Application Report
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Time Gain Control (Compensation) in Ultrasound Applications

Sanjay Pithadia, Rahul Prakash

ABSTRACT

This application report explains a vital functionality in Medical Ultrasound Systems called Time Gain Control or Time Gain Compensation (TGC). Starting from why TGC is important, with examples and requirements on the control signals for implementing TGC are explained in detail. The selection criteria and example circuits for external components (like Digital-to-Analog Converter (DAC) and Op-amp) are highlighted at the end.

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1 Introduction

Medical ultrasound imaging is a widely-used diagnostic technique that enables visualization of internal organs, their size, structure, and blood flow estimation. An ultrasound system uses a focal imaging technique that involves time shifting, scaling, and intelligently summing the echo energy using an array of transducers to achieve high imaging performance. The concept of focal point imaging provides the ability to focus on a single point in the scan region. By subsequently focusing at different points, an image is assembled. When initiating an imaging, a pulse is generated and transmitted from multiple transducer elements. The pulse, now in the form of mechanical energy, propagates through the body as sound waves, typically in the frequency range of 1 MHz to 15 MHz. The sound waves are attenuated as they travel through the objects being imaged. Most medical ultrasound systems use the reflection imaging mode. As the signal travels, portions of the wave front energy are reflected back towards the transducer.

Signals that are reflected immediately after transmission are very strong because they are from reflections close to the surface; reflections that occur long after the transmit pulse are very weak because they are reflecting from deep in the body. As a result of the limitations on the amount of energy that can be put into the imaging object, the industry developed extremely sensitive receive electronics with wide dynamic range. Received echoes from focal points close to the surface require little, if any, amplification. This region is referred to as the near field. However, echoes received from focal points deep in the body are extremely weak and must be amplified by a factor of 100 or more. This region is referred to as the far field. The receiver AFE has this unique challenge. It should be capable to adapt to both weak (far field) and strong (near field) received signals. This means that any strong echo must be conditioned so as to not saturate and distort the receive chain and any weak echo must be amplified while inducing minimal noise to determine the source of the echo. For this purpose, most of the receiver AFEs consists of:

- A highly linear low noise amplifier (LNA) – whose gain is digitally programmable. Sometimes it also has programmable input impedance for improved ultrasound probe matching characteristics
- A Voltage-Controlled Attenuator (VCAT) – controlled through high bandwidth analog pins, allowing for fast control (Note that some devices also provide digital attenuation control along with analog control. The digital control feature can eliminate the noise from the V_{CNTL} circuit and ensure better SNR and phase noise for the TGC path. However, this document talks about the analog approach only). This block is capable of increasing or decreasing the gain (linear in dB) using external signal. Typically, a differential control structure is used to reduce common mode noise.

The function of increasing and decreasing the gain according to the linear in dB scale is termed as Time Gain Control or TGC. Figure 1 shows the simplified block diagram of Ultrasound Receiver Analog Front End AFE58JD18 from Texas Instruments. It shows these blocks (in Grey color) that help in TGC functionality.

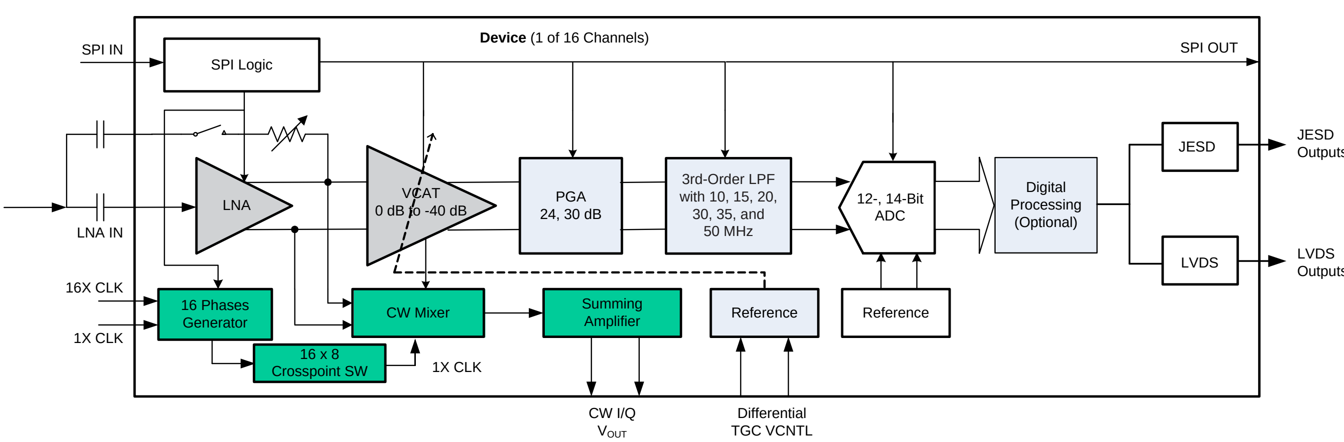


Figure 1. Simplified Block Diagram of AFE58JD18

2 Why is Time Gain Control (TGC) Needed?

Before discussing more details of how TGC is implemented, it is important to understand the function of TGC. If an ultrasound element in the transducer is approximated as a point transmitter, then the transmit wave spreads in that area while the power density of the wave-front falls off in a classic case as inversely proportional to the square of the distance from the transducer. Reflecting from a tissue target, the return signal also diminishes in the same proportions. Thus, the total round-trip spreading signal attenuation varies as the inverse of the transducer-to-target distance to the fourth power. Body tissue reduces the signal due to scattering and dissipation. A good rule of thumb for such attenuation is that it varies as 1 dB/MHz/cm of tissue thickness. While high-frequency signals are desirable because they provide higher resolution due to their shorter wavelength, they are more rapidly attenuated - decreasing the signal-to-noise ratio of deep penetrating signals.

During an ultrasound send-receive cycle, the magnitude of reflected signal depends on the depth of penetration. The purpose of TGC is to normalize the signal amplitude with time; compensating for depth. When the image is displayed, similar material should have similar brightness, regardless of depth and this is achieved by “Linear-in-dB” Gain, which means the decibel gain is a linear function of the control voltage. Figure 2 shows such an example of TGC for an Ultrasound image.

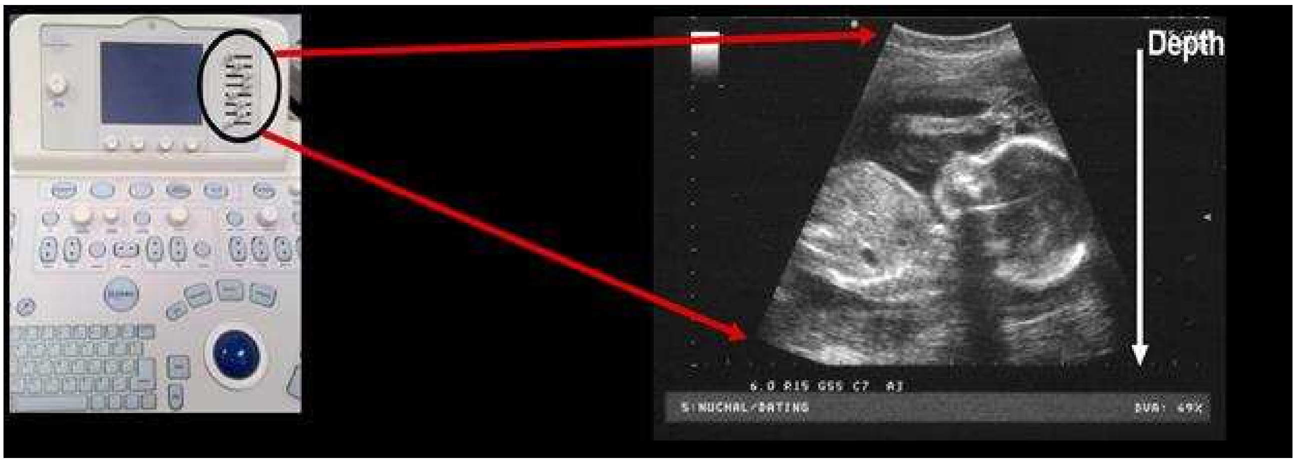


Figure 2. TGC for an Ultrasound Image

Going into more details, Figure 3 shows an example of B-mode TGC in action. As shown, a 5 MHz ultrasound signal enters the LNA with 350 mVPP single ended Near Field (NF) amplitude and 3.5 VPP differential NF amplitude appears at the LNA output (differential gain = 20dB) where the TGC equalizes the signal so that the ADC FS range of 3.12 VPP can be transversed to maximize the data acquisition resolution. Note that this is just an example taken from the *LM96511 Ultrasound Receive Analog Front End (AFE) Data Manual* (SNAS476).

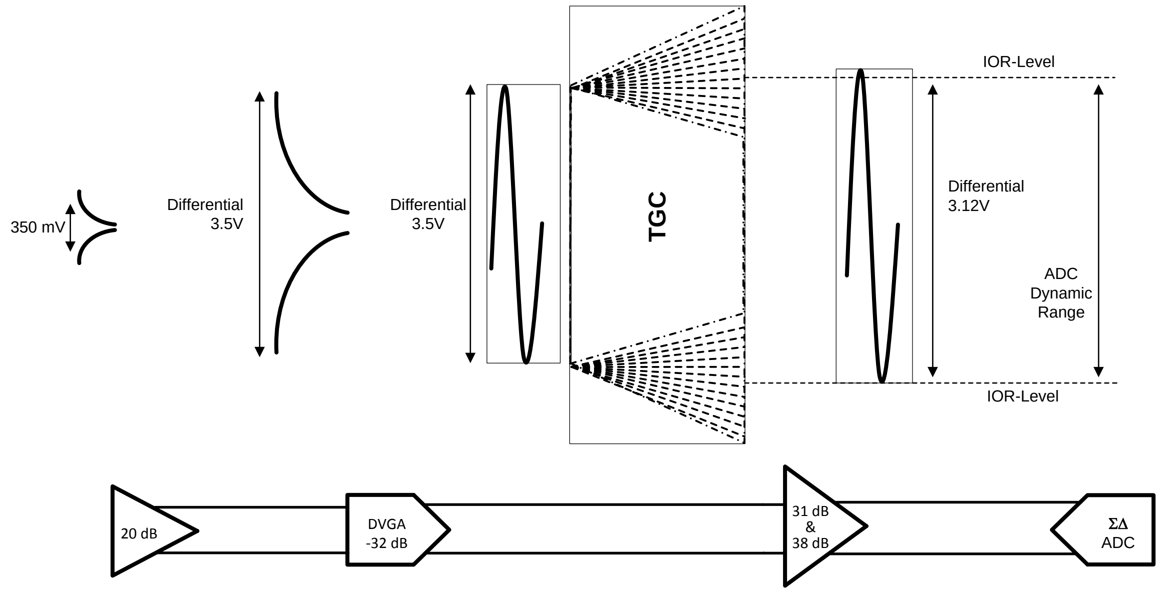


Figure 3. Typical TGC Operation at 5MHz

3 How Does the Attenuator Work?

Taking an example of AFE5812 from TI, the voltage-controlled attenuator is typically designed to have a linear-in-dB attenuation characteristic; that is, the average gain loss in dB (see Figure 4) is constant for each equal increment of the control voltage (V_{CNTL}).

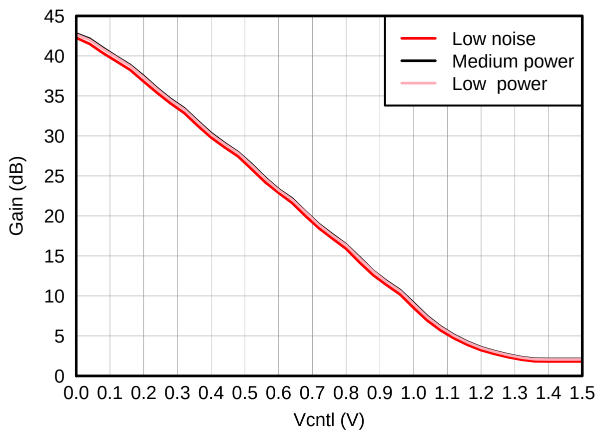
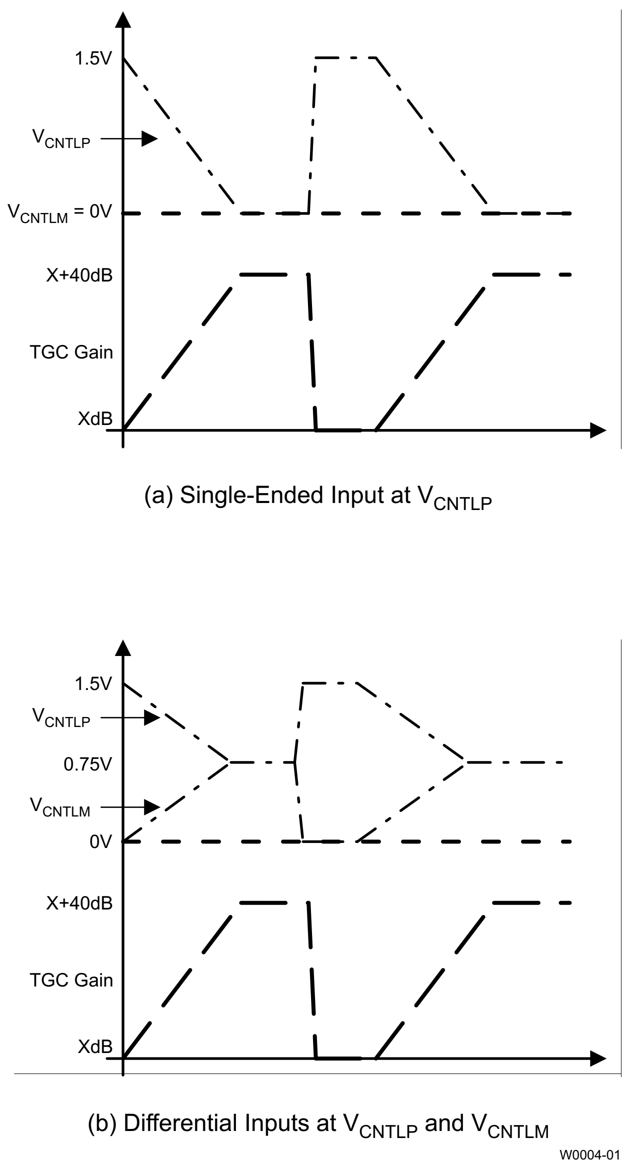


Figure 4. Gain vs. Control Voltage Graph Demonstrating Linear-in-dB Attenuation Characteristic

The attenuator is controlled by a pair of differential control inputs, the V_{CNTLM} and V_{CNTLP} pins. The differential control voltage spans from 0 to 1.5 V. This control voltage varies the attenuation of the attenuator based on its linear-in-dB characteristic. Its maximum attenuation (minimum channel gain) appears at $V_{CNTLP} – V_{CNTLM}$ = 1.5 V and minimum attenuation (maximum channel gain) occurs at $V_{CNTLP} – V_{CNTLM}$ = 0. When only single-ended $_{CNTL}$ signal is available, this 1.5-Vpp signal can be applied on the V_{CNTLP} pin with the V_{CNTLM} pin connected to ground; As Figure 5 and Figure 8 show, the TGC gain curve is inversely proportional to the $V_{CNTLP} – V_{CNTLM}$.



(a) Single-Ended Input at V_{CNTLP}

(b) Differential Inputs at V_{CNTLP} and V_{CNTLM}

Figure 5. V_{CNTLP} and V_{CNTLM} Configurations

4 What Characteristics are Required for Control Signal for TGC?

The control voltage input has few characteristics that help in defining the specs for the DAC and op-amp used for generating these signals:

- The control voltage input (V_{CNTLM} and V_{CNTLP} pins) represents a high-impedance input. The V_{CNTLM} and V_{CNTLP} pins of multiple AFEs can be connected in parallel with no significant loading effects.
- When the voltage level ($V_{CNTLP} – V_{CNTLM}$) is above 1.5 V or below 0 V, the attenuator continues to operate at its maximum attenuation level or minimum attenuation level, respectively.
- Noise requirements: Noise at the $_{CNTL}$ pins must be low enough to obtain good system performance because this noise is correlated across channels. Also, the V_{CNTLM} and V_{CNTLP} circuit achieves low noise to prevent the V_{CNTLM} and V_{CNTLP} noise being modulated to RF signals. V_{CNTLM} and $_{CNTLP}$ noise is recommended to be below 25 nV/√Hz at 1 kHz and 5 nV/√Hz at 50 kHz. In high-channel count premium systems, the V_{CNTLM} and V_{CNTLP} noise requirement is higher as shown in Figure 6.

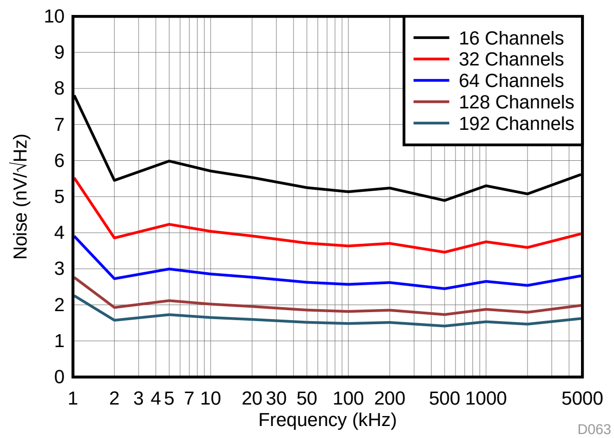


Figure 6. Allowed Noise on the V_{CNTL} Signal Across Frequency and Different Channels

- The AFE5812 gain-control input has a –3-dB bandwidth of approximately 800 kHz. This wide bandwidth, although useful in many applications (for example, fast $_{CNTL}$ response), can also allow high-frequency noise to modulate the gain control input and finally affect the Doppler performance. In practice, this modulation can be avoided by additional external filtering (RV_{CNTL} and CV_{CNTL}) at V_{CNTLM} and V_{CNTLP} pins as Figure 7 shows. However, the external filter's cutoff frequency cannot be kept too low as this result in low gain response time.

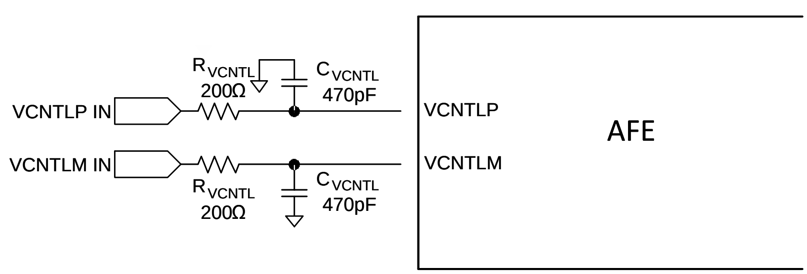


Figure 7. Filtering on V_{CNTLx} Pins

- Settling time requirement: Without external filtering, the gain control response time is typically less than 1 μs to settle within 10% of the final signal level of 1VPP (–6-dBFS) output as indicated in Figure 8.

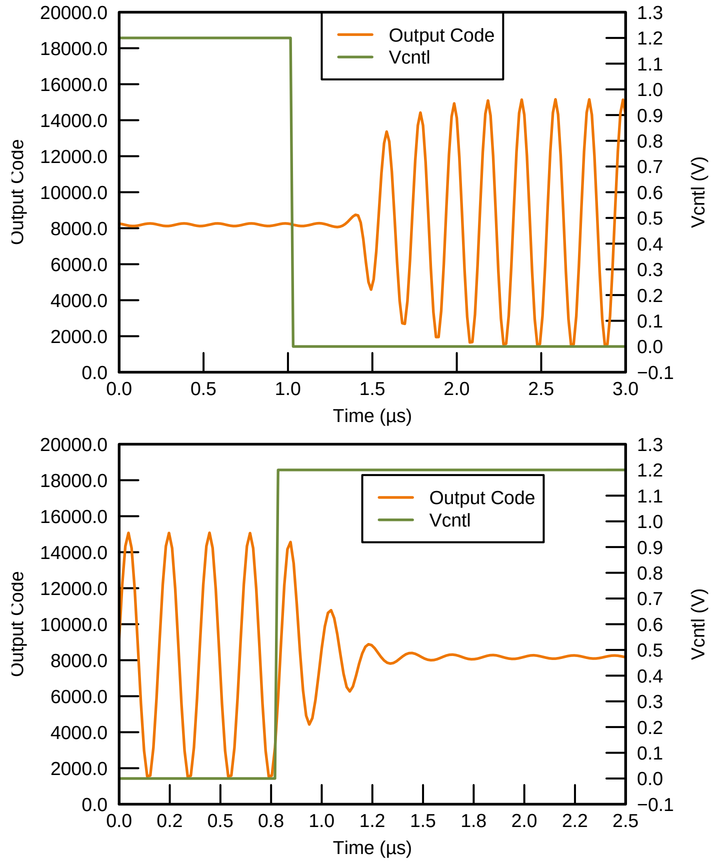


Figure 8. Control Voltage and Settling Time Relationships

5 Generating Control Signal for TGC Action

For such AFEs, which support analog control for TGC operation, an external circuitry using a DAC and an op-amp is used as highlighted in Figure 9. The input signal for the DAC is fed through FPGA available on beam forming board in ultrasound application.

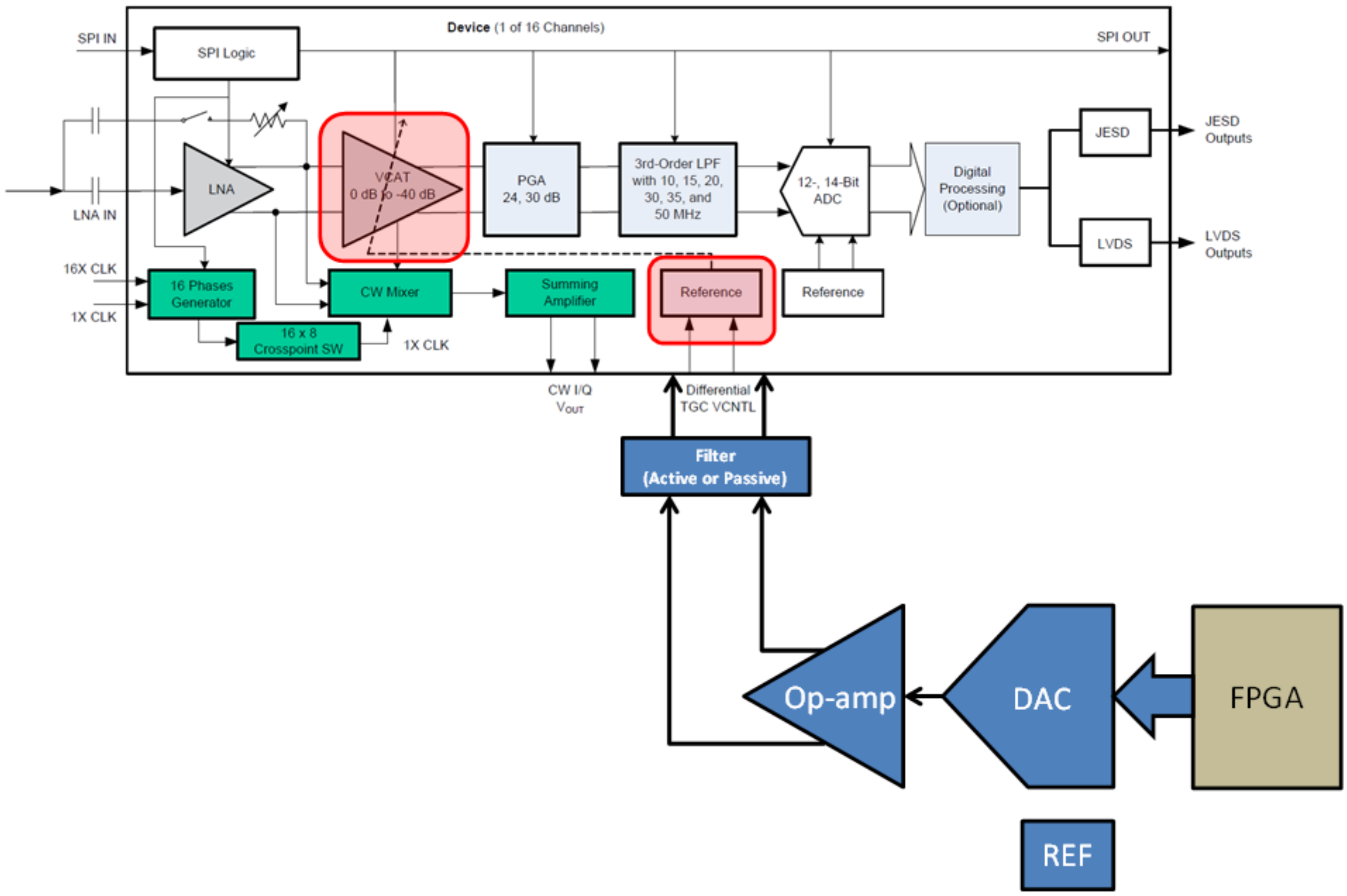


Figure 9. Analog Control for TGC Operation

Based on the previous section that states some of the requirements and characteristics of control signal waveform for TGC action, the DAC and op-amp can be selected.

For a DAC to be used in the TGC application, it should have the following specifications:

- Resolution and Vref decides the DAC output voltage (Vref/2^n) - Typically 8 to 12 Bits resolution is enough for TGC.
- Channel count : 1
- Settling Time : sub 1 µsec
- Output Update Rate : >= 1 MSPS
- Interface: The signals are coming from FPGA so in most cases DAC should support SPI interface. For some of the high-end Ultrasound applications, LVDS or JESD supports can also be useful.

For an amplifier to be used in the TGC application, it should have the following specifications. The basic functionality of op-amp is to buffer and filter to suppress low frequency noise.

- Should support differential or single-ended control voltage based on the requirement from AFE
- Output Common-Mode voltage Control (based on requirement from AFE)
- Noise requirements as per the AFE data sheet (for example AFE5812 has requirement of noise to be below 25 nV/√Hz at 1 kHz and 5 nV/√Hz at 50 kHz)

The op-amp can be external or can be integrated into the DAC.

Given below are some examples of generating control signal for TGC action.

6 Using Unbuffered R2R DAC

This approach uses a voltage output DAC having R2R architecture as shown in Figure 10. The output voltage has a typical requirement of low noise and fast settling, which means the output must be unbuffered and fast settling. In such scenario, a low noise external buffer must be used. The output can range from “0 to VREF” or “-VREF to +VREF”. The unbuffered voltage output R2R DAC requires a positive reference in order to generate a positive voltage output. The reference input impedance varies with DAC input code; hence, this topology requires reference drive circuitry to minimize the linearity errors. On the other hand, the output impedance remains constant with respect to DAC input code. This simplifies the output buffer design. Using this approach, the settling time is limited by compensation capacitor of the output buffer.

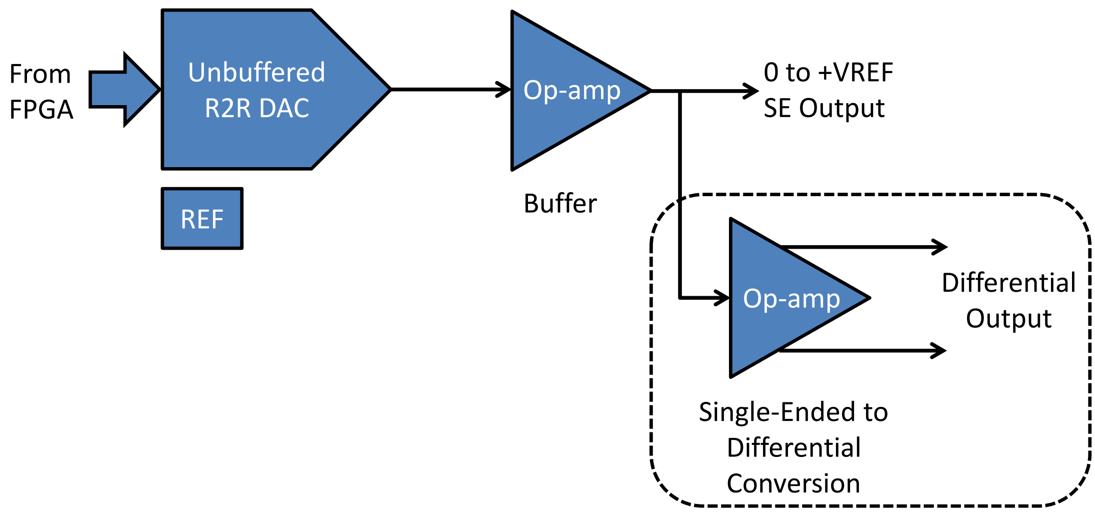


Figure 10. Using Voltage Output DAC for Generating TGC Signal

7 Using Current Output MDAC

This method uses a current output MDAC as shown in Figure 11. The reference pin of MDAC exhibits constant input impedance versus input code. Therefore, this approach does not require reference drive circuit. Additionally, faster settling time can be achieved since the MDACs outputs current instead of voltage. Note that the voltage on the output is inverted from the Vref pin. In order to achieve positive output from this architecture, either the reference must be inverted (see Figure 11) or the Vout must be inverted using additional op-amp (see Figure 12).

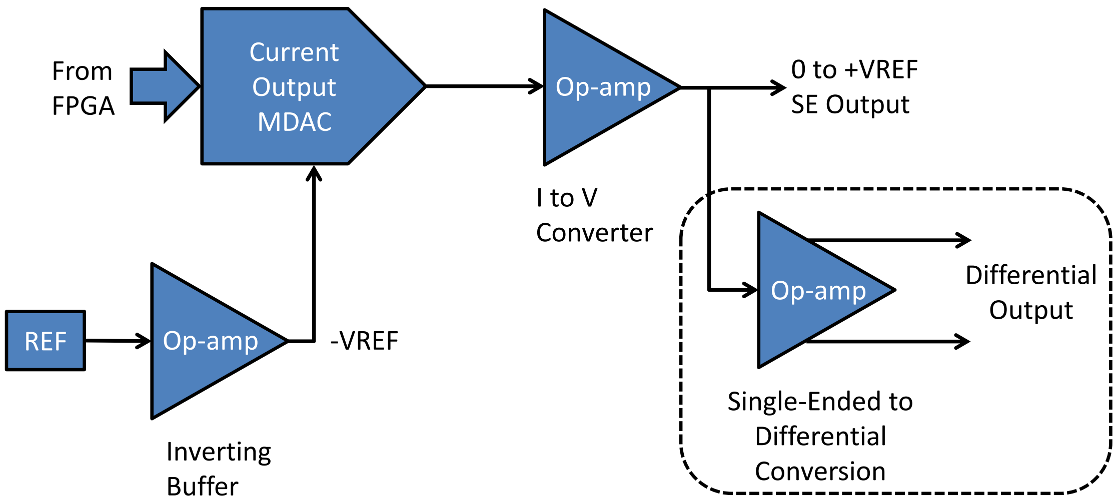


Figure 11. Using Current Output MDAC for Generating TGC Signal (Option # 1)

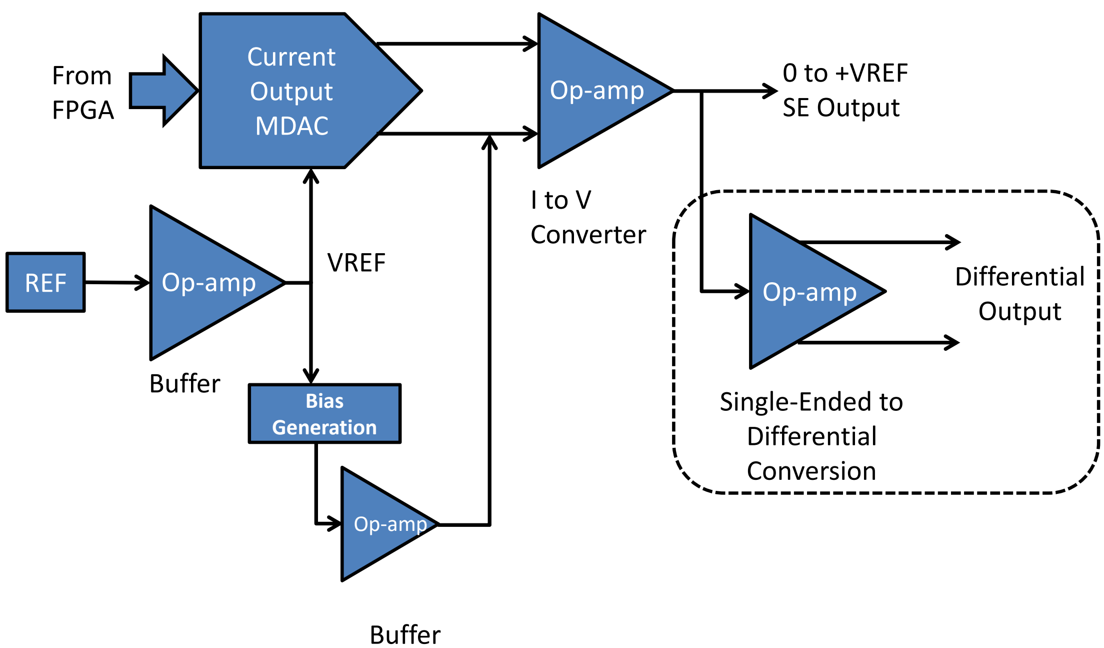


Figure 12. Using Current Output MDAC for Generating TGC Signal (Option # 2)

8 Using Two MDACs

The previous two approaches relied on DACs to provide single ended output before converting it into differential output as shown in Figure 13. This approach utilizes two MDACs to generate a differential signal. This requires that complimentary codes need to be written to the DAC channels, for example, DAC-A to zero and DAC-B to full scale is written. This approach helps in configurability but needs two channels of DACs, hence, increasing cost. There are DACs with dual-channel in a single chip. These DACs can also be used with a caution that if the write commands to the DACs are sequential; the differential signaling is achieved after the write to second channel of the DAC only.

9 Using High Speed DACs

Some DACs that support higher speeds are available with differential output. Such DACs help in interfacing the outputs directly (or with external differential buffer) with the AFEs. High speed DACs are also available with LVDS and JESD interface support. The drawback of such approach is the output voltage noise.

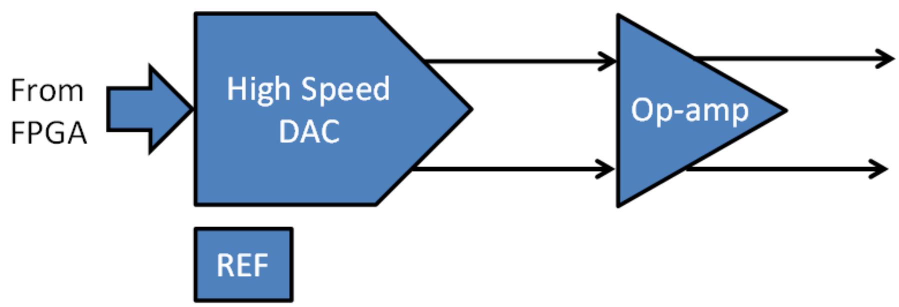


Figure 13. Using High Speed DAC for TGC Signal Generation

10 Conclusion

For any ultrasound application, TGC is an important phenomenon. The ultrasound receive AFE includes a voltage-controlled attenuator for implementing TGC functionality that operates using a control voltage generated using external circuitry. The control voltage characteristics are used for defining the external DAC and amplifier specifications. This application report explains the details of selecting DAC and amplifier and some approaches to use these circuits. Table 1 concludes with the pros and cons for each approach.

Table 1. Comparison of Different Approaches for TGC Signal Generation

Approach	Pros	Cons
Using unbuffered R2R DAC	Need positive reference	Requires external buffer
	Easier output drive	Requires reference drive circuitry to minimize the linearity errors
	Simplified output buffer design because of constant output impedance with respect to DAC input code	Higher settling time
Using current output MDAC	No buffer required for Vref as input is impedance is fairly constant	Vout is negative of reference
	Faster setting time than voltage output	Need to invert the reference
Using two MDACs	Configurability	Two channels of DAC required
Using high speed DACs	Easy interface for differential TGC signal	Higher output voltage noise

11 References

1. Texas Instruments, *LM96511 Ultrasound Receive Analog Front End (AFE) Data Manual* (SNAS476)
2. Texas Instruments, *AFE5812 Fully Integrated, 8-Channel Ultrasound Analog Front End with Passive CW Mixer, and Digital I/Q Demodulator, 0.75 nV/rtHz, 14/12-Bit, 65 MSPS, 180 mW/CH* (SLOS816)
3. Texas Instruments, *AFE58JD16 16-Channel Ultrasound AFE with 90-mW/Channel Power, 1-nV/√Hz Noise, 14-Bit, 65-MSPS or 12-Bit, 80-MSPS ADC and Passive CW Mixer* (SBAS737)
4. *TI Designs – Precision: Verified Design Single Supply Unipolar Multiplying DAC Reference Design* (TIDU300)
5. *TI Designs – Precision: Verified Design Voltage Mode Multiplying DAC Reference Design* (TIDUAF0)
6. *TI Precision Designs: Verified Design ±10V 4-Quadrant Multiplying DAC* (TIDU031)
7. *TI Designs – Precision: Verified Design Low-noise Precision Variable Reference* (TIDU543)

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