Ultrasound Analog Electronics Primer

by Bill Odom

INTRODUCTION

Modern technology is driving medical ultrasound machines to new heights of performance, resulting in images with new levels of clarity and resolution. Ultrasound is used for imaging in cardiac, obstetric, and many other diagnostic areas. Even as the abilities of the machines increase, the cost of machines is coming down. Although ultrasound relies substantially on digital processing, the key to its performance lies in a heavily analog technology. We will examine here the contributions of the analog and mixed-signal components used in ultrasound imaging. Naturally, since each element would by itself need a chapter or a book of its own to provide fully useful information for the system designer, this article is intended to provide an overview and furnish a basic understanding of medical ultrasound architecture. Though this article will barely scratch the surface of design objectives and rules; some of the issues to be raised will have relevance in a broader context of applications and are likely to be examined in greater detail in future articles.

Obtaining an Image

Images are obtained by sweeping a narrow beam of acoustic energy into a living body and analyzing the pattern of the energy reflected back by structures within the body, much like a search radar. Since the receiving transducers are dealing with analog signals, but the analysis is performed digitally, the signals must be digitized. Electrical pulses are applied to piezoelectric ceramic elements to generate the energy at transmitted frequencies from 2 to 20 MHz. The frequency used depends on the application. Higher frequencies provide the best resolution but have less penetration, since they attenuate faster as the signals move through the body. There are limits on how strong the high-frequency pulse can be, because excessive amounts of power are unhealthy for the patient. The most commonly used frequencies range from 2 to 7 MHz.

Return levels range from 1-V echoes near the surface of the body to less than 10 μV for images deep within the body. The signals are conducted to and from the ceramic elements in the hand piece to the front-end electronics via a cable, which will be subject to noise and attenuation. The wide range of signals must be amplified to 2 V for driving an analog-to-digital converter. To accomplish this, a *time-gain compensation (TGC) amplifier* is used. It will compensate for exponential signal decay by amplifying the signal by an exponential factor that depends on how long the machine has been waiting for the return pulse.

Power levels, frequencies used, amplification, and beam focus determine the clarity of the image. These things are controlled by the sonographer (technician), interacting with the system's inherent properties.

Imaging Modes Used

1. *Gray scale*—produces a basic black-and-white image. It will resolve artifacts a small as 1 mm. The display is made by transmitting bursts of energy and analyzing the return energy (as mentioned above).
2. *Doppler*—The best analogy to medical Doppler ultrasound is color Doppler weather radar. As the name suggests, Doppler modes detect the velocity of an object in motion by tracking the frequency shift of the return signal. These principles are applied in examining blood or other fluids flowing within the body. It is accomplished by transmitting a continuous wave into the body and producing a fast Fourier transform (FFT) of the return. The computational process will determine the frequency components of the signals from the body and their relationship as a function of fluid velocity. One bin will contain the fundamental transmitted frequency while other bins contain the Doppler shifted frequencies. 4× oversampling is often employed.
3. *Venous and arterial modes*—They employ Doppler in conjunction with the gray-scale mode. First the image of a vein or artery will be found. The operator will dial in a small cursor window around it. The Doppler is then engaged within the cursor area. The transmitted signal's Doppler frequency shift will be measured as discussed above. Audio will also be used with the cursor image. Venous flow produces a rushing sound (like a waterfall), while the thump of a pulse will indicate arterial flow. At the same time, blood velocity will be displayed on a digital readout. The sinus rhythm will be displayed as an X-Y plot on the screen. The velocity and rhythm displays are obtained by processing the audio signal from the Doppler shifts.

The Overall System

The block diagram (Figure 1) shows the elements of a system: transducer, multiplexer, transmitter and its beam-forming apparatus, transmit/receive (T/R) switches, low-noise amplifier, signal- and image-processing display, audio, A/D converter and its driver, the TGC amplifier. At the current state of the art, machines can employ as many as 256 channels (comprising 256 ceramic elements, amplifiers, ADCs, etc.).

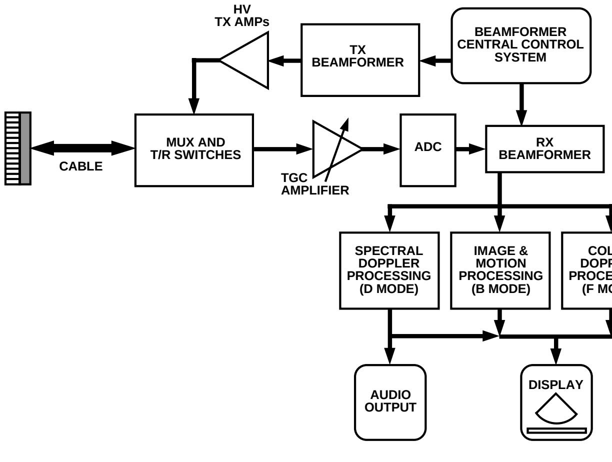

Figure 1. System block diagram.

Probes and Their Transmitted Signals

The probes will have a ceramic element for each channel (up to 256). The elements are made of a piezoelectric ceramic material such as lead zirconium titanate.

In some designs the pulses ring in bursts of a few cycles each time they get a short transmit pulse of about 100 ns ("ping and ring"). The excitation pulse amplitudes will be of the order of 100 V. The magnitude of the pulse will determine the amount of energy beamed into the patient.

In order to minimize distortion, some systems transmit a Gaussian pulse. Figure 2 contrasts the distorted spectrum of a broadband pulse after it is bounced around in the body. Its spectrum bears little resemblance to that of the transmitted pulse. The misshapen pulse will show harmonic distortion and unwanted spurious artifacts. On the other hand, the response to a transmitted Gaussian pulse spectrum looks much the same as when it went out, free of side lobes.

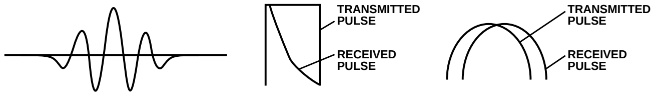

Figure 2. Waveform types (simplified): Gaussian burst, reflected flat-top pulse, and reflected Gaussian pulse.

The excitation pulse might be the output of a DAC, with the signal given the desired shape by a digital synthesizer. The low amplitude pulse will then be amplified to the required amplitude (approximately 100 V).

The receiver must have a wide bandwidth to accommodate the wide range of complex frequencies that must be handled in the DSP's FFT computation. Fast edge rates increase the demand for bandwidth.

Beam Steering and Focus

In the old days of radar, a dish or a banana-shaped antenna would rotate, looking for targets in all directions. As it slowly swept around, a magnetron would fire pulses of energy into the sky. Traveling at the speed of light, reflected energy would come back to the receiver before the antenna moved out of sync. Nowadays, the rotation is produced by phased arrays. The beam is manipulated by varying the phase and power of the signal between antenna radiators, and the beam is swept around the sky without any moving parts.

This is the same method used by medical ultrasound to sweep a beam of acoustic energy around the body. There will be programmed phase and amplitude shifts between the pulses of energy delivered to the piezoelectric elements arrayed in the transducer head. This will result in an incident beam of energy directed along a line into the body. The beam will be swept back and forth in the body like the radar across the sky.

Mux and T/R Switch

The signals to be transmitted must pass from the power amplifier to ceramics and the received signal from ceramics to the receiver. Since the 100-V Transmit and microvolt-level Receive signal must pass through the same cable, a T/R switch (transmit/receive) and multiplexer (mux) are required to steer the signals.

Receiver Beam Forming

The beam is focused by delaying each of the channels so that the return pulses from the *focal point (or area)* arrive at the processor at the same time (see Figure 3). The machine will establish the focal area as set by the operator. Beam forming is currently done with both analog and digital techniques. The machine will adjust the delay required for focus in calculating the position of the sweep line. It will compute the corresponding pixels of the display by using the delay required by each channel to focus the image. Newer machines have multiple focus zones.

Time Gain Control (TGC)

The TGC (time gain compensation) amplifier is a crucial link in the ultrasound signal path. It must have the ability to amplify signals ranging from a few microvolts to 1 volt up to one or two volts for the ADC. This gain will be exponentially increased along each transmit/receive sweep line. At the near end of the wedge, the gain will be very low. It will have to process the 1-V return signal right after the 100-V ceramic excitation pulse. As time after the excitation pulse passes, the gain will be swept into very high levels. This must be done while maintaining very low noise to avoid masking low-level signal coming from deep within the body. The operator will adjust the TGC amplifier control to improve the quality of the image. The AD604 <http://products.analog.com/products/info.asp?product=AD604> variable-gain amplifier, widely used in this application, has two channels that can accept a linear time sweep and produce an exponentially increasing gain with a 48-dB range (power ratio approaching 100,000:1).

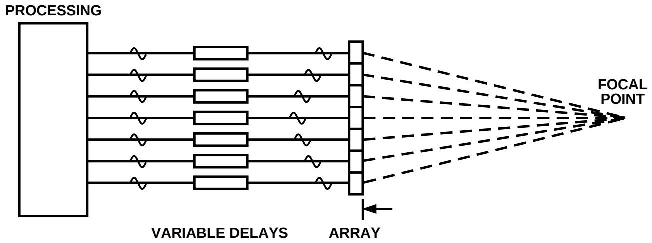

Figure 3. Beam focus using variable delay.

The A/D Converter

There are many sources of noise that combine at the input of the ADC, including body tissue, gain stages and cable noise. As the last link in the chain, it is important that the ADC itself have low noise. Its noise must not be confused with the surviving signal coming from the other components. Quantization noise is improved by using higher resolution converters. Many ultrasound systems use 10-bit converters with theoretical quantization noise of -61.7dB. Newer machines are using 12-bit converters, which bring the theoretical quantization noise down to <–73dB.

Many ultrasound designers are concerned with harmonic distortion and artifacts at frequencies close to the fundamental. Unlike a state trooper's Doppler radar, which deals with a large frequency shift when measuring the velocity of a speeding Honda, the Doppler modes of an ultrasound system measuring the velocity of blood in a vein or artery produce a shift of only a few hertz. In the FFT plot, the areas near the base of the fundamental frequency spike must be very quiet and free of spurious signals, often caused by ADC or system clock jitter, so as not to mask out this shift. Linearity of the converter is also important to the quality of Doppler ultrasound.

Low intermodulation distortion in an ADC will help to prevent the various harmonic artifacts of Doppler return from mixing to form aliases or adding to form large spurs. The reflected signals inside the body can be considered as multi-tone signals. If the ADC has poor harmonic distortion characteristics, the tones will combine with the ADC's harmonics, which could dwarf a low-amplitude return signal.

Many ultrasound manufactures use 4× oversampling for improving signal-to-noise and to reduce complexity in antialias filters. However, a 12-MHz mammography machine will need better than 48 MHz to accommodate the system. Oversampling rates are dictated by the ability of the signal processing chain to process the data stream.

Display

Once the points have been scanned, they must be displayed. Now consider how the machine places the images on the screen. It will calculate the location of a target on the screen based on the time delays from element to element in the row of ceramics in the hand piece. It judges depth based on how long it took the signal to come back from each ceramic element. The pixel values will be read out of memory and modulate the CRT trace.

The machine must compute the location of each point and add color. Perhaps it will average several received scans together. Then it will start the CRT sweep at the top of the fan-shaped display.

Harmonic Imaging

To gain the improved resolution from higher-frequency, while ameliorating the dilemma of depth of penetration vs. energy level, harmonic imaging is used. Harmonic imaging gathers increased resolution by processing the second harmonic of the fundamental transmit pulse. The harmonic is generated by the tissue itself or the use of contrasting agents injected into the tissue. This technology will put the pressure on amplifiers and ADCs to minimize additional harmonics by maintaining low harmonic distortion.

Future Component Requirements

There is an ongoing demand for lower power components. In earlier days in hospitals, portable meant that the bulky machine had big wheels, and that it could be powered from the 120-V/15-amp receptacle in a hospital room rather than the 220-V/30-A receptacles in Radiology. Nowadays, there is growing interest in installing ultrasound in emergency vehicles and making it really portable. Tendencies in component design support such momentum. For example previous high-speed 10-bit ADCs drew > 400 mW. That's a lot of power when there are 256 converters in close quarters. In contrast, the 10-bit, 40-MSPS AD9203 <http://products.analog.com/products/info.asp?product=AD9203> draws just 75 mW.

Cost has come down more than 2 to 3× from levels of a few years ago. This makes practical the use of higher-resolution, faster ADCs, such as the low-cost, 12-bit 65-MHz AD9226 <http://products.analog.com/products/info.asp?product=AD9226>.

More Things to Come

As time goes on it is logical to expect better images for less money. This will be made possible by ADC's with even higher resolutions and data rates. Many more samples can be made of reflected images as they arrive at the processor.

3-D imaging is now being developed. With these machines one can get a better overall view of an image, which can result in quicker and more accurate diagnosis and less unnecessary surgery.

More Information

Most ultrasound manufacturers maintain web sites <http://dir.yahoo.com/Business_and_Economy/Companies/Health/Medical_Equipment/Ultrasound/>. There are many technical articles and application notes available <http://dir.yahoo.com/Health/Medicine/Medical_Imaging/Ultrasound/>. Logistics prohibited the reproduction of ultrasound images here, but there are many available in cyberspace[1]. Be sure and check out 3-D images, they are awesome. So are the prospects for more widespread use of ultrasound as a rapidly maturing noninvasive imaging technology.

[1] <http://home.hkstar.com/~joewoo/joewoo2.html>

The author is indebted to Eberhard Brunner for conceiving the drawings used here.

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