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Controlled excitation of ultrasonic transducers

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Abstract

The reproducibility of ultrasonic measurements complicates the interpretation of measurement results. The signal from ultrasonic transducers varies for to several reasons, like manufacturing tolerances in a batch, cable length, amplifier properties etc. A known problem that is caused by this effect is the quantitative interpretation of C-scan images from laminates, particularly the porosity present in a laminate. For this type of application, one requires a high level of signal fidelity, or in other words, system independent measurements.
Ultrasonic transducers are commonly excited by a short electrical pulse, such that the temporal bandwidth of the transducers determines the shape of the signal. Instead, we propose to use an optimized sweep signal, such that after correlation the measured signal has a desired wavelet shape. The correlation is done with a specially designed correlation signal instead of using the transmitted sweep. During the design process of the sweep and correlation signal, the transfer function of the system, i.e., transducer and electronics is measured and transformed into a desired response independent of a specific transducer. This approach yields several advantages over conventional excitation, i.e., it provides higher temporal and spatial resolution, a better signal to noise ratio and allows system independent ultrasonic measurements.
The controlled excitation makes it possible to widen the frequency spectrum of a transducer by boosting the signals at frequencies where the transducer has a lower sensitivity. A bandwidth up to 150 % is not difficult to achieve with this technique.
The length of the sweep determines the signal to noise ratio, the correlation process has the same effect as averaging of signals, only it is much more efficient in time. Improvements up to 30 dB can be achieved compared to single pulse excitation.

Keywords : sweep, resolution, signal to noise ratio.

1. Introduction

Commonly ultrasonic transducers are excited with an electrical square wave or spike. The width of the square wave is matched to the frequency of the ultrasonic transducer such that the band limiting factor in the signal is the transducer itself. This approach yields minimal control over the emitted signal of the transducer. Moreover signals from the same type but different transducers may vary significantly. There are several reasons for this, i.e., manufacturing tolerances, pulser/receiver characteristics, cable length etc.
The variability of the signal from transducers may affect the performance of an inspection. It is well known that the inspection of laminates (sizing of porosity) suffers

from this effect. The heterogeneous layout of laminates and the interaction with defects are the main reason for this phenomenon.

Another drawback of the conventional way of exciting ultrasonic transducers is that the signal is in general rather band-limited, i.e., a limited temporal resolution. When designing ultrasonic transducers it is difficult to achieve a bandwidth of more than 100%. To increase the resolution, one could use higher frequencies. For example a 5 MHz signal with 100 % bandwidth yields the same temporal resolution as a 10 MHz signal with only 50 % bandwidth. This is illustrated in Figure 1, the envelopes of both signals are the same.

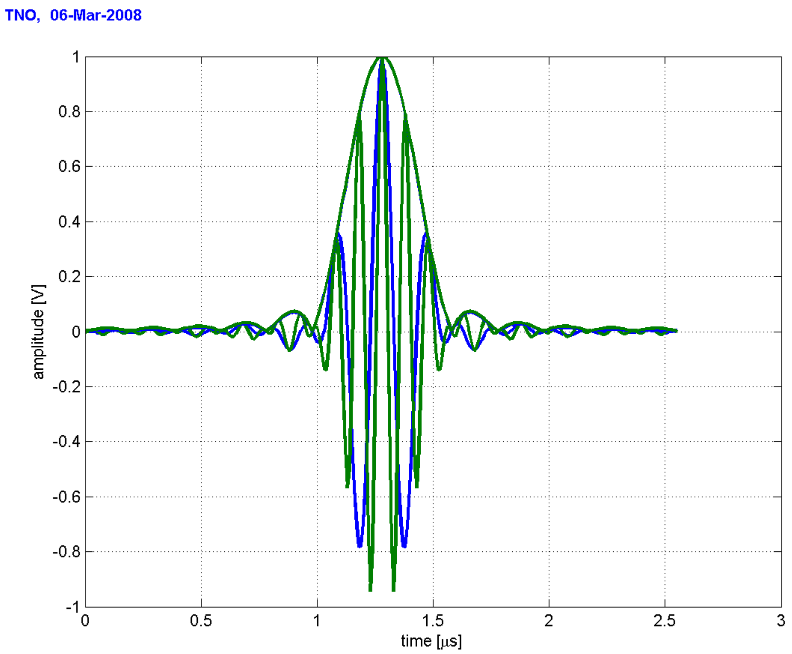

Figure 1 Comparison of temporal resolution, a 5 MHz signal with 100 % bandwidth yields the same temporal resolution as a 10 MHz signal with only 50 % bandwidth.

With controlled excitation it is possible to control the signal transmitted by the ultrasonic transducer and increase the bandwidth. This method is explained in the next section.

2. Controlled excitation

As mentioned before, normally an ultrasonic transducer is excited with an electrical pulse. We propose a new method of controlled excitation[3] in which the response of the transducer is measured during calibration and used to design an electrical excitation signal such that after this procedure the transducer produces the desired response. Essentially the transfer function of the transducer in combination with the used hardware is removed.

We will explain this approach in detail. Let’s assume that we excite an ultrasonic transducer with a known signal $s(t)$. The measured response in the frequency domain can be written as:

$$P(\omega) = H(\omega)S(\omega), \tag{1}$$

where $P(\omega)$ is the measured response and $H(\omega)$ is the transfer function of the system.

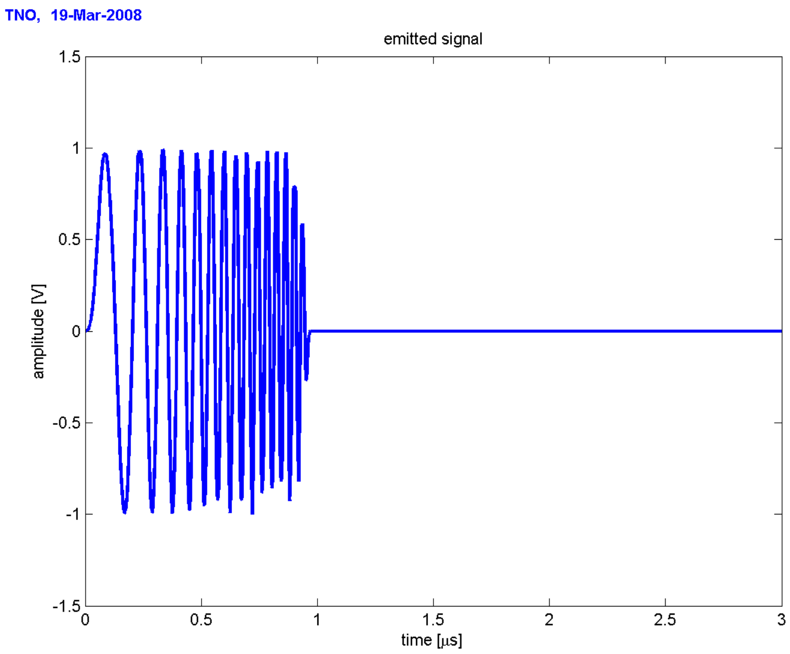

Figure 2 Initially emitted excitation signal, which is a short sweep. In this sweep the frequency is gradually increased.

We can define a desired response, $D(\omega)$ of the transducer. The desired signal, i.e., the highest possible resolution, is a zero phase signal with a cosine-shaped spectrum[1].
So we can now obtain a new excitation signal, $\breve{S}(\omega)$:

$$\breve{S}(\omega) = \frac{D(\omega)S(\omega)P^*(\omega)}{|P(\omega)|^2 + \lambda}, \tag{2}$$

where $P^*(\omega)$ is the complex conjugate of the measured response and λ is a stabilization constant to avoid boosting noise.
Initially a short sweep, or ultimately a pulse is used to avoid interference with other echoes during the calibration measurement. To extend the length of the sweep, a simple quadratic phase shift has to be applied.

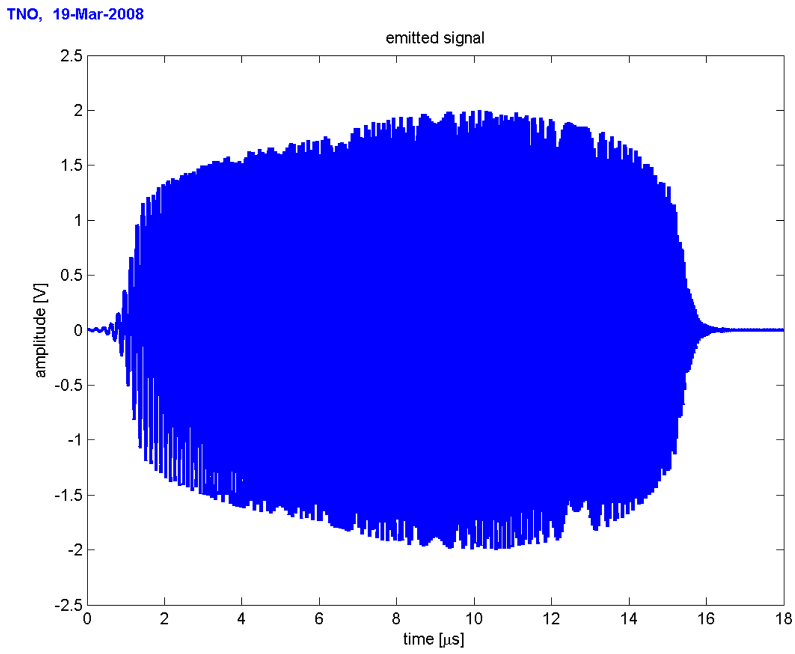

Figure 3 Optimized sweep signal. The length of the sweep is increased using a quadratic phase shift.

With this procedure a new sweep signal is obtained that yields the desired frequency response. In order to convert the measured signals to pulse-shaped signal a correlation signal has to be defined. This signal should have a flat amplitude spectrum to avoid coloring the noise and a phase such that the desired signal is zero-phase. A zero-phase signal is symmetrical around its center. It should be noticed that the travel time of a zero-phase should be determined from the center of the wavelet instead of the onset of the signal as is commonly done for transducer signals which a minimum phase.
A correlation signal, $\hat{C}(\omega)$ is now defined as:

$$\hat{C}(\omega) = \frac{S^*}{|S| + \lambda}, \qquad (3)$$

where λ is again a stabilization constant. After this procedure an optimized sweep and correlation signal is obtained, which is unique for a certain transducer or transducer pair.

Figure 4 shows a transducer response before and after sweep optimization. The difference in temporal resolution is immediately obvious, the additional ringing of the original response is removed. Moreover the signal derived from the optimized sweep has the desired shape.

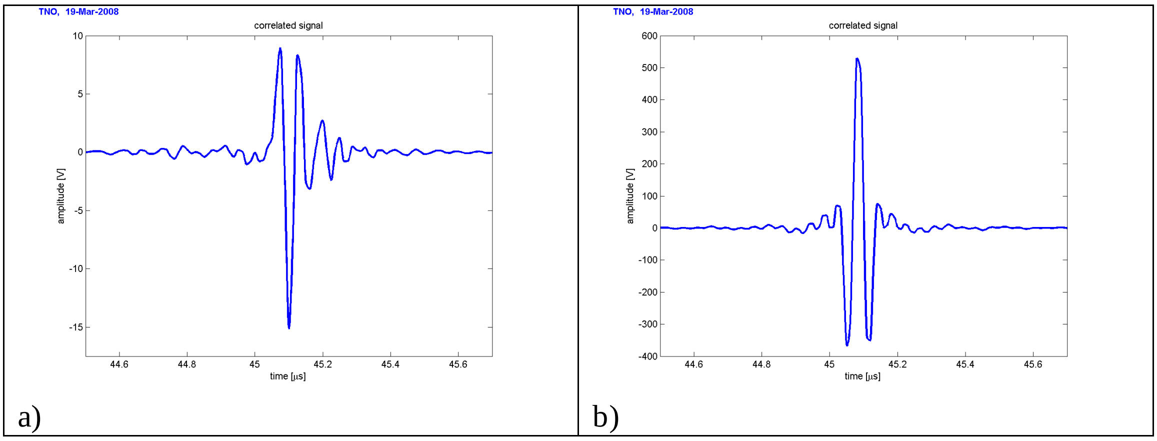

Figure 4 Transducer response before (a) and after (b) sweep optimization.

3. Signal to noise improvement

Normally a sweep signal is used for controlled excitation. Using correlation techniques the sweep signal is converted into a pulse. An additional feature of this approach is the improvement in signal to noise ratio compared to single pulse excitation. The improvement in signal to noise ratio depends on the center frequency and the sweep length. The improvement, assuming similar amplitudes of the excitation pulse and sweep, can be calculated:

$$\Delta SN = 20\log\sqrt{2 f_c T_{swp}}\,, \qquad (4)$$

where f_c is the center frequency of the transducer and T_{swp} is the sweep length.
Figure 5 shows the improvement in signal to noise ratio as function of the sweep length for a 10 MHz transducer. An interesting property of the curve is that the improvement in signal to noise ratio steeply increases for relatively short sweeps. A sweep length of only 10 μs increases the signal to noise ratio already with 23 dB. When increasing the sweep further to 50 μs, the improvement becomes even 30 dB.

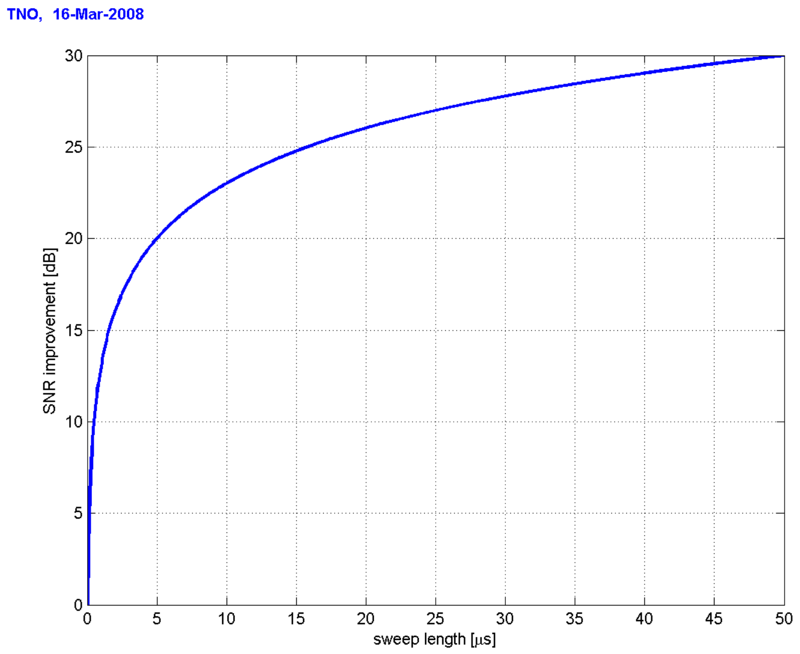

Figure 5 Improvement of the signal to noise ratio as function of sweep length. For relatively short sweeps improve the signal to noise ratio very efficiently.

In practical circumstances the sweep length can be limited, for example in pulse-echo measurements. Obviously one cannot transmit and record echoes at the same time with a single element transducer. It is our experience that this method can easily improve the signal to noise ratio with 20 to 30 dB.

Normal averaging could give the same improvement but this process is much slower in time and difficult to apply in high speed applications. To achieve a 30 dB improvement in signal to noise ratio, one would need to average 900 signals, which would be very time consuming! With the proposed method, the additional acquisition time using a sweep is only the sweep length itself.

4. Example

To illustrate the differences in image quality that can be obtained using this approach we show two C-scans of a bonded ceramic object with channel structures. We are interested in detecting defects at the bond interface. This can either be bubbles and defects originating from the channels. Figure 6 shows the original C-scan, in the indicated area's some defects are faintly visible. In area A an indication of some channels is visible. Area B contains some bubbles. However the image is a bit inconclusive.

Due to attention losses the signal from the high frequency focused transducer becomes predominantly low frequency. This yields a lower spatial resolution than would be possible.

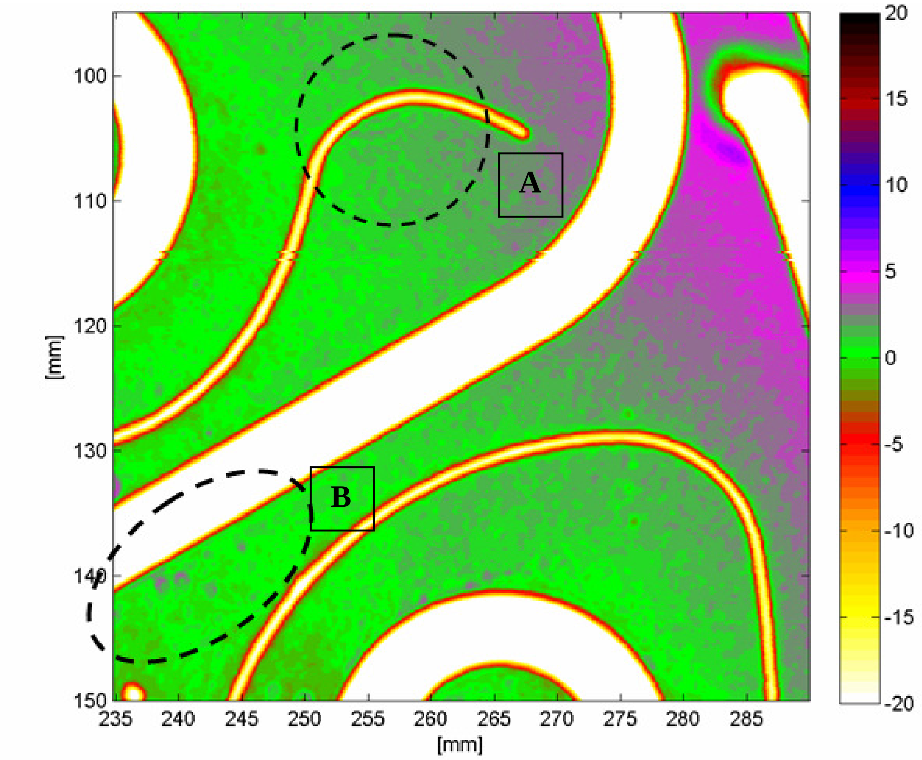

Figure 6 C-scan using pulse excitation, the scan reveals some defects but they do not show very pronounced.

An optimized sweep was created in the desired temporal frequency range. The length of the sweep was chosen such that after correlation still a good signal to noise ratio was obtained. Before correlation the signal was hardly visible in the noise, but after correlation a clear image was obtained revealing the defects much sharper as shown in Figure 7. The improved spatial resolution is mainly due to the much higher dominant frequency present in the signal.

In Area A, the channel structure is very well imaged, revealing much more details. Also the bubbles in area B are much better defined. The background looks noisier, but a closer look reveals that the structure is spatially coherent, revealing the microstructure of the bond interface. In Figure 6 the background looks much smoother, due to the lower dominant frequency. Since the response is frequency dependent, the overall background level is different between both scans. This is one of the reasons for differences when using different transducers. Because the transducer signal is much better defined, the C-scans turns out to be much better reproducible than with a conventional approach. Thus allows truly system independent inspections.

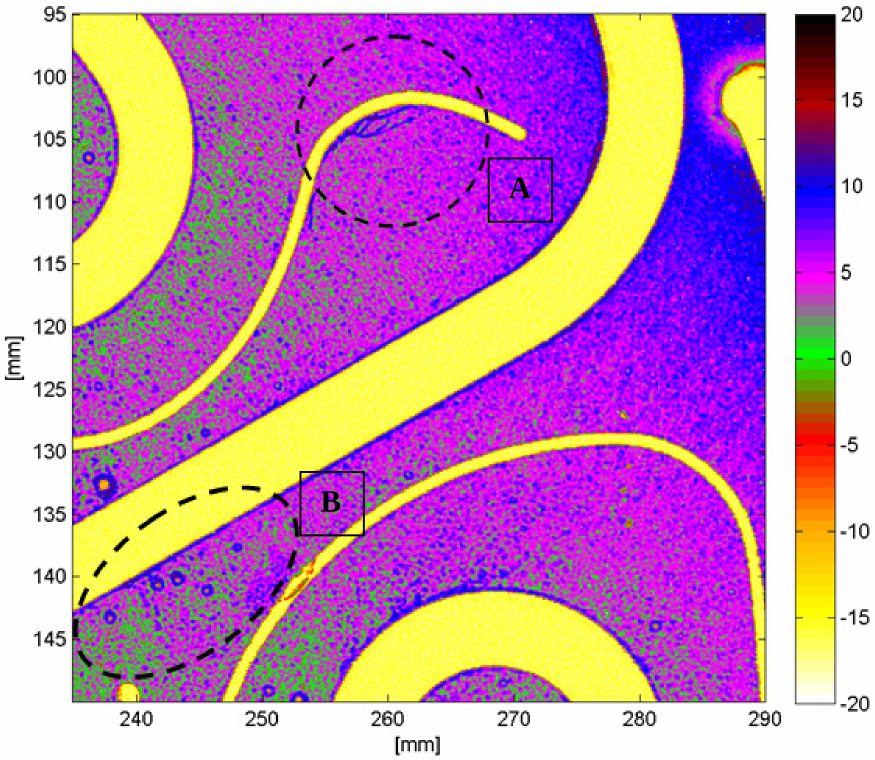

Figure 7 C-scan using an optimized sweep, the scan reveals much more detail compared to the original C-scan. For example the channel structure (region A) is much better resolved.

5. Conclusion

We have presented a method for optimizing sweep signals which allows us to improve the resolution and signal to noise ratio of ultrasonic measurements at the same time. The method involves a calibration step, where the transfer function of the system is determined and a desired response is defined. A sweep optimization procedure yields an optimized sweep and correlation signal. This method is also an efficient way to improve the signal to noise ratio. Improvements in signal to noise ratio up to 30 dB are possible, which is difficult to achieve with averaging due to the increased acquisition time. Experimental results demonstrate the power of this approach. It is possible to improve the resolution significantly while maintaining a high signal to noise ratio.

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