SPECKLE SUPPRESSION IN ULTRASONIC IMAGING

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Abstract. Materials with distinct coarse grains are difficult to inspect ultrasonically due to the scattering from the grain boundaries. In pulse-echo ultrasonic inspection small reflections scattered from the grain boundaries appear in the received image as speckle, often referred to as material noise. Material noise cannot be reduced by conventional time averaging, but can be suppressed by combining signals from different transducer positions or inspection frequencies. The frequency diversity approach has been used as an inspiration for several time-frequency signal processing techniques proposed for suppression of material noise. The most renowned of these algorithms is the Split Spectrum Processing (SSP). In the paper SSP with Consecutive Polarity Coincidence is compared to a recently presented algorithm based on Noncoherent Detection. The performance of the algorithms is illustrated using ultrasonic image data obtained from cast stainless steel with coarse grain structure.

Key Words. Ultrasonic nondestructive evaluation, Material noise, Signal processing, Split Spectrum Processing, Noncoherent Detection.

1. INTRODUCTION

Ultrasonic imaging, widely applied in noninvasive diagnostic medicine has also become an important tool in nondestructive evaluation (NDE) of engineering materials. One of the factors limiting the detection capability in coarse grain materials is the presence of interference noise (clutter, speckle) due to scattering from the interfaces of irresolvable material grains. Such interference noise, known in NDE as material noise [7] may mask targets of interest, e.g. material defects.

Material noise is different from thermal noise since it does not vary with time. This means that for each position of the ultrasonic transducer one particular noise realization is obtained. As a consequence, this type of noise cannot be reduced by conventional time averaging. However, due to its physical origin, material noise may be suppressed by combining signals from different transducer positions or inspection frequencies. These procedures are referred to as spatial diversity and frequency diversity, respectively.

The frequency diversity approach has been used as an inspiration for several time-frequency signal processing techniques proposed for suppression of material noise. The most renowned of these algorithms is the Split Spectrum Processing (SSP) [8], which utilizes a bank of bandpass filters for achieving the variation in inspection frequency, followed by a target extraction algorithm.

In our previous work the SSP technique has been extensively evaluated [2,3] and further developed [4]. The evaluations of common target extractors, such as Polarity Thresholding [1] and Amplitude Minimization [8] have proven that material noise can be significantly suppressed by means of SSP. However, some drawbacks were also noticed: the parameter tuning is very difficult, the temporal resolution is considerably reduced, and the processing is quite time consuming. The introduction of the Consecutive Polarity Coincidence (CPC) extraction algorithm [4] solved some of the parameter tuning problems, but the other remained.

In this paper the SSP-CPC algorithm is compared to a recently presented algorithm based on Noncoherent Detection (NCD) [5,6]. These algorithms can be seen as representatives for two different approaches to solve the clutter suppression problem: physical reasoning vs. modeling of material noise and defect response. Main issues discussed are clutter suppression performance, temporal resolution, parameter tuning and processing time.

2. SPLIT SPECTRUM PROCESSING

The SSP algorithm, illustrated in Fig.1, consists of a bank of Gaussian bandpass filters for signal expansion and a statistical processor for target echo extraction. The filter bank is used for obtaining a set of signals among which the noise components have been more or less decorrelated, while at the same time retaining a large degree of correlation for target echoes. Target echo extraction may then be implemented by applying a suitable measure of correlation to the generated set of signals.

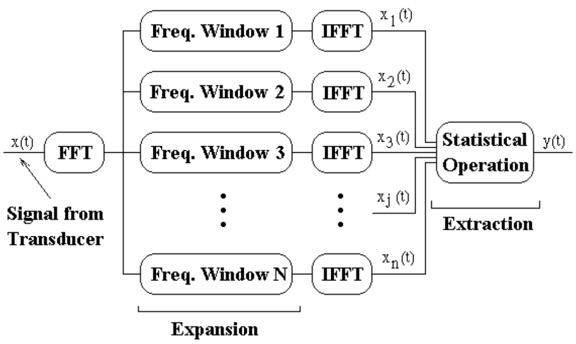

Fig. 1. Structure of the Split Spectrum Processing.

Simple target extractors such as the Polarity Thresholding (PT) and the Amplitude Minimization algorithms have been suggested and proven successful if the processing parameters have been correctly tuned. The far most important parameters, using these target extractors, are center frequency and bandwidth of the processing range. Even a slight deviation in the frequency range may result in target echo cancellation, since an output signal from a single filter containing no target information is sufficient for violating the algorithm operation principle [1,8]. Consequently, good a priori knowledge of the target echo spectrum is required for achieving adequate results. Unfortunately, the required data is not easily obtainable, as it depends on the transducer characteristics, the material structure, and the defect geometry.

2.1. Consecutive Polarity Coincidence

By using a slightly different interpretation of the PT procedure an adaptive algorithm able to automatically find the processing frequency range can be constructed. PT is based on the assumption that the ultrasonic target echo is spectrally similar to a band limited pulse with linear phase. Prior to application of the PT, the received ultrasonic signal is therefore decomposed by the SSP filter bank, which generates a time-frequency representation of the signal. The conventional PT detection algorithm utilizes the pulse characteristics by indicating a target echo at those instants of time where all the filter outputs share a common polarity. Obviously, the underlying assumption can be very easily violated, by reversing the polarity of a single filter output signal.

In a sense, the PT algorithm measures the resemblance to a predetermined hypothetical pulse, at each instant of time. However, the polarity of the filter outputs can be used to measure the similarity directly, without assuming a certain frequency range for the hypothetical pulse. For a certain instant of time, the polarities of the filter outputs originating from subsequent frequency bands constitute a binary sequence. By searching for the maximum length subsequence of consecutive polarity coincidences, one can obtain a direct measure of the spectral location of the best pulse that can be constructed within the processed frequency range. The length of the subsequence will correspond to the bandwidth of the pulse, and the starting index to the lower cut off frequency. For example, if the filter bank consists of 30 filters and the target echo is present in filters No. 5-27, then the conventional PT algorithm will most probably fail, while the CPC will report the presence of a pulse, i.e., a presumed target, with a bandwidth corresponding to 22 times the filter frequency distance. Hence, the CPC algorithm eliminates the need for careful tuning of the frequency range used for signal expansion.

2.2. Computer Simulation

The operation of the Consecutive Polarity Coincidence algorithm is illustrated using a computer generated signal which simulates a received ultrasonic signal acquired during inspection of a course material, see Fig. 2.

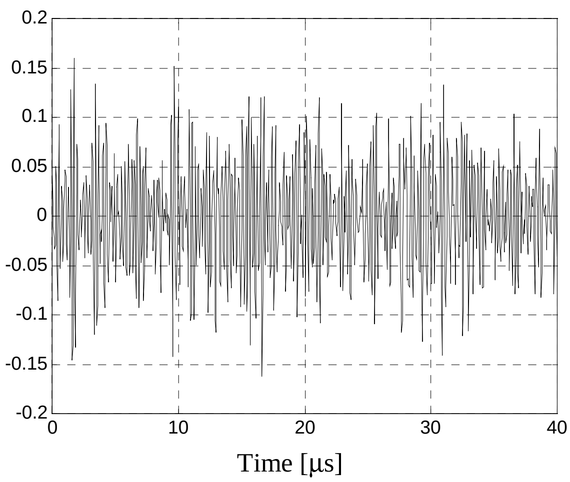

Fig. 2. Simulated ultrasonic response signal (A-scan).

The frequency contents of the target echo and the material noise were chosen to model the use of a transducer poorly suited to the material. The target echo, located at 28 μs, was modeled as a Dirac pulse and the material noise as white Gaussian noise. Gaussian bandpass filters, simulating the transducer and the filtering effect of the material, were then applied to the infinite bandwidth signal in order to simulate the ultrasonic response. Thus, the material noise was modeled as having a center frequency of 4 MHz, while the target echo was restricted to 2 MHz center frequency and a much narrower bandwidth than the material noise, see Fig. 3.

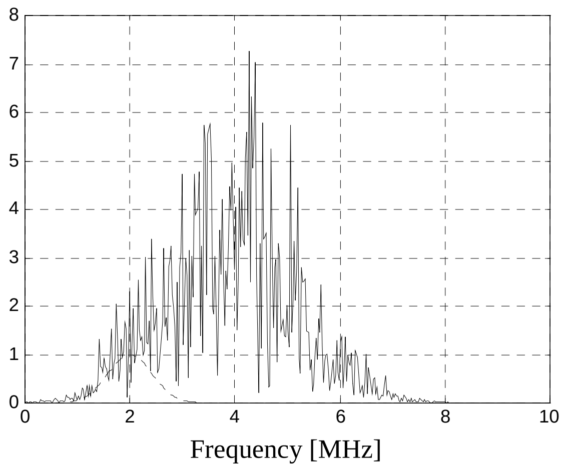

Fig. 3. Spectrum of simulated signal (target echo dashed).

The simulated signal was then processed by the SSP-CPC algorithm, utilizing a frequency range from 0.25 MHz to 7.75 MHz. The number of filters used was 307 and each filter had a bandwidth of twice the filter frequency separation. These parameters were determined in accordance with prior experiences of the PT algorithm [3]. Obviously, the very wide processing range will definitely include the target echo information, but will also result in a large number of filter outputs containing only material noise. The result of the CPC processing is illustrated in Fig 4, showing the maximum length subsequence of consecutive polarity coincidences, expressed in MHz, as a function of time. As expected from theory, the target is indicated by a peak in the CPC output.

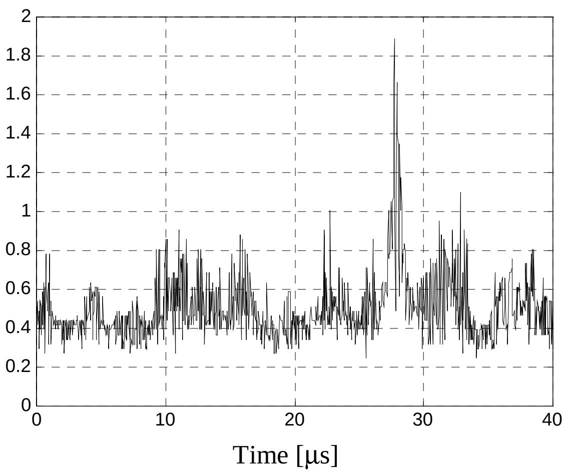

Fig. 4. Output from the SSP-CPC algorithm.

3. NONCOHERENT DETECTION

The noncoherent detector is well known from telecommunication, it is designed for detection of a bandpass signal $s(t)=A(t)\cos(2\pi f+\phi)$, when the phase angle ϕ is unknown (random). From a NDE perspective, the noncoherent detector is designed to detect a family of transients defined by the set of transients obtained by continuously varying the angle ϕ over the interval $[0,2\pi)$. Since it is impossible to exactly specify what transients to expect after propagation and reflection in NDE, the design of family detectors seems attractive.

For clutter suppression, the test statistic used by the noncoherent detector has been proposed as an interesting output signal [6]. This was motivated by the fact that, provided that transient and noise models are valid, the test statistic reflects the likelihood that a transient is present. In the algorithm proposed in [6] the noise model is obtained by estimating the noise autocorrelation function from the received ultrasonic data. The transient is modeled as a simple bandpass signal with lower and upper cut off frequencies f_{low} and f_{high}. The structure of the algorithm is displayed in Fig. 5. It should be noted that the filter construction process is part of the calibration procedure for the utilized transducer. The actual processing of the acquired ultrasonic data, employing the resulting filter, is very simple and may be performed in real time.

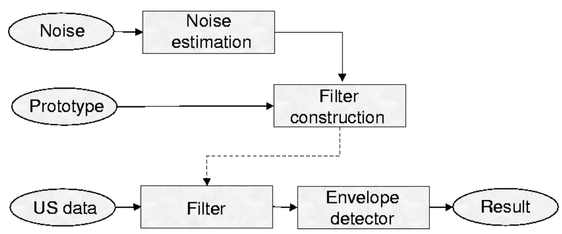

Fig. 5. Structure of the Noncoherent Detection.

An attractive property of the NCD algorithm is that small variations in the transient parameter values result in only small variations in the filter output. Consequently, near-optimal parameter values can easily be determined automatically using a suitable performance measure.

The type of performance measure to be used during filter construction depends on whether target echoes can be localized in the acquired ultrasonic data or not. If a special calibration block is available, the exact defect locations should be known. In this case the actual signal to noise ratio (SNR), i.e. target echo energy divided by noise power, can be computed and used as a performance measure.

It is also possible to construct a ”blind” performance measure working on data from an unknown object. Such an algorithm has to mimic the operator's way of looking at an unknown image, i.e., judging it as "good" if it has an ordered structure with a few peaks and "bad" if it is "noisy". One way of formalizing these vague criteria, which has turned out to be quite successful [5], is to utilize the concept of entropy, known from information theory. Signals that have an amplitude distribution with high entropy are characterized by a high degree of “disorder”. In ultrasonic NDE we normally look for a few pulses (echoes from flaws), i.e., an ordered signal. Thus, from an operator perception point of view, interesting results should be obtained if the ultrasonic data is filtered to yield low entropy amplitude distributions.

3.2. Computer Simulation

The operation of the NCD algorithm is illustrated using the same computer generated signal as in the previous section, see Fig. 2. First, the noise autocorrelation function was estimated from the first 26 μs of the signal, using a window with a length of 2.6 μs. Then, the transient prototype parameters were determined by maximization of the SNR of the filtered signal. The optimization procedure resulted in a target prototype with f_{low}=1.3 MHz and f_{high}=2.2 MHz. The output from the constructed filter is plotted in Fig. 6. A comparison with Fig. 4. indicates that the clutter suppression capability of NCD is at least as good as for SSP-CPC.

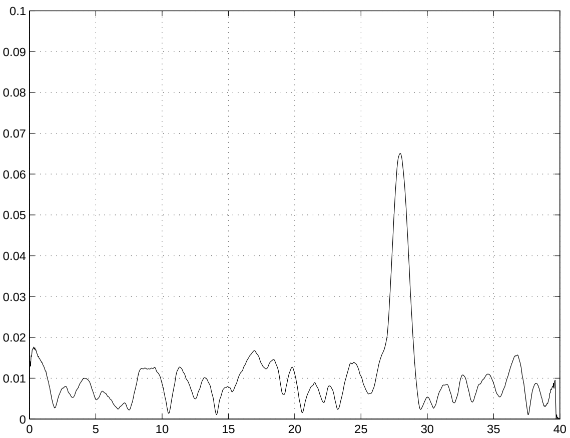

Fig. 6. Output from the NCD algorithm.

4. EXPERIMENTAL RESULTS

The SSP-CPC and NCD algorithms were experimentally evaluated with respect to clutter suppression performance and temporal resolution. The transducer employed for data acquisition was a Karl Deutsch S12 HB4, emitting longitudinal waves with a center frequency of 4 MHz. The inspections were performed with contact technique using a PC-based ultrasonic scanner. The received ultrasonic signals were sampled with a frequency of 40 MHz and a resolution of 8 bits, after which they were transferred to MATLAB™ for processing.

4.1 Speckle Suppression

Ultrasonic signals utilized for the clutter suppression evaluation were acquired from a test block made of coarse grain cast stainless steel with a structure similar to that found in certain parts of nuclear power plants. In the test block there were three side-drilled holes, with diameters 5 mm. 8 mm and 10 mm, located 40 mm below the top surface. The original B-scan image acquired from the specimen is shown in Fig. 7.

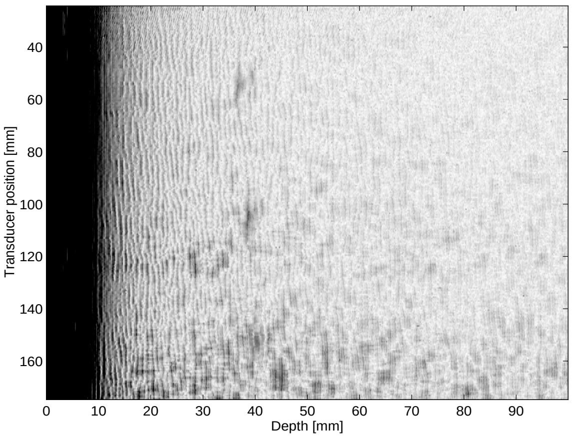

Fig. 7. Three side-drilled holes, located at transducer positions 50 mm(∅10), 100 mm(∅8) and 150 mm(∅5).

The B-scan was processed by NCD and SSP-CPC, yielding the results displayed in Fig. 8 and 9. The processing parameters were determined in the same way as in the computer simulations above. Thus, the SNR of the largest side-drilled hole were used as a performance measure for tuning the NCD transient prototype parameters, resulting in f_{low}=0.6 MHz and f_{high}=1.4 MHz. The SSP-CPC algorithm, utilizing a frequency range from 0 to 6 MHz, employed 203 filters, each with a bandwidth of twice the filter frequency separation. Evidently, both algorithms were able to significantly suppress the material noise and facilitate target detection. A closer evaluation shows that the NCD algorithm produced a higher SNR improvement.

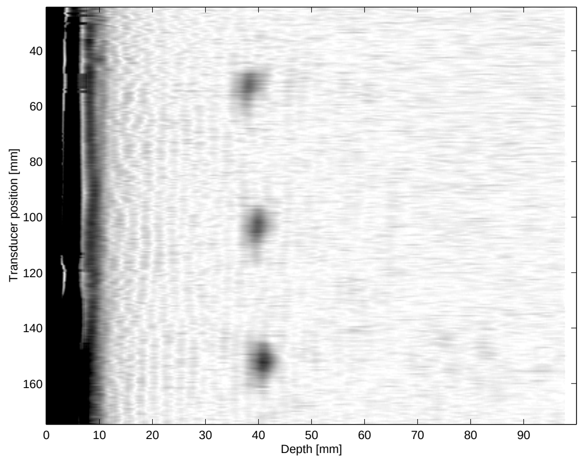

Fig. 8. Same as in Fig. 7, after processing by NCD.

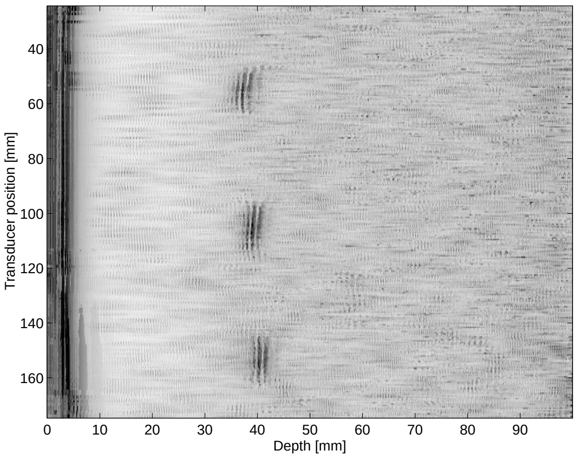

Fig. 9. Same as in Fig. 7, after processing by SSP-CPC.

4.2 Temporal Resolution

The temporal resolution of the two algorithms was estimated by processing signals containing two echoes separated in time, see Fig. 10. The distance was decreased until the echoes could no longer be resolved. In order to get ultrasonic signals with an arbitrary separation between the echoes the signals were generated in the computer, based on the measured transducer characteristics. The signals were then processed using the same filters that were employed in section 4.1.

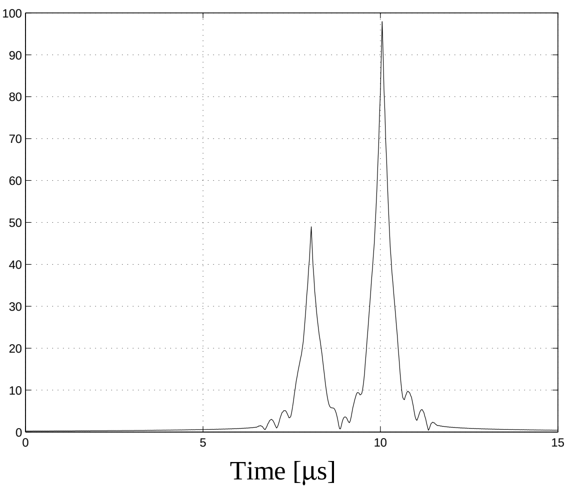

Fig. 10. Two echoes separated in time by 2 μs.

When utilizing the NCD technique there were no problems to resolve two echoes separated in time by 2 μs, see Fig. 11. Further reduction of the distance resulted in a smooth transition to one, wide echo. The same signal was also processed by the SSP-CPC algorithm, see Fig. 12. Obviously, in this case the temporal resolution is not good enough to detect both the echoes. By increasing the distance between the echoes the temporal resolution for the SSP-CPC, using the current parameter setting, was estimated to 6 μs, see Fig. 13. It should be noted that when decreasing the distance below 6 μs the peak corresponding to the smaller echo disappears very abruptly.

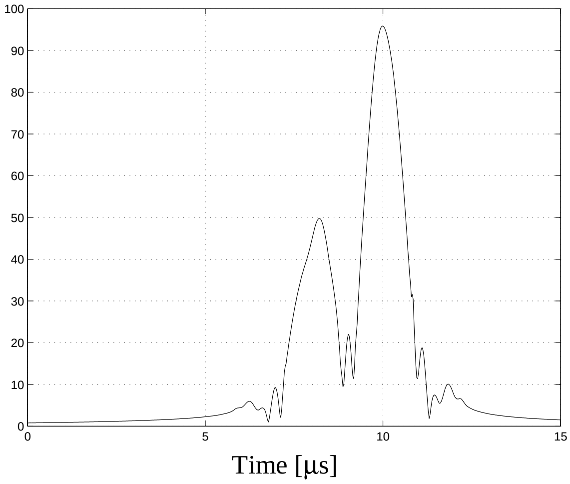

Fig. 11. Two echoes separated in time by 2 μs, after processing by NCD.

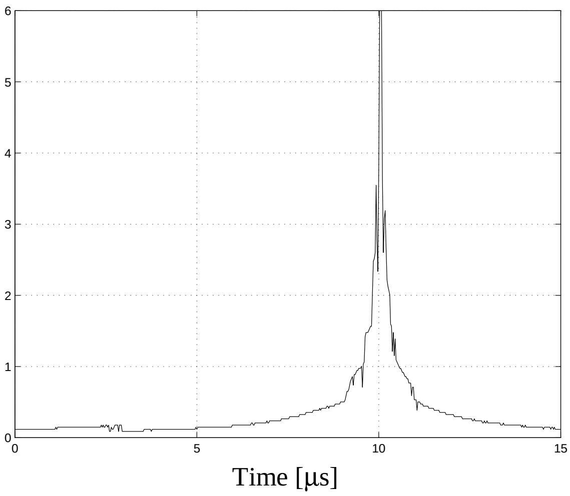

Fig. 12. Two echoes separated in time by 2 μs, after processing by SSP-CPC.

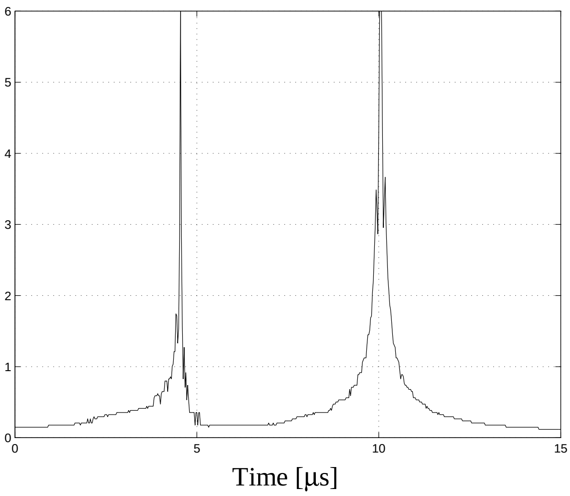

Fig. 13. Two echoes separated in time by 6 μs, after processing by SSP-CPC.

One should also note that the SSP-CPC output gives the *impression* of high temporal resolution due to its sharp shape. Unfortunately, this has nothing to do with the resolution but stems from the fact that SSP-CPC is detection oriented and nonlinear.

The temporal resolution of the SSP algorithm may be improved by increasing the bandwidth of the Gaussian filters in the filter bank. However, at the same time the clutter suppression performance is deteriorated. In order to get a temporal resolution comparable to the NCD the filter bandwidth had to be increased by a factor of three. Processing the ultrasonic B-scan image from Fig. 7 using this modified parameters resulted in the image shown in Fig. 14. Evidently, the signal to noise ratio has been significantly reduced compared to Fig. 9.

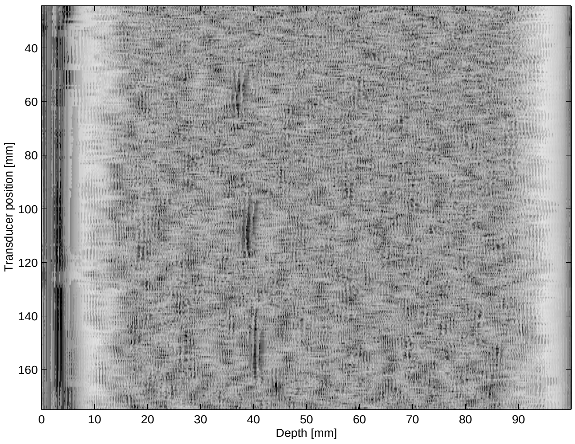

Fig. 14. Same as in Fig. 7, after processing by SSP-CPC with parameters modified to obtain improved temporal resolution.

5. SUMMARY AND CONCLUSIONS

In the paper a recently introduced algorithm, based on Noncoherent Detection, intended for suppression of material noise in ultrasonic images has been compared to the established Split Spectrum Processing scheme with a Consecutive Polarity Coincidence target extractor. The evaluation has concentrated on the clutter suppression performance and temporal resolution of the two different approaches.

The results clearly indicate that for a given temporal resolution the clutter suppression performance of the NCD is superior. By using more narrow filters in the SSP algorithm the performance can be increased to more or less the same level as for the NCD, but the temporal resolution is then significantly reduced. Due to its use of a bank of narrow bandpass filters, followed by a highly nonlinear target extractor, the SSP algorithm has an inherent relation between clutter suppression performance and temporal resolution. When employing the algorithm a tradeoff has to be made by the operator. The NCD, on the other hand, has the ability to fully utilize the temporal resolution allowed by the transducer and the inspected material.

Concerning parameter tuning, the differences between the evaluated algorithms should be small from an operator’s point of view. The situation will, however, be very different if a traditional SSP target extractor, such as Polarity Thresholding or Amplitude Minimization is used instead of the adaptive Consecutive Polarity Coincidence. Due to the parameter sensitivity of these algorithms and the highly nonlinear relation between the parameter values and the resulting output, tuning is nontrivial and tedious. Parameter tuning of the NCD algorithm is simple due to its smooth relation between parameter values and resulting output. Consequently, near-optimal parameter values can easily be determined automatically using a suitable performance measure.

Regarding processing time it should be noted that NCD is much faster than SSP. The reason is obvious: SSP utilizes a bank with a large number of filters, compared to one single filter for the NCD algorithm.

6. REFERENCES

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