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TUTORIAL 4696

Overview of Ultrasound Imaging Systems and the Electrical Components Required for Main Subfunctions

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Abstract: This application note is an introduction to ultrasound imaging systems. It discusses the trend towards smaller, lower cost, and more portable imaging solutions, while explaining what is required to maintain the performance and diagnostic capabilities found in larger cart-based systems. The system subfunctions and electrical components for an ultrasound system are outlined. This discussion focuses on transducers, high-voltage multiplexing, high-voltage transmitters, image-path receivers, digital beamformers, beamformed digital-signal processing, and display processing.

Overview

By transmitting acoustic energy into the body and receiving and processing the returning reflections, phased-array ultrasound systems can generate images of internal organs and structures, map blood flow and tissue motion, and provide highly accurate blood velocity information. Historically, the large number of high-performance phased-array transmitters and receivers required to implement these imaging systems resulted in large and expensive cart-based implementations. Recently, advances in integration have allowed system designers to migrate to smaller, lower cost, and more portable imaging solutions with performance approaching these larger systems. The challenge moving forward is to continue to drive the integration of these solutions, while increasing their performance and diagnostic capabilities.

Transducers

A critical component of this system is the ultrasound transducer. A typical ultrasound imaging system uses a wide variety of transducers optimized for specific diagnostic applications. Each transducer is comprised of an array of piezoelectric transducer elements that transmit focused energy into the body and receive the resulting reflections. Each element is connected to the ultrasound system with fine coaxial cables. Typical transducers have 32 to as many as 512 elements and operate at frequencies from 1MHz to 15MHz. Most ultrasound systems provide two to as many as four switchable transducer connectors to allow the clinician to easily switch among the various transducers for each exam type.

High-Voltage Multiplexing

A typical phased-array ultrasound system will have from 32 to as many as 256 transmitters and receivers. In many cases, the system will have fewer transmitters and receivers than the number of available transducer elements. In these cases, high-voltage switches located in the transducer or system are used as multiplexers to connect a specific

transducer element to a specific transmitter/receiver (Tx/Rx) pair. In this way, the system can dynamically change the active transducer aperture over the available transducer element array.

The requirements for these switches are severe. They must handle transmit pulses with voltage swings as large as 200V$_{P-P}$ and with peak currents up to 2A. They must switch rapidly to quickly modify the configuration of the active aperture and maximize image frame rate. Finally, they must have minimal charge injection to avoid spurious transmissions and associated image artifacts.
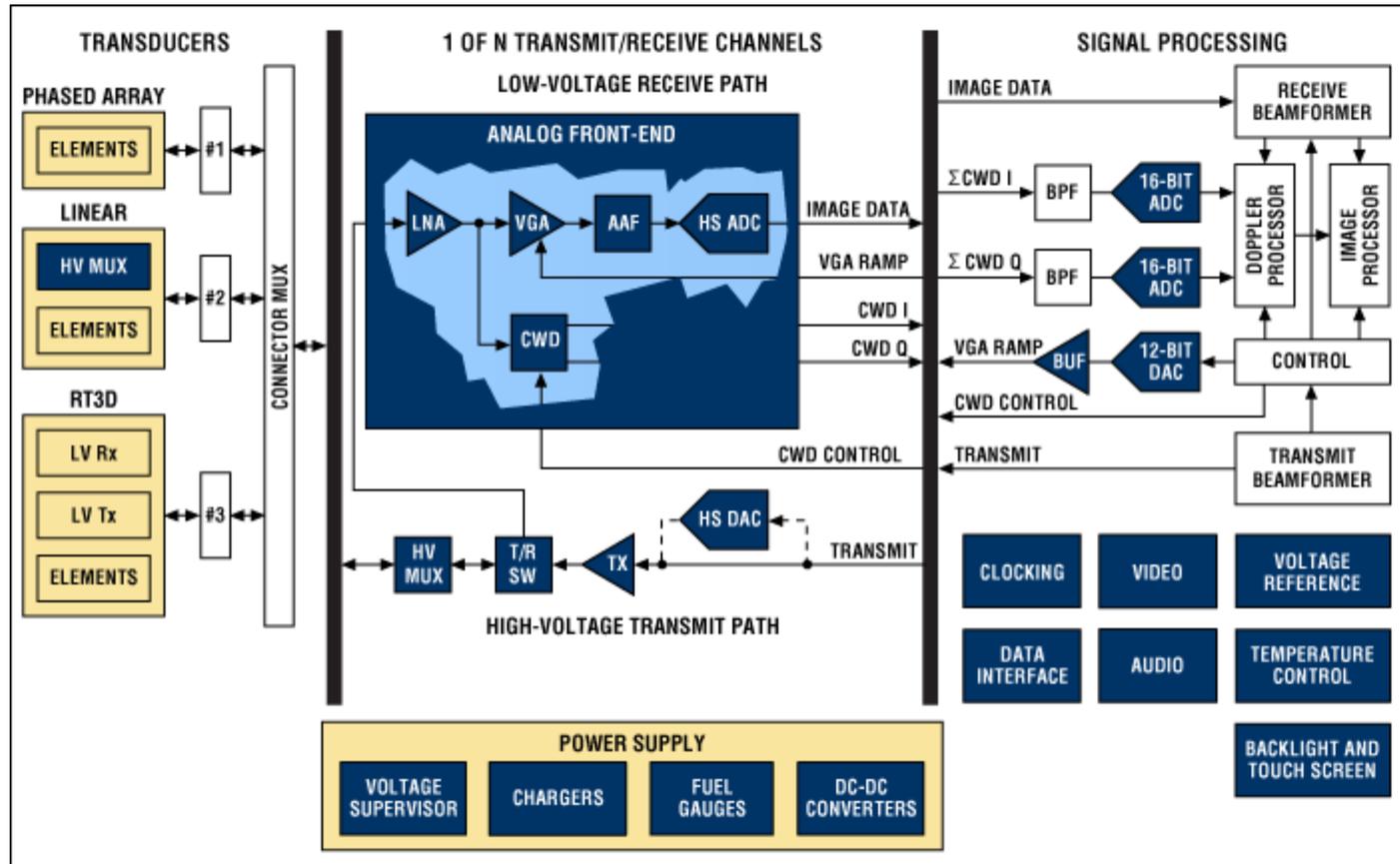

Functional block diagram of an ultrasound imaging system. For a list of Maxim's recommended ultrasound solutions, please go to: www.maximintegrated.com/ultrasound.

High-Voltage Transmitters

A digital transmit beamformer typically generates the necessary digital transmit signals with the proper timing and phase to produce a focused transmit signal. High-performance ultrasound systems will generate complex transmit waveforms using an arbitrary waveform generator to optimize image quality. In these cases, the transmit beamformer generates digital 8-bit to 10-bit words at rates of approximately 40MHz to produce the required transmit waveform. Digital-to-analog converters (DACs) are used to translate the digital waveform to an analog signal, which is then amplified by a linear high-voltage amplifier to drive the transducer elements. This transmit technique is generally reserved for more expensive and less portable systems, as it can be very large, costly, and power hungry. As a result, the majority of ultrasound systems do not use this transmit-beamformer technique, but instead use multilevel high-voltage pulsers to generate the necessary transmit signals. In this alternate implementation highly-integrated, high-voltage pulsers quickly switch the transducer element to the appropriate programmable high-voltage supplies to generate the transmit waveform. To generate a simple bipolar transmit waveform, a transmit pulser alternately connects the element to a positive and negative transmit supply voltage controlled by the digital beamformer. More

complex realizations allow connections to multiple supplies and ground in order to generate more complex multilevel waveforms with better characteristics.

The slew rate and symmetry requirements for high-voltage pulsers have increased in recent years due to the popularity of second-harmonic imaging. Second-harmonic imaging takes advantage of the nonlinear acoustic properties of the human body. These nonlinearities tend to translate acoustic energy at fo to energy at $2f_O$. Reception of these second-harmonic signals has, for a variety of reasons, produced better image quality and is now widely used.
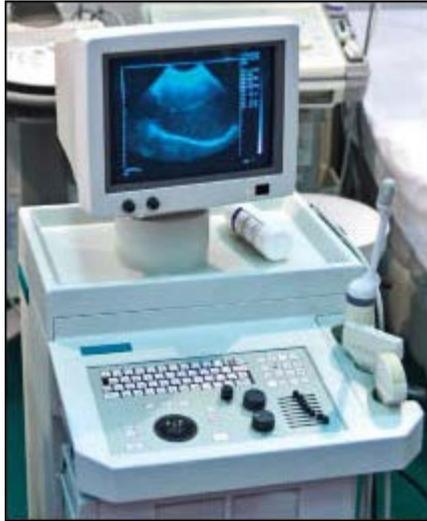
There are two basic methods used to implement second-harmonic imaging. In one method called standard-harmonic imaging, the second-harmonic of the transmit signal is suppressed as much as possible. As a result, the received second-harmonic derives solely from the nonlinear behavior of the body. This mode of operation requires that second-harmonic content of the transmit energy be at least 50dB below the fundamental. To achieve this, the duty cycle of the transmit pulse must be less than ±0.2% of a perfect 50% duty cycle. The other method, called pulse inversion, uses inverted transmit pulses to generate two phase-inverted receive signals along the same image line. Summation of these two phase-inverted receive signals in the receiver recovers harmonic signals generated by nonlinear processes in the body. In this pulse-inversion method, the summed phase-inverted transmit pulses must cancel as much as possible. To do this, the rise and fall times of the high-voltage pulsers must match very closely.

Image-Path Receivers

The ultrasound image-path receivers are used to detect 2D as well as pulsed-wave Doppler (PWD) signals necessary for color-flow imaging and spectral PWD. The receivers include a Tx/Rx switch; a low-noise amplifier (LNA); a variable-gain amplifier (VGA); an anti-alias filter (AAF); and an analog-to-digital converter (ADC).

Tx/Rx Switch

A Tx/Rx switch protects the LNA from the high-voltage transmit pulse and isolates the LNA's input from the transmitter during the receive interval. The switch is usually implemented using an array of properly biased diodes which automatically turn on and off when presented with a high-voltage transmit pulse. The Tx/Rx switch must have fast recovery times to ensure that the receiver is on immediately after a transmit pulse. These fast recovery times are critical for imaging at shallow depths and for providing a low on-impedance to ensure that receiver noise sensitivity is maintained.

Low-Noise Amplifier (LNA)

The LNA in the receiver must have excellent noise performance and sufficient gain. In a properly designed receiver the LNA will generally determine the noise performance of the full receiver. The transducer element is connected to the LNA through a relatively long coaxial transducer cable terminated into relatively low impedance at the LNA's input. Without proper termination the cable capacitance, combined with the transducer element's source impedence, can significantly limit the bandwidth of the received signal from a broadband transducer. Termination of the transducer cable into a low impedance reduces this filtering effect and significantly improves image quality. Unfortunately, this termination also reduces the signal level at the input to the LNA and, therefore, tends to reduce the receiver's sensitivity. Consequently, it is important for the LNA to have active-input-termination capability to provide the requisite low-input impedance termination and excellent noise performance required under these conditions.

Variable-Gain Amplifier (VGA)

The VGA, sometimes called a time gain control (TGC) amplifier, provides the receiver with sufficient dynamic range over the full receive cycle. Ultrasound signals propagate in the body at approximately 1540 meters per second and attenuate at a rate of about 1.4dB/cm-MHz roundtrip. Immediately after an acoustic transmit pulse, the received "echo" signal at the LNA's input can be as large as $0.5V_{P-P}$. This signal quickly decays to the thermal noise floor of the transducer element. The dynamic range required to receive this signal is approximately 100dB to 110dB, and is well beyond the range of a realistic ADC. As a result, a VGA is used to map this signal into the ADC. A VGA with approximately 30dB to 40dB of gain is necessary to map the received signal into a typical 12-bit ADC used in this application. The gain is ramped as a function of time (i.e., "time gain control") to accomplish this dynamic range mapping.

The instantaneous dynamic range of an ultrasound receiver is also very important; it affects 2D image quality and the system's ability to detect Doppler shifts and thus blood or tissue motion. This is especially true in second-harmonic imaging where the second-harmonic signals of interest can be significantly less than signals at the transmit fundamental. It is also the case in Doppler modes where small Doppler signals can be located within 1kHz or less of very large signals from tissue or vessel walls. As a result, both the broadband and near-carrier SNR is of prime interest, and is often limited by this stage of the receiver.

Anti-Alias Filter (AAF) and ADC

The AAF in the receive chain keeps high-frequency noise and extraneous signals that are beyond the normal maximum imaging frequencies from being aliased back to baseband by the ADC. Many times an adjustable AAF is provided in the design. To avoid aliasing and to preserve the time-domain response of the signal, the filter itself needs to attenuate signals beyond the first Nyquist zone. For this reason Butterworth or higher-order Bessel filters are used.

The ADC used in this application is typically a 12-bit device running from 40Msps to 60Msps. This converter provides the necessary instantaneous dynamic range at acceptable cost and power levels. In a properly designed receiver, this ADC should limit the instantaneous SNR of the receiver. As previously mentioned, however, limitations in the poor-performing VGAs many times limit receiver SNR performance.

Digital Beamformers

The ADC's output signals are typically routed to digital-receive beamformers through a high-speed LVDS serial interface. This approach reduces PC-board (PCB) complexity and the number of interface pins. The beamformer contains upconverting lowpass or bandpass digital filters which increase the effective sample rate by as much as 4x to improve the system's beamforming resolution. These upconverted signals are stored in memory and appropriately delayed, and then summed by a delay-coefficient calculator to yield the appropriate focus. The signals are also appropriately weighted, or "apodized," using an apodization calculator before summing. This step appropriately windows the receive aperture to lower the side-lobe interference of the receive beam and improve image quality.

Beamformed Digital-Signal Processing

Received, beamformed, digital ultrasound signals are processed for visual and audio output using a wide variety of DSP and off-the-shelf PC-based computer solutions. This process can generally be separated into B-mode or 2D image processing, and Doppler processing associated with color-flow image generation and both PWD and continuous-wave Doppler (CWD) spectral processing.

B-Mode Processing

In B-mode processing, the RF beamformed digital signal is properly filtered and detected. The detected signal has an extremely wide dynamic range, which the B-mode processor must digitally compress into the visible dynamic range available for the display.

Color-Flow Processing

In color-flow processing, the RF digital beamformed data is digitally mixed by using quadrature local oscillators (LOs) at the transmit frequency to do the complex mixing into I and Q baseband signals. As a result, each sample of the acoustic receive line has associated magnitude and phase values assigned. In color-flow processing, 8 to 16 acoustic lines are typically collected along the same image path line in order to measure Doppler shifts. Reflections from moving blood flow or from moving tissue along that image path will create a Doppler shift and, therefore, change the phase of the baseband I/Q samples where that shift occurred. The color processor determines the average phase shift versus time for each point along that image path over the 8 to 16 lines; the processor also assigns a color to represent that average velocity. In this way, a two-dimensional color representation of blood or tissue motion can be made.

Spectral Doppler

In spectral processing, the beamformed digital signals are digitally filtered, mixed to baseband by using quadrature local oscillators (LOs) at the transmit frequency, and then sampled at the transmit pulse repetition frequency (PRF). A complex, fast Fourier transform (FFT) is used to generate an output spectrum representing the velocity content of the

signal. The signal magnitude for each bin of the FFT output is calculated and compressed to optimize the available, visible display dynamic range. The signal magnitude is finally displayed versus time on the ultrasound display.

With CWD the signal is processed in much the same way. In addition to processing these signals for display, the spectral processor also generates left and right stereo audio signals that represent positive and negative velocities. A DAC converts these signals which are used to drive external speakers and headphones.

Display Processing

The display processor performs the computations necessary to map the polar-coordinate, acoustic image data from the B-mode or color-flow processor into the rectangular-coordinate bitmap image to avoid image artifacts. This processing is generally referred to as R-θ conversion. The display processor also performs other spatial-image-enhancement filtering functions.

Continuous Wave Doppler (CWD)

CWD is a modality available in most cardiac and general-purpose ultrasound imaging systems, and it is used to accurately measure the higher-velocity blood flows typically found in the heart. In CWD mode, the available ultrasound transducer elements are split into equal halves about the center of the transducer aperture. Half of the elements are used as transmitters to produce a focused acoustic CWD transmit beam; the other half of the elements serve as receivers to produce a focused receive beam. The signals applied to the transmit elements are square waves at the Doppler frequency of interest, typically 1MHz to 7.5MHz. Transmit jitter needs to be minimized to avoid phase-noise generation that can adversely affect Doppler phase-shift detection. The transmit beam is focused by properly phasing the signals applied to the transmit elements. In a similar way, the CWD received signals are focused by phasing and summing the signals from each receive element. Because the transmitters are on simultaneously with the receivers in this mode, the Doppler signals of interest are typically within a few kilohertz of a very large receive signal that is generated by reflections from stationary tissue at the transmit fundamental. The dynamic range necessary to handle this large signal is well beyond the range of the VGA, AAF, and 12-bit ADC in the image-receive path. As a result, an alternative high-dynamic receive solution for CWD is necessary.

CWD receivers are typically implemented in one of two ways. In one method high-performance ultrasound systems typically extract a received CWD signal at the LNA output. Complex mixers at an LO frequency equal to the transmit frequency are then used to beamform the signals and mix them to baseband for processing. The phase of the I/Q LOs can be adjusted on a channel-by-channel basis to shift the phase of the received CWD signal. The output of these mixers is summed, bandpass filtered, and converted by an ADC. The resulting baseband beamformed signal is in the audio range (100Hz to 50kHz). Audio-frequency ADCs are used to digitize the I and Q CWD signals. These ADCs need significant dynamic range to handle both the large low-frequency Doppler signals from moving tissue and the smaller signals from blood.

The other method to receive a CWD signal uses delay lines and is usually employed in low-cost systems. In this implementation signals are again extracted at the LNA's output and converted into current signals. A crosspoint switch sums channels with similar phases into 8 to 16 separate output signals, as determined by the receive beamformer. Delay lines are used to delay and sum these signals into a single beamformed signal at the RF frequency. This signal is then mixed to baseband using an I/Q mixer with an LO at the transmit frequency. The resulting baseband audio signal is filtered and converted to a digital representation.

Related Parts		
MAX1437B	Octal, 12-Bit, 50Msps, 1.8V ADC with Serial LVDS Outputs	Free Samples
MAX1438B	Octal, 12-Bit, 64Msps, 1.8V ADC with Serial LVDS Outputs	Free Samples
MAX14802	Low-Charge-Injection, 16-Channel, High-Voltage Analog	Free Samples

	Switches	
MAX14803	Low-Charge-Injection, 16-Channel, High-Voltage Analog Switches	Free Samples
MAX14805	16-Channel (Two Banks of 8-Channel), High-Voltage Analog Switches	Free Samples
MAX14806	16-Channel (Two Banks of 8-Channel), High-Voltage Analog Switches	Free Samples
MAX19526	Ultra-Low-Power, 8-Channel, 12-Bit, 40Msps ADC	Free Samples
MAX19527	Ultra-Low-Power, Octal, 12-Bit, 50Msps, 1.8V ADC with Serial LVDS Outputs	Free Samples
MAX19528	Ultra-Low-Power, 8-Channel, 12-Bit, 64Msps ADC	Free Samples
MAX2077	Octal-Channel Ultrasound Front-End	Free Samples
MAX2078	Octal-Channel Ultrasound Front-End with CW Doppler Mixers	Free Samples
MAX2079	Low-Power, High-Performance, Fully Integrated Octal Ultrasound Receiver (Octal LNA, VGA, AAF, ADC, and CWD Beamformer)	Free Samples
MAX4936	Octal High-Voltage Transmit/Receive Switches	Free Samples
MAX4937	Octal High-Voltage Transmit/Receive Switches	Free Samples
MAX4938	Octal High-Voltage Transmit/Receive Switches	
MAX4939	Octal High-Voltage Transmit/Receive Switches	
MAX4940	Dual/Quad, Unipolar/Bipolar, High-Voltage Digital Pulsers	Free Samples
MAX4940A	Dual/Quad, Unipolar/Bipolar, High-Voltage Digital Pulsers	Free Samples

More Information

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Other Questions and Comments: http://www.maximintegrated.com/contact

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