THE APPLICATION OF SIGNAL PROCESSING TECHNIQUES FOR THE ULTRASONIC INSPECTION OF COMPLEX MATERIALS

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Abstract: Complex materials such as multilayer bonded composites present fresh challenges for non-destructive testing. Many materials are highly attenuating due both to losses in the bulk material and propagation losses at interfaces. Additionally, some new composite materials exhibit resonances due to the geometry of the laminar structures, and require special consideration. These applications have required the development of more rapid and flexible ultrasonic techniques for production inspection that are capable of performing non-standard measurements on difficult structures.

This paper describes recent developments by NDT Solutions concerning ultrasonic data analysis and inspection techniques for the testing of composite structures. Examples from current applications utilising DSP pulse compression techniques and arbitrary function generators will be presented.

Introduction: With the introduction of materials such as multilayer bonded composites has come an increased level of inspection difficulty due to complex wave propagation characteristics of some of these materials. Standard ultrasonic pulse based techniques are often not sufficient for the inspection of these materials due to filtering effects or lack of dynamic range. This paper explores some of the limitations of pulse based inspection methods and demonstrates signal processing techniques that can be employed to give an improved inspection capability. Whilst these methods in themselves are not new, recent hardware and software developments by system integrators have now made it possible for these signal processing techniques to be readily used in a production environment.

A typical ultrasonic pulse and its frequency response are shown in figure 1.

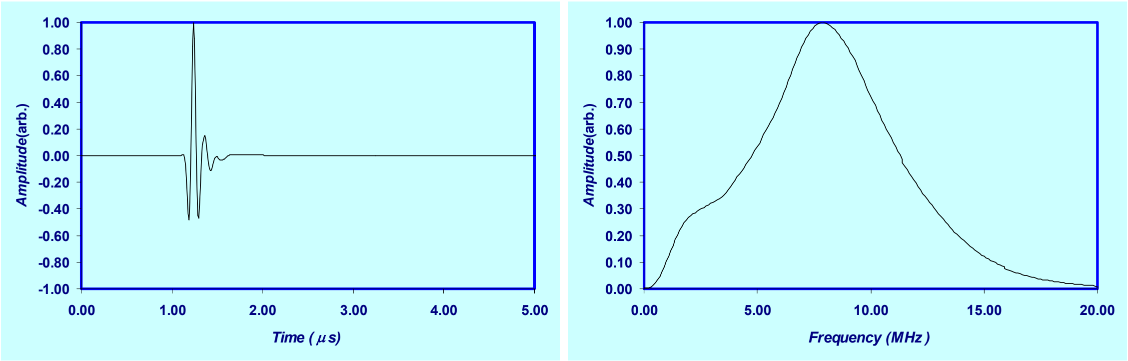


Figure 1: Typical ultrasonic pulse and frequency response.

The short duration time domain response of the pulse is required for good pulse definition when examining thin materials or for the detection of near and far surface defects. This is reflected in the frequency response which is relatively broad band. However these benefits are gained at the expense of dynamic range and sensitivity and many complex materials will modify a broadband signal to such an extent that the received signals are not of sufficient quality to easily perform the inspection. These filtering effects and their influence on the time and frequency domain response of a broad band pulse are shown in the following figure.

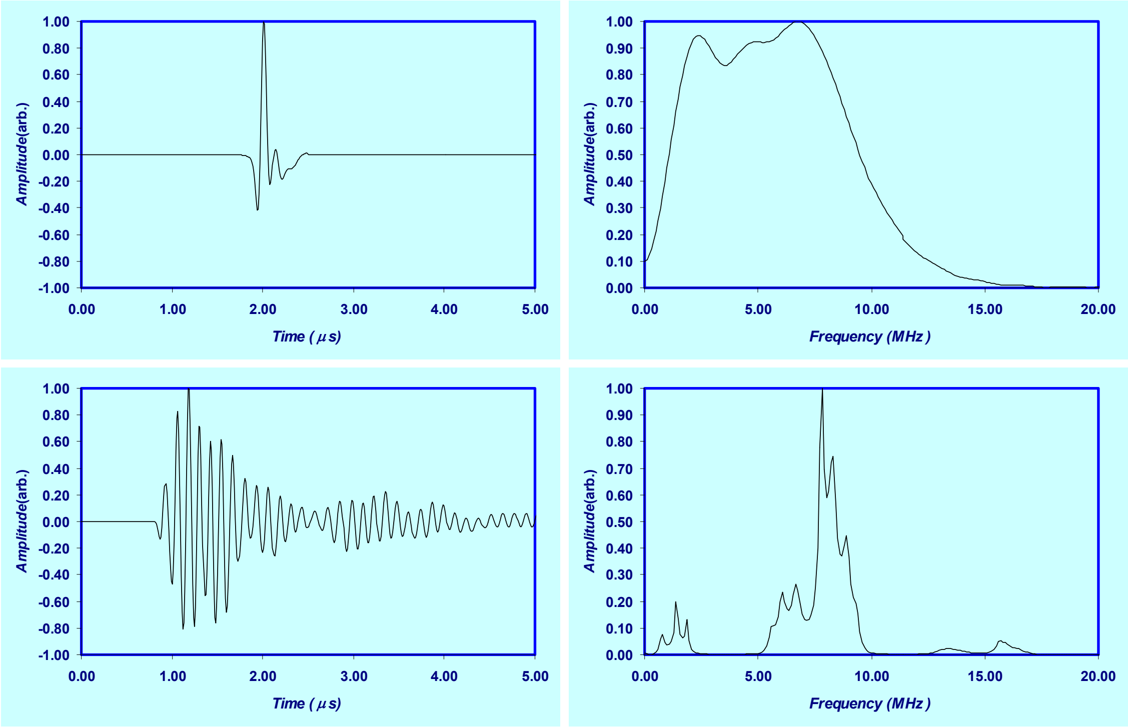


Figure 2: Effects of signal filtering from complex materials on the time and frequency domain response of the signal shown in figure 1.

In a practical situation an operator will use the features of a standard ultrasonic flaw detector system such as pulse width control, receive amplifier filtering, time corrected gain and signal averaging or smoothing to modify the received signal. Whilst in some cases this can give an improved signal for defect detection there are many other options for signal excitation and data processing that offer the ability to tailor the signal for a particular structure type and provide enhanced dynamic range and signal to noise performance over pulsed based excitations.

The majority of these improved methods are based on pulse compression techniques utilising long duration, wide bandwidth excitation signals such as psuedo random noise sequences or chirps [1,2]. The principle property of these signals is related to their time-bandwidth product which is considerably larger than that of a pulse based excitation.

Typical time and frequency domain responses for a noise sequence and a chirp are given in the following figures.

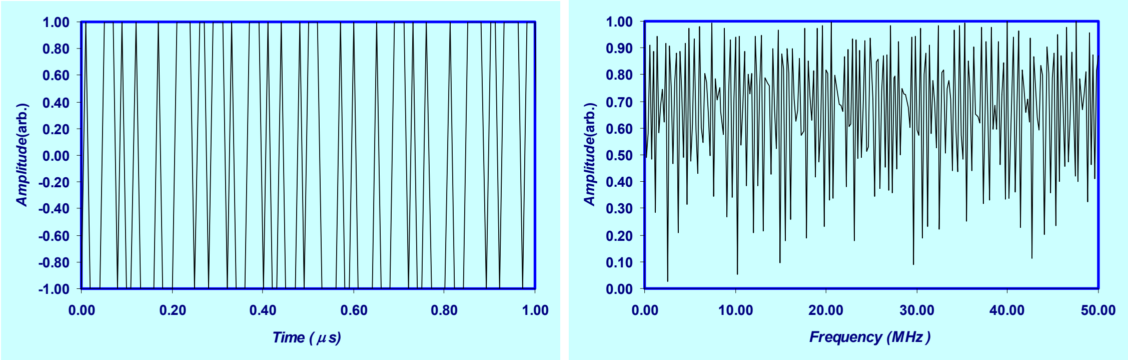


Figure 3: Pseudo random noise sequence and its frequency response.

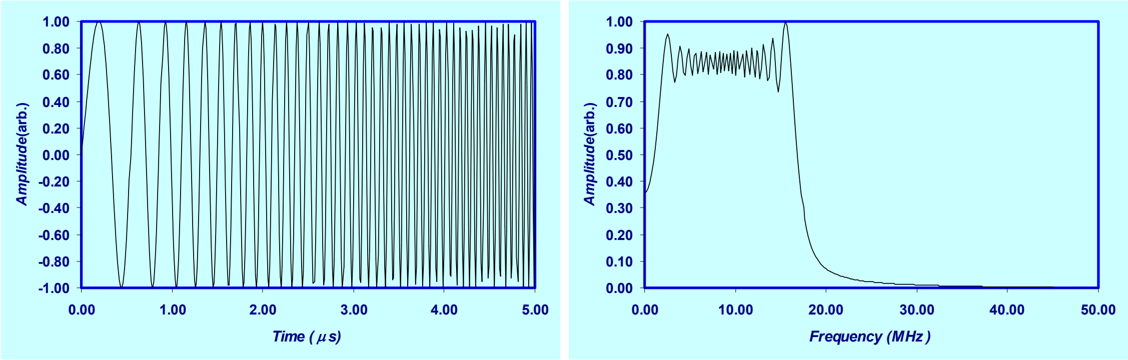
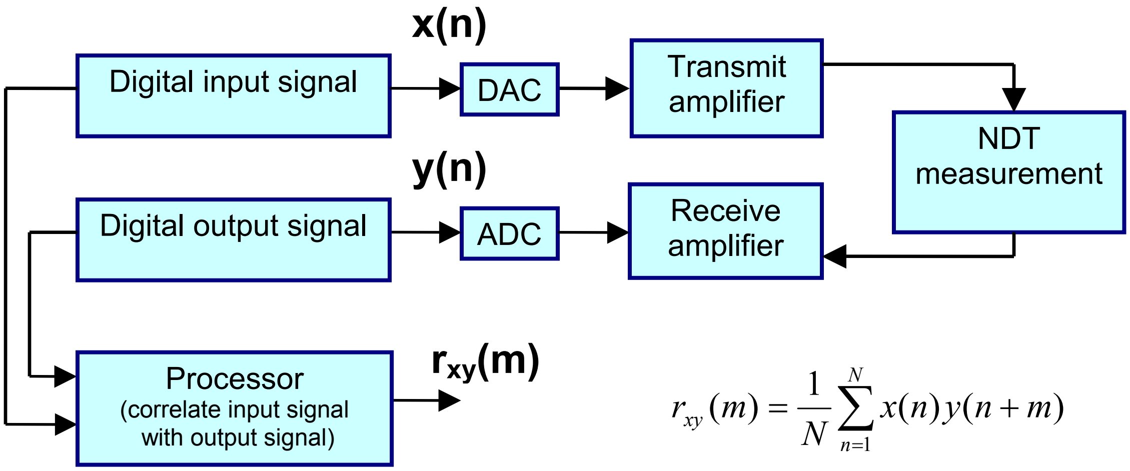


Figure 4: Broadband chirp and its frequency response.

The principal benefit of using high time-bandwidth product signal is that it is possible to put more energy into the material thus giving better signal to noise performance and dynamic range. In order to take advantage of these benefits it is necessary to apply a signal processing operation to the received signals in order to recover a pulse-like signal required for the inspection. This operation is known as cross-correlation and enables long duration, broadband signals with high energy to be translated in to short duration broadband signals suitable for NDT inspections. A diagram of the cross-correlation operation for a chirp sequence is shown in the following figure.



$$r_{xy}(m) = \frac{1}{N}\sum_{n=1}^{N} x(n)y(n+m)$$

Figure 5: Cross-correlation process applied to NDT measurements.

One of the benefits of using a digital excitation source is that it is possible to 'pre-colour' the excitation signal to emphasis particular frequencies and to compensate for the filtering effect of the material being inspected or the transducer [3]. For a chirp excitation this is achieved by simply modifying the amplitude of the frequencies of interest. In the following example a Hanning widow has been applied to the chirp illustrated in figure 1 to emphasis frequencies in the pass band of the transducer.

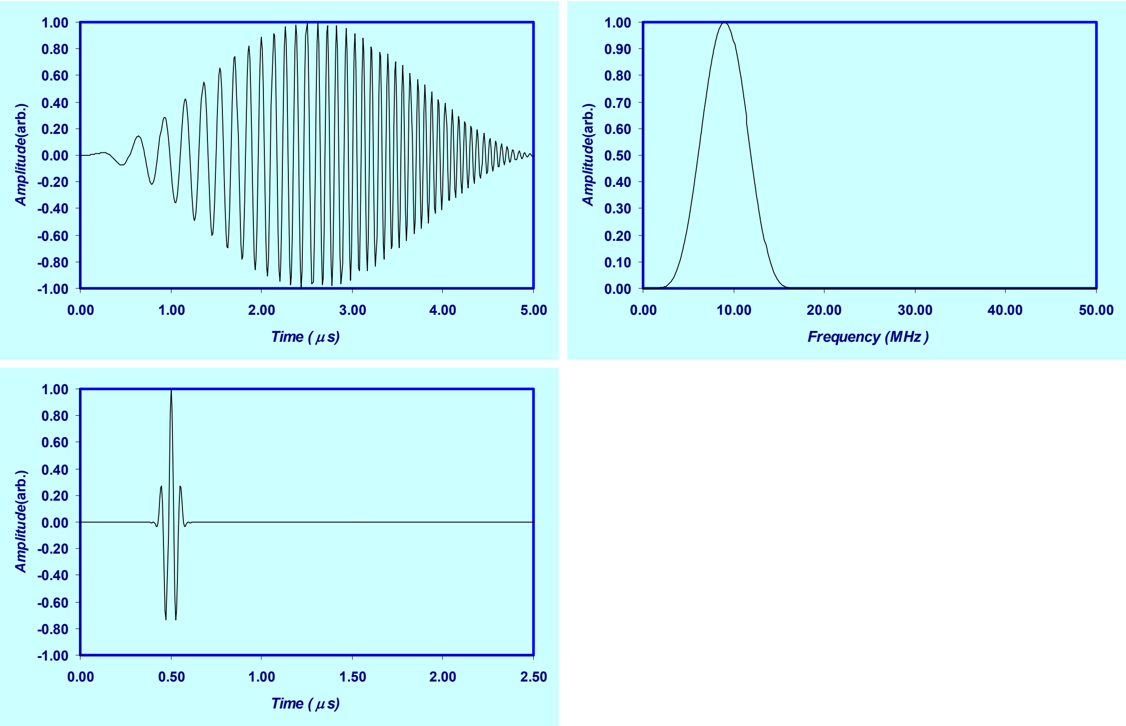


Figure 6: Effect of precolouring of chirp sequence shown in figure 4 and pulse response of the chirp after cross-correlation.

The practical implementation of the techniques described above for routine inspection of complex material is described in the following section.

Results: The practical implementation of these techniques requires hardware and software which is capable of generating, receiving and processing signals in real-time and in an application which is convenient for NDT. A solution to this requirement has been developed by NDT Solutions (UK) in collaboration with UTEX Scientific (Canada) to provide a hardware and software solution that can be readily used for manual and automated inspections.

The first example explores the dynamic range benefits that can be gained from using pulse compression techniques with a complimentary noise sequence. In this example it is required to analyse both a high and low amplitude signal in the same measurement cycle. With a conventional system this can sometimes be achieved by use of time corrected gain but this is not possible if the difference between the signal amplitudes is very large or if the signals are very close together.

The following figure shows the measured signal from a 10 MHz probe after digitisation at 100 MHz with an 8 bit analogue to digital converter. The detail of the low amplitude signal is shown to the right of the main figure.

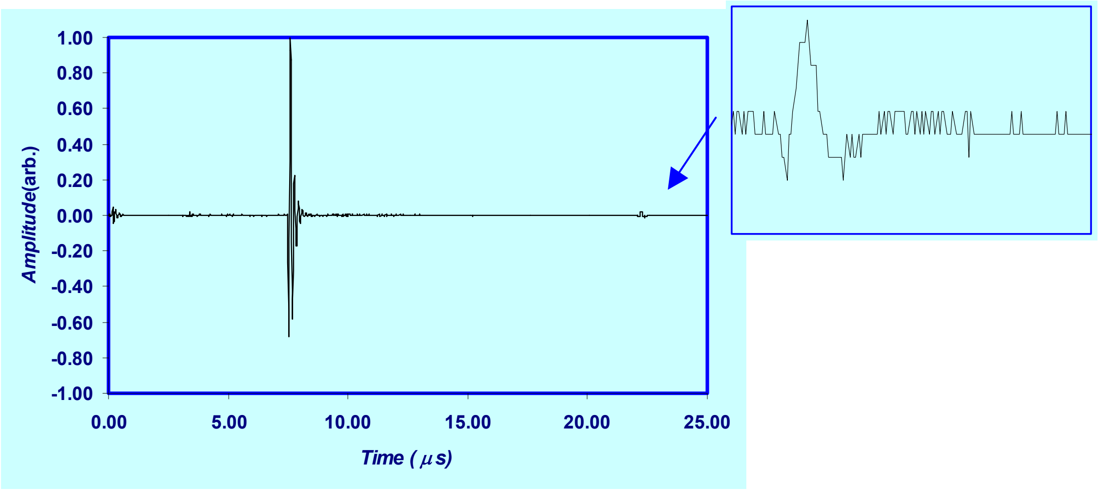


Figure 7: Traditional pulsed based measurement showing poor dynamic range.

It can be seen that the low amplitude signal is poorly defined due to lack of dynamic range during digitisation. This problem could be overcome by use of signal averaging to improve the effective signal to noise ratio but the number of averages required (about 500) would not be practical for an NDT inspection.

The following figures show the same measurement made with a Golay noise sequence which requires only 2 excitations of the transducer.

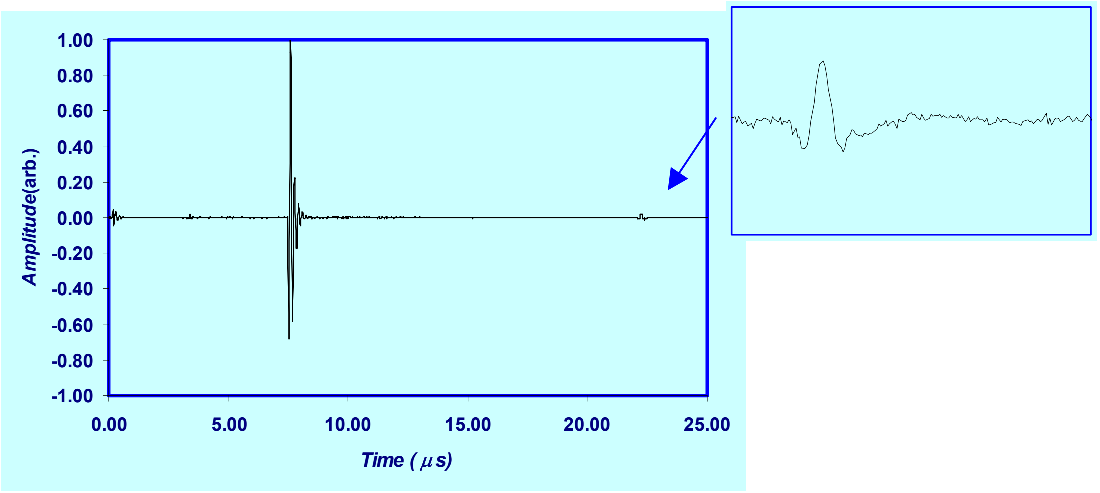


Figure 8: Measurement of figure 7 made with a Golay sequence.

It can be seen that measured low amplitude signal is better defined than the pulsed based measurement. With modern computing the processing required to generate this result can be carried out in real-time during the measurement making this technique practical for most inspection systems [4].

The following example shows the benefit from using pulse compression techniques to improve the signal to noise ratio. The following figure shows a pulsed based measurement on a attenuating adhesive layer in through transmission at a high receive gain (60 dB) using a 10 MHz transducer. The pulse width (100 ns) was set to optimally excite the probe and the pulser voltage was set to 100 V.

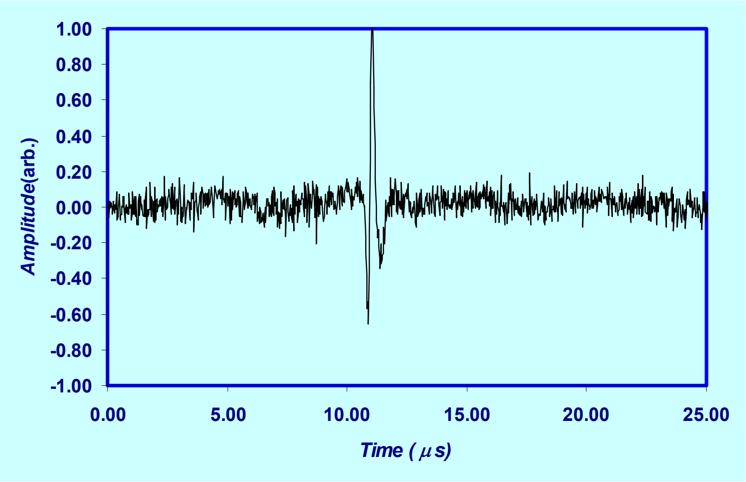


Figure 9: Pulsed based immersion measurement made on a lossy adhesive layer.

It can be seen that the main signal is very noisy and that smaller signal features would be difficult to identify.

The following figure shows the same measurement made with a 512 point chirp excitation (2 MHz to 10 MHz) at 50 V with receiver gain maintained at 60 dB.

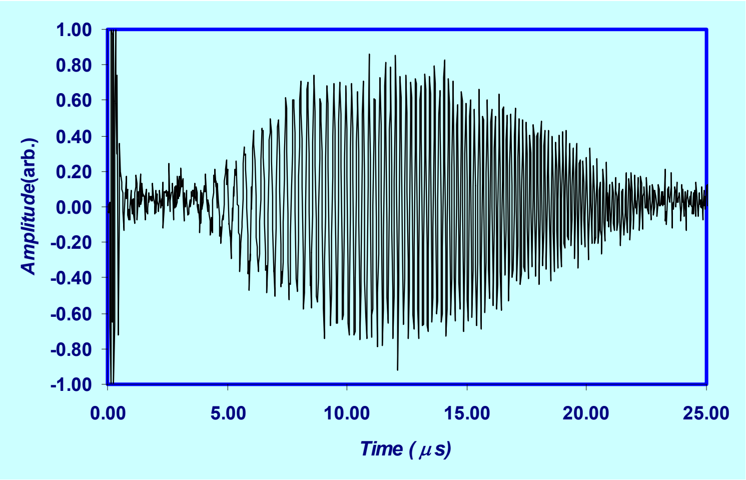


Figure 10: Measurement of figure 9 made with a chirp excitation.

Note that the received chirp before processing has the same noise level as the pulsed based measurement but then after processing the noise floor is dramatically reduced as shown in the following figure.

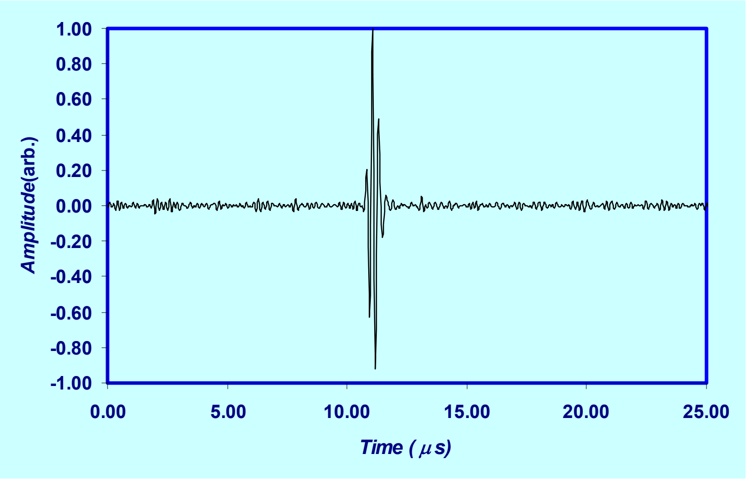


Figure 11: Recovery of pulse after cross-correlation of chirp shown in figure 10.

The signal to noise reduction is a function of the excitation signal length. The signal to noise performance of the ultrasound excitation and receiver system was measured as a function of signal length as shown in the following diagram.

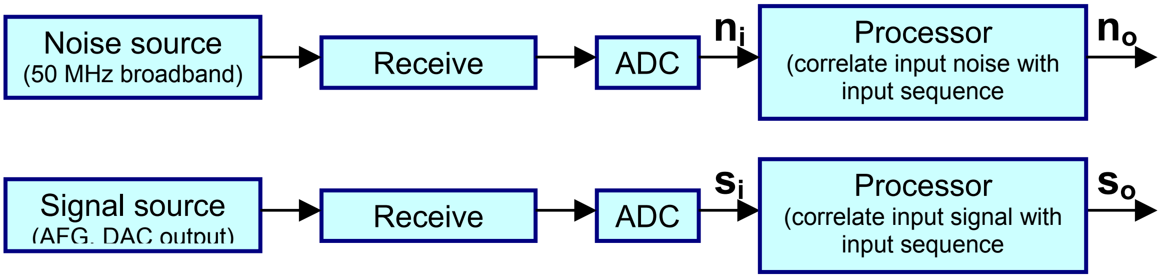


Figure 12: Measurement procedure for signal to noise measurements.

The measured signal to noise values were then compared to theoretical signal to noise performance should be observed as shown in table 1.

$\mathrm{SNR} = 20 \log10(s_o/n_o) - 20 \log10 (s_i/n_i)$		
Sequence length	**SNR dB (measured)**	SNR dB (Theoretical)
512	30	**30**
1024	30	**33**
2048	33	**36**
4096	37	**39**
8192	**40**	**42**

Table 1: Comparison of measured and theoretical signal to noise ratio as a function of signal length.

It can be seen that there is good agreement between the measured and theoretical values.

Discussion and conclusion: The use of pulse compression techniques can alleviate the need for expensive digitisation hardware or signal averaging for the inspection of high loss materials. By using an arbitrary function generator to produce the excitation signal it is possible tailor the signal for a particular inspection or to compensate for the filtering effects of the material being inspected.

With modern computing and recent developments by NDT system integrators it is now possible to employ signal processing methods for routine inspections. This paper has demonstrated that pulse compression techniques have clear advantages over standard pulse based measurements without compromising inspection speed or capability.

References:

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