Application Report
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# Ultrasonic Sensing Basics for Liquid Level Sensing, Flow Sensing, and Fluid Identification Applications

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## ABSTRACT

The need for accurate and reliable sensors is growing in so many markets around the world, such as industrial and manufacturing, automotive, medical, energy, and smart grid applications. The designers and end-users of these sensors are counting on newer technologies that use less power and deliver higher accuracy -- technologies that will eliminate moving parts and allow sensing in remote locations and in less-than-ideal conditions.

One of the most effective areas of sensor technology is ultrasonic, the science that measures the time interval between an ultrasonic signal that is sent and received, or what is commonly referred to as "time-of-flight" (TOF). TI is leveraging its ultrasonic expertise to deliver new signal conditioning solutions to fluid level sensing, fluid identification, flow metering, and distance sensing customers with its latest products (TDC1000 and TDC7200) based on time-to-digital converters (TDCs).

This application note provides an introduction to how Texas Instruments Ultrasonic Sensing solutions (TDC1000 and TDC7200) can be applied to popular applications such as liquid level sensing, flow sensing, and fluid identification.

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## 1 General Theory of How Ultrasonic Sensing Works

For single transducer in fluid level, fluid identification, and distance applications, the TDC1000 AFE excites the sensor and detects the echo once it returns, as shown in Figure 1. The AFE excites the transducer by hitting it with a series of pulses and with frequencies in the range of kHz to MHz. The TDC1000 allows a maximum number of 31 pulses to excite the sensor, and its frequency can have a range from 31.25 kHz to 4 MHz.

The excitation of the sensor is marked with a START pulse, while the echo is denoted with a STOP pulse. The difference in time between START and STOP time-of-flight (TOF) indicates the fluid level, fluid ID/concentration, and distance.

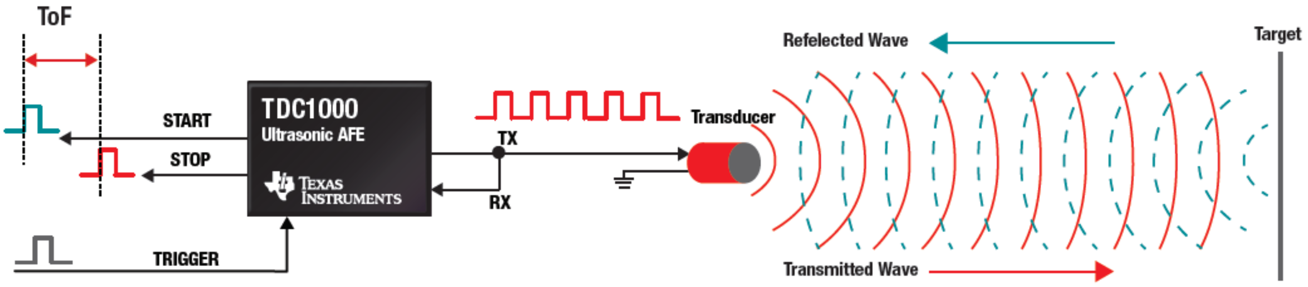


Figure 1. How Ultrasonic Works for Single Transducer Measurement

For dual transducers applications such as flow meter (Figure 2), the TDC1000 AFE utilizes the transducers in a pitch-and-catch fashion. In this method, transducer A is excited by the TDC1000 while transducer B acts as a receiver to generate STOP pulses. The time-of-flight (TOFAB) between excitation and STOP pulses indicates the distance between the transducers. A differential ToF, $\text{TOF}_{AB} - \text{TOF}_{BA}$, needs to be done to find the flow of medium (water or gas) between the two transducers.

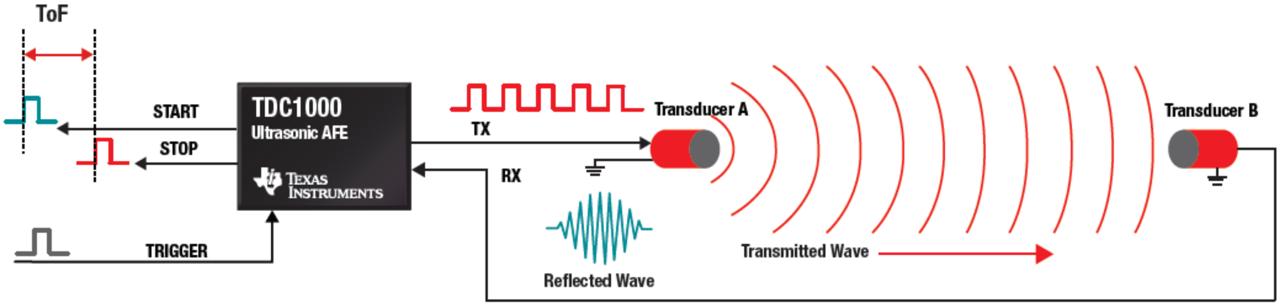


Figure 2. How Ultrasonic Works for Dual Transducer Measurement

Further information on how ultrasonic is used in fluid level sensing, fluid identification, flow metering, and distance sensing applications will be discussed in the next sections.

## 2 TDC1000: Ultrasonic Analog-Front-End and TDC7200: Time-to-Digital Converter

TI's TDC1000 (Figure 3) is an analog-front-end IC that drives ultrasonic transducers in sensing applications. As the first ultrasonic sensing AFE from TI, the TDC1000 offers a number of key features and benefits, including very low sleeping power and programmable modes that enable the lowest power solutions, boosting battery life for flow meter applications. Along with a companion device, TI's TDC7200 time-to-digital converter (Figure 4), the solution offers high levels of accuracy in the picosecond range for zero and low-flow.

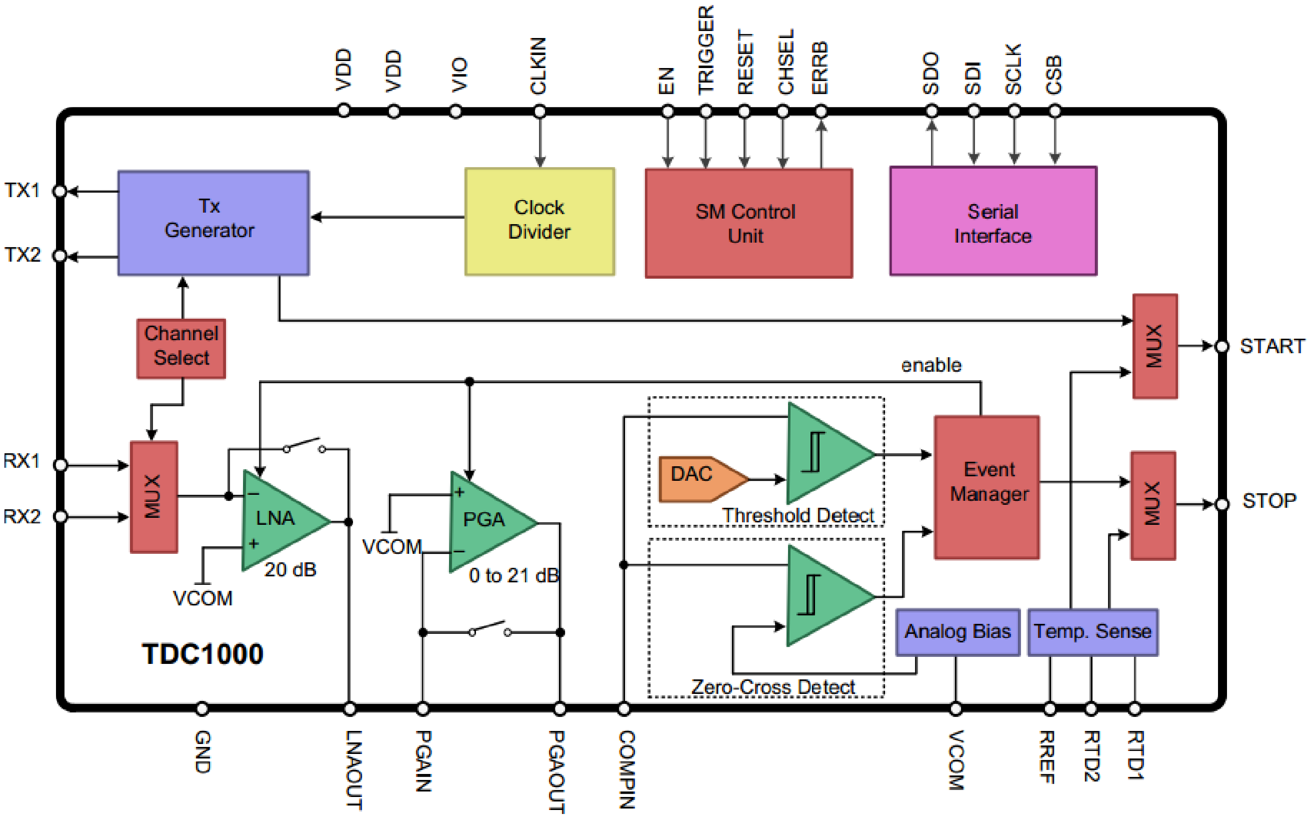


Figure 3. TDC1000 Block Diagram

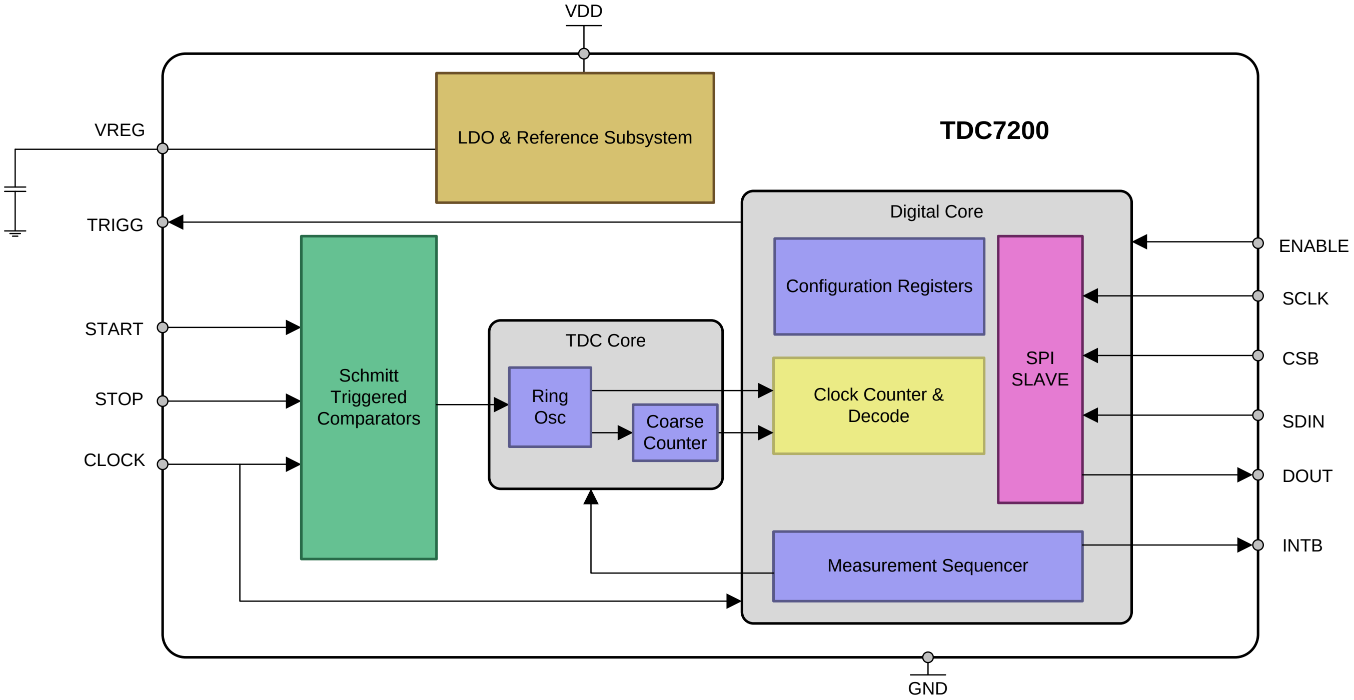


**Figure 4. TDC7200 Block Diagram**

The TDC1000 gives you flexibility in programming, for multiple transmit pulses, signal thresholds, and gain, to accommodate multiple applications and systems, and varying tank or pipe sizes. And one of the most valuable features that TI provides you is the complete system solution. The TI Designs library gives you complete reference designs that include AFE, TDC, MCU, wireless, power, and source code for easy-to-implement measurement and sensing solutions. One of the TI Designs for ultrasonic is the TIDA-00322, an automotive fluid level/quality measurement using ultrasonic.

## 3 Application No. 1: Fluid Level

The TDC1000 is ideal for many sensing applications, and some of the most common involve managing fluids. Figure 5 shows a diagram for detecting fluid level in a container. Ultrasonic sensors are mounted on the bottom or top of the tank to determine the level of the fluid.

The TDC1000, ultrasonic AFE, excites the non-intrusive transducer with 1 to 31 pulses. The sensor continuously transmits pulses of high frequencies (typically 1 MHz) into the fluid. Then the TDC1000 reports the time-of-flight (TOF) that the wave takes to transmit to the liquid surface, and reflect back to the sensor. Referencing the speed of sound in the fluid and using the equation TOF = (2* fluid level) / (fluid speed of sound), the exact distance of the liquid surface from the sensor can be calculated with high accuracy.

For example, assume that the transducer is mounted at the bottom of a water tank, and the TDC1000 reports a TOF of 1 ms. Knowing that the speed of sound through water is approximately 1480 m/s at 25°C, the fluid level can be calculated as:

$$\text{TOF} = (2 * \text{fluid level}) / (\text{fluid speed of sound}) \tag{1}$$

$$\text{Fluid level} = (\text{TOF} * \text{fluid speed of sound}) / 2 \tag{2}$$

$$\text{Fluid level} = (1\text{ms} * 1480\text{ m/s}) / 2 \tag{3}$$

$$\text{Fluid level} = 0.74\text{m} \tag{4}$$

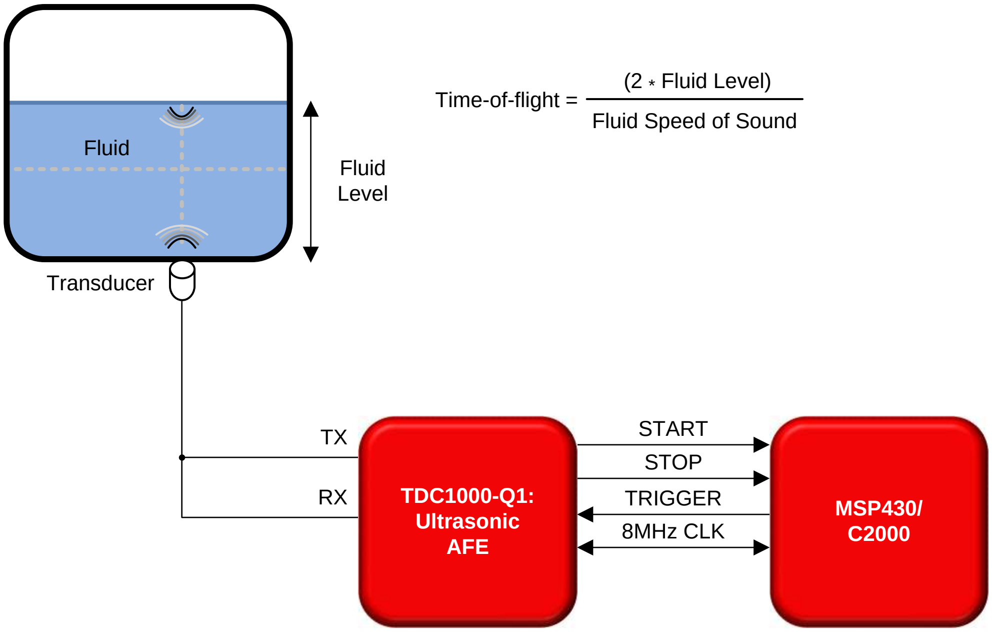


Figure 5. Fluid Level Measurement Using Ultrasonic

For more information on how to select or mount ultrasonic transducers to the outside of a tank, see Application Note: *How to Select and Mount Transducers in Ultrasonic Sensing for Level Sensing*, SNAA266. In addition to this application note, there are videos, application notes, and other design tools available at http://www.ti.com/ultrasonic.

## 4 Application No. 2: Fluid Identification / Concentration

Now, let's add to that level application, and see how fluid identification (ID) works. Fluid ID is the same as fluid level detection, except that the sensor is typically mounted on the side of the tank, as shown in Figure 6.

Again, the TDC1000 excites the sensor, and then it reports the time the wave takes to transmit and reflect back. Since the exact distance is known, and time-of-flight (TOF) is measured, the speed of sound through the fluid can be calculated, and checked against a look-up-table to identify the fluid.

For example, assume the distance of the tank is 0.1m and TDC1000 reports a TOF of 134µs, we can calculate the fluid speed of sound as:

$$\text{TOF} = (2*\text{distance})/\ (\text{fluid speed of sound}) \tag{5}$$

$$\text{Fluid speed of sound} = (2*\text{distance})\ /\ (\text{TOF}) \tag{6}$$

$$\text{Fluid speed of sound} = (2*0.1\ \text{m})\ /\ (134\ \mu\text{s}) \tag{7}$$

$$\text{Fluid speed of sound} = 1490\ \text{m/s} \tag{8}$$

Using a look-up-table and knowing that the temperature is approximately 25°C, we can figure out that the unknown liquid inside the tank is oil.

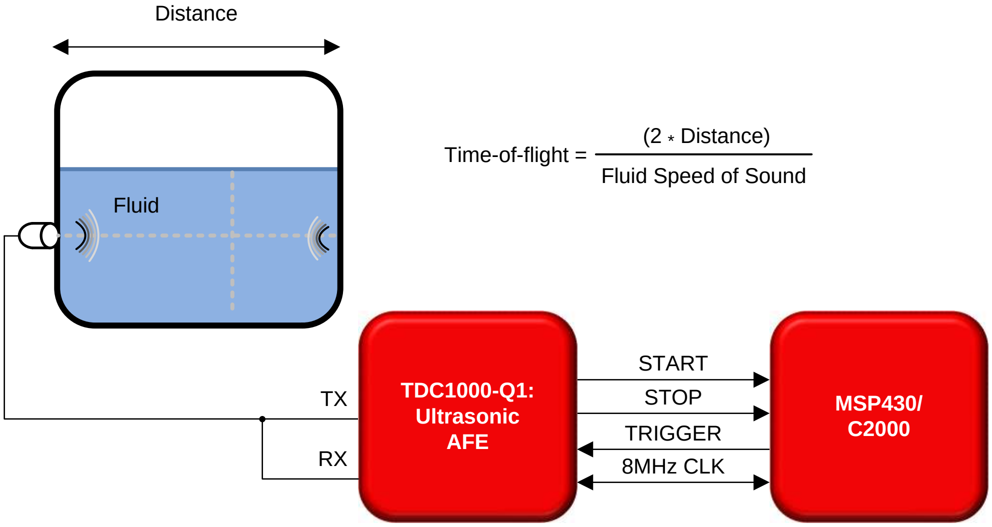


**Figure 6. Fluid Identification / Concentration Using Ultrasonic**

For more information on performing Fluid Identification or determining Liquid Contamination, see Application Note: *Ultrasonic Sensing for Fluid Identification and Contamination*, SNAA265. In addition to this application note, there are videos, application notes, and other design tools available at http://www.ti.com/ultrasonic.

## 5 Application No. 3: Flow Meter

Another key application – especially in the energy market – is flow metering. For this application, the transducers can be mounted non-intrusively side-by-side (Figure 7), or at opposite angles.

The TDC1000 excites both sensors, and reports the difference of the transit time propagating in – and against – flow direction. Transducer A operates as a transmitter during the upstream cycle and as a receiver during the downstream cycle, and transducer B operates as a receiver during the upstream cycle and as a transmitter during the downstream cycle. An ultrasonic flow meter operates by alternating transmit and receive cycles between the pair of transducers and accurately measuring the time-of-flight (TOF) of both directions.

Accuracy is very important for zero flow measurements, and thus, picosecond time capture is critical. For this reason, the TDC7200 time-to-digital converter is introduced as a stop watch device. Other applications that do not require picosecond accuracy can just use an MCU as the time-to-digital converter.

For example, assume the following parameters are known:

- Diameter of the pipe D = 5 cm
- Length between the transducers = 10 cm
- TDC1000 reports a time-of-flight from transducer A to B ($TOF_{AB}$) as 101.3512 µs
- TDC1000 reports a time-of-flight from transducer A to B ($TOF_{AB}$) as 101.3515 µs
- Water speed of sound c = 1480 m/s at 25°C

We can calculate the velocity of the water through the pipe using the following equations:

$$TOF_{AB} = \frac{\left(\frac{D}{2}\right) + L + \left(\frac{D}{2}\right)}{\text{Water speed of sound} + (\text{flow rate})} = \frac{D + L}{c + v} \tag{9}$$

$$TOF_{BA} = \frac{\left(\frac{D}{2}\right) + L + \left(\frac{D}{2}\right)}{\text{Water speed of sound} - (\text{flow rate})} = \frac{D + L}{c + v} \tag{10}$$

$$\Delta TOF = (TOF_{BA}) - (TOF_{AB}) \tag{11}$$

$$v = \frac{\Delta TOF \times c^2}{2 \times (D + L)} \tag{12}$$

$$v = \frac{(101.3515\ \mu s - 101.3512\ \mu s) \times \left(1480 \frac{m}{s}\right)^2}{2 \times (0.05\ m + 0.1\ m)} \tag{13}$$

$$v = \text{flow rate} = 2.1904\ \text{mm/sec} \tag{14}$$

We can convert this velocity to liter per hour (l/h) using the following equations:

$$\text{Flow rate}\left(\frac{l}{h}\right) = \left(\text{flow rate} \frac{m}{sec}\right) \times \left(\frac{3600\ \text{second}}{\text{hour}}\right) \times \left(\pi \left(\frac{D}{2}\right)^2\right)\left(\frac{1\,\text{liter}}{10^{-3} m^3}\right) \tag{15}$$

$$\text{Flow rate}\left(\frac{l}{h}\right) = \left(2.1904 \times 10^{-3} \frac{m}{sec}\right) \times \left(\frac{3600\ \text{second}}{\text{hour}}\right) \times \left(\pi \left(\frac{0.05}{2}\right)^2\right)\left(\frac{1\,\text{liter}}{10^{-3} m^3}\right) \tag{16}$$

$$\text{Flow rate}\left(\frac{l}{h}\right) = 15.5 \frac{\text{liter}}{\text{hour}} \tag{17}$$

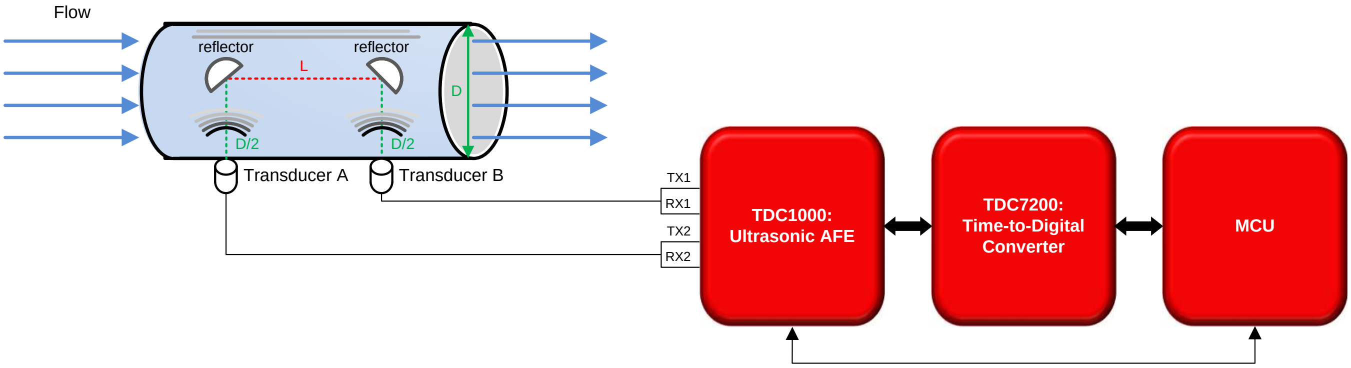


Figure 7. Flow Meter Using Ultrasonic

For more information on Water Flow Sensing, see Application Note: *Ultrasonic Sensing for Water Flow Meters and Heat Meters*, SNIA020. In addition to this application note, there are videos, application notes, and other design tools available at http://www.ti.com/ultrasonic.

## 6 Application No. 4: Distance/Proximity Sensing

Figure 8 shows one more example of ultrasonic sensing that's very popular - proximity and distance sensing. The concept for this application is the same as fluid level detection, but now we are measuring in air instead of fluid.

For this application space, there are two devices from Texas Instruments to consider. The operating principles of each device (TDC1000 and PGA450) are similar but each has its unique advantages. In short, the TDC1000 is best for detecting objects at shorter distances with higher levels of accuracy (better than 1cm) while the PGA450 is excellent for detecting objects with cm accuracy at multiple meters. Again, the TDC1000 and PGA450 AFEs excite the sensor, which then transmits high frequencies – typically 40 kHz - into air. The transmitted wave hits the target object, then returns to the sensor, and the TDC1000 then reports this time-of-flight, and distance can be calculated.

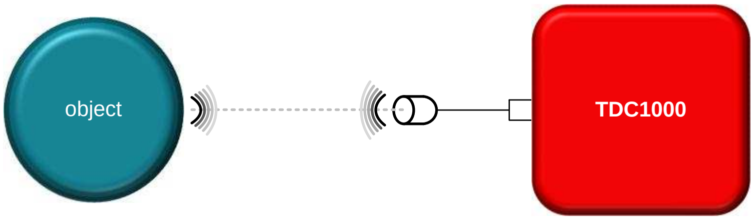
For example, assume the TDC1000 reports a TOF of 2 ms, and knowing that the speed of sound through air at 25°C is approximately 346 m/s, the distance of the object can be calculated as:

$$\text{TOF} = (2\text{*distance})/\ (\text{air speed of sound}) \tag{18}$$

$$\text{Distance} = (\text{TOF} * \text{air speed of sound}) / 2 \tag{19}$$

$$\text{Distance} = (2\text{ms} * 346\text{ m/s}) / 2 \tag{20}$$

$$\text{Distance} = 0.346\text{ m} \tag{21}$$



$$\text{Time-of-flight} = \frac{(2 * \text{Distance})}{\text{Air Speed of Sound}}$$

Figure 8. Proximity/Distance Sensing Using Ultrasonic

## 7 Conclusion

Fluid level sensing, fluid identification, flow metering, and distance sensing are just some of the applications where the TDC family and other technology from TI can bring you the complete flexible solution with high accuracy and far less power consumption in sensor solutions. See http://www.ti.com/product/tdc1000 and http://www.ti.com/ultrasonic for product information, including reference designs, evaluation modules, online design tools, and other resources from TI.

# Revision History

**Changes from Original (March 2015) to A Revision** **Page**

- Added paragraph to the *ABSTRACT* section, *"This application note provides an introduction..."*.......................... 1
- Moved and renamed Section 2 *How Ultrasonic Works* To: Section 1 *General Theory of How Ultrasonic Sensing Works*. 2
- Added text and URL link "*For more information...*" following Figure 5 .................................................... 5
- Added text and URL link "*For more information...*" following Figure 6 .................................................... 6
- Added text and URL link "*For more information...*" following Figure 7 .................................................... 8
- Added URL link to the ultrasonic web page in Section 7 ........................................................................ 8

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