Improving ultrasound imaging with integrated electronics

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Abstract-
This paper presents an integrated electronic preamplifier design based on discrete components and evaluates its impact on image performances. The electronic, located close to the transducer, incorporates all useful functions to ensure compatible direct connection with most ultrasound scanners available on the market today. People who has worked on this subject know that numerous challenges and problems have to be overcome : high voltage bypass, preamplifier protection cells, miniaturization, power dissipation, electronic stability and many other constraints. We will discuss different unavoidable tradeoffs, starting with electrical performances and then with practical aspects. Our electronic solution has been evaluated with different probe configurations, namely a 5 MHz Phased Array and a 9.5 MHz Linear Array probe. Images have been acquired and analysis of signal to noise ratio (SNR) performed to quantify the gain in image quality.

I. INTRODUCTION

Nowadays, many efforts are made to improve performances of transducers to fit with the new specifications required by recent ultrasound systems.

For ultrasound probe manufacturers, working on the acoustic material is the most common way to reach this goal. The objectives to fulfill are always challenging. Sensitivity, bandwidth and homogeneity have to be increased while crosstalk between channels has to be lowered.

Improving all these different characteristics becomes mandatory to increase significantly the image quality and depth within a given frequency range.

Currently, the main path of investigations explored comes essentially from mechanical and material adjustments around the ultrasound piezoelectric material. Typical adjustments consist in modifying geometric aspect, piezoelectric substrate composition and arrangement [7], backing, matching layers and lens.

To meet these new requirements, some answers can effectively be found by acting directly on each mechanical component of the transducer but other significant improvements may also be made by working on the immediate transducer electrical interface and its corresponding electrical path (typically micro coaxial) to the ultrasound system. One knows [1] well the important energy losses which exist because of large impedance mismatch between a typical 50 ohms coaxial cable and the active material. An ideal transducer should present a 50 ohms real part impedance on its whole bandwidth to ensure optimal power transmission. Unfortunately, its high-tuned nature and its dependence on acoustical charge actually prevent us from meeting these requirements. In order to obtain the least bad power transfer between the transducer and the cable (hence toward the ultrasound scanner preamplifier), a tuning network may be used. The simplest circuit is an inductor being the complex conjugate impedance of the input impedance of the transducer calculated at the resonance frequency. However, such passive adjustments may bring some drawbacks inherent in network configurations and components. Tuning network exhibits the best result at a specific frequency, generally the center frequency of the transducer, but its effectiveness is reduced as one moves away from this point. Inductors may also have some homogeneity defaults. Besides, it is often necessary to take care about board design in order to avoid electromagnetic crosstalk. In other specific cases, we can also notice noise generation or couplings by magnetostriction effect.

These issues, combined with losses in the micro coaxial cable (typically 2 to 3 dB @ 10 MHz over the cable length), contribute to increase distortion, degrade the signal to noise ratio and consequently reduce the quality of image especially on far-field.

According to what we discussed previously, it is obvious that preamplifiers integration closest to the transducer has to be designed and evaluated in order to further advance performances of the imaging system [1].

Figure 1 shows a functional diagram of a typical configuration.

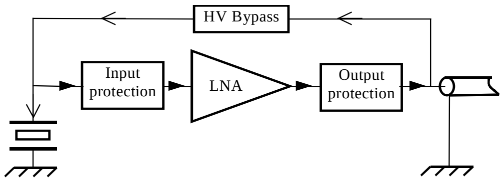

Figure 1 : Functional block diagram of a transducer preamplifier

II. DESIGN

Protection circuit is one of the main problems that we have to face, given that we need to use the same path to transmit HV pulses above 100V from the ultrasound scanner, and be able to apply an amplification on the returned echoes few hundreds of nanoseconds later. Many studies [2-4] have been undertaken trying to find acceptable tradeoffs between load, recovery time, noise and power consumption.

Our first choice has been to focus on a very common circuit based on diode bridge principle [4]. However, for power dissipation considerations, poor power supply rejection and many other evident reasons described in article [5], we chose a protection circuit using high breakdown voltage (250V) MOSFET transistors connected in a symmetrical current generator configuration as shown in Figure 2.

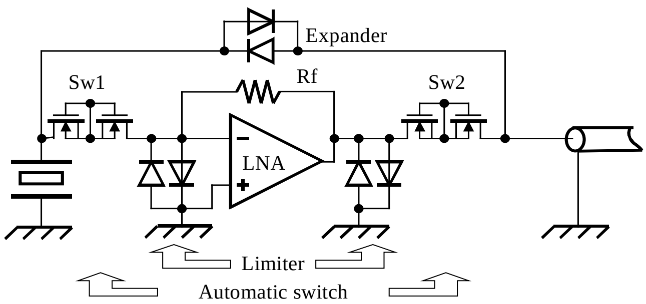

Figure 2 : Preamplifier and protection circuit for ultrasound transducer

To further protect the preamplifier, two back to back coupled diodes were added to both sides of the preamplifier.

During emission, the expander diodes conduct and the power is transferred to the transducer. Then, entering receiving mode, expander diodes stop conducting, thus allowing weak signals to be driven to the preamplifier input.

As previously mentioned, a lot of functionalities have to be dealt with and it may be necessary to promote some features at the expense of others, so that the overall tradeoff fits best with our application. During the preamplifier design the emphasis was put on:

- Power consumption: effective power management and cooling strategy are important since we can only dissipate a limited amount of heat within the probe handle. Operational amplifiers featuring low power consumption are available but they unfortunately demonstrated both poor bandwidth and noise performances.
- Stability: inverting preamplifier configuration was preferred. This topology prevents from latch up or oscillation phenomena via HV bypass and ensures DC stability in comparison with non-inverting configuration. In the same objective, particular attention was taken to avoid the use of reactive components in the preamplifier chain. Furthermore, this disposition contributes to reduce ringing and overload phenomena which are major drawbacks as long as each line should be able to transmit HV pulses to the transducer and receive faint backed-echoes immediately after. Finally, experiments confirm that the choice of the current amplifier configuration is more suitable than the voltage gain in presence of parasitic capacitance.
- Space saving: Operational preamplifiers require less external components than their discrete counterparts (just one feedback resistor and mandatory decoupling capacitors).

The best configuration that was defined to choose the preamplifier comes with the following characteristics.

Main receiving characteristics for one cell	
Current consumption at power supply ±3V	3.45 mA ≈20mW/Chanel
Gain	20dB (50 Ω input/output)
Bandwidth[1]	DC to 41 MHz (50 Ω input/output set-up)
Noise RTI[2]	2nV/sqrt(Hz) (50 Ω input) + LNA 20dB
Input impedance[1] @ 5 MHz	Low, $\lvert Z_{in}\rvert$=20Ω, depends essentially on MOSFET RDSon
Output impedance[1] @ 5 MHz	$\lvert Z_{out}\rvert$=23Ω
Crosstalk between two adjacent channels[1]	-48dB at 1MHz -40dB at 10MHz
Gain dispersion[1]	±0.5dB
Recovery time	Less than 1µs
Number of discrete components	11

[1] Measurement on Agilent® E5100A.
[2] Noise measurements were done by measuring RMS voltage with Tecktronics oscilloscope TDS3024B (input bandwidth limited to 20MHz). A 20dB Low noise preamplifier (OPA847) was inserted to be sure to be above the instrument's noise level.

III. IMPLEMENTATION

For the first implementation, it was decided to work with a base of 32 channels and 16 channels per board respectively of 75x34 and 75x18 mm (Figure 3). The board sizes have been defined large enough to make layout, assembly and testing easier. All 32 preamplifier cell components populate each side of the circuit. 1.27mm pitch connectors are used to interface inputs, outputs and power supply with the coaxial cables.

To address more than 32 channels, several cards can be plugged together to a backplane board located on the back side of the transducer. This board enables both mechanical and electrical connections between all the preamplifier boards. The outputs of the preamplifier are fed to the receiving stages of the ultrasound system via standard bulk coaxial cable interface. The Figure 3 illustrates this configuration through the use of 128 and 64 channels arrays.

Figure 3 : From left to right picture of 9.5 MHz 128 elements linear array (pitch=200µm) and 5 MHz 64 elements phased array (pitch=150µm).

IV. EXPERIMENTS AND RESULTS

A. Electro-Acoustic characterization

Evaluation of the preamplifier SNR improvement with different configurations of acoustic arrays was made by using pulse-echo measurements on a flat target immersed in water tank.

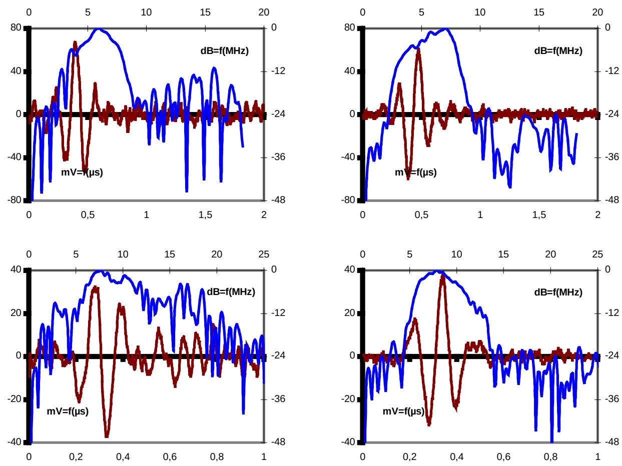

Figure 4 : Experimental elementary time and frequency pulse-echo responses of PA5 (top) and LA9.5 (bottom) reflected from water silicon rubber interface without preamplifier (on the left side) and with preamplifier (right side) .

To reduce the overall signal to noise ratio of the element under investigation, a weak reflectivity target (silicone rubber) was used and positioned in far-field : 110µs for PA5 and 235µs for LA9.5. Measurement settings are as follows : Parametrics® 5072 pulser/receiver; Energy = 1; Gain 40 dB without preamplifier and 20 dB with preamplifier. Qualitatively Figure 4 shows a significant improvement of the SNR which will be confirmed with B-mode image analysis.

B. Ultrasound imaging characterization

A quantitative assessment on B-mode ultrasound images is performed with different probes (piezocomposite linear and phased arrays, CMUTs array). Ultrasound phantom images are acquired and different algorithms can process image assessments with quantitative parameters such as SNR, resolutions or contrast [6].

Transducer's heads are connected with and without electronics to a clinical ultrasound system. Between ultrasound images, only the variable gain amplification (VGA) of the ultrasound system will be objectively adjusted to compensate the presence or not of the electronics. The system gain is fixed to have interpretable images without preamplifiers, thus closely to the maximum limit of the system. When preamplifiers are inserted, the system gain is decreased until we get comparative images reaching the same mean intensity level (sum of all squared intensity pixels within the image).

The here below graph exhibits SNR behavior as a function of depth for a typical linear array probe without preamplifiers. SNR is shown for different values of the variable gain amplification (VGA) of the system. Under a 60% VGA value, the image looks too much dark and will be useless in a diagnosis stage. Furthermore, these curves demonstrate that above 60 % VGA, SNR tends to a constant maximum value. It emphasizes that useful signal is amplified by the gain system, but also electronic noise with a comparative level.

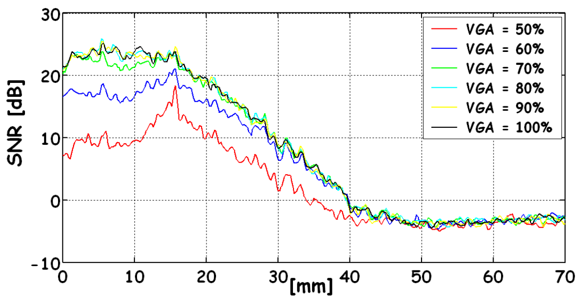

Figure 5 : Example of SNR behaviour as a function of image depth for different values of VGA (linear array probe without electronics).

The depth where SNR falls below 0dB means that no more distinctions can be done between electronic noise and signal on the ultrasound images. This threshold will be used as the penetration depth parameter and correlates well with visual sensation. Hence, according to Figure 5, increasing system gain doesn't result in any improvement neither in SNR, nor in penetration depth.

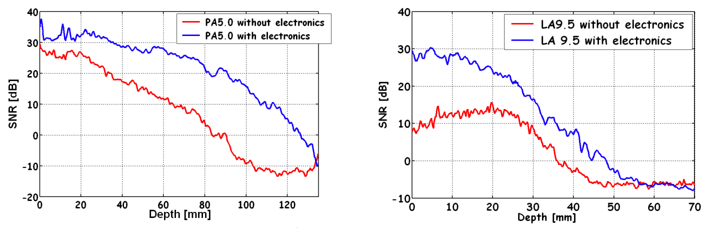

Figure 6 : Comparisons of SNR with LA 9.5 and PA5.0 probes

The SNR is also presented in Figure 6 for two investigated probes with and without electronics. The PA5.0 probe shows an improvement of the SNR (10-20dB), and a significant additional depth of penetration (33mm).
The LA9.5 probe exhibits more specifically a relevant SNR enhancement in near-field (20dB) and a penetration depth increase of 12 mm.

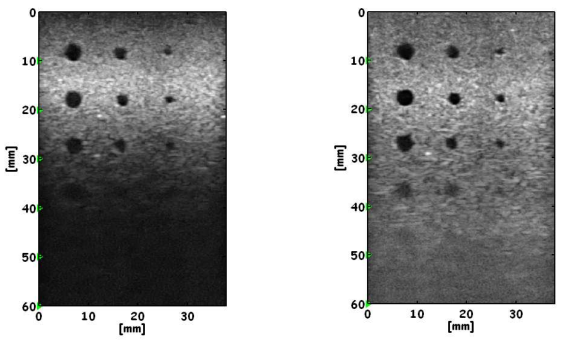

Figure 7: Anechoic targets for LA9.5 probe (from left to right VGA at 100% without electronics & 57% with electronics)

We observed that better SNR results in a deeper penetration (Figure 7), allowing the observation of additional structures or tissues. Moreover, it gives us a boost in other imaging performances. For instance, the lateral resolutions (Figure 8) calculated in near field are significantly enhanced with the LA9.5 combined with electronics. For the PA5.0, another example is presented in Table 1 where the correlation coefficients between anechoic targets and perfect numerical targets are found superior, thus demonstrating a better sensitivity to high contrast.

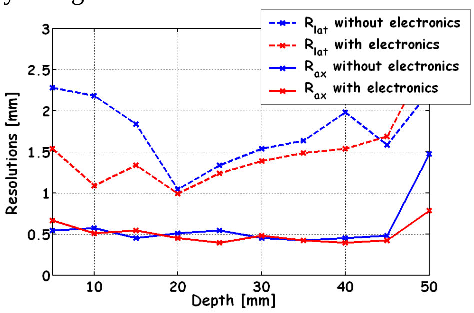

Figure 8 : Lateral resolutions results for the LA9.5 probe

PA5.0 Target Diameter	without electronics	with electronics
4mm	0.70	0.76
3mm	0.58	0.66

Table 1 : Averaged values of the correlation coefficients from anechoic targets computed for the PA5.0 probe.

V.CONCLUSION

We described a preamplifier topology compatible with most ultrasound system architectures, able to significantly increase the SNR (at least 10dB) while maintaining or improving image resolution characteristics. This design has been qualified with different piezoelectric transducer configurations (PA5 and LA9.5). Expected improvements in terms of penetration depth have been effectively demonstrated. Moreover, an unexpected gain in lateral resolutions and contrast has also been noticed. During this work, although not presented in this paper, other investigations on CMUTs (Capacitive Micromachined Ultrasonic Transducers) were conducted with comparable improvements in imaging performance.

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