IMPACT OF ELEMENTS SENSITIVITY AND PULSE EXCITATION ON PHASED ARRAY IMAGING

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Abstract

Ultrasonic inspection using phased-array technology is reaching a stage of maturity in many countries. Although most concepts used in conventional NDT still apply, phased-array has its own specificities that change the way we need to think about them. This paper presents the impact of the element sensitivity variation on the echo-transmittance curve pattern. It can be demonstrated that variations in elements sensitivity significantly impact the usual echo-transmittance patterns found in conventional UT. Experimental results present typical curves for linear array and demonstrate how both angular corrected gain and time corrected gain features can compensate for these variations.

The second part of this paper revisits the way an array transducer can be excited. With the advances in transducer array manufacturing and material properties, NDT equipment manufacturers now have access to high quality, large bandwidth transducers. Experimental results using negative square pulsing, bi-polar pulsing and spike pulsing are presented, with their impact on pulse duration, echo amplitude and overall signal quality.

Part 1 – Echo-Transmission - Introduction[1]

The basic physics principles of beam divergence, near field and far field sound pressure are still fully valid when performing phased array ultrasonic inspection. It is important to have a deep understanding of these concepts to avoid erroneous measurements. As phased array transducers are composed of multiple elements, typically ranging from 16 up to 128 elements, the echo-transmission at the wedge/part interface is significantly affected by the elements sensitivity uniformity. This first part of the paper presents the preliminary results obtained when measuring echo-transmittance.

[1] Please take note that at the time of publishing this paper, data analysis was still being completed. Consequently, only preliminary results are presented. Exhaustive analysis will be presented at conference time.

Echo-transmittance curves were obtained using a 5MHz 32 elements transducer attached to a 35 degree crosslinked polystyrene shoe, commercially known as rexolite. A sectorial scan with angle sweep of 30° to 75° was defined. The first 16 elements of the array were used when the array was positioned on a IIW block. The sensitivity of each element is shown below.

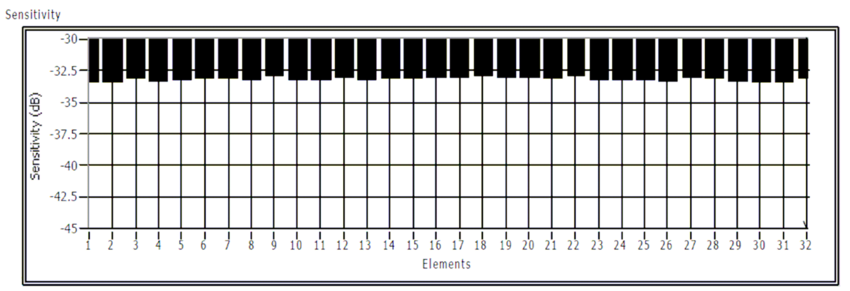


Figure 1: Element sensitivity with a max deviation from average of 0.31 dB

Echo-transmittance curve

Figure 2 shows a typical example of the echo transmittance curve obtained with such a setup. Compared to the theoretical figure provided by Krautkrämer (Figure 3), it appears clearly that lower angles are more affected than higher angles. This interesting result demonstrates that with phased array, the beams formed at lower angles are those suffering the most prominent sound pressure loss due to the low contribution of each element.

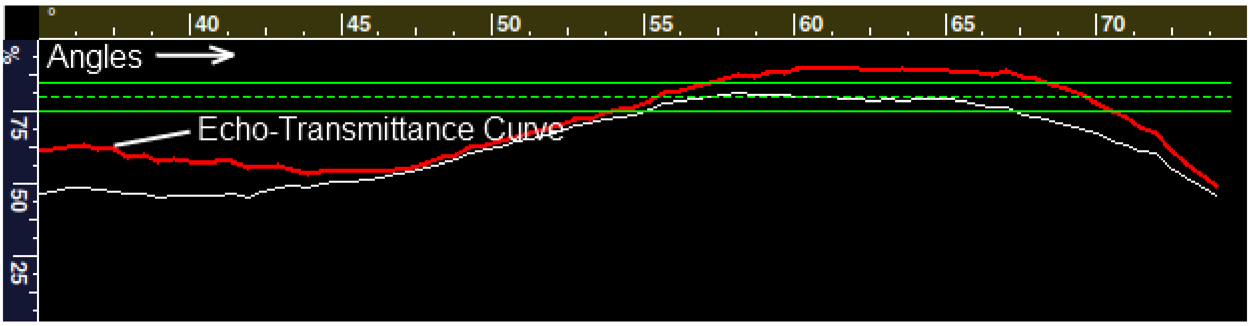


Figure 2: Example of echo-transmittance curve on IIW radius at 100mm with an unfocused array transducer

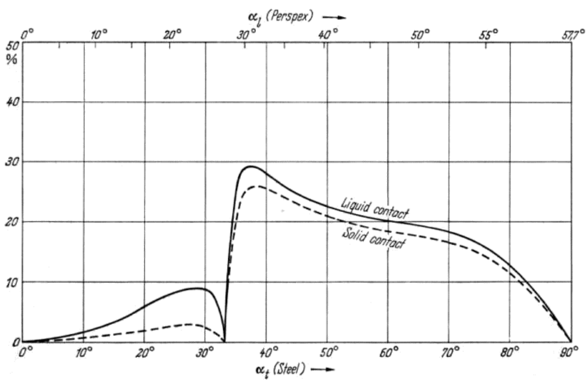


Figure 3: Echo-transmittance curve for a Perspex/Steel interface.

A good example of element contribution effect can be illustrated by considering a -12dB and a -6dB shut-off threshold. This threshold is based on the theoretical beam divergence equation provided by

Krautkrämer. In other words, for a given element, if the beam divergence reaches the shut-off threshold, then this element is considered as not contributing enough to the beam forming and is turned off.

Table 1: Example of element contribution at low angle

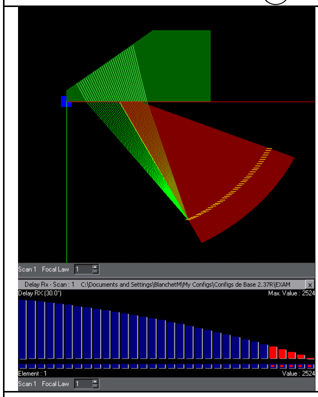
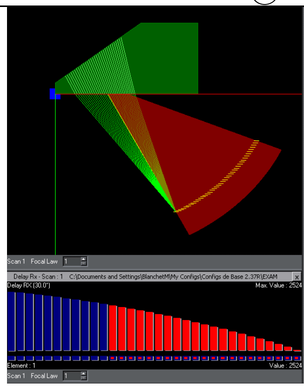
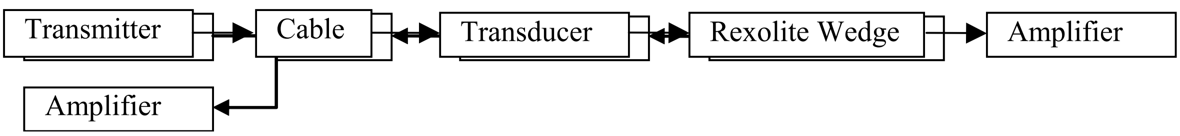
Setup with a 5MHz 32 elements array attached to a 35° wedge, S-scan ranging from 30° to 70°	
Shut-off threshold @ -12dB	Shut-off threshold @ -6dB
	
4 Elements turned off on first beam	21 Elements turned off on first beam

Table 1 shows that by using a threshold of -12dB, only 4 elements would be turned off (red bars), while using a -6dB threshold would result in 21 elements being turned off. Hence, the energy sent by the elements located in the upper part of the array quickly decreases at low refracted angles. Each echo-transmittance curve pattern generated by this method would then differ from a pattern obtained with a conventional crystal. Further study of the element sensitivity variation will reveal that they have a measurable impact on echo-transmittance patterns.

Part 2 – Pulse drive shape - Introduction

While designing a phased array system, various avenues have to be explored in order to get the best performances out of the array transducer. As ultrasonic phased array units are predominantly broad band systems, they cover a wide range of frequencies, typically from 1MHz to 20MHz. The impedance between the phased array unit and transducer-cable assembly should ideally match perfectly to insure an ideal energy transfer. However, since impedance depends on frequency; no specific tuning can be performed on the system side to insure a perfect match with all transducer frequencies. Therefore impedance tuning has to be done on the transducer-cable assembly side. In the figure below, we illustrate that the signal goes from the transmitter to the amplifier through the cable, the transducer and the wedge. At the interface of each of these components, the signal is affected by a certain level of impedance mismatch. This mismatch, although directly affecting signal quality, can't be controlled by the instrument itself. Hence, in this study, the influence of the pulse shape is examined, and its effect on the signal quality is demonstrated.



Co
mponents affecting signal quality between transmitter and receiver

Tests conducted in this experiment have been carried on a 32 elements 5MHz array transducer with an elevation of 12 mm and a width of 0.762 mm. The transducer specification sheet indicates an average bandwidth of 97% and ringdown time at -20dB of 191ns. A negative voltage of up to 300V is supported. The array was attached to a flat 25.4mm thick crosslinked polystyrene shoe. The last matching layer of the transducer has been designed for this material. Comparison tests have also been carried out using transducers at frequencies of 2.25MHz and 7.5MHz respectively.

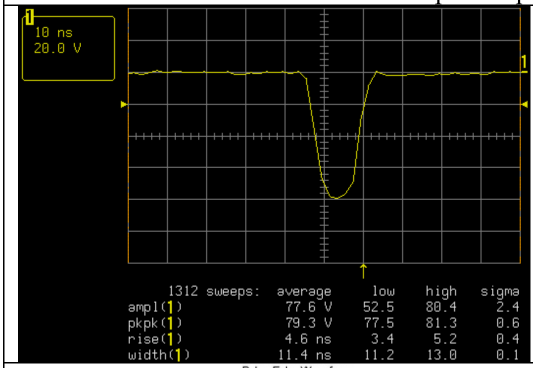
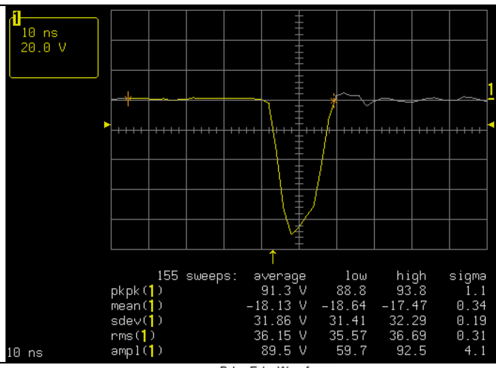
The phased array unit used for these tests has an output impedance of approximately 20 Ohms. Compared to a conventional unit with a typical output impedance of 5 Ohms, this value seems considerable. However, since the phased array unit has 16 actives pulsers and use multiplexers to pulse over up to 64 channels, the impedance is higher due to the additional multiplexing circuitry. On the other hand, we can attain an efficient energy transfer by deactivating the damping resistor during transmission and by using it in reception to obtain a 50 Ohms input impedance, which allows a better match with the coaxial cable.

Effect of pulse drive shape

The choice of the driving waveform can significantly affect the signal to noise ratio (SNR) and the strength of the pulse-echo amplitude. Spike impulses pulsers are widely used on the market because they are easy to manufacture and produce a short pulse length, generally associated with a broad bandwidth. However, the crystal generally doesn't have a resonant frequency that match the spike impulses driving it, resulting in weak echoes. In that case, square unipolar pulses might be preferred, since a better control of the pulse width can be achieved and a short pulse length can still be obtained. Because of that improved control, transducers can be excited at their resonant frequencies. Bipolar pulses require a more complex push-pull circuitry but have the advantage of generating stronger pulses, achieving better SNR. The pulse width, as in the case of the unipolar pulses, can also be controlled extremely well insuring uniformity over all phased array channels.

Shown below are various pulse shapes with the resulting pulse-echo waveform using the 5MHz transducer. The pulses shown have been acquired by pulsing into a resistive load of 50Ohms. Two different hardware platforms were available. Setup E had the ability of performing pulses ranging from -100V to +12V (with no load) while Setup G could go from -100V to +100V (with no load). The pulse width (PW) and the voltage (V) with no load are indicated in the table. Each pulse-echo waveform has been obtained by pulsing into a rexolite shoe while maintaining the instrument gain at 10dB for Setup E and 4dB for Setup G. Amplitude values of Setup G can be doubled to compare them, because of the 6dB differences, for these specific images.

Table 2: Images of pulse drive shape in a 50 Ohms load and echo waveform into a rexolite wedge

<table>
<tr><td>Setup E</td><td>Setup G</td></tr>
<tr><td colspan="2">Spike impulse with PW=10ns and V =-100V</td></tr>
<tr><td>
</td><td>
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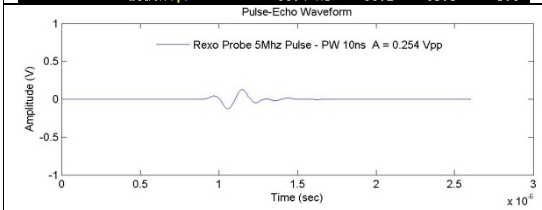
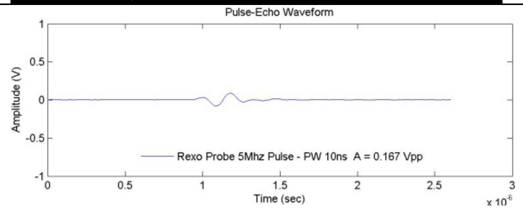
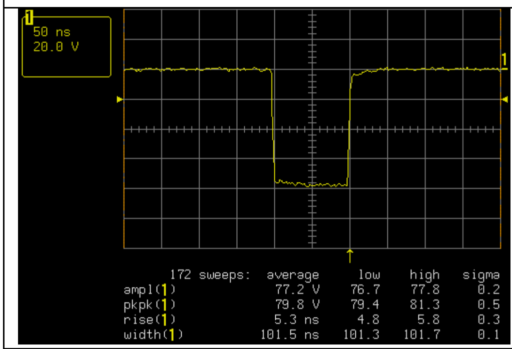
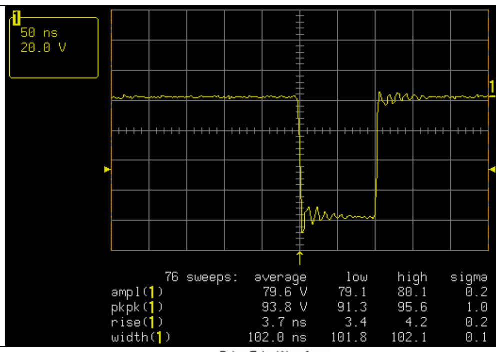
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Negative unipolar pulse with PW=100ns and V=-100V</td></tr>
<tr><td>
</td><td>
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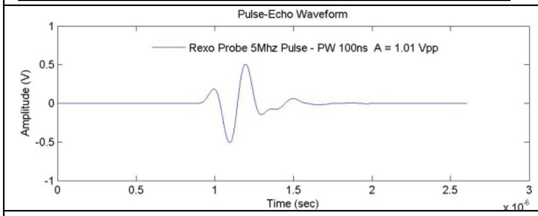
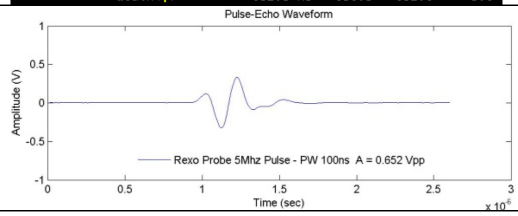
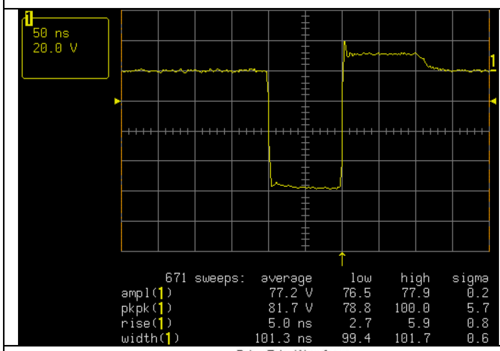
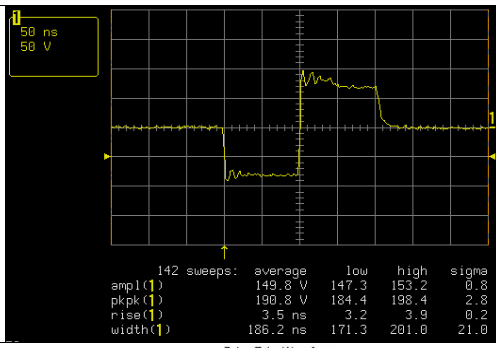
<tr><td>
</td><td>
</td></tr>
<tr><td>Bipolar pulse with PW=100ns and V= -100 to +12V</td><td>Bipolar pulse with PW=100ns and V= -100 to +100V</td></tr>
<tr><td>
</td><td>
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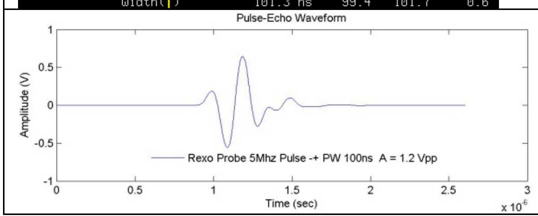
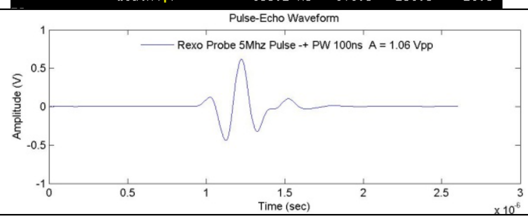
<tr><td>
</td><td>
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In order to see the effect of the pulse shape on the various parameters affecting signal quality, pulse-echo waveforms have been acquired over a wide range of pulse width. This approach facilitates the interpretation of the four selected parameters as a function of the pulse width and pulse drive shape.

By looking at chart 1[2] we can notice that whatever the pulse shape, the optimal amplitude response is always obtained with a pulse width of approximately 85ns which is slightly under the theoretical value of 100ns for a 5MHz probe. However, this result does vary of a few nanoseconds from one element to another on an array transducer. Thus, an average value has to be used when setting the pulse width on a phased array unit.

These curves also clearly demonstrate that spike impulses, in this case represented by pulse width values under 40ns, can't generate strong pulse echoes. Hence, higher voltage and/or higher gain are required to reach the equivalent signal strength of a unipolar or bipolar square pulse.

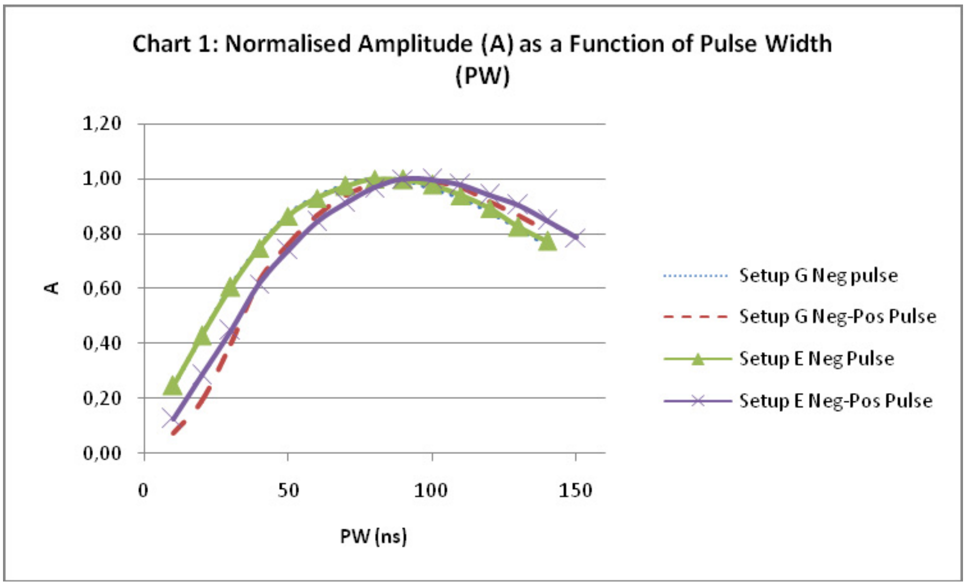


Chart 2 shows the variations of the center frequency which, again, follows the same trend whatever the type of pulse driving the array. As expected, shorter pulse width generates higher center frequencies. Reducing the pulse width is equivalent to exciting the probe at higher frequencies, keeping in mind that for a given frequency PW = 1/2f where f is the nominal frequency. Surprisingly, although the general trend looks the same, the transducer vibrates at its center frequency for different pulse width values, depending on the pulse drive shape. In the case of the negative square pulse, center frequency was reached when excited with a pulse width of about 25ns, which is actually a spike impulse. With the bipolar pulse, center frequency is reached with a pulse width value close to 75ns.

This latest result set indicates that spike impulses can be advantageous over unipolar negative pulses when bandwidth and axial resolution are critical. As it can be seen on charts 3 and 4, the highest values of bandwidth and the lowest values of pulse length are reached when the unipolar pulse is close to its resonant frequency i.e. at 25ns, a value corresponding to a spike impulse. The

[2] Dotted line is hidden by line with triangles as negative pulse of Setup E and Setup G are almost identical.

bandwidth of the unipolar pulse decreases with increasing values of pulse width. The pulse length follows the reverse trend and increases with increasing pulse width. Hence, short pulse echo responses and wide bandwidth are obtained with spike impules, bearing in mind however that it comes at the cost of a poorer SNR due to the need for a higher gain.

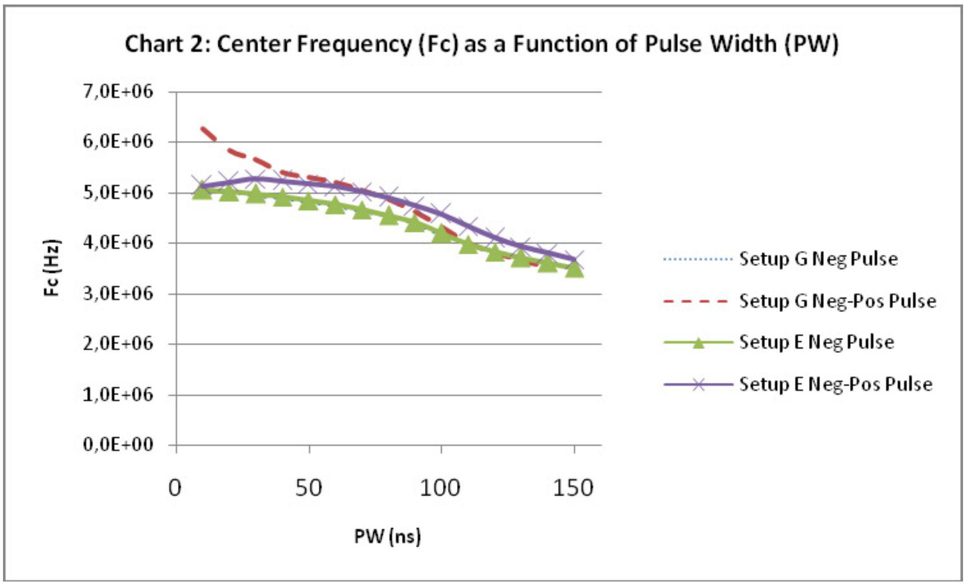
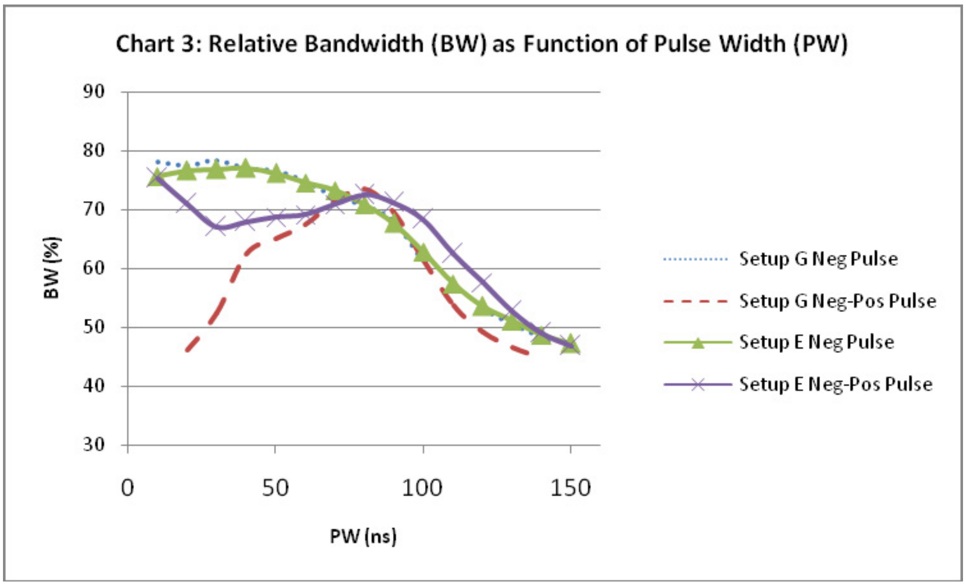
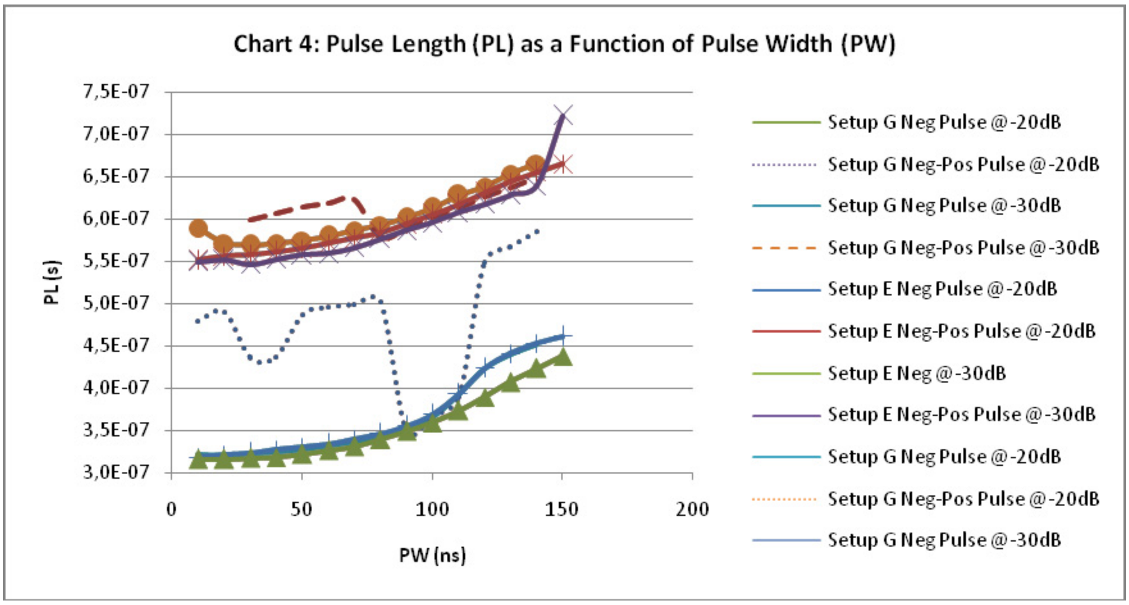
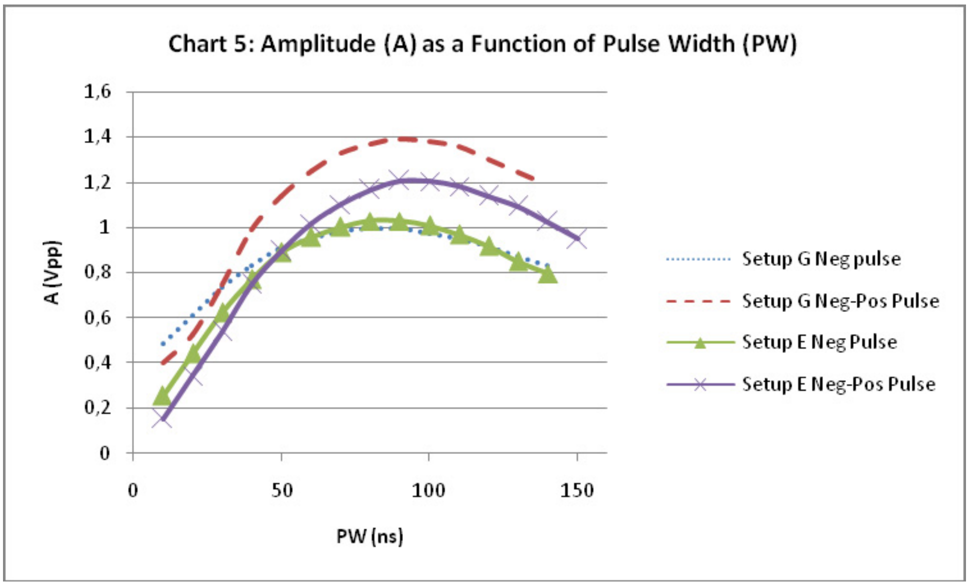


Chart 3 reveals another interesting fact. While resonant frequency is obtained at short pulse width for unipolar pulses, it has been mentionned earlier that for bipolar pulses resonant frequency is reached at values closer to the nominal frequency. Looking at chart 3 this means that the maximum bandwidht for bipolar pulses is reached just around the resonant frequency. This result is of vital importance because it allows to conclude that bipolar pulses are the best compromise in terms of signal quality among spike impulse and unipolar pulse. Indeed, with bipolar pulses, the optimal transducer response is obtained at its resonant frequency. The maximal amplitude signal, the exact center frequency, the widest bandwidth and a short pulse length are all achieved at the resonant frequency.



When comparing the two bipolar pulses of each setup, it is obvious that the -100V/+12V (Setup E) provides a more uniform response over a wider range of pulse width. The -100V/+100V (Setup G), though offering much stronger signal amplitude when looking at the absolute values of chart 5, suffers from much longer pulse length and its bandwidth decrease quickly outside the resonant frequency zone. For these reasons, Setup E can be considered as the best compromise. An additional advantage of the setup E over the Setup G is its lower power consumption. For battery-operated phased array units, this aspect is of paramount importance.





Conclusion

The first part of the paper presented preliminary results showing the different echo-transmittance curve pattern obtained using an array transducer. It has been demonstrated that lower refracted angles are those suffering the most of the low contribution coming from element located in the upper part of the array. Further work has to be completed in order to illustrate the effect of element sensitivity variation.

The second part of this paper has identified the benefits and drawbacks of three different pulse drive shapes on signal quality. Spike impulses provide the shortest pulse length and hence a better axial resolution. However, since the pulse-echo amplitude is function of the pulse width, spike impulse echoes are weak in comparison to unipolar or bipolar pulses. Unipolar pulses can be an efficient and fairly cheap alternative solution to spike impulses when deeper sound penetration is required. This comes with the drawback of a frequency shift into the waveform spectrum to a lower value and a slightly narrower bandwidth. Finally, the bipolar pulse drive has been identified as the optimal way of exciting the transducer. Bipolar pulses provide stronger pulse-echo signals, a frequency spectrum centered on resonant frequency, optimal bandwidth at the resonant frequency and pulse widths comparable to those of unipolar pulses. A -100V/+12V configuration appears to be the sweet spot in terms of image quality and power consumption. Further investigation will be pursued to improve the bandwidth results that were obtained.

Acknowledgments

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