Don't Be Blinded by Your Amplifier's Slow Overload Recovery

Ultrasound receivers are frequently exposed to overload conditions during B-mode and Pulsed Doppler operation. These conditions can saturate the amplifiers and/or the ADC within the receive Amplifier Front-End (AFE) signal chain. An ultrasound receiver with poor overload recovery characteristics can greatly complicate design, significantly reduce image quality, and lengthen time-to-market. This article reviews ultrasound system design challenges with regard to overload recovery, and presents a new family of ultrasound receiver ICs which address the shortcoming of currently available solutions.

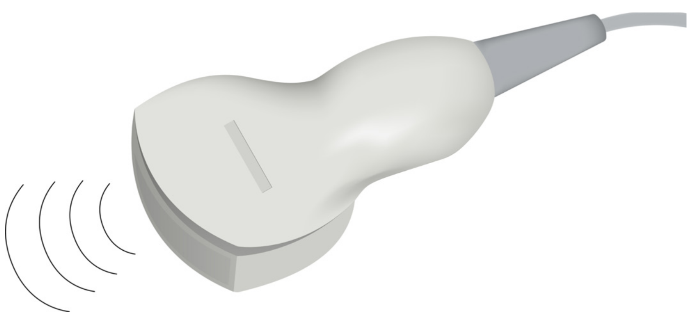

Figure 1. Ultrasound Probe and Waves Illustration

The Ultrasound System

Ultrasound has a wide range of medical applications, including imaging, blood flow measurement, cancerous lesion detection, bone densitometry and needle or catheter guidance.

The ultrasound transmitter applies acoustic waves to the body with a ultrasound probe that contains a piezoelectric transducer (Figure 1), and the ultrasound receiver picks up the echoes reflecting from the body structure, generally by means of the same piezoelectric transducer. Figure 2 is a high-level illustration of the ultrasound system.

In a Pulsed Wave (PW) ultrasound system a high voltage pulse stimulates the piezoelectric transducer (a crystal), housed in the ultrasound probe, causing a corresponding mechanical compression (a reverse piezoelectric effect) and creating the ultrasound compression/relaxation wave that traverses through the body. This wave, focused using phased array techniques in the lateral plane and through a lens in the elevation plane (see Figure 6), propagates through the body and through the various body substances (soft tissue, bone, fat, and blood). At each substance boundary, a portion of the compression wave is reflected back to the transducer. Since sound travels at a relatively constant velocity, the delay of the returning pulse represents the distance of the target, while the Doppler frequency shift provides information about the motion of the target. The reflected signal is processed and displayed as an image on a screen. The electric signals to/from the probe are generally processed in the 'cart', a mobile structure including transmitter circuitry, the analog front-ends, the processing unit and the display.

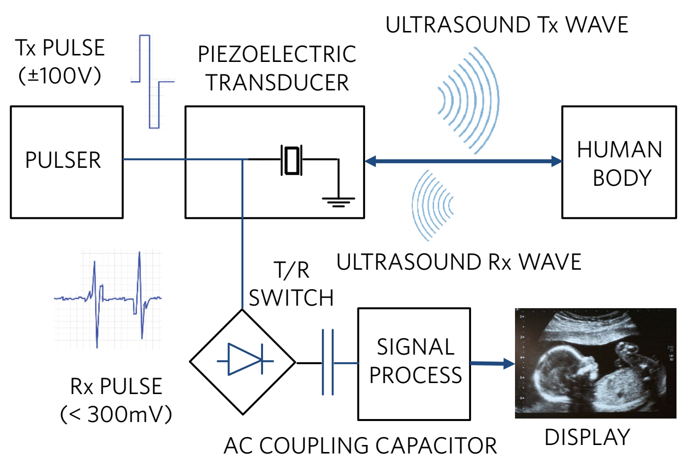

Figure 2. Ultrasound System

The Receiver Channel

Figure 3 shows the receiver channel in greater detail. The AC signal received through the capacitor bank C is amplified by the low-noise amplifier (LNA) and the variable gain amplifier (VGA) before being digitalized by the ADC.

Two back-to-back protection diodes before the input coupling cap C limit the voltage at the receiver input chain. In the presence of large input signals, they can become forward biased, and the input is held at a V_{BE}(on) above or below ground.

These protection diodes are designed so that the V_{BE}(on) voltages, typically about 1V, are significantly greater than the linear input range of the LNA.

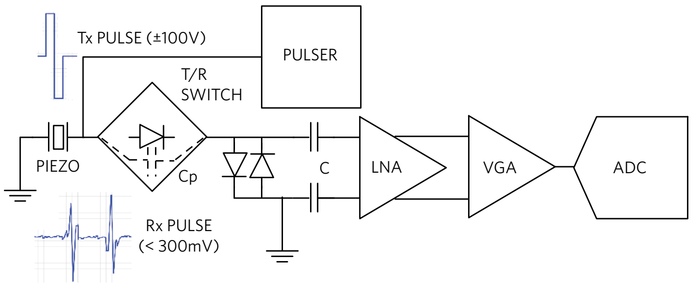

Figure 3. Ultrasound Pulser and Receiver Chain

In front of the receiver chain there is a Transmit/Receive (T/R) switch (Figure 4), separating the high voltage transmit signals from the low voltage receive domain. The T/R switch isolates the receiver during the high voltage transmission bursts. The traditional implementation of the TR switch is a simple diode bridge, biased "on" during both the transmit and receive intervals. This implementation forces the protection diodes to limit the amplitude of the input signal when the transmitter is active. Modern pulsers have the ability to bias off the bridge during the transmit interval to better isolate the receiver. The T/R switch is closed when the four diodes in the bridge are forward biased and open when they are reverse biased.

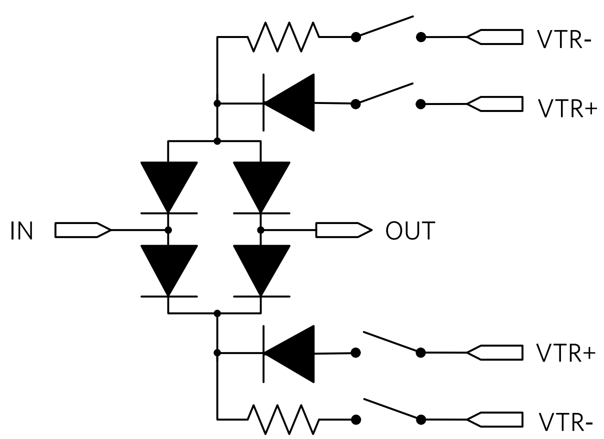

Figure 4. The Transmit/Receive (T/R) Switch

Since ultrasound signals are attenuated as they travel through the body, the reflected (received) signal is much smaller than the transmitted signal. Its detectable peak at the input of the LNA is limited by the linear input range of the LNA, typically $500mV_{PP}$ at an LNA gain of 18dB. Since the received signal is AC, it will ride on top of any offset at the output of the LNA. Such an offset will reduce the effective range of operation of the LNA before saturation. Note that one rail, either the top voltage rail or the bottom voltage rail, will usually saturate before the other.

From the output of the LNA, the AC signal and any offset propagates into a variable gain amplifier (VGA) stage or a voltage-controlled attenuator (VCAT) followed by a fixed gain stage, where the gain (or voltage-controlled attenuation) is programmed to change as a function of time to compensate for the signal attenuation in tissue.

Figure 5 shows the typical time varying gain profile of the receiver channel for a 3.5MHz probe. The 120µs long gain ramp amplifies the input signal exponentially over time (linearly in dB) to match the attenuating effects of the human body. Thus, the minimally attenuated signals reflected from the near field tissue (near the front of the gain ramp) will see minimum gains, while the significantly attenuated signals received from the far field (near the back of the gain ramp) will see maximum gains.

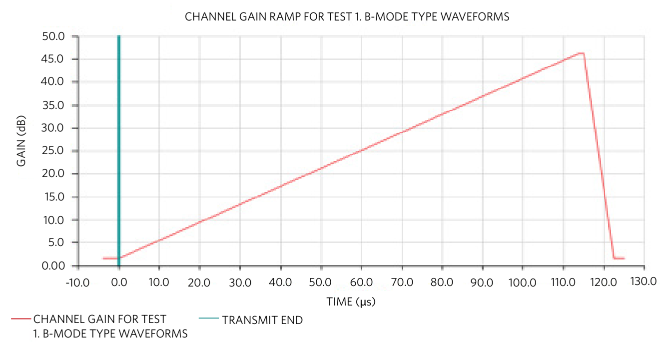

Figure 5. Typical Receiving Channel Gain Profile

Using this technique, signal reflections from deep inside the body (far field) can be picked up and processed by the ultrasound receiver electronics.

Figure 6 illustrates the echoes from the near and far fields. Low frequency probes (2MHz to 3MHz center frequencies) can typically see reflections from over 20cm of tissue. (The roundtrip time for signals traveling at the speed of sound is 13µs/cm or 260µs for 20cm). The gain profile assures that the received signals have an amplitude unaffected by distance for a significant duration of a single transmit interval. Naturally, any fixed DC or dynamic offset built up on the input AC coupling capacitor receives the same treatment and is exponentially amplified over time!

The Overload Recovery Challenge

Overload conditions can occur during the transmit interval when transmit pulses couple into the receiver input through the transmit/receive (T/R) switch. They can also occur during the receive interval due to large input signals caused by strong reflectors.

During the transmit phase, large signals can be directly coupled into the receiver input or capacitively coupled into the receiver depending on the T/R switch architecture. The large transmit coupled signals can directly saturate the receiver or can cause problematic charge buildup on the Rx input coupling capacitors that take a long time to discharge.

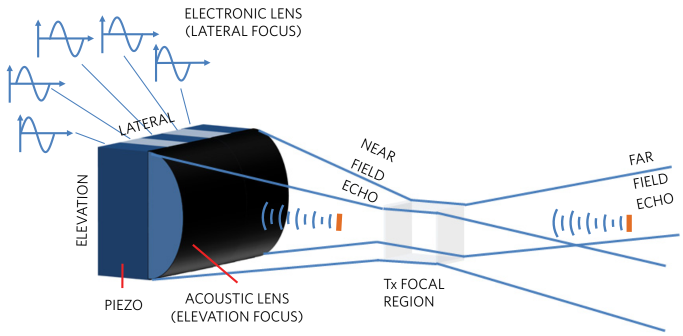

Figure 6. Near and Far Field Echoes

The condition can be challenging during transmit events such as B-mode or Pulsed Wave Doppler (PWD) bursts and particularly challenging during prolonged elastography push pulses. During these events, current feedthrough partially blinds the receiver by charging the input coupling capacitors (bank C in Figure 3) and limiting the available dynamic range of the receiver.

During the receive interval, strong specular reflections in the near field can also cause significant overload recovery problems, even when the gain is set low or in the mid-range where the gain is set high. Doppler imaging modes are particularly challenging. The small return signals from blood can sometimes require high receive chain gain in order to push them above the ADC noise floor, increasing the likelihood of Rx signal chain saturation from stronger reflections near the area of interest. Saturation conditions within the receiver will temporarily corrupt the digitized results, effectively blinding the receiver after those saturation conditions are removed and while the amplifier recovers.

Each of these overload problems can "blind" the receiver for an extended period of time by reducing the available ADC dynamic range, making it difficult to see small signals in the presence of larger ones or by losing the Rx signal altogether. The blindness will persist until the receive chain amplifiers and ADCs fully recover.

One important task for a designer of ultrasound equipment is to choose an ultrasound Rx AFE that has good overload recovery characteristics. An ultrasound system with fast overload recovery time ensures that minimum valuable information is lost after a saturation event. Stated plainly, it can make the difference between a radiologist successfully spotting a small mass of abnormal tissue in a patient, or properly seeing the vascularization of tissue in difficult-to-image organs such as the kidney or liver, and missing such clues all together.

Overload from "On" T/R Switch

The transmit signal is often a high voltage pulse (±100V) with high slew rate (dV/dt), centered at ground (see Figure 2). If the T/R switch remains on during the Tx pulse, with bias current flowing in the diodes, the output will try to follow the input until one of the two back-to-back input protection diodes becomes forward biased. The input is then held at a fixed V_{BE}(on) above or below ground. As a result, the LNA will go into an overload condition at the beginning of a transmit burst. Given that it is important to be able to receive superficial echoes in the near-field as soon as reflections begin to arrive from tissue discontinuities, the LNA and associated input coupling capacitor must be designed to quickly recover from the overload condition. It is important not to lose information from these returning echoes while the LNA is recovering, and is thus blind until normal linear operation is restored. The roundtrip time for a transmit pulse to traverse the lens is typically 2µs to 4µs, so it is important that the LNA recovers from a strong overload condition in less than 2µs. A well-designed LNA should recover in 0.6µs to 0.8µs.

C_pdV/dt Feedthrough Current

Whether the T/R switch is biased on or off, it has the unfortunate characteristic of having a parasitic capacitance (C_p) from its input to output. This is a significant problem with diode bridge based T/R switches, and a somewhat less significant problem with active T/R switches. Large transmit pulse swings with fast slew rates and high dV/dt can cause substantial feedthrough current that charges the input AC coupling capacitor. This limits the dynamic range of the receiver by adding a DC error component to the input signal. This DC error component slowly bleeds off the coupling capacitor. Until it bleeds off entirely, the LNA and VGA amplifiers will amplify this error component and present the results to the ADC. The LNA+VGA gain can become quite high, up to 40dB and beyond. For instance, if these dV/dt feedthrough currents charge up the AC input coupling capacitor by 10mV, this would add a 10mV error component to the AC signal of interest. A 10mV error with 40dB of gain will cause a shift of 500mV in the common-mode signal of the VGA output away from the center of the ADC's input range, potentially causing one-sided saturation of the AC signal of interest, and thus eroding a significant portion of the available ADC dynamic range.

If we closely examine the buildup of charge on the AC input coupling capacitor, we will find that the charge buildup results from one or both of two problems:

Problem 1: Asymmetric transmit pulses where the time duration at the positive voltage is different from the time duration at the negative voltage.

These pulses can cause small mismatches in the LNA input bias currents or in the currents flowing through the devices that set the LNA input common-mode voltage. These current mismatches are not necessarily symmetric, and will be integrated over different transmit voltage positive and negative duration times, effectively charging the AC input coupling capacitor and causing a DC error (offset) voltage at the input of the LNA.

Problem 2: Asymmetric transmit pulses with different rising and falling slew rates at the T/R switch input.

These can also cause AC coupling capacitor charge mismatches and DC offsets, since asymmetric and opposing CpdV/dt currents through the parasitic capacitance (C_p) across the T/R switch may not cancel completely (see Figure 2). It can take hundreds of microseconds for this charge to bleed off.

This input offset is subsequently amplified by the LNA gain. The LNA gain is generally a fixed value, for example 18dB. Thereafter, the offset is further amplified by the variable gain amplifier (VGA), or alternatively a voltage-controlled attenuator followed by a fixed gain amplifier stage. In B-mode imaging, the VGA gain will increase linearly in dB with time to compensate for tissue-based compression wave attenuation. Since the signal of interest rides on top of the offset in both amplifying stages (LNA and VGA), there could be both significant one-sided saturation within the VGA gain stage as well and a significant one-sided overrange condition at the ADC input, as the ADC tends to saturate before the VGA. The use of a DC-blocking digital highpass filter (DHPF) can generally remove this undesirable offset component from the digitized data, However, the use of the ADC's full-scale range is compromised in the process and often necessitates a corresponding reduction in VGA gain to keep the amplifier output stages and the ADC out of saturation. In other words, in the presence of significant DC offset, for a given image, the ultrasound technician may be forced to reduce the gain to keep the Rx signal chain from saturating. With less gain, some of the small second harmonic echoes and the small blood echoes will disappear below the noise floor of the ADC, thus deteriorating image quality.

Overload from Transmit Events

Overload from an "on" T/R switch or a CpdV/dt feedthrough current, discussed previously, are associated with transmit events. It is important that the receiver recovers fully from these overload events in less time than it takes for the compression wave to propagate through the ultrasound lens. In a well-designed receiver, this time should be in the range of 0.6µs to 0.8µs or less.

Overload from Strong Specular Reflections

Additional saturation problems can occur during normal B-mode, tissue harmonic imaging (THI), or during Doppler imaging—PW or Color Flow (CF) —well after the Tx pulses are finished and receive information is being processed. That is, there can be overload problems due to normal receive events.

Specular reflections from large, smooth tissue boundaries can have echoes of a magnitude large enough to saturate either the LNA or, more frequently, the VGA stages. This happens particularly in the near-field close to the ultrasound probe or from deeper within the tissue when the receive chain gain is turned up high. It is important that both the LNA and the VGA of a good ultrasound receiver recover quickly from strong specular reflections. A well-designed receiver under these conditions should recover ideally in 20ns to 25ns, as it will be temporarily blinded until the recovery is completed.

The phase shift of the signal must be preserved under medium saturation conditions (0dB to 6dB of saturation) to enable Doppler imaging. The receiver recovery performance is particularly important in Doppler imaging, as blood vessel walls can have relatively strong reflections compared to the red blood cell reflections within the vessel. The gain must be turned up to see the small reflections of the blood, creating a situation where the vessel wall reflections could saturate the LNA/VGA. Without a fast LNA/VGA recovery, the receiver will not be able to see the adjacent blood signals beyond the vessel wall during color flow imaging.

It should be noted that not only can the LNA/VGA stage be saturated during these specular reflection events, but so too will the ADC that follows them. The ADC should also be designed for a fast recovery from an overrange condition. In a well-designed receiver, only 1 clock cycle (25ns at 40MHz) should be needed before the ADC returns to normal operation after a saturation event occurs.

Common Solutions and Their Shortcomings

The LNA and VGA stages, as well as the ADC, should be designed such that they all recover quickly from an overload condition, since the receiver will be effectively blind until the recovery has finished and image quality can suffer or the Doppler phase shift information cannot be preserved.

In dealing with asymmetric CpdV/dt currents building up charge on the input AC coupling capacitor, some solutions utilize shunt inductors in parallel with the protection diodes, or utilize a feedback circuit around the LNA to try to compensate for the charge built up during the Tx burst (Figure 7), or both. In a feedback scheme like the one shown below, the input offset caused by the Tx burst is cancelled by injecting a charge in the bottom AC coupling capacitor, developing an offset identical to that of the top capacitor, assuming the system remains linear in the process.

With this type of a compensation circuit there can be problems when the LNA strongly saturates. At the same time there is a need to keep the feedback loop that corrects for the offset of the input AC coupling capacitor fully operational. During the overload event, the offset feedback circuit is broken while the LNA is saturated. To make matters worse, during this same overload event, significant charge can be built up across the input AC coupling capacitor.

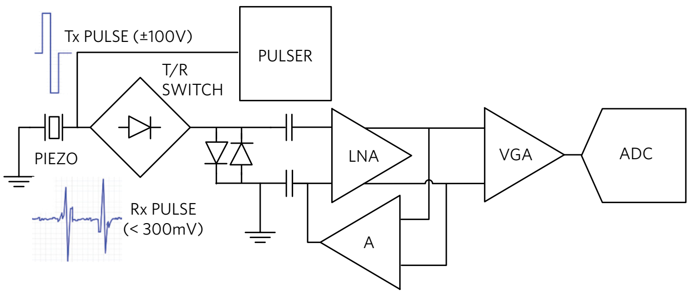

Figure 7. Typical Offset Cancellation Scheme

Thus, when the LNA does recover from deep saturation conditions, which can take some time, the offset feedback circuit, which must be in a slow feedback loop, will take additional time to compensate for any built-up DC offsets, usually quite significant during such overload events. To preserve amplifier stability, the offset feedback loop must be much slower than the feedback loop that sets the LNA active input impedance. Thus, the recovery of both the amplifier and its correction loop must be considered. Overload recovery curves for these types of implementations often show only a VGA (or VCAT+FG) stage recovery, while staying silent about LNA recovery.

A complete representation of the circuit's overload recovery should show:

- The LNA overload recovery without subsequent saturation of the VGA stage.
- The VGA stage overload recovery.
- Some proof that dynamic range has not been significantly compromised by DC offset buildup.

Unfortunately, not all ultrasound Rx AFE manufacturers provide the adequate overload recovery documentation that is necessary to make an informed device selection.

An Ideal Solution

The ideal solution must provide fast recovery of both the LNA and VGA amplifier stages during both the transmit and the receive intervals. Special care needs to be taken with the design of the LNA AC-coupled input stage, as the first stage must be kept out of deep saturation, a condition that can frequently occur around the Tx burst and can cause notoriously slow recovery times. Another important feature of an ideal solution is to interrupt the DC chain at the output of the LNA by means of a second bank of AC coupling capacitors (C1 in Figure 8). Any Tx-burst related offset is blocked from going to the VGA and getting further amplified, preventing it from limiting the dynamic range performance of the receiver.

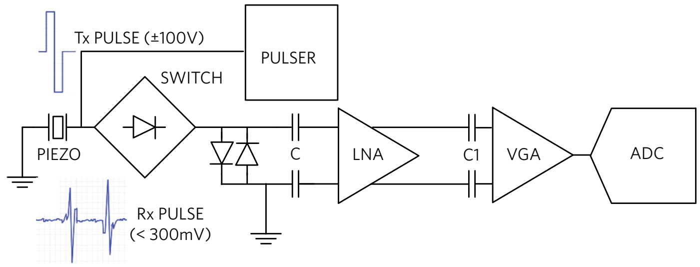

Figure 8. Ideal Offset Cancellation Scheme

The MAX2084 device from Maxim Integrated implements the strategy outlined. It provides substantial improvements to all critical overload conditions: T/R switch in receive mode, input AC coupling capacitor offset management, strong specular reflections in the near field, as well as relatively stronger reflections adjacent to smaller blood cell reflections during Doppler imaging. Further, this receiver does not need additional shunt inductors in parallel with the protection diodes to help manage charge on the input coupling capacitors.

Only one clock cycle is needed before the ADC returns to normal operation after a saturation event occurs. Figure 9 shows the LNA overload recovery time from a large input. In this condition, the LNA recovery time can be seen as the small continuous wave signal begins to pass through the LNA normally; the recovery time is clearly less than two 4.8MHz cycles or < 0.4µs.Note that the decaying signal component is due to the behavior of the analog highpass filter formed by the AC coupling capacitor and the input impedance of the VGA input stage, which has a time constant of about 1.3µs and settles within a few microseconds.

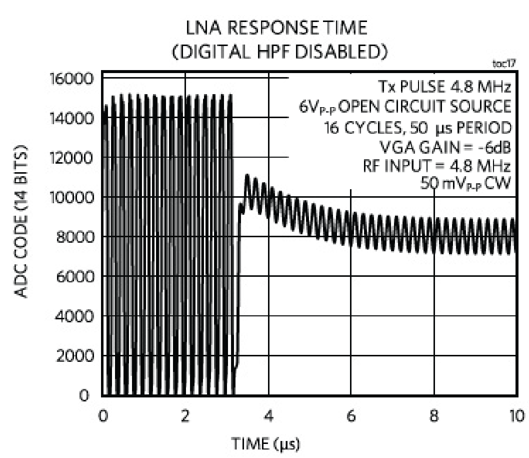

Figure 9. LNA Overload Recovery Time

Figure 10 shows the VGA overload recovery time from a small input offset. In this condition, the VGA recovery time is about one ADC clock cycle.

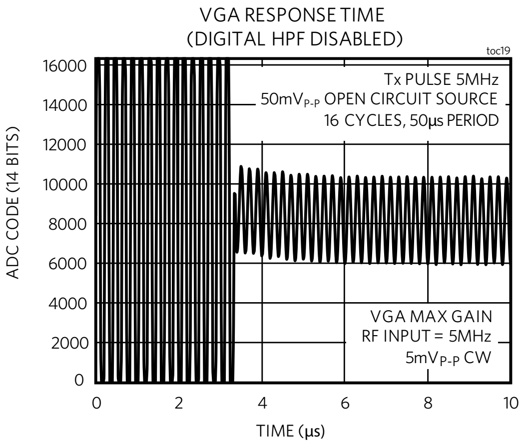

Figure 10. VGA Overload Recovery Time

Figures 11 and 12 show the efficacy of the AC coupling capacitors between the LNA and VGA stages. Figure 11, shown earlier and repeated here for convenience, shows the gain control profile used for a B-mode test where ±100V Tx pulses are followed by a receive chain interrogation. A curvilinear transducer with a 3.5MHz center frequency is used with a general-purpose ultrasound phantom. Figure 12 shows the digitized results from the receive chain with the digital highpass filter bypassed during the application of the gain ramp of Figure 11. As discussed earlier, for normal B-mode time gain control, the receiver gain profile increases exponentially over time (linearly in dB) to match signal attenuation characteristics of ultrasonic compression waves in tissue. Accordingly, we would expect to see a flat response (centered around the ADC's zero code) if there were no residual problems with Tx-burst induced offsets. Conversely, if there were any offset problems, you would see the ADC code increase exponentially as the gain increased over time. This is clearly not the case with the results shown in Figure 11, where the flatness of the curve indicates absence of offset.

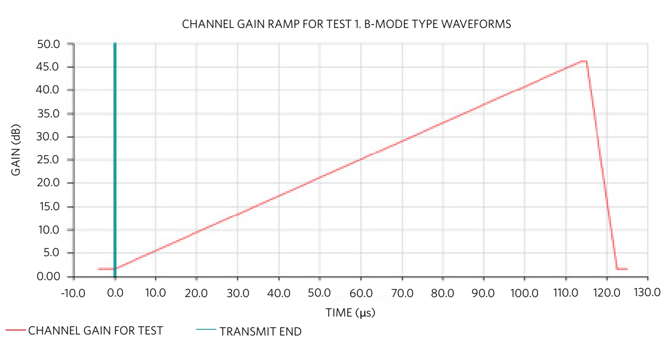

Figure 11. Gain Profile for Full Tx/Rx Chain B-mode Overload Recovery Test

A full overload recovery report is available, showing good recovery performance with even more challenging gain profiles, such as those used in Color Flow or even more challenging Tx-burst conditions, such as for elastography. Contact Maxim design support for more information.

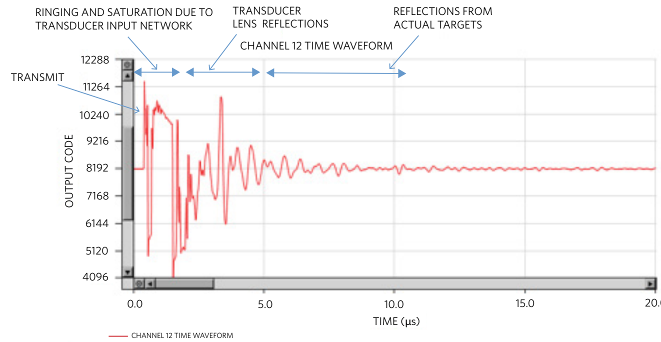

Figure 12. Receive Data Digitized Results

The IC includes an octal Continuous Wave Doppler (CWD) beamformer for a full Doppler solution as shown in Figure 13.

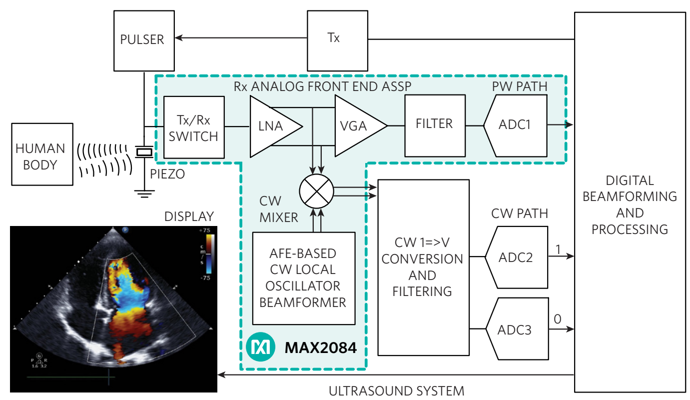

Figure 13. Integrated Ultrasound Receiver with T/R Switch

Conclusion

The causes and effects of overload in the ultrasound receiver chain during transmit and receive intervals were discussed in detail. Shortcomings of current solutions were highlighted. A new solution was introduced which implements fast recovery amplifiers and a new technique to manage offset error generated from the Tx burst by placing AC coupling capacitors between the LNA and the VGA. This solution prevents the offset error from propagating to the VGA stage. The result is a substantial improvement in dynamic range performance for the entire receive interval, after the initial Tx-burst related LNA saturation and input AC coupling capacitor charge buildup. Thus, overload induced blind-spots are minimized during imaging.

Choosing an ultrasound receiver with good overload recovery characteristic can greatly simplify HW/SW design and debug challenges, speeding up time-to-market, and considerably enhancing image quality.

Glossary

Active input impedence of LNA: The input impedance of the LNA set actively via a control loop as opposed to passively, via a resistor.

Active T/R switch: A switch built with a transistor rather than Diode Bridge and having other circuitry on board to minimize parasitic charges transfer to the output.

B-Mode. Brightness or 2D mode: The transducer scans a plane through the body that is viewed as a two-dimensional grey scale image on screen.

CF Imaging. Color flow imaging: Combines anatomical information from ultrasonic pulse-echo techniques with velocity information from ultrasonic Doppler techniques to generate color-coded maps of tissue velocity superimposed on grey-scale images of tissue anatomy.

Curvilinear transducer: A device that fits better on the abdomen allowing for a wider field of view than its linear counterpart.

CW imaging: Continuous wave imaging employs a constant (not pulsed) modulated ultrasound source. Continuous sending and receiving allows accurate measurement of high-velocity target motion but cannot resolve its location; that task is left to PW.

Elastography: Medical imaging that maps the elastic properties of soft tissues by measuring the velocity of a shear wave generated by the application of an ultrasound pulse (Push Pulse).

FG: Fixed gain

Lens: A silicone lens inside the probe that focuses the ultrasound beam.

Mid-range: See near field.

Near field: The ultrasound beam has the shape of a cylinder squeezed in the middle. The initial converging zone (Fresnel Zone), adjacent to the transducer, is the near field. The subsequent diverging zone (Fraunhofer zone) is the far field. The in-between zone is the mid-range.

Probe: An ultrasonic transducer that converts ultrasound waves to electrical signals or vice versa.

Pulser: A device generating a high voltage pulse (±100V commonly) with high slew rate (dV/dt) centered on ground.

Push pulse: A high energy pulse capable of generating a shear wave in body tissue, used to test its elasticity.

PW: Employs a pulsed ultrasound source. Pulsed sending and then receiving allows accurate targeting of a given location: sound travels at constant velocity and hence delay in the returning pulse correspond to distance.

Specular reflection: A full reflection as if from a mirror. From an object much bigger than the incoming signal's wavelength.

Scattered reflection: A partial reflection from an object having a size comparable to the incoming signal's wavelength.

Second harmonic imaging: The transmitted wave after reflection gets distorted by the non linear response of the body tissue. The second harmonic component of the received signal caused by this distortion has better quality when used in B-mode imaging than the fundamental transmit frequency.

TGC: Time gain control of the receiver gain as a function of time accounts for the attenuation of the received signals returning from deeper tissue depth.

THI: Tissue harmonic imaging is the same as second harmonic imaging.

Tx/Rx: Transmit/Receive

Transducer: An array of narrow piezoelectric elements.

VCAT: Voltage-controlled attenuator

VGA: Variable gain amplifier

Ultrasound: Sound wave above the 20 to 20,000 cycle (Hz) audible range.

Ultrasound phantom: A device that is scanned or imaged in medical imaging to evaluate and tune the performance of other imaging devices.

Learn more:

MAX2084 16-Channel, High Performance, Low Power, Fully Integrated Ultrasound Receiver with T/R Switch

Article originally published in Electronic Design.

Design Solutions No. 4

Rev 0; December 2018

Visit the Maxim Support Center

Find More Design Solutions

Maxim Integrated
160 Rio Robles
San Jose, CA 95134 USA
408-601-1000
maximintegrated.com/design-solutions