Ultrasonic Sensing for Water Flow Meters and Heat Meters

Bahram Mirshab

ABSTRACT

Ultrasonic flow meters are gaining wide usage in commercial, industrial and medical applications. Major benefits of utilizing this type of flowmeter are higher accuracy, low maintenance (no moving parts), non-invasive flow measurement, and the ability to regularly diagnose health of the meter. This application note is intended as an introduction to ultrasonic time-of-flight (TOF) flow sensing using the TDC1000 ultrasonic analog-front-end (AFE) and the TDC7200 picosecond accurate stopwatch. Information regarding a typical off-the-shelf ultrasonic flow sensor is provided, along with related equations for calculation of flow velocity and flow rate. Included in the appendix is a summary of standards for water meters and a list of low cost sensors suitable for this application space.

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1 Introduction

In Figure 1, a typical ultrasonic flow sensor is shown. The flow sensor consists of a pipe with a nominal diameter “D” and two piezoelectric transducers placed at fixed distance “L” from each other. The transducers are mounted in a protective housing. The housing and the transducers are inserted into holes in the pipe, exposing inner covers of the transducers to the fluid in the pipe. Two acoustic reflectors in the pipe direct the ultrasonic signals from one transducer to the other, as shown in Figure 1. The path between two transducers via acoustic reflectors (as shown in Figure 1, for example) is referred to herein as a single path, and correspondingly, a sensor with a single path is referred to as a single path sensor.

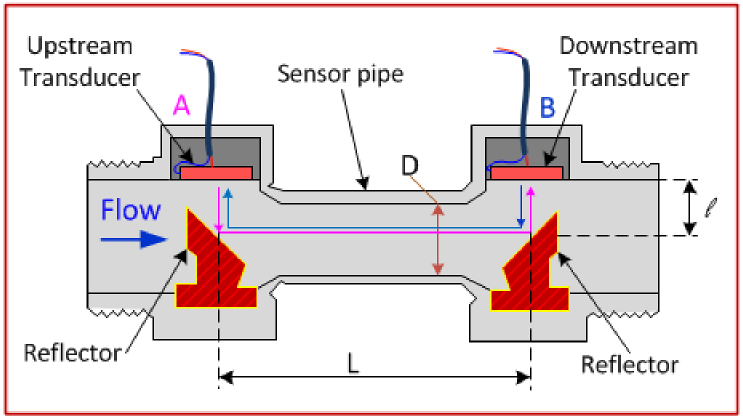

Figure 1. Ultrasonic Water Flow-meter Pipe

The single path sensor of Figure 1 is used for flow applications where the diameter of the pipe is small. For larger diameter pipes, sensors with multiple paths are used.

In addition to the integrated transducer style of ultrasonic flow sensor (as illustrated in Figure 1, for example), other types of ultrasonic flow sensors are available with clamped-on transducers. However, this article is limited to reflective-type single path sensors such as shown in Figure 1 by way of example.

2 Time-of-flight Measurement Sequence

Referring to Figure 2, a measurement sequence begins by exciting one of the transducers in a pair, (for example, “A” in Figure 1), by applying a burst of pulses to the transducer (in Figure 2, three TX pulses are used). The frequency of the excitation signal should be equal to the resonance frequency of the transducer. For water flow applications, transducers with a resonance frequency of one to three MHz are used.

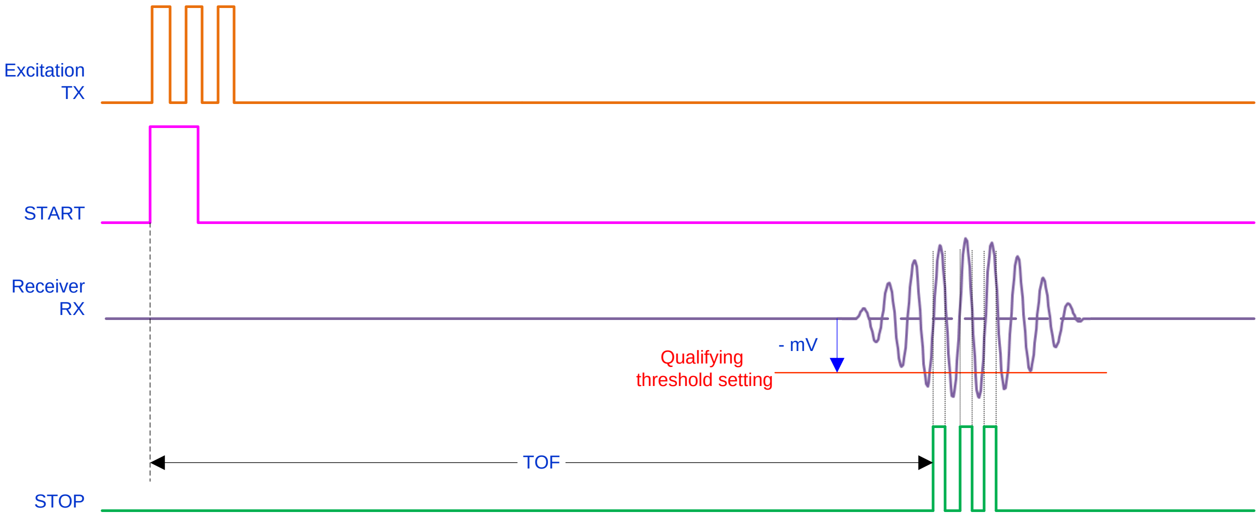

Figure 2. Ultrasonic Signal Measurement Sequence

The transducer generates ultrasonic pressure pulses that are directed towards the second transducer (for example, “B” in Figure 1) via the acoustic reflectors in the pipe. As the first pulse is being applied to the transducer, a START signal is generated to mark the beginning of the “time-of-flight” measurement.

On the receiver side, the electronic circuits in the path condition the received signal (for example, received at transducer “B”) and generate a STOP pulse to mark the time each ultrasonic pulse is received. The time taken for the ultrasound wave to travel from one transducer to the other (for example, the time between the START and the first STOP pulse) is referred to as the Time of Flight (TOF). A stop watch is used to measure the TOF time internal, in this case TOF_{AB}.

After receiving the signal, the receiving transducer (for example, “B” in Figure 1) switches to transmitting a set of ultrasonic pressure pulses, which are then received by the other transducers in the path (for example, “A” in Figure 1), and TOF measured (for example, TOF_{BA}). The difference between TOF_{AB} and TOF_{BA} is proportional to the velocity of the flow of the medium (for example, fluid or gas) in the pipe.

3 Volumetric Flow Calculations

The expressions for calculating the TOF between two transducers is given as:

$$\text{TOF} = \frac{\text{distance between the transducers}}{\text{speed of sound}} \tag{1}$$

Referring to Figure 1 , the expressions for TOF for downstream (TOF_{AB}) and upstream (TOF_{BA}) are:

$$\text{TOF}_{\text{AB}} = \frac{1}{C}\ell + \frac{L}{C+V} + \frac{1}{C}\ell \tag{2}$$

$$\text{TOF}_{\text{BA}} = \frac{1}{C}\ell + \frac{L}{C-V} + \frac{1}{C}\ell$$

where

- ℓ = D/2: D is the inner diameter of the pipe
- C = Speed of sound in the medium
- V = Average Velocity of the medium in the pipe (3)

Rearranging the terms and solving for V:

$$\begin{aligned}\Delta \mathrm{TOF} &= \left(\frac{D}{C}+\frac{L}{C-V}\right)-\left(\frac{D}{C}+\frac{L}{C+V}\right)\\ &= \frac{L2}{C-V}-\frac{L2}{C+V}\\ &= \frac{(C+V)L-(C-V)L}{C^2-V^2}\end{aligned} \quad (4)$$

$$\Delta T\ (C^2 - V^2) = 2 * L * V \quad (5)$$

Since C >> V:

$$(C^2 - V^2) \sim C^2 \quad (6)$$

and therefore:

$$\Delta T * C^2 = 2 * L * V \quad (7)$$

$$V = \frac{\Delta T * C^2}{2L} \quad (8)$$

3.1 Calculation of Volumetric Flow Rate, Q

The relationship for calculate the volumetric flow rate is:

$$Q = K * V * A$$

where

- K = Pipe calibration factor depending on the sensor
- V = Average velocity of the medium in the pipe
- A = The cross-sectional area of the flow meter pipe (9)

TDC 1000 uses zero-crossings to generate the START and STOP signals. At low flow rates, the difference between TOF_{AB} and TOF_{BA} is very small; for this reason, a highly accurate timer such as TDC7200 with picosecond resolution is required.

4 Ultrasonic Analog-front-end Integrated Solutions for Flow Measurement

Figure 3 illustrates a block diagram for a water flowmeter including a complete integrated electronics solution from Texas Instruments. The sensor interface consists of a TDC1000 integrated AFE and a TDC7200 integrated precision picosecond-accuracy stop watch. A discrete sensor interfacing solution is available, which includes a TS3A44159 analog switch from Texas Instruments, along with a few passive components.

The sensor interfacing circuit solution is provided to reduce, or effectively eliminate, the effect of a mismatch of transducers on measurement accuracy in static flow conditions, especially in lower cost ultrasonic flow sensors.

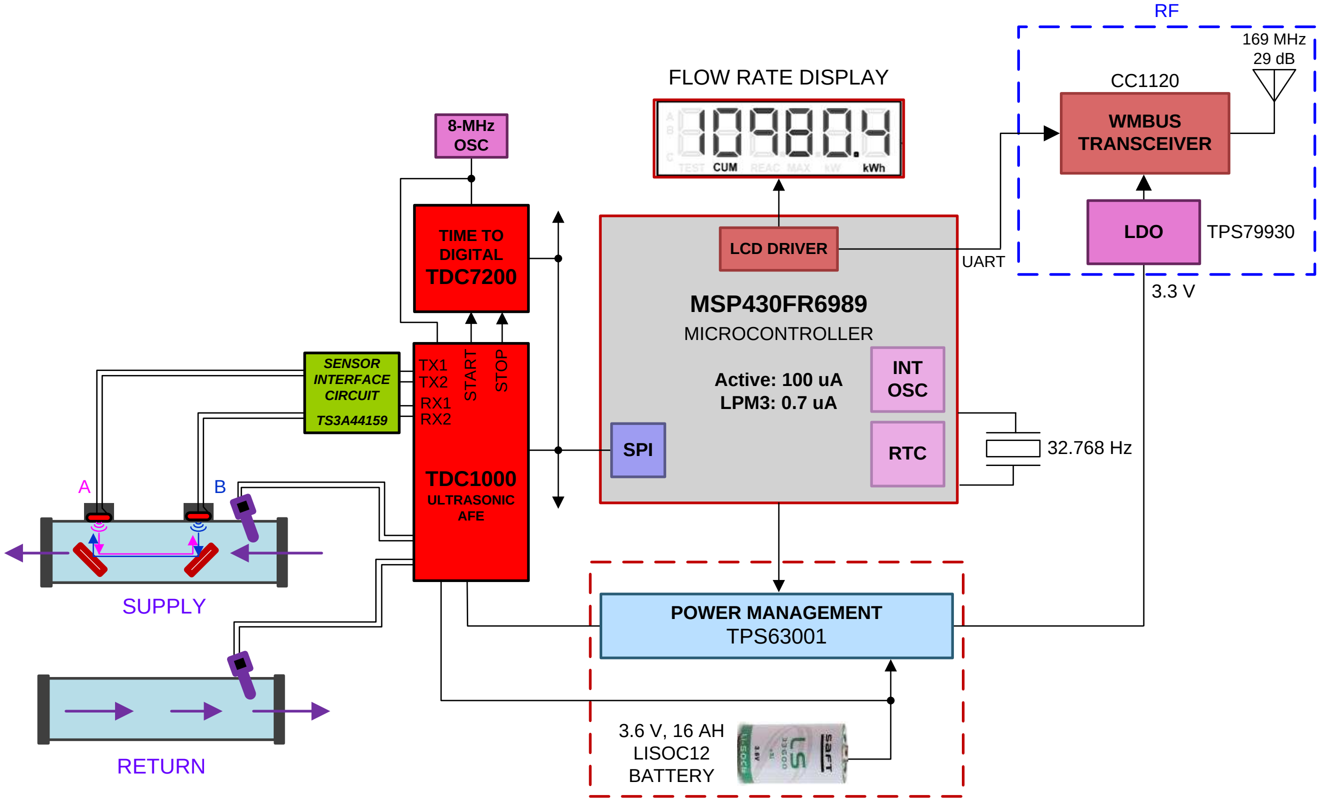

Figure 3. Texas Instruments Complete Solution for Water and Heat Meter Application

5 Choosing an Ultrasonic Flowmeter Sensor

System requirements, standards, and cost dictate the choice of flow meter sensors. Water is a good medium for propagating ultrasonic pressure pulses, and the most common sensors for water applications have a resonance frequency in a MHz range, such as 1 MHz.

An off-the-shelf ultrasonic heat/water meter sensor is available from Audiowell International. The sensor includes two ultrasonic transducers and the brass pipe assembly as shown in Figure 4. This sensor can be obtained from the source included in the reference section.

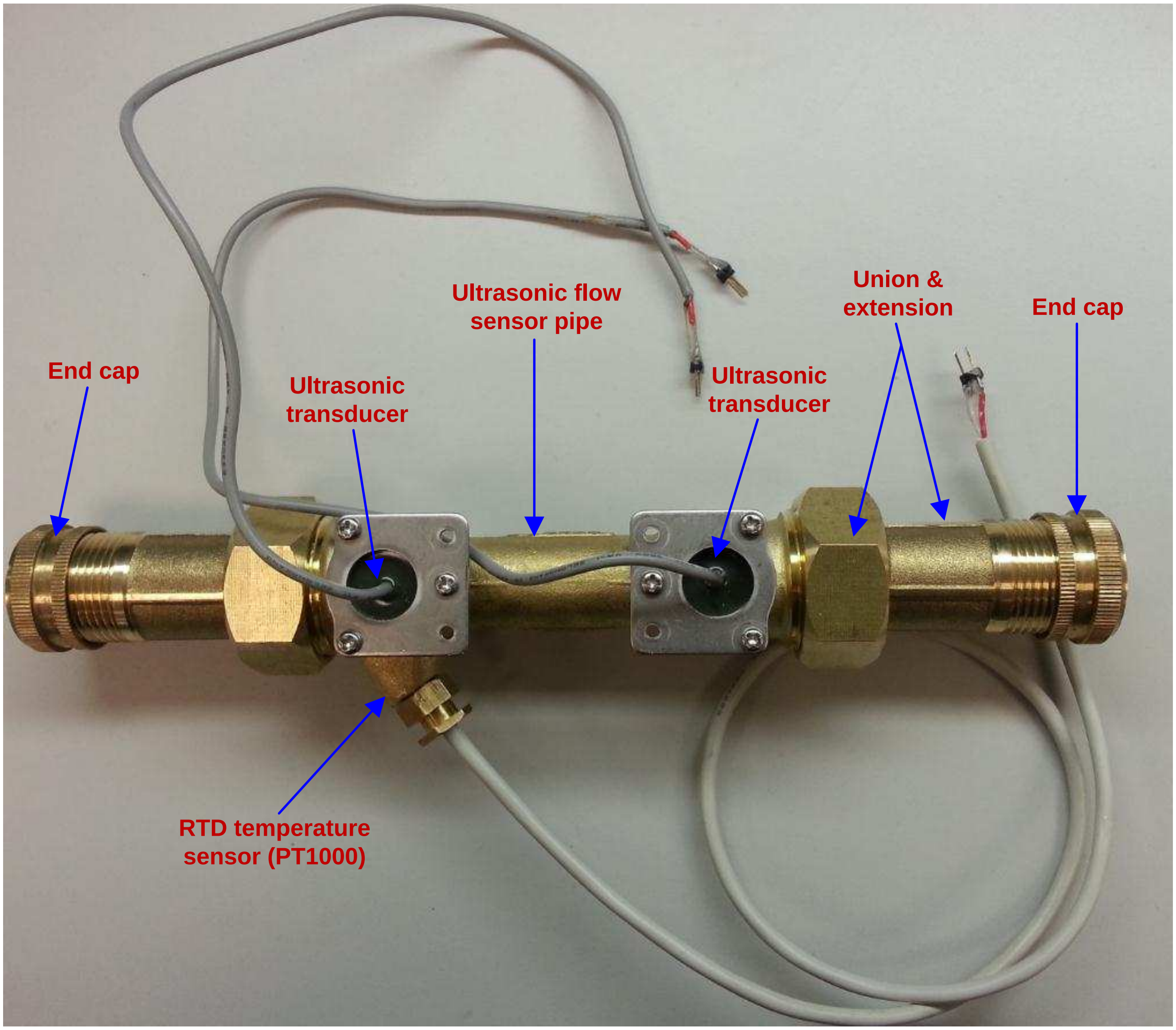

Figure 4. Audiowell Ultrasonic Flow-meter Sensor Pipe

6 Measurement Accuracy Considerations

6.1 Measurement Challenges at Zero Flow

In ultrasonic transit-time water fluid and gas flow meters, a difference in upstream and downstream TOF, or delta TOF (ΔTOF), is measured to calculate flow velocity. To reduce a possibility that the meter detects a false flow, under no-flow (or near zero flow) conditions, the upstream and downstream TOF should ideally be the same, and the difference (ΔTOF-offset) should be negligible over the temperature range of the medium.

6.1.1 Zero-flow ΔTOF-offset Correction

The meters are typically "dry calibrated" before being installed in the field. The steps involve calibration of the time delays due to electronics, cables and transducers, the calibration of ΔTOF-offset correction for each acoustic path, and calibration based on geometrical parameters. Various ΔTOF-correction approaches may be used by different manufacturers, but they are similar, and have the same purpose: to reduce false flow detection and improve accuracy at low and no-flow conditions ("zero flow adjustment"), without significantly affecting the accuracy in high-velocity conditions.

6.1.2 Improving Zero-flow-offset and Offset Drift Over Temperature

To improve, or effectively eliminate, ΔTOF-offset at static flow conditions, a highly symmetrical transmit and receive signal path is needed. The electrical impedance of the path can be controlled using an impedance matching solution, based on the principal of electroacoustic reciprocity. A well implemented impedance matching feature results in the operation of the circuit in a "sufficiently reciprocal" way. The benefit of such a feature is substantial reduction of effort in ΔTOF calibration, because a well-matched transmit receive path reduces the error to a negligibly small amount, and results in a very small drift of the error at zero flow over the operational pressure and temperature ranges, irrespective of mismatch of the transducers.

Figure 5 and Figure 6 are illustrative. The effect of temperature on resonance frequency and amplitude in two transducers in a single path sensor are shown in Figure 5.

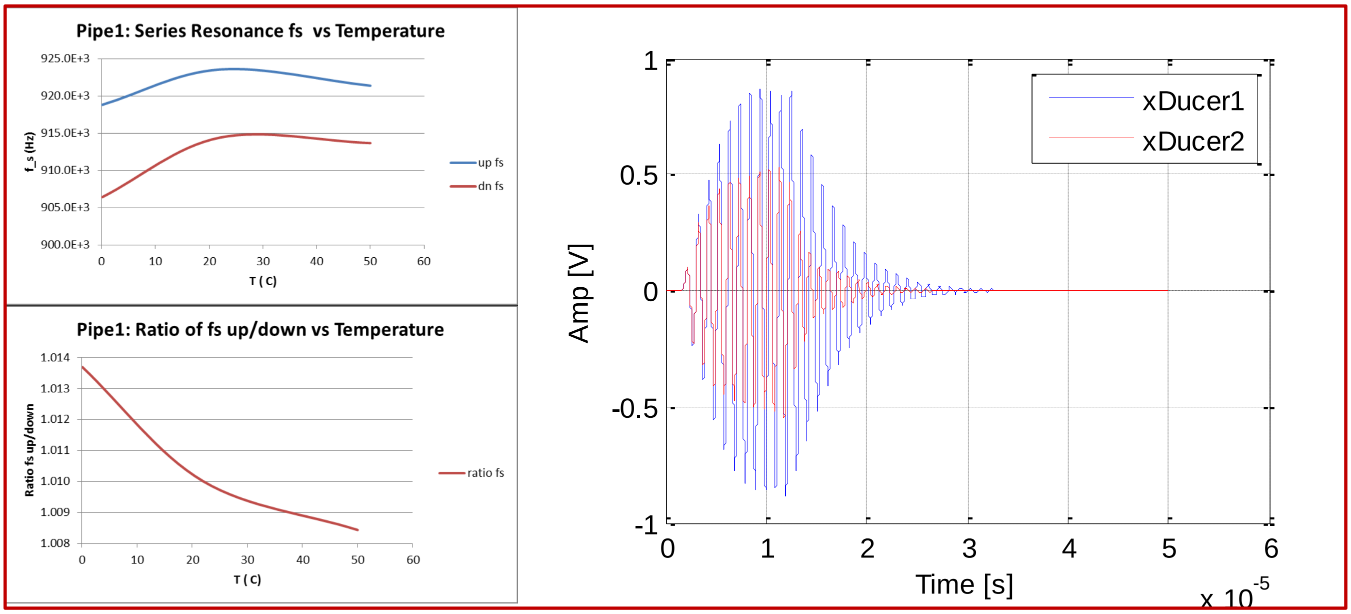

Figure 5. Effect of Temperature on Transducer Resonance Frequency and Amplitude, no Sensor Interfacing Circuit

As seen in Figure 5, there may be a significant mismatch between two transducers used in a sensor, especially in low-cost sensor. The mismatch introduces ΔTOF-offset and drift of offset over the temperature range of the medium.

Figure 6 shows the effect of temperature on transducer resonance frequency and amplitude for the same two transducers using an impedance-matching circuit. As seen on the right of Figure 6, signals of the two transduces maintain substantially the same amplitude over the temperature range due to the usage of a sensor interfacing circuit, and as seen on the left of Figure 6, the ΔTOF-offset drift is substantially reduced (for example, to approximately 25 ps or less for STOP pulses 1 and 5).

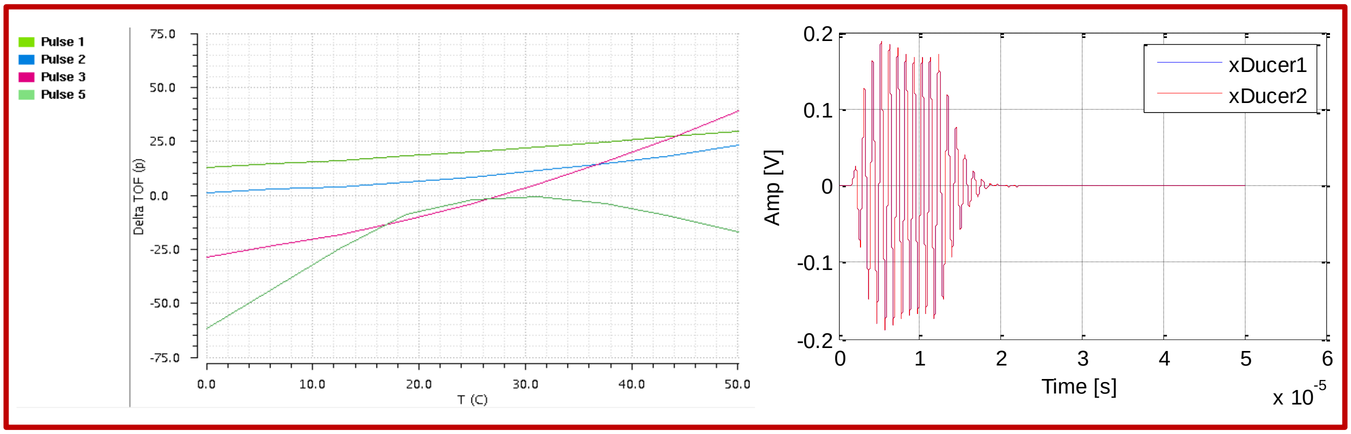

Figure 6. Effect of Temperature on Transducer Resonance Frequency and Amplitude, with Sensor Interfacing Circuit

A remarkable benefit of using the sensor interfacing circuit designed by Texas Instruments is that a lower cost sensor can be used to achieve high accuracy at zero-flow condition, without the need for tedious calibration to adjust the offset error over the temperature range.

Figure 7 and Figure 8 provide another comparison of the improvement that may be achieved using the sensor interfacing circuit.

Figure 7 provides results of a test for an ultrasonic flow meter pipe with no sensor interfacing circuit, over a temperature range of 20 °C to 50 °C. As can been seen, the ΔTOF-offset at zero flow drifts over ±450 ps. A reason for this drift is the unbalanced change of impedance of the two transducers. Change of impedance of a transducer results in a change of the resonance frequency of the transducer, introducing phase shift and added inaccuracies over the temperature range.

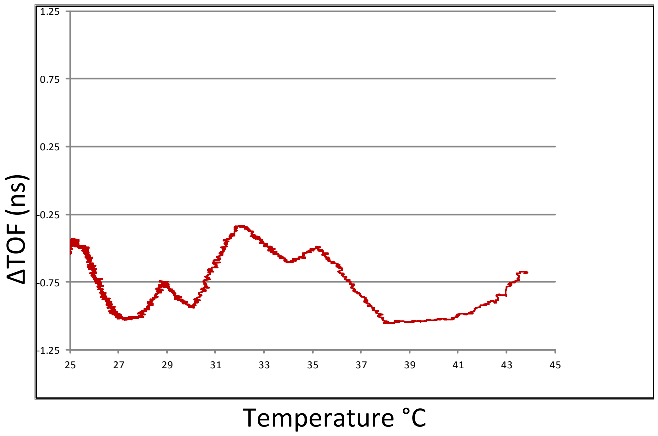

Figure 7. Drift, in the Absence of the Sensor Interfacing Circuit

Figure 7 provides results for the same meter, using a sensor interfacing circuit. The results shown below are preliminary and lower drift over temperature can be achieved by optimizing the impedance matching network.

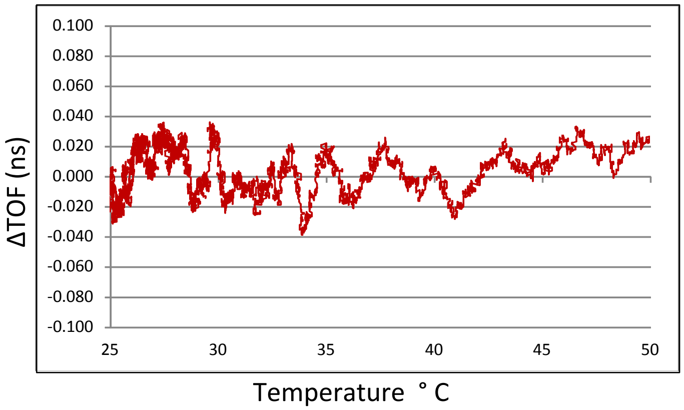

Figure 8. Drift, in the Presence of the Sensor Interfacing Circuit

As seen in the graphs, the drift is significantly reduced using the sensor interfacing circuit from Texas Instruments. Figure 9 illustrates the Texas Instruments's sensor interfacing circuit for a TDC1000. The circuit includes a TS3A44159 bi-directional 4-channel single-pole double-throw (SPDT) analog switch.

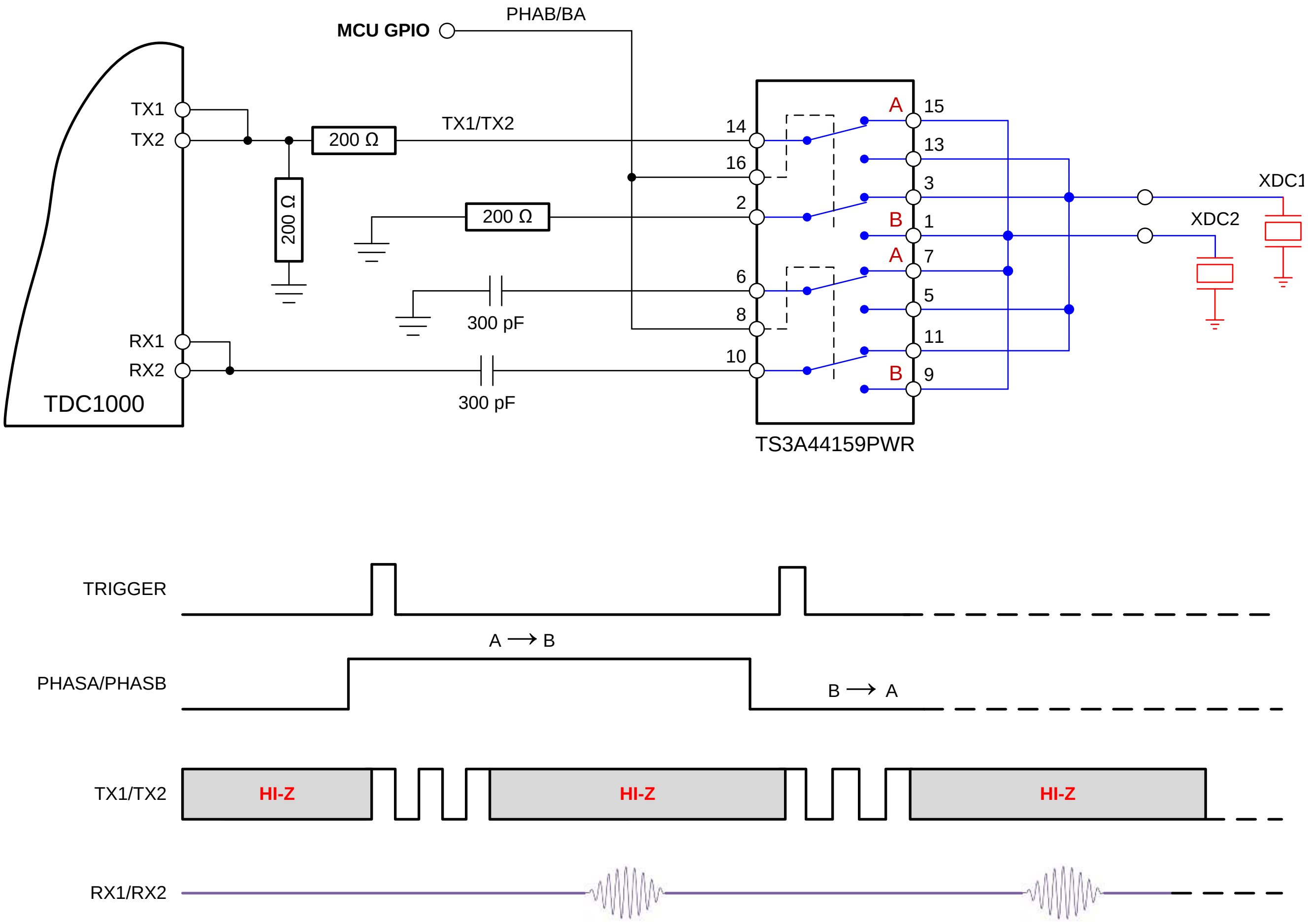

Figure 9. TDC1000 Sensor Interfacing Circuit

7 Conclusion

Ultrasonic flow meters are gaining wide usage in commercial, industrial and medical applications due to their low power consumption, low maintenance, and high accuracy. In this application note you learned how Texas Instruments's TDC1000 and TDC7200 are utilized to make ultrasonic flow metering easy while still meeting the system requirements. In addition to this application note, there are videos, an application widget, EVMs, and additional application notes to assist you with your ultrasonic needs. Links to some of these items are listed below and can be found collectively at http://www.ti.com/ultrasonic.

1. TDC1000-TDC7200EVM: http://www.ti.com/tool/tdc1000-tdc7200evm
2. How to Design with Ultrasonic Sensing - SNAA220: http://www.ti.com/lit/an/snaa220/snaa220.pdf

Appendix A

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Flow Meter Transducers and Standards

A.1 Ultrasonic Flow Meter Transducer Manufacturers

Table 1. Ultrasonic Flow Transducer Manufacturers

APPLICATION	MANUFACTURER	SENSOR/TRANSDUCER PART NUMBER	F_{RES} (HZ)
Heat/water	AudioWell	Brass Pipe For Heat meter DN25. Ultrasonic flow sensor AW5Y0980K04L193Z	1000
Heat/water	AudioWell	Brass Pipe For Heat meter DN20. Ultrasonic flow sensor AW5Y0980K08L151Z	1000
Water flow	Shenzhen Dianyingpu Technology Co.,Ltd	DYP-UL006	1000
Water flow	ZHEJIANG JIAKANG ELECTRONICS CO., LTD.	PSC1.0M020100H2AD0-B0	1000
Water flow	Shenzen Yujie Elect. Co	http://www.szyujie.com/en/products.asp?typeID=324125898 HJ-2112.1M	1000
Gas flow	Hopesound Ceramics		
Gas flow	SECO SC125	SC125	200
Gas flow	Morgan	09204-00	200
Gas flow	Fuji Ceramics	FUS-200A	200
Water flow	Morgan Ceramics	09262/000	1000
Gas flow	Morgan Ceramics	09204-00	200

A.2 Water Flow Meter Standards for Legal Metrology Applications

Water meter approvals such as provided by BS 5728 (United Kingdom), EN14154 and EEC (European Union), and AWWA (American Water Works Associations) were implemented to unify independent country requirements under one approval certification process. It became evident that an international standard was needed, hence, ISO 4046 was implemented, and then the International Organization of Legal Metrology was established (OIML). OIML R49 was legally adopted for metering of cold water, and represents a combination of features from BS 5728, ISO 4064, EN 14154 and many other standards. There are about fifty member states of OIML around the world, adopting the metering requirements established by the OIML R49 test requirements.

The United States follows OIML, and also AWWA standards.

A.2.1 Nomenclature

There are some differences between flow rate symbols of OIML and ISO. The flow rate error tolerance curve for ISO has four key points, Qmin, Qt, QN and Qmax. OIML similarly has four key points, Q1, Q2, Q3 and Q4, but the two ranges are not directly comparable.

In summary, the following in Section A.2.1.1 applies.

A.2.1.1 ISO Nomenclature

- Qmin = Minimum Flow
- Qt = Transitional Flow
- QN = Nominal (Average) Flow
- Qmax = Maximum Flow

Table 2 provides an example of accuracy requirements for a class C water meter.

Table 2. Example of the Accuracy Requirements for Water Flow Application

MEASUREMENT	CLASS C REQUIREMENT
Minimum flow (Qmin)	15 l/h
Transition flow (Qt)	22.5 l/h
Maximum flow (Qmax)	3000.0 l/h
Accuracy	Qmin ≤ Q ≤ Qt ± 5%
	Qt < Q ≤ Qmax ± 2%

A.2.1.2 OIML Nomenclature

Q1 = Minimum Flow. Q1= Q3/(Q3/Q1) where (Q3/Q1) has a value of either 250, 200 or 160.

Q2 = Transitional Flow. Q2 = Q1 + 60% or Q2/Q1 = 1.6.

Q3 = Selected from a defined specified list as shown in OIML R49-1 3.1.3.

Q4 = Maximum Flow. Q4 = Q3 + 25% or Q4/Q3 = 1.25.

The above is a guide to switching between ISO and OIML nomenclatures.

Revision History

DATE	REVISION	NOTES
April 2015	*	Initial release.

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