Application Report
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Ultrasonic Sensing Basics

Mubina Toa, Akeem Whitehead

ABSTRACT

Ultrasonic sensors use sound waves above the 20 kHz range to detect objects in proximity, similar to how bats use echolocation to maneuver without colliding into obstacles. In the automotive space, ultrasonic sensors are prevalent for ADAS (Advanced Driver-Assistant Systems) applications, specifically for parking assist where 4–16 sensors are used to detect obstacles when parking a vehicle. In the industrial space, ultrasonic sensors are used in robotics and other applications that require reliable presence, proximity, or position sensing. This application report discusses what ultrasonic time-of-flight sensing is, as well as system considerations and what additional factors affect ultrasonic sensing.

Contents

Trademarks

1 What is Ultrasonic Time-of-Flight Sensing?

This section discusses the physics of sound waves and the benefits of using ultrasonic sensors in a variety of applications.

1.1 Principles of Ultrasound

Ultrasonic sensors can measure distance and detect the presence of an object without making physical contact. They do so by producing and monitoring an ultrasonic echo. Depending on the sensor and object properties, the effective range in air is between a few centimeters up to several meters. The ultrasonic sensor (or transducer) generates and emits ultrasonic pulses that are reflected back towards the sensor by an object that is within the field of view of the sensor.

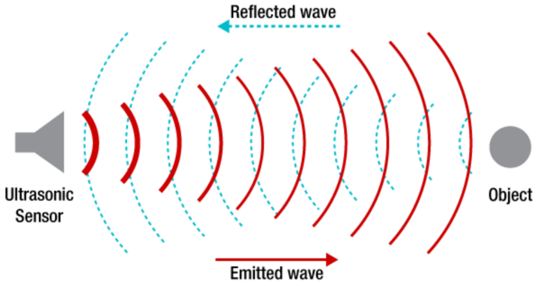


Figure 1. Ultrasonic Time-of-Flight Measurement

The ultrasonic sensor is a piezoelectric transducer, which is able to convert an electrical signal into mechanical vibrations, and mechanical vibrations into an electrical signal. Therefore, in a monostatic approach, the ultrasonic sensor is a transceiver which operates as both a speaker and microphone at a single frequency.

The sensor is able to capture the difference in time between the emitted and received echo. Because the speed of sound is a known variable, the captured round-trip time can be used to calculate the distance between the sensor and object. Equation 1 shows the Ultrasonic Distance Calculation.

$$d_{OneWay} = \frac{t_{RoundTrip} \times V_{Sound}}{2} \tag{1}$$

This method of ultrasonic sensing is a time-of-flight measurement based on the propagation time of sound. Note that the velocity of sound through air varies by temperature. In dry air at 20°C (68°F), the speed of sound is 343 m/s, or a kilometer in 2.91 s. For more information on the relationship between the velocity of sound and temperature, see Section 3.4.

1.2 Why Use Ultrasonic Sensing?

Ultrasonic sensors can detect a variety of materials, regardless of shape, transparency, or color. The only requirement for ultrasonic sensing is that the target material is a solid or liquid. This enables contactless detection of:

- Metal
- Plastic
- Glass
- Wood
- Rocks
- Sand
- Oil
- Water
- Other hard, non-sound absorbent materials

These materials are able to reflect sound back towards the sensor through the air. Certain objects can be more difficult to detect, like angled surfaces that direct the echo away from the sensor, or permeable targets like sponge, foam, and soft clothing. These absorb more reflected ultrasonic energy.

1.3 How Does Ultrasound Compare to Other Sensing Technologies?

Infrared (IR) sensors can be used for obstacle detection because of their high resolution, low cost, and fast response times. However, IR sensors require knowledge of the surface properties prior to implementation due to their non-linear characteristics and dependence on reflectance properties. Various surface materials reflect and absorb IR energy differently, so target material identification is required for accurate distance measurements.

Optical-based sensing technologies have a similar principle to ultrasonic technology. Instead of using sound waves, however, optical technology uses LEDs to emit light waves and detect the time-of-flight, which can then convert based on the speed of light principle. The speed of light is much faster than the speed of sound, therefore optical-based sensing is faster than ultrasonic. It does have limitations in bright ambient lighting conditions and smoky or foggy environments, however, as these environments make it difficult for the light receptor to detect the emitted light. Optical sensing also has limitations in detecting clear materials like glass or water. Light passes through these materials, whereas ultrasonic bounces off.

Radar and LIDAR-based technologies aim to provide a multi-point array of data, instead of a single time-of-flight measurement. This allows for highly accurate data points and the ability to map out and distinguish tiny moments within the environment. However, the increased functionality makes these systems much more expensive than the other solutions mentioned previously.

Table 1 summarizes differences between PIR, ultrasonic, optical ToF, and mmWave.

Table 1. Proximity Sensing Technology Comparison

	Passive Infrared	**Ultrasonic**	**Optical ToF**	**mmWave**
Detection Range	0.1 to 5 m	0.1 to 10 m	0.01 to 20 m	0.01 to 100+ m
Resolution	Few cm	Few mm (transducer dependent)	Few mm (optics dependent)	Few mm (range dependent)
Field of View	Up to 180°	5° to 120°	0.15° to 120°	5° to 160°
Current Consumption	<5 mA	72 mW to 336 mW (active) 2-9 mW (standby/sleep)	100 µW to 200 mW (active) ~ 80 µW (standby/sleep)	0.5 W to 1.5 W
Solution / Module Size	Medium	Medium	Small	Large
Aesthetics	Requires lens to achieve range and wide field of view	Exposure to medium for longer range	Hidden behind dark glass	Penetrates most materials (not metal)
Measuring Medium Speed	Infrared light (emitted by object)	Sound	Light	Light
Single Sensor System Cost (US$)	< $1	$1 - $3	$1.5 - $4	$18 - $26
Key Differentiation	• Limited performance in high heat environments and corner regions • Insensitive to slow motion • Prone to false positives	• Effectively detect solid and transparent glass surfaces • Able to detect objects in a smoke/gas-filled environment	• Target localization (up to 3 zones of detection) • Precise long-range measurements	• Provides range, velocity, and angle data • Can penetrate non-metal materials • Intelligent object differentiation

To view TI's full proximity sensing table, refer to TI's proximity sensing technology infographic.

1.4 Typical Ultrasonic-Sensing Applications

There are three types of ultrasonic-sensing applications:

- **Ranging Measurement:** Periodically records the distance of one or more objects moving to or from the sensor within each time-of-flight transaction. The rate at which the distance updates is dependent on how long the sensor waits in the echo-listen mode. The longer the sensor waits for the echo, the further the detectable range.

  Examples: Ultrasonic park assist sensors, obstacle avoidance sensors in robotics, level transmitters

Further reading: *Ultrasonic Terrain-Type and Obstacle Detection for Robotic Lawn Mowers* tech note (SLAA910).

- **Proximity Detection:** A significant change to the ultrasonic echo signature corresponds to a physical change to the sensing environment. This binary approach of ultrasonic sensing is less dependent on range, and more dependent on echo signature stability.

  Examples: Cliff and edge detection in robots, object detection, vehicle detection in parking space, security, and surveillance systems

  Further reading: *Using Ultrasonic Technology for Smart Parking and Garage Gate Systems* tech note (SLAA911).

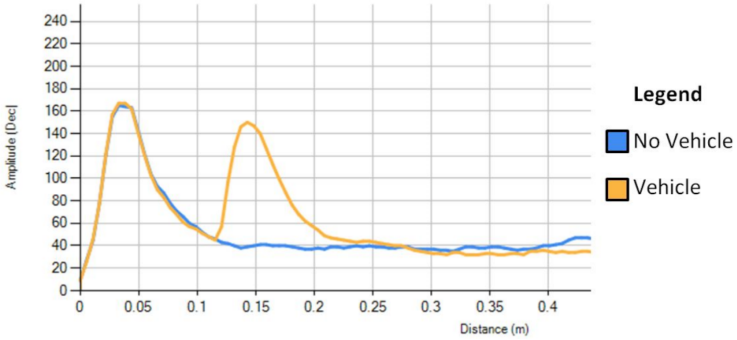


Figure 2. Echo Response for Vehicle Presence

- **Surface Type Detection:** Using raw ultrasonic echo data, and not the time-of-flight measurement, material softness and hardness can be indirectly measured with ultrasonic measurements. Ultrasonic sound waves bounce off harder surfaces towards the transducer with fewer losses, which provides a stronger echo response in return. Softer objects, like foam and carpet, absorb many of the sound waves and provide a weaker echo response.

  Examples: Floor type detection in vacuum robots, terrain type detection in robotic lawn mowers

  Further reading: *Ultrasonic Floor-Type and Cliff Detection on Automated Vacuum Robots* tech note (SLAA909).

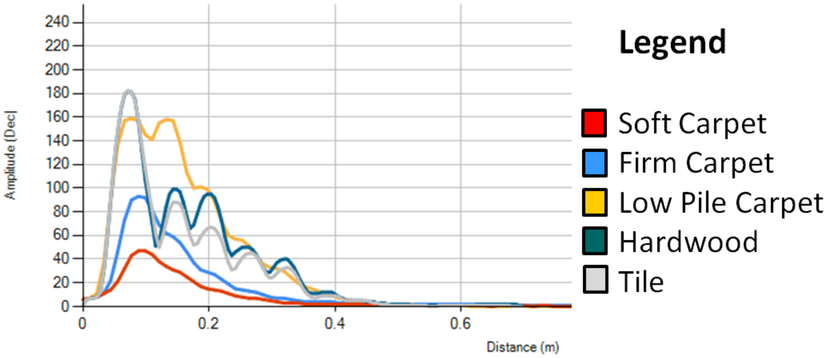


Figure 3. Ultrasonic Surface Type Detection

2 Ultrasonic System Considerations

The ultrasonic system consists of the:

- Transducers or ultrasonic sensors
- Analog Front End (AFE) to drive the transmitter and condition the received signal
- Analog-to-digital converter (ADC)
- Additional signal processing capabilities to add intelligence to the measured data

The analog front end portion is responsible for driving the transducer, as well as amplifying and filtering the received echo data to make it ready for further processing. Signal processing is either fully done by the control unit in discrete and AFE solutions, or shared between the control unit and the integrated DSP in the ASSP solution with its in-chip intelligence.

2.1 Introduction to the Ultrasonic System

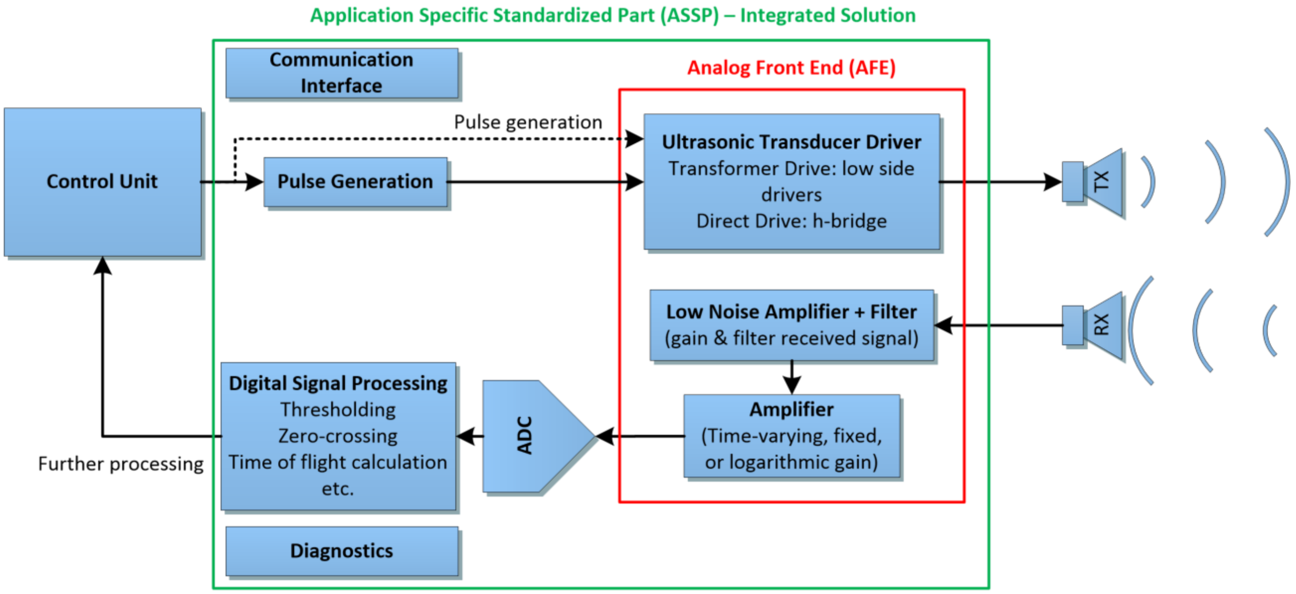


Figure 4. Ultrasonic System Level Block Diagram

Ultrasonic systems can:

- Be fully discrete (composed of amplifiers, filters, diodes, and other passive components)
- Be an integrated AFE
- Be an Application Specific Standardized Part (ASSP) with some signal processing capabilities on chip
- Be fully integrated with an MCU on-chip

Note that transducer selection is a key factor in the overall performance of the ultrasonic module. The rest of this section discusses how to choose a transducer based on its type, topology, and frequency, as well as what optimization techniques can be used to achieve better performance.

For TI's list of recommended transducers compatible with TI ultrasonic devices, download the *PGA460 Transformer and Transducer Listings* zip file.

2.2 The Ultrasonic Echo and Signal Processing

TI recommends to drive transducers with a sine or square wave at their center frequency to achieve the best results. Most integrated solutions have an output driver consisting of low-side drivers to drive a transformer in a transformer-drive situation, or FETs in an h-bridge configuration for a direct drive solution.

After the transducer sends out an echo at its resonant frequency, the system must then listen for return echoes which are a result of an object in the transducer's field of view. Ultrasonic systems typically filter the return echo to remove noise and gain the signal up before it goes to an ADC. Some ways to gain the ultrasonic system are as follows:

- **Digital Gain / Fixed Gain:** apply a fixed gain to the entire ultrasonic echo.
- **Time-Varying-Gain:** apply a gain that is dependent on how far out an object is. Often, objects that are further out in time produce a weaker echo response and objects that are closer produce a stronger echo response. To combat this, to prevent saturation of the close signals, and to be able to identify the further objects, one may choose to gain their system such that a small gain is applied early in time, and a larger gain is applied further out in time. This gives the user flexibility to configure their gain

based on their system requirements.

- **Automatic Gain Control / Logarithmic Amplifier:** a logarithmic amplifier approach is a way to achieve automatic gain control when dealing with input signals that are both high and low in amplitude. A log amp gains an input signal based on the log scale which helps get a stronger echo response from weak signals while also appropriately gaining the strong signals but preventing saturation, similar to the time-varying-gain approach. Whereas the time-varying-gain method is dependent on where an object is in time, the logarithmic amplifier is dependent on the actual echo of the input signal itself with no dependency on time.

Designers can check the zero-crossing frequency data to verify that the return echo is that of the transducer. This can also be used to detect doppler-shifts, which is the change in frequency of the emitted sound wave, to detect motion and its direction.

Once the return signal has been filtered and gained appropriately, the data can be sent to the ADC for further signal processing. Figure 5 shows the signal from the ADC output.

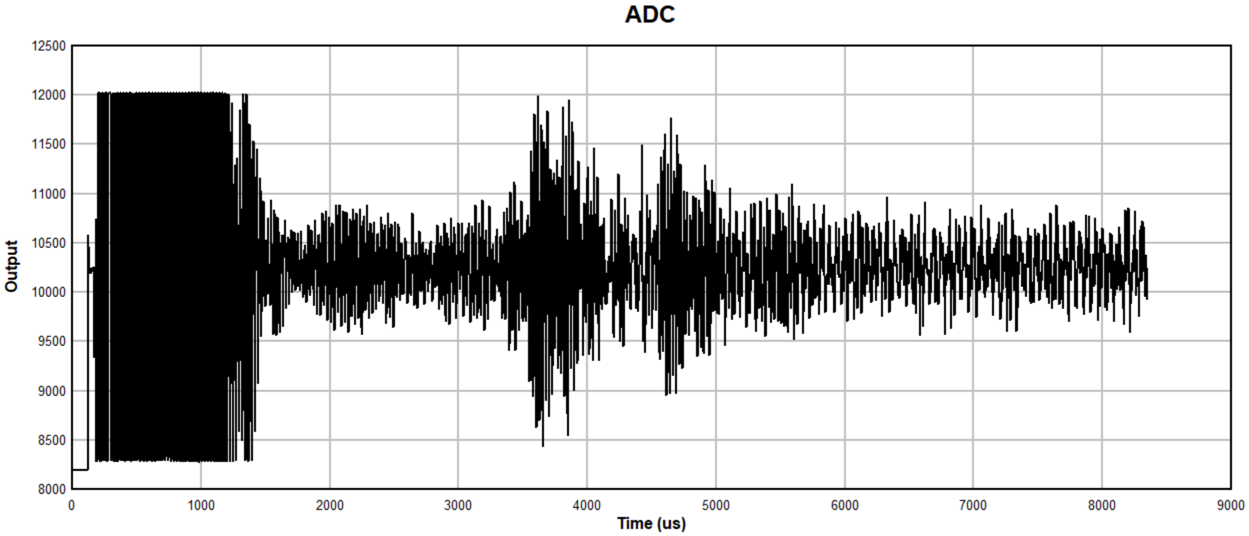


Figure 5. Typical Output From ADC

After the signal is digitized, it is ready to go to a digital signal processor (DSP) or an MCU for further processing. First, it goes through a bandpass filter to reduce any out-of-band noise.

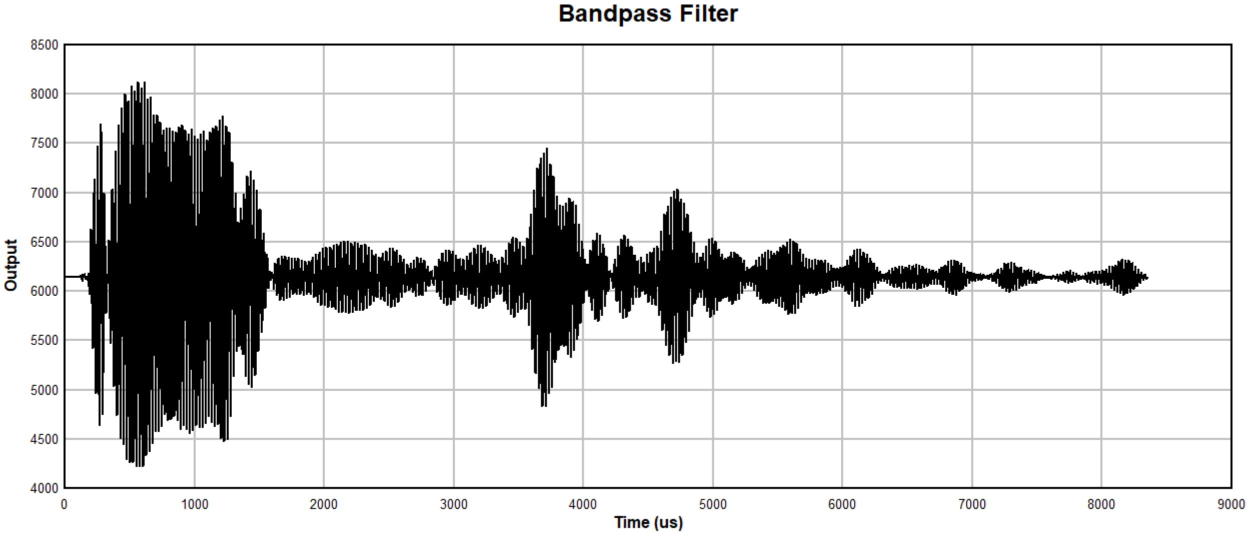


Figure 6. Typical Output From Bandpass Filter

The next stage is to rectify the signal to extract the absolute value of the signal as shown in Figure 7.

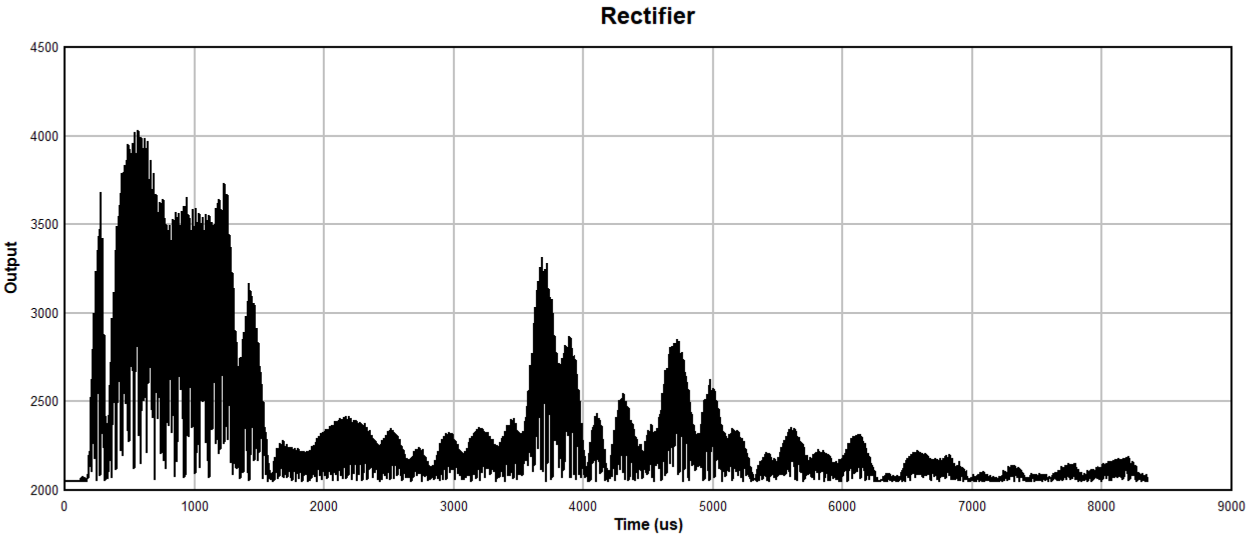


Figure 7. Typical Output From Rectifier

After rectification, there is often a peak hold in place before a low-pass filter is applied to ensure the peak amplitude of the rectified signal is not filtered out. Together with the peak hold and low-pass filter, a demodulated output can be produced as shown in Figure 8. This makes it easy to apply thresholds to further customize the signal to eliminate noise and extract time-of-flight data and echo width and amplitude information. The demodulated signal is also referred to as an envelope signal.

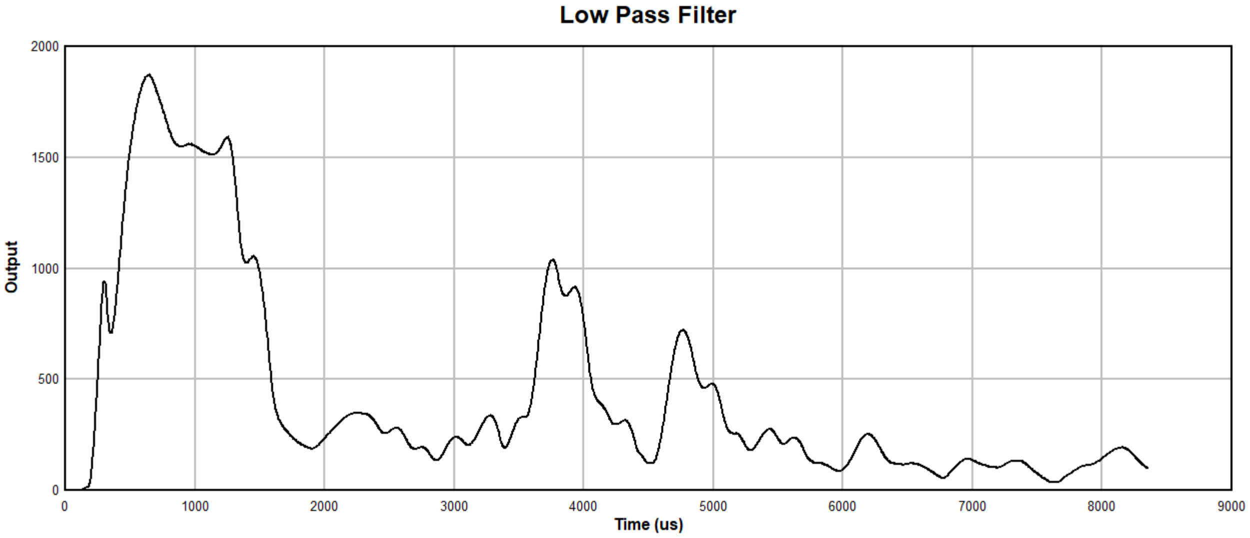


Figure 8. Typical Output From Low-Pass Filter

2.3 Transducer Types

Transducers come in two types: closed-top and open-top. Although open-top transducers are lower cost, and require a smaller driving voltage to achieve maximum Sound Pressure Level (SPL), they are unreliable in harsh environments. Exposure to rain, dust, and other contaminants will damage the sensor.

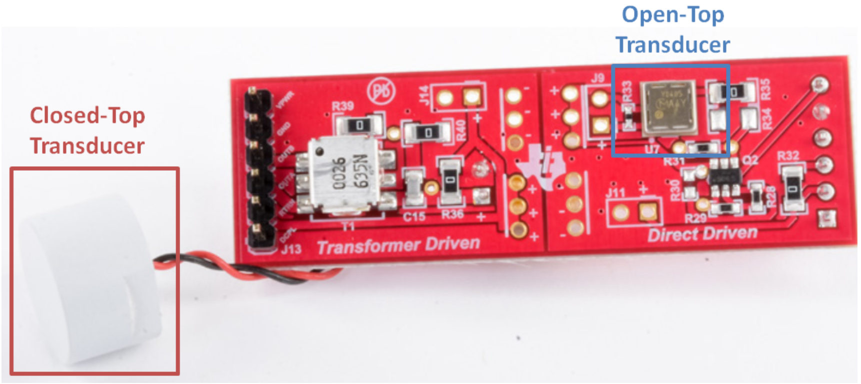


Figure 9. Closed-Top and Open-Top Transducers (From PGA460EVM)

2.4 Transducer Topologies

Two transducer topologies are available: monostatic or bistatic. Topology must be based on the short range requirement.

Monostatic topology is when a single transducer both transmits an echo and listens for returning echoes. This is the lower-cost method preferred in most applications. The drawback of the monostatic transducer topology is that the excitation ringing-decay of the sensor creates a blind zone that limits the minimum detection range. In a monostatic configuration, this blind zone can be reduced by adding a damping resistor. More information can be found in Section 2.6.

To eliminate this ringing decay, a bistatic topology must be used where there are two separate transducers — one for transmitting and one for receiving. The drawback to using the bistatic approach is that additional calibration required, as the designer must consider the angle of the incoming echo at the receiver when computing the time-of-flight calculation.

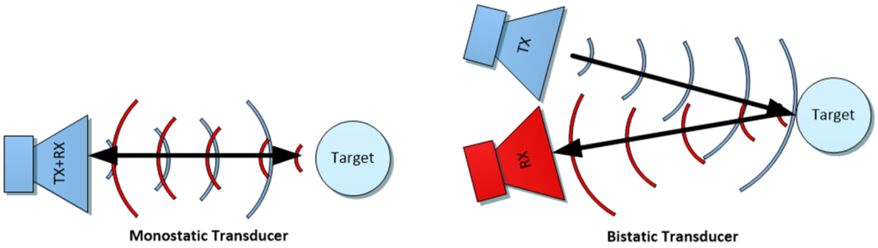


Figure 10. Monostatic vs Bistatic Configuration

2.5 Transducer Frequencies

Ultrasonic transducers operate at frequencies in the range of 30–500 kHz for air-coupled applications. As the ultrasonic frequency increases, the rate of attenuation increases. Thus, low-frequency sensors (30–80 kHz) are more effective for long range, while high-frequency sensors are more effective for short range. Higher frequency sensors (80–500 kHz) also reduce the ringing-decay, which allows for a shorter minimum detection range. For liquid level sensing, transducers in the 1-MHz range are often used. For more information on liquid level sensing using ultrasonic technology, read *Ultrasonic Sensing Basics for Liquid Level Sensing* application report (SNAA220).

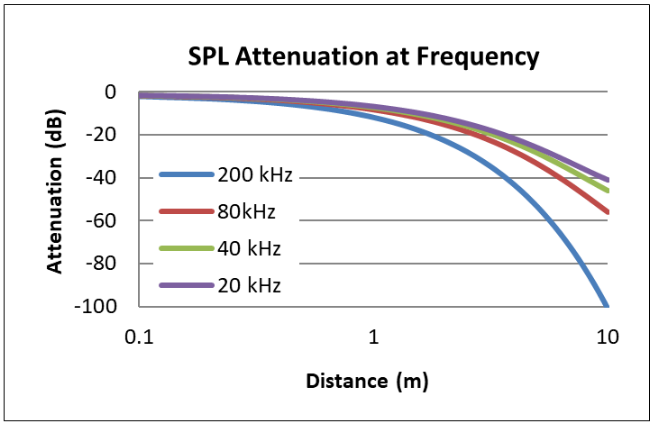


Figure 11. Correlation of Distance Measured and Frequency

The relationship between frequency, resolution, directivity, attenuation, and distance can be observed with the following relation:

↑ Frequency :: ↑ Resolution :: ↑ Narrower Directivity :: ↑ Attenuation :: ↓ Distance

Transducers can have narrow (15°) to wide field of views (180°). The higher the frequency, the narrower the field of view. A narrow field of view using a low-frequency transducer can also be achieved by adding a "horn" around the transducer to direct its echoes into a more narrow pattern.

2.6 Transducer Drive (Transformer Drive & Direct Drive) and Current Limit

There are two ways to drive a transducer: in transformer mode or in direct drive mode. This is determined based on the maximum drive voltage (thus a higher current limit) of the selected transducer. Although direct drive is the lower-cost driving technique, it is typically intended for short range, open-top applications. Transformer drive maximizes closed-top transducer requirements (beyond 100 Vpp), but it also requires additional calibration at mass production. Figure 12 shows the non-linear relationship between transducer (XDCR) drive voltage, and the percent of the sound pressure level that is transmitted. Note that blindspot lengths increase with higher current limits.

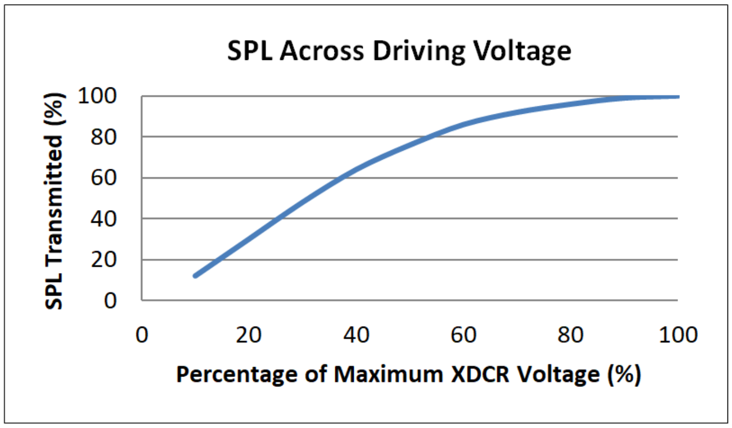


Figure 12. SPL Across Driving Voltage

2.7 Pulse Count

Pulse count is another parameter in the ultrasonic-sensing system. It is defined by the number of pulses emitted by the transducer. The larger the pulse count, the larger the SPL will be, but the minimum detection range will be less optimal as the transducer is bursting for a longer period of time.

2.8 Minimum Detection Range

The minimum detection range of ultrasonic systems is determined by the properties of the transducer itself and the way it is pulsed. The blindspot, or transducer ringing-decay time, is caused by the resonant energy oscillating at the base of the transducer in a monostatic configuration (that is, one that both transmits and receives). Higher frequency transducers have smaller ringing-decay times, thus reducing the minimum range. Using this approach, however, will reduce the sensing range. Using a bistatic approach can eliminate this ringing behavior, as this setup isolates the sending and receiving transducers, but it will be double the cost of a monostatic solution.

Another way to reduce the blindspot is by lowering the pulse count and lowering the current limit. This may reduce the strength of the echo that is returned, however.

If a low-frequency, monostatic setup must be used, and if lowering the pulse count and current limit decrease the integrity of the received echo, additional passive components may be introduced to reduce the blindspot. A damping resistor in the range of 500 Ω to 25 kΩ may be added in parallel to the transducer to reduce the ringing-decay time.

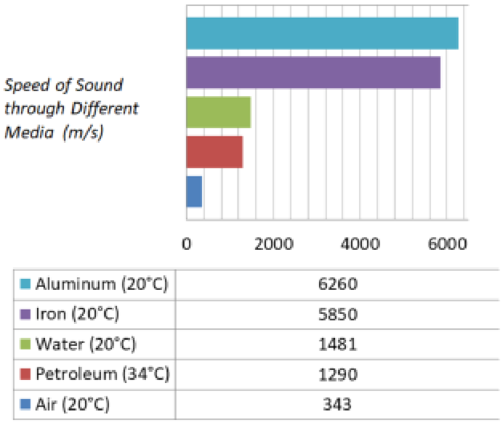
For more information on how to optimize the ultrasonic setup, see the *PGA460 Ultrasonic Module Hardware and Software Optimization* application report (SLAA732).

3 What Factors Influence Ultrasonic Sensing?

Sound waves at a frequency of 20 kHz or greater are referred to as ultrasonic because this frequency range is inaudible to humans.

3.1 Transmission Medium

Transmission properties, and the speed of sound, change across different mediums. An ultrasonic sensor is optimized for sound wave propagation through air, liquids, or solids, but rarely for more than one type of transmission medium. Ultrasonic attenuation in the air increases as a function of frequency, so air-coupled ultrasonic applications are limited to frequencies below 500 kHz. Liquid and solid applications can use transducers in the low MHz range for high-accuracy applications.



🟦 Aluminum (20°C)	6260
🟪 Iron (20°C)	5850
🟩 Water (20°C)	1481
🟥 Petroleum (34°C)	1290
🟦 Air (20°C)	343

Figure 13. Speed of Sound Through Different Media

3.2 Acoustic Impedance

Sound waves can travel through various types of medium to detect objects with significant acoustic impedance mismatch. Acoustic impedance (Z) is defined as a product of density and acoustic velocity. Air has much lower acoustic impedance compared to most liquids or solids.

Table 2. Acoustic Impedances of Target Materials

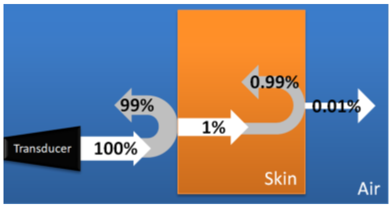
Material	Density $\left(\mathrm{kgm}^{-3}\right)$ (2)	Acoustic Velocity $\left(\mathrm{ms}^{-1}\right)$ (3)	Acoustic Impedance $\left(\mathrm{kgm}^{-2}\mathrm{s}^{-1} \times 10^{6}\right)$ (4)
Air	1.3	330	.00429
Water	1000	1450	1.45
Muscle	1075	1590	1.70
Aluminum	2700	6320	17.1
Iron	7700	5900	45.43
Steel	7800	5900	46.02
Gold	19320	3240	62.6
Skin	1109	1540	1.6

The difference in acoustic impedance (Z) between two objects is defined as impedance mismatch (see Equation 5). The greater the impedance mismatch, the greater percentage of energy is reflected at the boundary between the two mediums.

$$\text{Reflection Coefficient} = R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \tag{5}$$

Example 1: Air and skin:

Figure 14. Reflection Coefficients for Skin and Air Boundaries



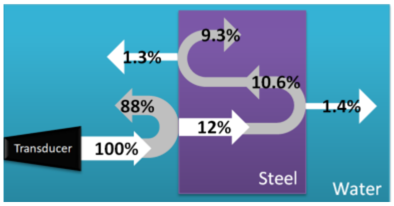
The acoustic impedance of air is .00429 and the acoustic impedance of skin is 1.6. Putting these values in the reflection coefficient yields Equation 6:

$$\left(\frac{Z_{Skin} - Z_{Air}}{Z_{Skin} + Z_{Air}}\right)^2 = \left(\frac{1.6 - 0.00429}{1.6 + 0.00429}\right)^2 = 0.99 \tag{6}$$

Performing this calculation at every boundary dictates how much energy is reflected back, how much is absorbed within the material, and how much is permeated through.

Example 2: Water and steel:

Figure 15. Reflection Coefficients for Water and Steel Boundaries



Similarly, for liquid-based detection, a water and steel boundary reflects back 88% of the transmitted echo using the same equation (Equation 6).

3.3 Radar Cross Section

Radar cross section is how well a target is able to reflect ultrasonic waves back to the transducer. Curved objects or tilted objects may scatter the majority of ultrasonic waves transmitted towards the object, which provides a weak echo response. Surfaces that yield the strongest echo response when facing the sensor are:

- Large
- Dense
- Flat
- Smooth

Objects that meet these criteria, like a wall or floor, yield the best responses. Small objects, or objects that partially deflect sound (like people, animals, or plants), will reduce the sensing response. A flat object should face the sensor at a 90° angle, when possible, to maximize sensing response. Round or rigid surfaces enable larger angular deviations. Figure 16 shows the reflected ultrasonic wave from the surface of a target based on the target's shape.

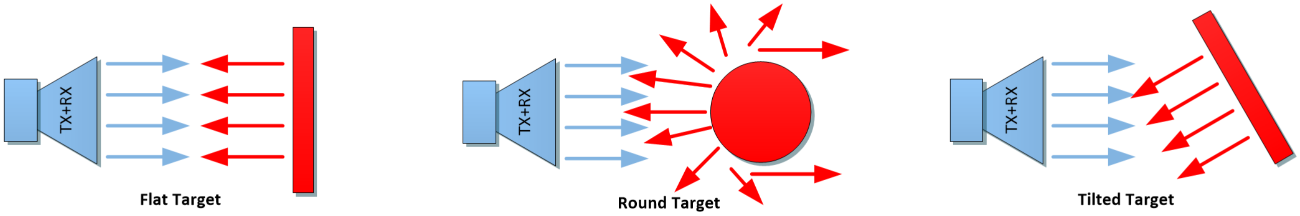


Figure 16. Ultrasonic Echoes Based on Target Shape

Equation 7 defines the radar cross section of a target (σ):

$$\sigma = \text{Projected cross section} \times \text{Reflectivity} \times \text{Directivity} \tag{7}$$

3.4 Ambient Conditions (Temperature, Humidity, Debris)

The velocity of an air-coupled ultrasonic echo is influenced by external environmental parameters, such as temperature, humidity, and in-band ambient noise. The sensing range decreases as either temperature increases. Although the sensing rate also decreases as humidity increases, this can often be neglected, as the effects are minimal. The rate of attenuation across temperature and humidity is non-linear.

$$V_{Sound} = 331\frac{m}{s} + \left(0.6\frac{m}{s°C} \times \text{Temperature}\ (°C)\right) \tag{8}$$

Airborne debris such as dust, rain, or snow can weaken the ultrasonic energy and alter the field-of-view of the sensor. The performance of a closed-face transducer is not affected by minor dust or dirt deposits. However, if the sensor is partially submerged in water, or covered in mud, snow, or ice, ranging performance will diminish.

4 Device Selection

It is important to choose an ultrasonic solution based on the system where it will reside. Table 3 shows TI's ultrasonic-sensing products:

Table 3. Device Selection

	TDC1011 / TDC1000	**TUSS4470**	**TUSS4440**	**PGA460**
Device type	Analog front-end	Analog front-end	Analog front-end	Analog front-end + digital signal processor (integrated)
Supported transducer frequencies	31.25 kHz – 4 MHz	40 kHz – 1 MHz 40 – 440 kHz (pre-drive)	40 – 400 kHz	30 – 80 kHz & 180 – 480 kHz

Table 3. Device Selection (continued)

	TDC1011 / TDC1000	TUSS4470	TUSS4440	PGA460
Channel count	TDC1011: 1 Channel TDC1000: 2 Channel	1 Channel	1 Channel	1 Channel
Drive topology	Direct drive (max 5V)	- Direct drive (max 36 V) - Pre-drive	Transformer drive	- Transformer drive - Direct drive with added FETs
Gain stage	Fixed gain (20 to 41 dB)	86 dB logarithmic amplifier	86 dB logarithmic amplifier	6 point time-varying gain (32 to 90 dB)
Outputs	- Zero crossing - Echo start and stop pulse	- Analog echo envelope - Zero crossing - Envelope threshold detect	- Analog echo envelope - Zero crossing - Envelope threshold detect	- DSP processed output (time-of-flight, amplitude, width) - Echo data dump (down-sampled echo envelope) - Raw digital data path (ADC, bandpass filter, rectifier, lowpass filter)
Temperature sensor	Interface to RTD	No	No	On-chip temperature sensor
Diagnostics	None	SPI diagnostics	SPI diagnostics	- System diagnostics (frequency, decay, excitation voltage) - Supply diagnostics (overvoltage)
Automotive qualified device	TDC1011-Q1 TDC1000-Q1	N/A	N/A	PGA460-Q1
Output interface	SPI	- SPI for programming - Analog output	- SPI for programming - Analog output	- USART (UART + SPI) - OWU - TCI

For more information, visit ti.com/ultrasonic.

5 Additional Resources

- BOOSTXL-PGA460 product page
- Texas Instruments, *Ultrasonic Sensing with the PGA460-Q1* training video
- Texas Instruments, *PGA460 Frequently Asked Questions (FAQ) and EVM Troubleshooting Guide* application report (SLAA733)
- Texas Instruments, *PGA460 Ultrasonic Module Hardware and Software Optimization* application report (SLAA732)
- Texas Instruments, *PGA460 Transformer and Transducer Listings* zip file (SLAC787)

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from B Revision (January 2020) to C Revision	Page
• Changed the *Ultrasonic System Level Block Diagram*	5

Changes from A Revision (October 2019) to B Revision	Page
• Changed Table 3	12

Changes from Original (September 2019) to A Revision	Page
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