

PGA460 Ultrasonic Module Hardware and Software Optimization



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ABSTRACT

This document introduces all of the necessary design and environmental considerations when developing and optimizing an ultrasonic sensor module using the PGA460. Ultrasonic modules behave differently across various temperatures, transmission mediums, targets, and transducers types. Building the module, therefore, requires an understanding of the different ultrasonic components available for pairing, and a feasibility analysis of how external factors will impact the minimum and maximum detectable range. The PGA460 device can accommodate a variety of use-cases, and is able to provide feedback to compensate or retune the system for potential variation.

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1 Trademarks

All trademarks are the property of their respective owners.

2 Overview

The Texas Instruments PGA460 ultrasonic sensor signal conditioner acts as the driving source and receiving amplifier for the accompanying ultrasonic transducer. An ultrasonic module, therefore, does not perform uniformly across all application types because effectiveness of the ultrasonic module is primarily dependent on the characteristics of the transducer and external factors. This application report discusses how to best select the required components, including the transducer type, driving mode, and passive tuning components. After hardware selection, this document provides the procedure to configure the PGA460 settings based on the performance requirements of the application.

3 External Performance Factors

Several external factors determine the overall performance of the performance of the ultrasonic module. These factors include minimum required distance, maximum required distance, target size, target material, target speed, transducer placement, environmental noise, environmental temperature, and environmental stability. Without considering these factors, the user may not be able to detect the intended target with the recommended signal-to-noise (SNR) ratio of 3:1. A large SNR is required to reliably and repeatedly detect a target when using the PGA460-based threshold mapping.

3.1 Range Requirements

Firstly, consider the minimum and maximum range requirements. A common range requirement for air-coupled ultrasonic transducer measurements is, but not limited to, object detection between 30 cm to 8 m. Short-range measurements are a challenge for single-transducer configurations, whereby the transducer acts as both the transmitting and receiving element. Because of the resonant behavior of transducers, residual energy will oscillate within the transducer for a short duration immediately after excitation. This short post-burst duration is referred to as the ringing or decay time. The decay time is based on the equivalent model of the transducer, how long and strongly the transducer is excited, the matched or unmatched resonance frequency of the driver components (based on secondary leakage inductance of the transformer), and resonant frequency offset from the center-frequency of the band-pass filter.

[Section 4.4](#) presents the techniques on external matching network-compensation design for improved short-range performance. The matching network consists of inductive, capacitive, and resistive components, which can be optimized to reduce decay time and improve the minimum distance that can be measured using an ultrasonic sensor. Long-range measurements are less of a concern because the decay profile has typically subsided to the same level as the noise floor at the time of object detection. When using a dual-transducer (bi-static) configuration, which includes a separate transducer dedicated exclusively to transmitting, and another transducer dedicated to receiving, the decay time becomes irrelevant because the receiving transducer is only excited by the returning ultrasonic echo. Dual-transducer configurations are recommended for very short object detection (at nearly 0 cm).

Long-range detection must account for the attenuation of ultrasonic energy as it attenuates through air. The rate of attenuation is primarily dependent on frequency. The relationship of transducer frequency to maximum detectable distance is provided as the following:

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

Ultrasonic energy does not decay linearly across distance. [Figure 3-1](#) shows the attenuation of sound pressure by distance and frequency.

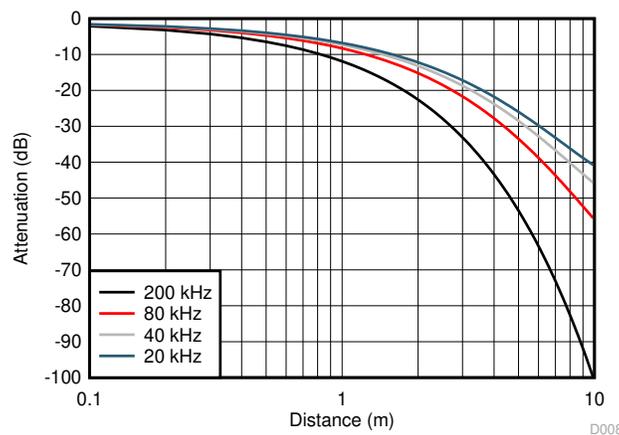


Figure 3-1. Attenuation Characteristics of Sound Pressure by Distance

The benefits of high-frequency transducers include an increase to resolution and focused directivity (forward facing beam pattern), but the disadvantage is the increase to attenuation. The rate at which the ultrasonic energy experiences scattering and absorption while propagating through the medium of air increases with frequency and therefore the decrease in maximum detectable distance.

3.2 Detectable Target and Objects

The type of target from which the ultrasonic echo reflects from will impact the returning echo strength. For example, a large, flat steel wall provides a greater return echo compared to a narrow tree. This difference is because a combination of the acoustic impedance, surface coarseness, orientation, and maximum cross section of the target.

Acoustic impedance is based on the density and acoustic velocity of a given material, and is important to determine the amount of reflection that occurs at the boundary of two materials having different acoustic impedances. The acoustic impedance of air is four orders of magnitude less than that of most liquids or solids; therefore, the majority of ultrasonic energy is reflected to the transducer based on the difference in reflection coefficients. However, lighter materials with low densities or significant amount of air gaps, such as sponge, foams, and loosely woven fabrics, tend to absorb more ultrasonic energy. [Table 3-1](#) shows an example listing of characteristics of various material types as they relate to air-coupled ultrasonic absorption.

Table 3-1. Acoustic Impedance Of Various Materials

Material	Density (kgm ⁻³)	Speed of Sound (ms ⁻¹)	Acoustic Impedance (kgm ⁻² s ⁻¹ x 10 ⁶)
Air	1.3	330	0.000429
Sponge	100	750	0.075
Fat	925	1450	1.38
Water	1000	1450	1.45
Soft tissue	1050	1500	1.58
Muscle	1075	1590	1.70
Aluminum	2700	6320	17.1
Steel	7800	5900	46.02
Iron	7700	5900	45.43
Gold	19320	3240	62.6

A flat or smoother surface results in the strongest reflections, while a coarse or ridged surface causes the ultrasonic echo to scatter in multiple directions, reducing the return strength in the direction of the transducer. The amount of surface area at a right angle to the transducer provides maximum returns. This surface area is defined as the maximum cross section (σ), which measures of the ability of the target to reflect sonar signals in direction of the sonar receiver, in m², and applies to both ultrasonic sonar and radar applications. [Table 3-2](#) provides a description of how the sonar cross section of certain targets impacts performance.

Table 3-2. Sonar Cross Sectional Comparison

Target	Maximum Sonar Cross Section	Advantage	Disadvantage
Sphere	$\sigma_{\max} = \pi \times r^2$	Nonspecular	Lowest RCS for size; radiates isotopically
Cylinder	$\sigma_{\max} = (2 \times \pi \times r \times h^2) / \lambda$	Nonspecular along radial axis	Low RCS for size; specular along axis
Flat rectangular plate	$\sigma_{\max} = (4 \times \pi \times l^2 \times w^2) / \lambda^2$	Largest RCS for size	Specular along both axes; difficult to align

Depending on the target, the sonar cross section can be averaged based on size and orientation to determine the reflected portion of incident power in units of sound pressure. [Table 3-3](#) lists example targets in relation to sonar cross section as they equate to point-like targets to show the effects of target strength.

Table 3-3. Sonar Cross Sectional Comparison

Target	Sonar Cross Section (dB)
Rodent	-20
Human	0
Automobile	20
Truck	25

**Table 3-3. Sonar Cross Sectional Comparison
(continued)**

Target	Sonar Cross Section (dB)
Corner reflector	40

3.3 Ambient Environment

Changes to temperature, humidity, and air pressure influence the speed of sound and the transmission impedance characteristics of the transducer just as a variable parallel load at the transducer would. Temperature has the greatest impact on the performance of ultrasonic sensors. Sound and heat are both forms of kinetic energy, whereby an increase to temperature yields an increase to the rate of molecular vibration. Because of the fluctuation in molecular vibration, sound waves are able to travel from 300 to 400 m/s. Use [Equation 1](#) to calculate the speed of sound in air (v) as a dependency to temperature (T).

$$v = 331 \text{ m/s} + 0.6 \text{ m/s/}^{\circ}\text{C} \times T \quad (1)$$

[Table 3-4](#) shows the speed of sound across temperature.

**Table 3-4. Speed of Sound in Air Across
temperature**

Temperature ($^{\circ}\text{C}$)	Speed of Sound (m/s)
-40	307
-30	313
-20	319
-10	325
0	331
10	337
20	343
30	349
40	355
50	361
60	367
70	373
80	379
90	385
100	391
110	397
120	403

When converting the round-trip time of an ultrasonic time-of-flight based echo, the speed of sound must be considered in order to prevent $\pm 15\text{cm}$ of error to the distance equivalent of the target.

The resonant frequency of the transducer decreases as temperature increases. Therefore, to compensate for the point at which the phase change will occur, the transducer must be driven at an offset frequency, or external passive components must be introduced beyond a certain temperature to retune the resonance towards the nominal frequency. The PGA460 device offers a temperature decoupling mode to introduce additional passives in parallel to the transducer beyond a user-specified temperature.

4 Component Selection

When the environmental considerations have been accounted for, selection of the sonar configuration, ultrasonic transducer type, transducer frequency, and driver mode is required.

4.1 Sonar Configuration

Air-coupled ultrasonic transducers can be used in a wide variety of applications, from automotive park assist and autonomous robotics, to paper counting and room occupancy detection. The most basic approach to ultrasonic measurements is to use a mono-static configuration for linear time-of-flight ranging. This measurement requires a single transducer to serve as both the transmitter and receiver. The mono-static configuration has limitations to the minimum detectable distance because of the ringing-decay time, and limitations to the maximum detectable distance because of the loading-resonant effects of the transformer or driver circuit.

For improvements to both the minimum and maximum range requirement, a bi-static configuration is required to separate the transmit and receive functions to two independent transducers. The bi-static option allows for near 0-cm detection, especially when the receiving transducer is recessed in comparison to the transmitting transducer. For angular orientation, tracking, and triangulation, three or more ultrasonic transducers are required, whereby each transducer is paired with an independent PGA460 device. A single PGA460 device can support the mono-static or bi-static configuration for standalone purposes. Figure 4-1 shows an example of the mono-static and bi-static configurations.

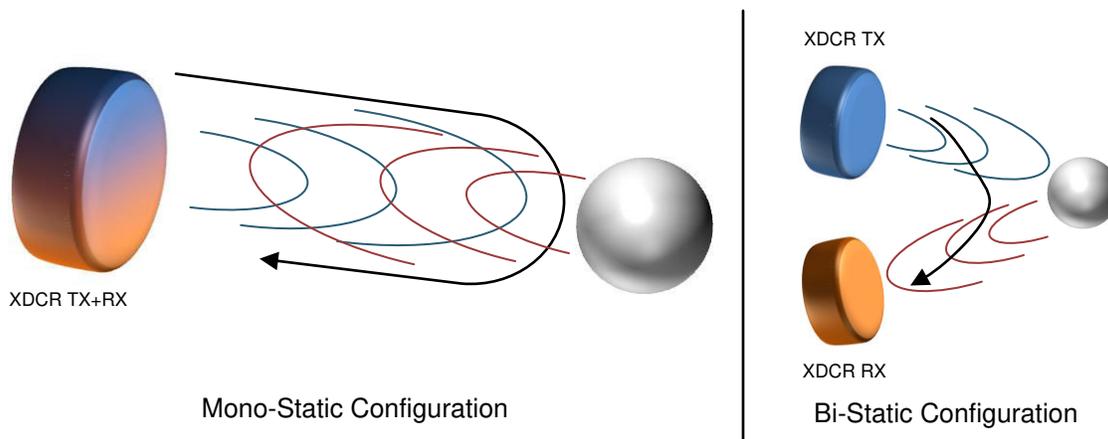


Figure 4-1. Sonar Configurations

4.2 Transducer Selection

Transducer selection initially requires consideration to the operating environment. If the transducer module will be exposed to the outdoors, positioned in an active warehouse or production floor, or is highly mobile, such that water droplets, dirt, or airborne debris are present, a closed-top or closed-face transducer is recommended. Closed-top transducers are typically hermetically sealed to prevent the piezoelectric membrane from being damaged by environmental debris or alien particles, and are able to tolerate a wider temperature range. As a result of the additional protective overhead from closed-top transducers, the piezoelectric membrane must be excited with a sinusoidal voltage averaging 100 V_{PP}. If the protective overhead is not required, and the transducer will be operating in a controlled, indoor environment, open-top transducers are available as an alternative. Open-top transducers offer an increase to driver and receiver sensitivity since the piezoelectric membrane is directly exposed to air, and less acoustic impedance mismatch exists at the face of the transducer. Open-top transducers typically require ten times less in their driving voltage requirement, averaging 10 V_{PP}.

4.3 Driver Selection

Transducers require a sinusoidal or square wave voltage driver to properly excite the piezoelectric membrane for oscillation at the specified resonant frequency. Because the wide variety of air-coupled transducers of the open and closed-top types, maximum drive voltage specifications typically range between 5 V_{PP} to 200 V_{PP}. The driving voltage specification is important to consider when wanting to maximize the amount of sound pressure level (SPL) generated for long-range measurements. SPL is defined as the logarithmic measure of the effective or RMS sound pressure of a sound relative to the threshold of hearing reference value, measured in decibels

(dB). At the maximum driving voltage specification, the amount of SPL a transducer is able to generate is saturated, such that driving a transducer beyond the maximum driving specification will not yield in any additional gains. Figure 4-2 shows the typically relationship between driving voltage and transmittable SPL.

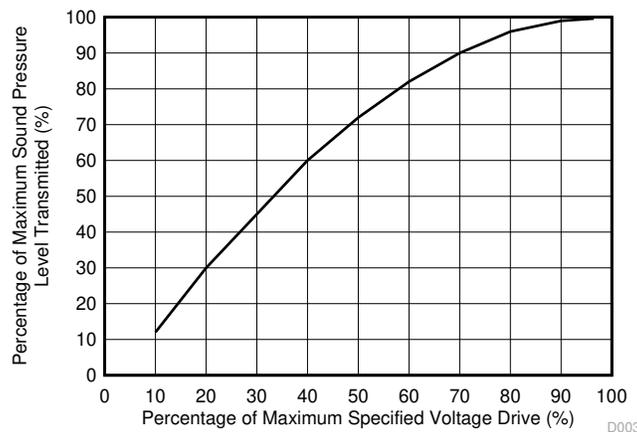


Figure 4-2. Voltage Driver Versus Sound Pressure Level

To generate a large driving voltage averaging 100 V_{PP} for closed-top transducers, a single-ended or center-tap transformer is typically paired with the transducer, such that the primary-to-secondary turns ratio acts as a times ten multiplier. This ratio is a common turns ratio assuming a PGA460 supply voltage of 6 to 18 V DC. The transformer driver mode enables a low-voltage DC reference to be amplified at the secondary as a sinusoidal waveform. If a smaller driving voltage averaging 10 V_{PP} is required for open-top transducers, the transformer can be replaced with a direct driver using either a half-bridge or full-bridge driver configuration. The direct-driver mode allows the PGA460 device and transducer to reference the same supply voltage without the need for any boost circuitry to excite the transducer. The PGA460 device can only use the mono-static configuration in half-bridge mode. The full-bridge mode is only compatible in the bi-static configuration when using the PGA460 device. Closed-top transducers can be direct driven for short to mid-range applications but will not generate the maximum amount of transmittable SPL for long-range applications.

4.4 Passive Tuning

Transducer and transformer modeling must be considered when optimizing the ultrasonic module for short-range measurements to minimize the ringing-decay time of mono-static configurations.

4.4.1 Impedance Gain-Phase Analyzer

An impedance gain-phase analyzer is an instrument that allows a frequency of the transducer to be swept and plotted against impedance (Ω) and phase ($^\circ$). An example instrument is the HP 4194A impedance gain-phase analyzer. The equivalent circuit of the transducer can be extracted using these plots when fitted with a Butterworth-Van Dyke (BVD) model. BVD parameter fitting is a built-in function on some analyzers, or can be fitted using a numerical computing environment such as MATLAB.

The example in Figure 4-3 shows the analyzer plot of a transducer swept from 35 kHz to 70 kHz. The peak in the phase angle (red) indicates the resonant center-frequency of the transducer. The impedance (purple) corresponds to the reactive components or the inductive and capacitive properties of the transducer. At resonance, the current and voltage are in phase, resulting in a 0° phase angle which is observed as the mid-point of the rising impedance slope.

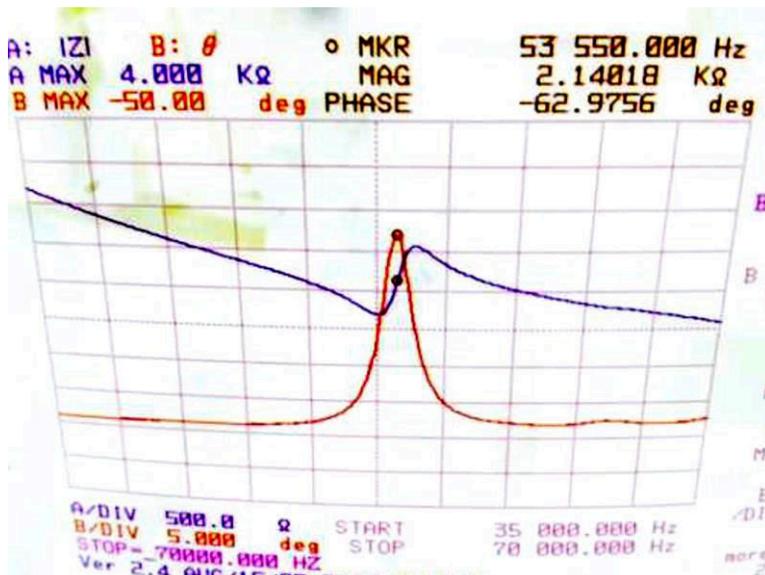


Figure 4-3. Impedance Gain Phase Plot of Transducer Using Analyzer

4.4.2 Tuning Capacitor

When using the transformer driven mode, the equivalent circuit of the transformer introduces additional parasitics. The parasitic characteristic with the greatest performance-impact is the secondary-side leakage inductance (L_{SEC}) of the transformer. The transducer resonates most efficiently at a single frequency. For instance, a 40-kHz transducer cannot be driven at 20, 30, or 50 kHz; any drift from the resonant frequency yields a loss in SPL. When the series inductance is introduced to the transducer, the driving frequency, equivalent BVD model of the transducer, and effective versus expected receiving frequency will be at a mismatch. To match the secondary inductance of the transformer to the resonant frequency of the transducer, a tuning capacitor (C_{TUNE}) is added in parallel to the transducer (see Figure 4-4).

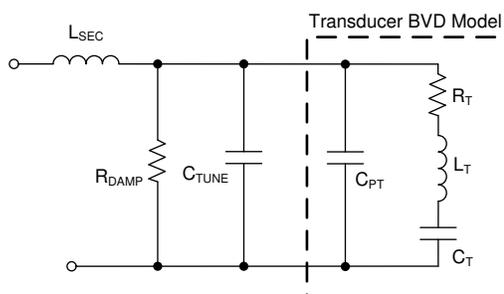


Figure 4-4. Transducer and Transformer Electrical Model With Tuning Components

Use Equation 2 to calculate the value of C_{TUNE} .

$$C_{TUNE} = \frac{C_T \times L_T}{L_{SEC}} - C_{PT} \quad (2)$$

If the tuning capacitor is too large, the attenuation factors increases significantly. Typical values for tuning capacitance ranges from 100 pF to 2000 pF. When driving the transducer in half-bridge configuration and full-bridge, configuration resonance is primarily dependent on the transducer and therefore a tuning capacitor is not required.

4.4.3 Damping Resistor

The damping resistor (R_{DAMP}) is a resistor added in parallel to the transducer to help reduce the ringing-decay time without jeopardizing the driver strength to maximize long-range measurements. A damping resistor can benefit both the transformer driven and bridge driven modes as a bleed-out resistor immediately at post-

excitation. The damping resistor has minute-loading effects on the transducer during the bursting and receive segments and therefore a damping resistor is recommended for any mono-static configuration. Because of the complexity and number of components at the transducer, optimizing the value of R_{DAMP} is currently an arbitrary process of monitoring the decay profile by trial and error. Given that the value of R_{DAMP} ranges from 500 Ω to 25 k Ω , TI recommends to use a potentiometer to sweep and fine-tune the value for the specific sensor, driver, and component combination.

4.4.4 Tunable Transformer

In addition to the appended tuning capacitor, variable coil transformers offer the ability to further tune the secondary-side inductance of the transformer. The tunable transformer can be adjusted by the top notch of the screw-type transformer, which is especially useful for systems that require short-range optimization. To observe the effects of tuning the transformer, the ringing-decay profile or low-noise amplifier output must be monitored. [Figure 4-5](#) shows the ringing-decay profile of a transducer before and after the transformer is tuned for a $-600\text{-}\mu\text{s}$ (+10 cm) improvement.

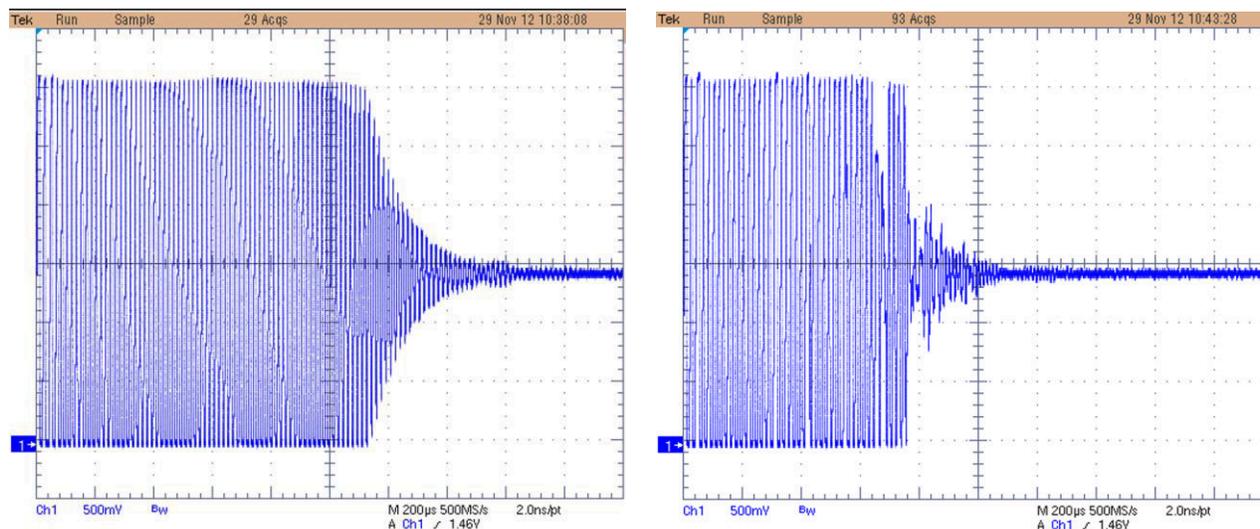


Figure 4-5. Ringing-Decay Time Before and After Tuning of Variable Coil Transformer

5 PGA460 Parameters

Optimization is the most cost efficient and least time consuming when all parameters are controlled by and verified in software. The integration of all key operating parameters of the PGA460 device enables software based performance sweeps and automated module characterization. This section lists the PGA460 registers and parameters from greatest importance to least importance. The ultrasonic module example used for this section assumes the use of a Murata MA58MF14-7N closed-top transducer and EPCOS B78416A2232A003 fixed center-tap transformer at a voltage reference of 12 V DC.

5.1 Center Frequency

Pulse generation is achieved by a burst-control logic circuit with a pulse frequency that can be configured from 30 kHz to 80 kHz in 251 steps, or from 180 kHz to 480 kHz, and is configured by the FREQ bit in the PGA460 EEPROM. Given the 200-Hz step resolution, the optimal resonance frequency can be located if the transducer is swept within its specified range of tolerance.

The example in [Figure 5-1](#) shows how much the returning peak amplitude can vary when execute a burst and listening cycle at each frequency value within a ± 2 -kHz single-increment sweep for the nominally 58.5-kHz transducer. In this example, a frequency of 58.6 kHz produced the best peak result, without extending the decay time.

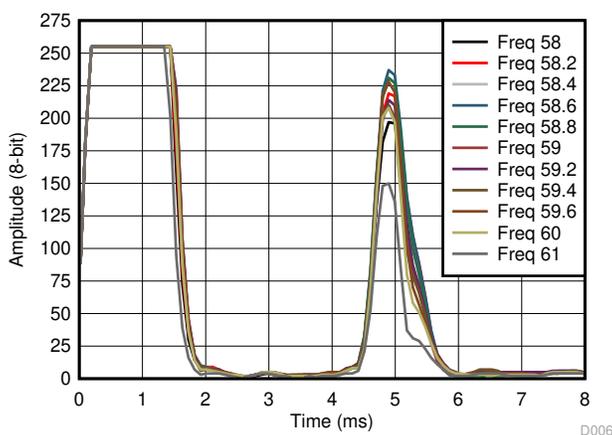


Figure 5-1. Echo Data Dump for Resonant Frequency Sweep of 58.5-kHz Transducer

5.2 Pulse Count

A trade-off exists between a large pulse count and short ringing-decay period. The larger the pulse count value, the longer the transducer excitation length, the more energy is required, and the more time the transducer spends ringing upon release. As a result, detecting short-range objects becomes difficult. However, if short-range detection is not a concern, then optimizing the point of SPL saturation of the transducer will help to preserve energy in the long term. The transducer itself cannot infinitely generate more sound pressure level by exceeding the driving voltage or pulse-count specification. Instead, if the transducer is over-supplied and over-excited, the transducer characteristics can be change and life-cycle can be reduced.

The example in [Figure 5-2](#) shows at which point the SPL of the transducer becomes saturated because of pulse count. For this particular transducer in the example, the peak amplitude did not improve beyond 20 pulses. This transducer should not be pulsed more than twenty times per burst cycle as specified in the data sheet of the transducer.

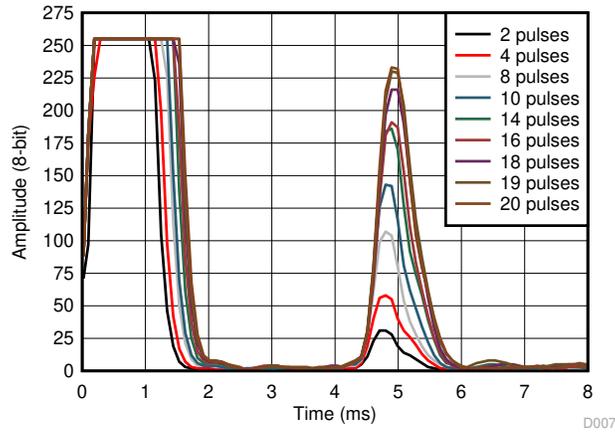


Figure 5-2. Pulse Count Increased from 2 to 20 to Determine Pulse-Count Limit

5.3 Current Limit

A current limit is most relevant for transformer driven modules because a transformer-driven solution typically requires higher drive currents through the primary windings as compared to the bridge-driven mode. However, depending on the transducer paired with the bridge driven solution, the current limit can still have an impact on maximum sound pressure level generated.

The example in [Figure 5-3](#) shows that the transformer-driven solution is very sensitive to the current limit and approaches saturation near the 450 to 500-mA maximum limit offered by the PGA460 device. A smaller current limit also yields a shorter decay time and therefore has the benefit of a median current limit for short-to-mid range evaluation.

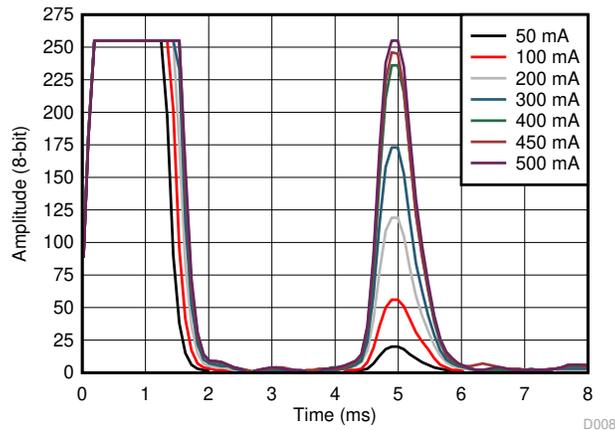
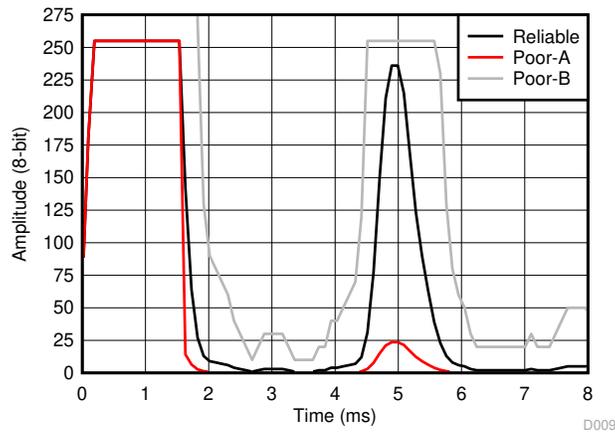


Figure 5-3. Current Limit Increased from 50 mA to 500 mA

5.4 Time-Varying Gain and Digital Gain

The gain features should be implemented in a manner that allows the peak echo to nearly be saturated without truncating the peak. This implementation ensures that the maximum SNR is captured in order to set the threshold timing and levels with the most amount of granularity. The gain features do not necessarily enhance the SNR but rather scale the echo data dump result to size.

The example in [Figure 5-4](#) shows a reliable echo data dump output versus two less favorable outputs.



- RELIABLE** Peak-echo amplitude nearly saturated. Properly scaled SNR of 3:1.
- POOR-A** Echo amplitude too low because time-varying gain is too low and no digital gain is applied.
- POOR-B** Saturated peak clamps the amplitude and effectively reduces the SNR. Also increases decay time.

Figure 5-4. Reliable vs Poor Examples when Using TVG and Digital Gain

The time-varying gain should increase and ramp more aggressively over time to compensate for the attenuation of sound. The digital gain multiplier is intended to help scale mid-to-long range echoes.

5.5 Threshold

Setting the threshold is the most important feature to optimize, such that no false positives or noise transients trigger the device to calculate distance, amplitude, and width of unwanted signals, but also ensure enough margin is provided to ensure worst-case (weak) reflections from targeted objects can be recognized. By default, and for initial evaluation, TI recommends settings the threshold at 50% of the averaged peak of the return echo.

The example in [Figure 5-5](#) shows how the threshold was set for a reliable echo data dump. With the noise floor at a maximum value of 24, and an echo peak at 236, the 50% segment is at 130. The ultrasonic measurement result corresponds to the actual distance calculated and observed on the echo data dump profile.

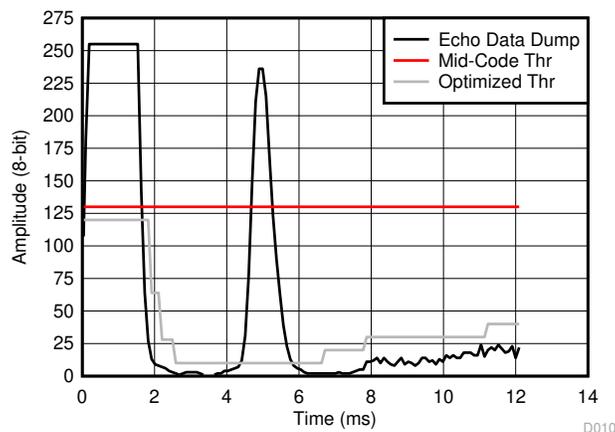


Figure 5-5. Threshold Mapping Around Echo Data Dump

The closer the threshold is set to the base of the echo, the more stable and accurate the result will be; however, this also increases the risk for false positives, unless the noise is known to be steady, controlled, or repeatable.

6 End-of-Line Calibration

The combination of the PGA460, an ultrasonic transducer, and a transformer can vary the performance of the sensor module because of the independent range of tolerance of each element. As a result, the transmitting sound pressure level and receiving sensitivity of each module may not be identical, and performance losses in the detectable minimum and maximum distances is likely to result. To avoid such performance losses, and identify defective modules, functional tests and tuning procedures can be applied to each element.

6.1 Transducer Parameters

For this discussion, calibration of a single transducer will be used as an example, although the techniques also apply to the bi-static configuration.

6.1.1 Optimal Frequency and Sound Pressure Level Measurements

The resonant frequency of the transducer typically has a tolerance of $\pm 5\%$ or ± 2 kHz from the nominal frequency at a given temperature. To measure the resonance frequency of the transducer, two methods are available: PGA460 frequency diagnostics and external microphone measurements.

6.1.1.1 Frequency Diagnostic Feature of PGA460

The PGA460 device offers a feature to measure the ringing-decay frequency of the transducer. The user has the ability to set the start time (FDIAG_START) and window length (FDIAG_LEN) of the frequency measurement to validate the performance and proper tuning of the transducer. In addition, a frequency error feature is implemented in the PGA460 device to signify that the measured transducer frequency is outside of the limits set by the FDIAG_ERR_TH threshold parameter. Both the measured frequency and error status can be read through any of the interface options.

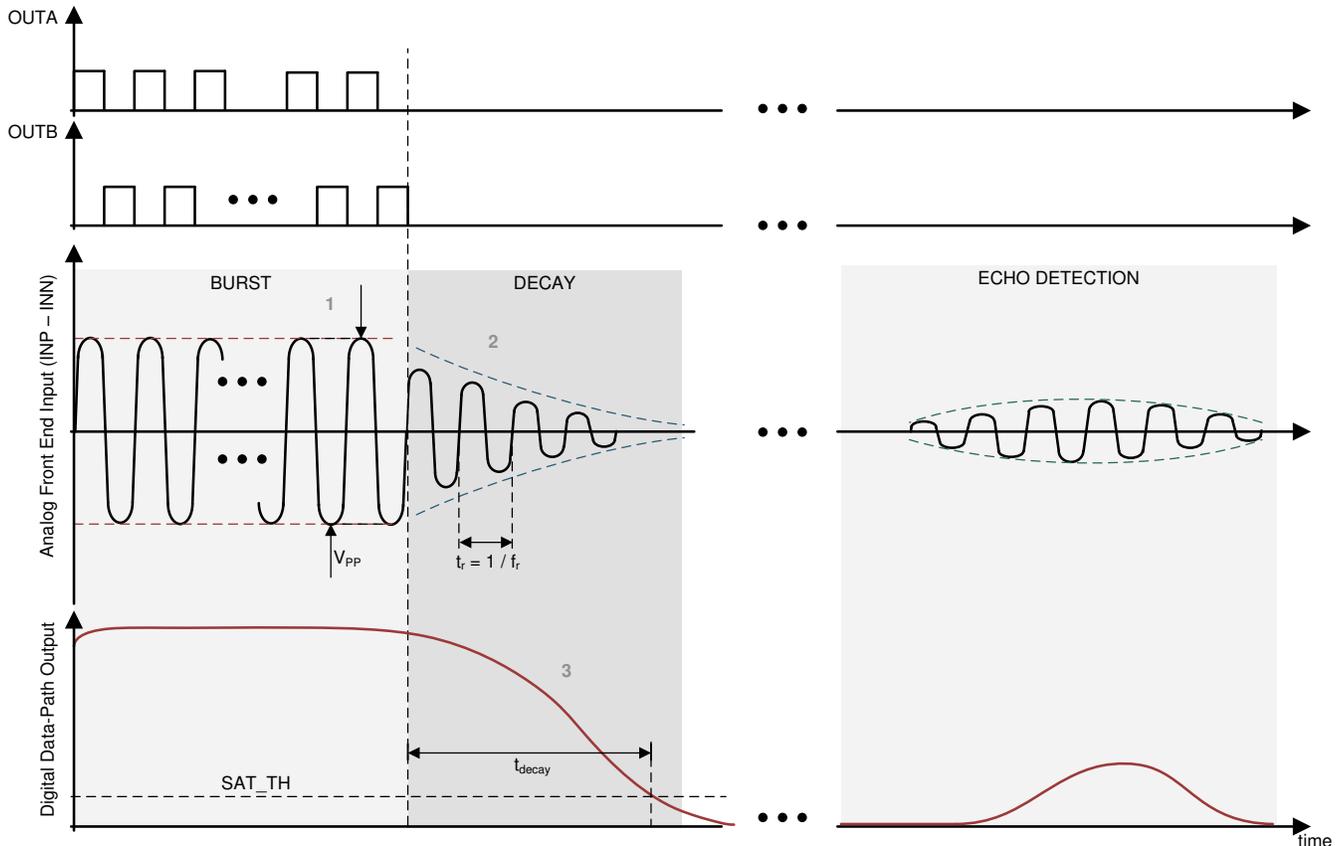


Figure 6-1. Frequency Diagnostic Timing Diagram

6.1.1.2 External Microphone

To monitor both the emitted frequency and SPL of the transducer in amplitude, an external microphone must be used, such as the G.R.A.S. 46BF Free Field Microphone, with an oscilloscope. To convert the peak-to-peak SPL from voltage to dB, use [Equation 3](#) and [Equation 4](#).

$$\text{SPL Pa} = V_{\text{Measured}} \text{ mV}_{\text{RMS}} / 3.4 \text{ mV} \tag{3}$$

$$\text{SPL dB} = 20 \times \log_{10} (\text{SPL Pa} / P_0) \tag{4}$$

where

- P_0 is reference sound pressure of 20 μPa

In the example in [Figure 6-2](#), the green waveform represents the driving voltage across the transducer and the purple waveform represents the ultrasonic echo captured by the external microphone at 30 cm. Both the frequency and dB equivalent can be monitored using this method.

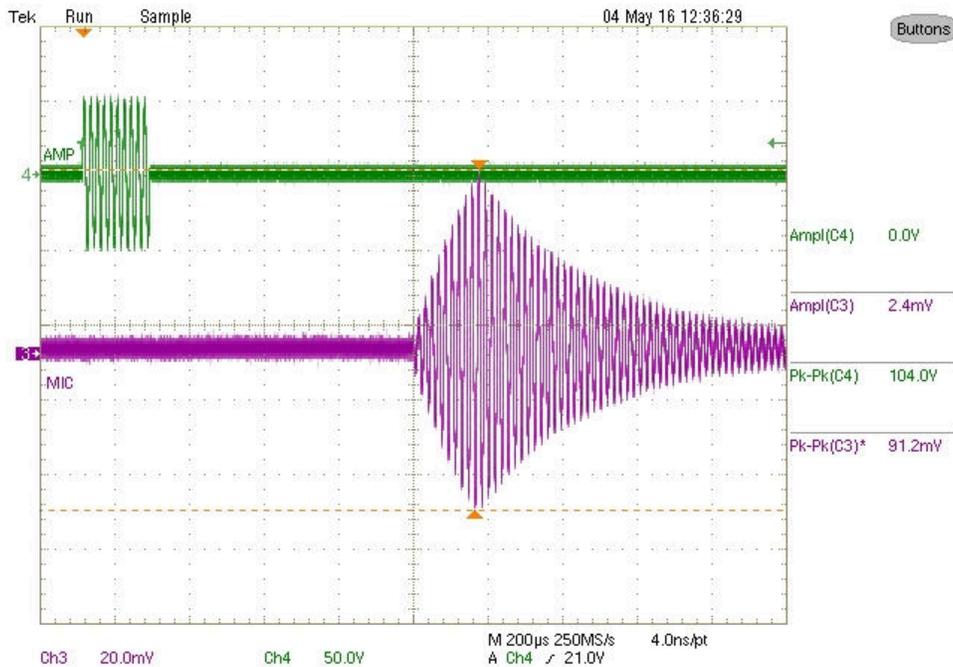


Figure 6-2. Sound Pressure Level as Voltage Equivalent

7 Revision History

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

Changes from Revision * (February 2017) to Revision A (April 2021)	Page
• Updated Sonar Configurations image.....	7

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