI Advanced Configuration

3 Test Results

The test results in Figure 3-1 show the captured ADC waveform and Figure 3-2 shows the sensor readings as the device starts operation from an initial off state. The circled section shows the absolute TOF values when the machine is off. At this point, the gas inside the pipe is simply air. Since air is approximately 21% oxygen, you can use this as a calibration point for the system.

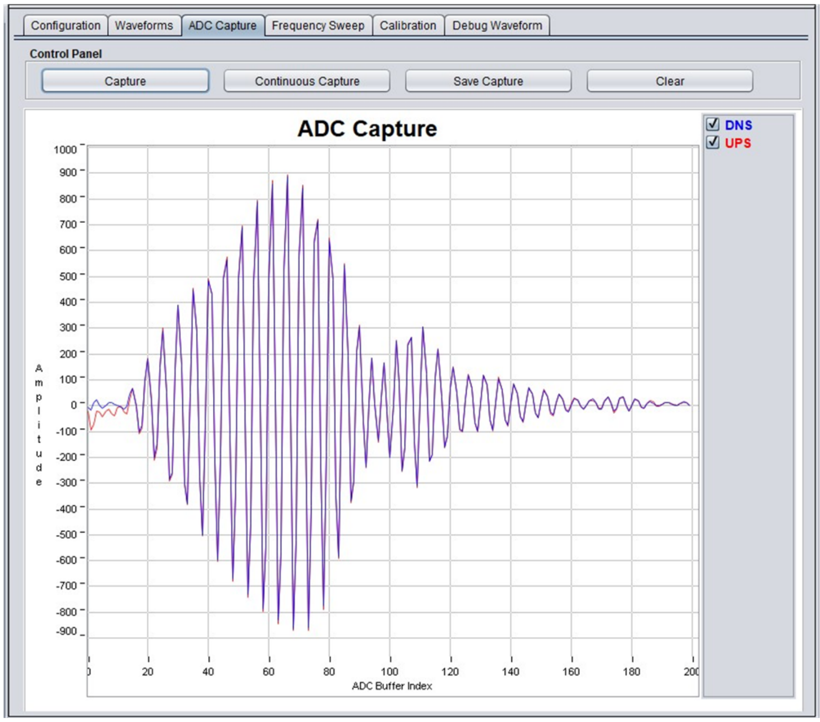


Figure 3-1. ADC Capture and Experimental Results

Figure 3-2. Waveform Results

The pulses from the pulsed oxygen concentrator can be seen in the Waveforms Window. In order to extract the oxygen concentration, save the data as a .cvs file and do the conversion in a spreadsheet.

4 Extracting O_2 Concentration

Table 4-1. Spreadsheet Example

	A	B	C	D	E	F
1	Absolute TOF UPS (µs)	Absolute TOF DNS (µs)	Velocigty of Gas Flow (m/s)	Speed of Sound in Gas Medium (m/s)	Oxygen Concentration (%)	Calibration Parameter
2	132.9382	132.9738	-0.04426	330.936511	21.04397223	14.6

1. Use TOF values to calculate velocity of gas flow.
   a. For cell C2 “=(0.044/2)*(1/(B2*0.000001) - 1/(A2*0.000001))” – Using Equation 2.
2. Use TOF values to Calculate speed of sound in gas medium.
   a. For cell D2 “=(0.044/(B2*0.000001) - C2)”
      i. Solving for C in (1) -> C = (L / T_{12}) - V
3. Calculate Oxygen concentration.
   a. For cell E2 “=100*((1.4*8.314*295.85/(D2+F2)^2)-(28/1000))/(4/1000)” – Using Equation 4.
4. Calibrate measurements.
   a. Since the oxygen concentration in this measurement is known to be 21% (Air), change the value of cell F2 until Cell E2 equals 21%. In this case, many sample points were taken with air and averaged.
   b. The calibration parameter “14.6” can now be applied to the whole data set.
   c. This calibration parameter is unique to this specific set-up. A calibration procedure must always be performed for any new implementation.
5. Applying calibrated equation to dataset.

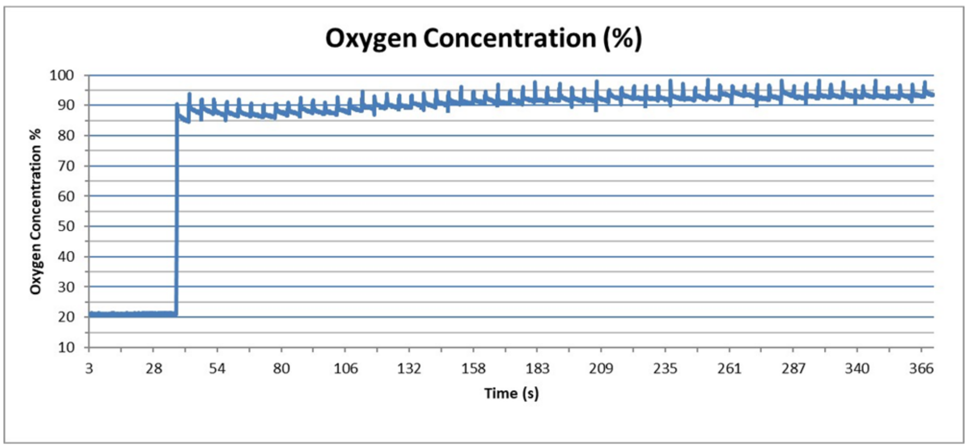


Figure 4-1. Oxygen Concentration Extraction

As it can be seen in Figure 4-1, the oxygen concentration ramps up from 21% to 93.4%. Based on the manufacturer’s certification report for the specific unit used, our system was 0.8% off from the specified oxygen concentration. This was all achieved using air as a single calibration point and could easily be implemented with the MSP430FR6043.

Table 4-2. Performance and Comparison

Parameter	Zirconium Sensor	Competing USS Solution	TI's USS
Measurement Range	0.1% - 100%	0% – 100%	0% - 100%
Accuracy	± 3% - 0.5% FS	±3 - 1.8% FS	± 1.7% – 0.5% RD
Power Consumption	1 – 10W	0.6W	660 µW @10SPS
Warm up time	~60s	NA	NA
Response time	4s – 30s	0.5s	78ms
Output Stabilization time	2 – 10 minutes	NA	NA
Lifetime	1-3 years	> 5 Years	> 5 Years

4.1 Note on Achieved Accuracy

In this specific experiment, 0.8% accuracy was achieved using air as the single calibration point. The reason for the accuracy specification to have a range of ± 1.7% – 0.5% RD is that the accuracy is highly dependent on the geometries and architecture of the transducer set-up. Thus, these are accuracy values that were achieved experimentally using different size pipes across a range of flow rates and concentration ranges. These values should be interpreted as accuracies that can be achieved.

5 OpenSCAD 3D Test Fixture

OpenSCAD is a freely available CAD tool that enables parametric generation of 3D models, which can be exported for 3D printing. The parametric 3D test fixture used in this document is available from TI.

The OpenSCAD parametric design used in these experiments is shown below:

```
TRANSDUCER_RADIUS=8.25;
PIPE_RADIUS=8.5;
PIPE_LENGTH=70;
CHANNEL_WIDTH=6;
CHANNEL_HEIGHT=12;
ULTRASONIC_ANGLE=35;
ULTRASONIC_LENGTH=60;

union(){
difference(){

    union(){
        translate ([0, 0, -25])
        rotate([0, 0, 0])
           cylinder (h = PIPE_LENGTH, r = PIPE_RADIUS);

        translate ([-(PIPE_RADIUS+9), .1, -14.9])
        rotate([0, ULTRASONIC_ANGLE, 0])
           cylinder (h = ULTRASONIC_LENGTH, r = TRANSDUCER_RADIUS+2);
    }

union(){
        translate ([-(CHANNEL_HEIGHT/2), -CHANNEL_WIDTH/2, -25])
        rotate([0, 0, 0])
           cube ([CHANNEL_HEIGHT,CHANNEL_WIDTH,PIPE_LENGTH]);

        translate ([-(PIPE_RADIUS+9), 0, -15])
        rotate([0, ULTRASONIC_ANGLE, 0])
           cylinder (h = 150, r = TRANSDUCER_RADIUS);
    }
}
union(){
        translate ([-(CHANNEL_HEIGHT/2), -CHANNEL_WIDTH, -15])
        rotate([0, 0, 0])
           cube ([CHANNEL_HEIGHT,CHANNEL_WIDTH/2,PIPE_LENGTH-20]);

        translate ([-(CHANNEL_HEIGHT/2), CHANNEL_WIDTH/2, -15])
        rotate([0, 0, 0])
           cube ([CHANNEL_HEIGHT,CHANNEL_WIDTH/2,PIPE_LENGTH-20]);

}}
```

6 References

- Texas Instruments: *Quick Start Guide for Gas Flow Meter User's Guide*
- Texas Instruments: *Ultrasonic sensing subsystem reference design for gas flow measurement*
- Ultrasonic Flow Transducers
- OpenSCAD

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