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AN INVESTIGATION INTO THE ENGINEERING CONSIDERATIONS REQUIRED TO DESIGN AN ULTRA LOW NOISE LOGARITHMIC AMPLIFIER FOR AN ULTRASOUND IMAGING SYSTEM

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ABSTRACT

Ultrasound imaging instruments and other "radar" type systems frequently employ variable gain amplifiers to effectively process signals of high dynamic range. One such device uniquely suited for this task is the logarithmic amplifier. Presented in this paper are many of the key design issues and solutions concerning the enhancement of one particular company's ultrasound system.

INTRODUCTION

Ever since Lee DeForest created the first true power amplifier, uncountable man hours have been spent developing linear devices and circuits. Occasionally the need arises for a nonlinear amplifier. Logarithmic amplifiers, or log amps for short, are typically employed in systems where it is advantageous to compress a signal of large dynamic range into one of much smaller dynamic range. An ultrasound imaging instrument is one such system. These systems must recover and process signals which have been highly attenuated due to scattering and losses. In many scanners only the relative amplitude of the signal and its time of arrival are important. Log amps may be used compress these signals and allow the inspection of relative changes in the signal's amplitude as opposed to its absolute value.

There are four basic topics which must be tackled in proper order:

1) The requirements of the amplifier must be determined. A successful design requires the marriage of an amplifier to the sensor, the converse will not work.

2) Low noise design concepts must be understood before a circuit can be optimized for low noise.

3) A log amp must be chosen which will best fit the needs of the system. A "drop-in" replacement for the current amplifier is highly desirable.

4) Practical considerations always require some preplanning and compromises.

Due to publishing constraints the length of this article has been limited. The interested reader is welcome to contact the author for a more detailed report.

AMPLIFIER REQUIREMENTS

The Transducer:

The key element of any ultrasound instrument is the transducer; it is the backbone of the system. This cannot be overstressed. For an engineer or product development team engaged in the design of a new ultrasound system, the selection of the piezoelectric element will be one of the first and most important design decisions made. The two primary specifications for the finished product will be its scan depth and its resolution. To achieve high resolution, a sensor must be chosen having a characteristic frequency such that the wavelength of acoustic energy in the media will be approximately the same size as the smallest object to be sought during a scan. To achieve an adequate scan depth, the sensor must be capable of converting any returning ultrasound waves into electrical signals for processing. No amount of creative signal processing can retrieve a signal where there isn't one to be recovered.

In the system under consideration, the sensor was not specifically chosen to meet the acoustic requirements but was instead chosen to meet stringent mechanical requirements which allow the instrument to fulfill unique medical needs. This is not surprising since all designs of reasonable complexity require compromises during their construction. However, in order to meet the ever present demands of competition the manufacturer wishes to increase the scan depth of the instrument without changing transducers. Thus the engineer is faced with the task of optimizing the second most important component in the system - the logarithmic amplifier.

As mentioned above, a transducer must be selected to meet the needs of the designer and in order to meet the scan depth requirement the engineer must insure that the transducer will still provide an output in response to the waves which are highly attenuated upon their return to the probe. All electrical devices whose temperature is above absolute zero will produce thermal noise. It is this noise which represents the fundamental limit of sensor usefulness.

Determining the Transducer's Noise Level:

Noise data was not available from the transducer's manufacturer and thus it was determined experimentally. Thermal noise may be calculated from the equation [1]:

$$V_t^2 = 4\ k\ T\ R(f)\ dF \qquad (1)$$

where: V_t = total RMS noise voltage
k = Boltzman's Constant, 1.38×10^{-23}
T = temperature, °K
$R(f)$ = resistance or real portion of impedance
dF = bandwidth or element of integration

Ultrasound pulses launched by the element into the media consist of about three cycles of a 10MHz sinusoid. An examination of the spectra of this pulse showed a significant amount of energy up to and beyond 25MHz. If the instrument is to have sharp resolution then the log amp must therefore have wide bandwidth, covering the range of about 5MHz to 25MHz. With a reasonable bandwidth in hand, the overall minimal noise voltage may be predicted from equation 1.

To use equation 1, the input impedance of the complete probe assembly needed to be determined over the band of interest. Impedance measurements were made at frequencies from 1MHz to 20MHz in 2MHz intervals (the range of the available equipment). Using these data points the thermal noise was estimated by trapazoidally integrating Re$\{Z_{in}\}$ over the 1MHz to 20MHz band. These calculations showed that the thermal noise mechanism contributes about 3uV of noise voltage over this frequency range. However, the transducer is a resonant device and the resistive portion of the impedance was increasing rapidly above 15MHz. I suspect that a significant amount of noise will be contributed by the sensor in the 20MHz to 25MHz band. A conservative estimate of 6uV of noise will be used to compensate for what could not be measured.

LOW NOISE DESIGN

The Noise Model:

An excellent source of information is the book: Low Noise Electronic Design by Motchenbacher and Fitchen [4]. I can't begin to present all of the pertinent details of noise analysis without simply plagiarizing their work. However, I will point out the significant details as they apply to this project.

Motchenbacher and Fitchen recommend the following model be used for noise analysis:

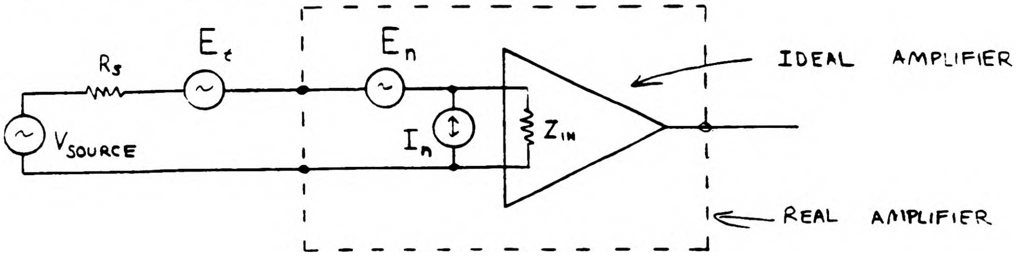

FIGURE 1, The noise model

Both E_n and I_n are required to adequately represent the function of the amplifier.

Since we are dealing with AC sources of different frequencies it is not permissible to simply add the effects of these sources. The resultant noise quantity must be calculated from the square root of the sum of the squares if the sources are uncorrelated. Since the adopted convention is to use power in all noise calculations, the square noise voltage will be handy to work with. Hence if we want to find the effect of multiple uncorrelated noise sources we may apply superposition to square of each noise source and obtain a resultant square noise voltage.

For the above noise model the expression for equivalent input noise is:

$$E_{ni}^2 = E_t^2 + E_n^2 + I_n^2 R_s^2 \qquad (2)$$

E_n may be determined by setting $R_s = 0$, measuring the amplifier's output, and dividing by its gain. I_n will be producing an input voltage via the amplifier's input resistance and thus may be found by replacing R_s with a large resistance (remove the probe from the log amp input), measuring the amplifier's output, and dividing by its gain. E_n and I_n vary with frequency, Q-point, and type of input device.

For the noise model above, it can be shown that the noise figure may be represented by:

$$NF = 10 \log \frac{E_t^2 + E_n^2 + I_n^2 R_s^2}{E_t^2} \qquad (3)$$

where $E_t^2 = 4\ k\ T\ R(f)\ dF$

It should be pointed out here that if the NF of an existing system is 3dB or lower, then at least half of the noise is emitted from the source. Further reductions in the noise of the amplifier will provide little improvement.

To obtain the smallest contribution of noise from the amplifier we must somehow adjust the input resistance of the amplifier such that the total equivalent input noise reaches a minimum value. So, do we make $R_{in} = R_s$? No! This only maximizes signal flow from sensor to amplifier, it has absolutely nothing to do with minimizing noise. To minimize E_{ni}^2, we must find R_s such that NF is at a minimum, or $dNF/dR_s = 0$. Solving for R_s yields: $R_s = E_n/I_n$. This is very important. If we have the luxury of adjusting the biasing of the amplifier (and hence R_{in}), it may be possible to minimize noise and maximize signal power flow at the same time. Unfortunately it's not that simple when R_s is a function of frequency and it's even worse when the source has resonance points. Perhaps an impedance equalizing network can be placed between the probe and the log amp. An arrangement such as this will make noise reduction much simpler.

Choosing the Best Semiconductor Device:

To achieve good noise characteristics, the signal source must be followed by the proper amplifier. Bipolar transistors are best suited as input devices in amplifiers where a low impedance source must be used (50Ω to 1KΩ). Higher impedance sources work best when followed by FET input amplifiers (R_S = 100KΩ and up). When the source impedance is very low a transformer may be required to bring the impedance up to a more manageable level.

This application would seem to call for a bipolar input stage since the average value of R_s is around 20Ω, but not just any bipolar device will do. Careful consideration must be employed when selecting a transistor. For instance, PNP devices tend to be quieter than NPN ones. Also, IC designs tend to be noisier than discrete component designs. My recommendation is to use either the MAT-02 (NPN device) or the MAT-03 (PNP device) matched differential pairs marketed by PMI Inc. [5]. The need for a differential pair will be discussed next. One last handy detail to note is that the noise performance of each of the three basic amplifier configurations is about the same (common emitter, common base, and common collector). This gives the designer some extra flexibility.

THE LOGARITHMIC AMPLIFIER

Log amps have been in existence for quite some time and consequently there are numerous versions to choose from. I believe that a log amp based upon the dual gain/lin-limit technique will be ideal for this application. A block diagram of its circuit is shown in figure 2; its operation is compared to an ideal logarithmic compression in figure 3.

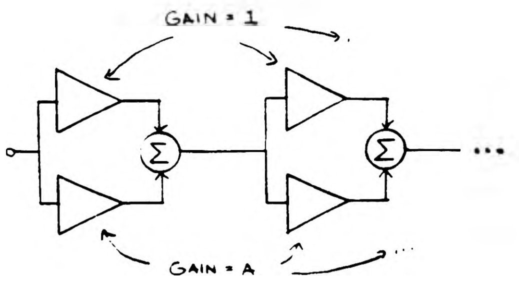

FIGURE 2

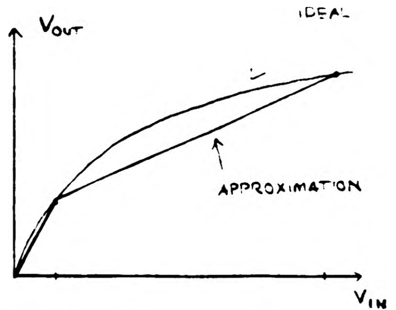

FIGURE 3

Lin-limit is a truncation of the words "linear" and "limit". The lin-limit log amp is composed of several dual gain stages. For small signals, all amplifiers will be active. For input signals of increasing amplitude, successive stages will fall into limit, reducing the overall gain, and compressing the signal. The unity gain amplifiers simply pass the signal on to following stages and must be prevented from falling into limit [1,12].

The log amp's output will eventually be processed through a detector where the amplitude of each echo will be extracted and measured. The lin-limit technique allows the use of only one detector as opposed to other designs which incorporate multiple detectors. Since the current system also uses only one detector the proposed log amp could therefore serve as a "drop-in" replacement for the current circuit.

Since this particular system does not require precise logging action, a few stages of higher gain will suffice. This is important for two reasons. First, fewer stages allows for a simpler and smaller circuit. Second, a low overall noise figure requires that at least the first stage have high gain. The differential amplifier seems to be the best candidate for the dual gain stage. It is of common emitter design and provides a high power gain. Perhaps most important of all is the fact that differential amplifiers do not saturate. Saturation causes amplifiers to become sluggish. A basic schematic of one dual gain/lin-limit stage is shown below. Note that the collector resistor provides a convenient summing point:

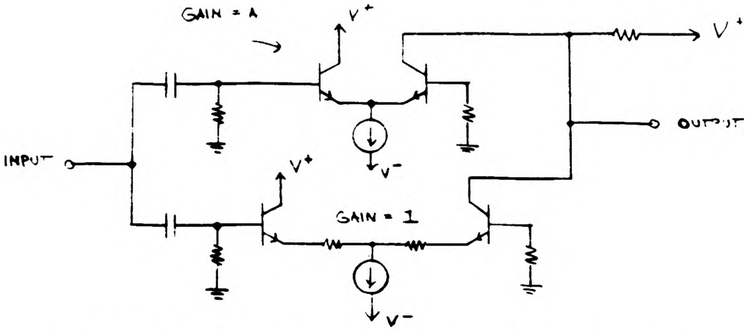

FIGURE 4, The dual-gain stage

The log amp which is currently in use has a theoretical small signal gain of 105dB, or 178,000 V/V. However, only about 80dB of the 105dB is available for use since noise and low level oscillations use up its first 25dB of amplification. This is no simple problem to overcome. For the replacement amplifier, four dual gain stages each with a small signal gain of about 18 will provide an overall gain of 105dB.

PRACTICAL CONSIDERATIONS

Rarely does a circuit behave exactly as we would like it to and so is the case with this log amp. In practice there are hundreds of decisions to be made before the final product emerges, too numerous to discuss here. However, there are a few key points which will be addressed:

1) Limiting the amplifier's bandwidth.
2) Grounding and shielding precautions.
3) Justifications for using linear circuit theory to analyze a non-linear amplifier.

Limiting the Amplifier's Bandwidth:

There are two fundamental problems experienced by the designers of high gain/high bandwidth amplifiers:

1) Bandwidth breeds noise.
2) High gain helps promote the threat of oscillations.

As discussed above, noise voltage increases with bandwidth; however, resolution requires bandwidth. To resolve this conflict more compromises must be made. It is difficult to say exactly where the log amp's cutoff points should be placed. Cutoff frequencies of about 5MHz and 25MHz should be adequate and some experimentation will be required. These figures were chosen after viewing the spectra of the ultrasound signals on a spectrum analyzer, they are not values which must be strictly adhered to.

More threatening is the possibility of rampant oscillations. Oscillations are almost unavoidable in situations such as this and if not minimized they will "use up" the small signal compression capabilities of the log amp and thus limit the system's useful scanning depth. To perform this feat, several sources recommend placing a bandpass filter in the middle of the log amp [1,7].

Filter design is an art in itself. However, after sifting through various texts on the subject there is one filter was found which has some promising features: the Gaussian-Transitional filter [8]. This filter follows a Gaussian frequency response out to a cutoff frequency after which it changes to a Chebyschev response. A relatively high order will be required for the bandpass filter since the log amp will be applying more amplification to the smaller signals.
Perhaps neutralization may be helpful in stubborn cases.

Grounding and Shielding:

Proper grounding and shielding techniques are often over looked in the initial design stages. It has always been my philosophy to install what ever may be necessary in the preliminary stages rather than scramble to squeeze them in later when things go awry. A high gain amplifier such as this will be prone to oscillations if improper or insufficient techniques are applied.

There are three points which require recognition. First, careful attention must be applied to the circuit layout. Often neglected is the return path that each signal must use. It is critically important to follow the physical path from each high frequency source to its load **and back again** to its source. If the returning signal is forced to wander very far from its outgoing path, a larger than necessary loop will be enclosed by this current and an extra inductance will be created in the circuit. Unwanted mutual inductances may easily couple energy from the log amp's output back to its input causing oscillations.

Second, I highly recommend that each half of the log amp be placed in a metal enclosure containing three compartments, two for each half of the log amp and one for the filter which joins the two. Also, be careful to avoid mounting the filter coils in a manner which allows mutual coupling, this can severely alter its frequency response.

Third, don't forget to apply proper grounding and shielding techniques to the rest of the system. One particular source of noise which must be carefully suppressed is the scanning motor which resides in the probe along with the transducer. Currently the positive lead of the motor connects to the system via a small choke while the return lead of the motor does not. A significant improvement in noise suppression may be obtained by feeding power to the motor through a bifilar wound coil. This device will insure that both motor leads are isolated from the system. I have observed a few cases in the past where brush noise was traveling from the commutator, out through the "unchoked" motor lead, and back to the commutator via the motor case. The addition of bifilar chokes completely severed all troublesome loops and eliminated the interference.

Justification for Using Linear Circuit Theory in a Non-Linear Circuit:

By now I'm sure that the attentive reader has wondered why linear circuit theory has been applied to a nonlinear amplifier. The lin-limit design is only an approximation of an ideal logarithmic response. Lin-limit log amps are constructed of linear amplifiers and their transfer functions are piecewise linear. Thermal noise is only troublesome when its level is near that of the smallest signals to be processed. When this occurs, the lin-limit log amp will be operating in its first linear segment. As long as the amplifier operates within the first linear segment, the application of linear circuit theory is permissible.

CONCLUSIONS

This project was initiated by the desire to increase the scan depth of an existing ultrasound scanner. The current system is unshielded and is troubled by noise and low level oscillations. Presented in this paper are guidelines which the manufacturer may follow to upgrade the system. A four stage lin-limit log amp incorporating dual gain stages will be an ideal replacement. The amplifier should be divided into two halves and a high order Gaussian-Transitional bandpass filter placed between them. The entire three module assembly should be placed in a metal shielding enclosure having separate compartments for each module. Once assembled, few modifications will be required of the existing system and this assembly will be a near drop-in replacement for the current log amp. Finally, all sources of interference within the system should be minimized. One such conspicuous source is the scanning mechanism drive motor. The use of a bifilar choke to isolate it from the rest of the system is highly recommended.

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