SUPPRESSING ULTRASONIC GRAIN NOISE USING NONCOHERENT DETECTION

L. Ericsson, T. Stepinski and M. G. Gustafsson
Uppsala University, Signals and Systems, Box 528, SE-751 20 Uppsala, Sweden
http://www.signal.uu.se

ABSTRACT

Ultrasonic nondestructive testing of metals with coarse material structure is difficult due to the scattering from the large grains. In pulse-echo inspection the backscattering from the grain boundaries appear in the received ultrasonic images as clutter, often referred to as grain noise. The effect becomes very distinct for ultrasonic waves with lengths in the same range as the grain size. Consequently, the most suitable frequency range for the ultrasonic transducer utilized for the inspection is determined by the material. Thus, in order to obtain adequate results during inspection a special transducer should be manufactured for each material composition. In practice, this approach is neither technically nor economically feasible; instead a suitable transducer must be selected from a limited set. The resulting ultrasonic images will in many cases be characterized by high grain noise level or low temporal resolution. An alternative approach is to utilize a transducer with a frequency range as wide as possible and then apply advanced digital signal processing in order to adapt the effective frequency range to the inspected material. In the paper, such a signal processing algorithm, based on the concept of noncoherent detection, is presented. The performance of the algorithm is illustrated using ultrasonic images acquired from specimens made of cast stainless steel and copper with large grains. The material structures are similar to those found in nuclear power plants and in canisters intended for long term storage of nuclear waste.

1 INTRODUCTION

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 grain noise [1]. In order to reduce material noise and make ultrasonic testing feasible the wavelength of the ultrasound must be large compared to the average size of the grains, i.e., the frequency must be sufficiently low. Thus, the most suitable frequency range for the ultrasonic transducer utilized for the inspection is determined by the material.

Therefore, in order to get adequate inspection results a special transducer should be manufactured for each material composition. In practice, this procedure is not possible and a suitable transducer must be selected from a limited set. In general, the result will be ultrasonic signals with lower signal to noise ratio or lower resolution than when a transducer with an optimized frequency response is employed.

Furthermore, even if a transducer very well suited to the inspected material is available, it may still be necessary to employ transducers with different frequency responses for detection and sizing of defects. The limitations imposed by the material force the transducer designer to make a trade-off between sensitivity to grain noise and

temporal resolution. Thus, during inspection one transducer has to be utilized for detection, and then the detected defects have to be reinspected with another transducer.

The ideal solution to the problems mentioned would be to have a transducer with a variable frequency response. Unfortunately, such transducers can not be manufactured. An alternative, feasible, approach is to utilize a transducer with a frequency range as wide as possible and then apply digital signal processing in order to modify the frequency contents of the received ultrasonic signals. The effective frequency response of the ultrasonic system can then be easily adapted to different materials and the same ultrasonic signals may be used for both detection and sizing. In this report, such a signal processing algorithm, based on noncoherent detection (NCD), is evaluated. NCD has for a long time been used within the field of telecommunication and has recently been adapted to ultrasonic nondestructive testing [2,3].

In order to evaluate the NCD technique ultrasonic signals have been acquired from test samples made of cast stainless steel and copper, containing artificial defects. Data were recorded using a computerized ultrasonic instrument/scanner, using several different transducers. The signals were then processed using a MATLAB™ implementation of the algorithm.

2 NONCOHERENT DETECTION

The noncoherent detector, which is well known from telecommunication [4], 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 [2]. 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 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_{lower} and f_{upper}. The structure of the algorithm is displayed in Fig. 1. 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.

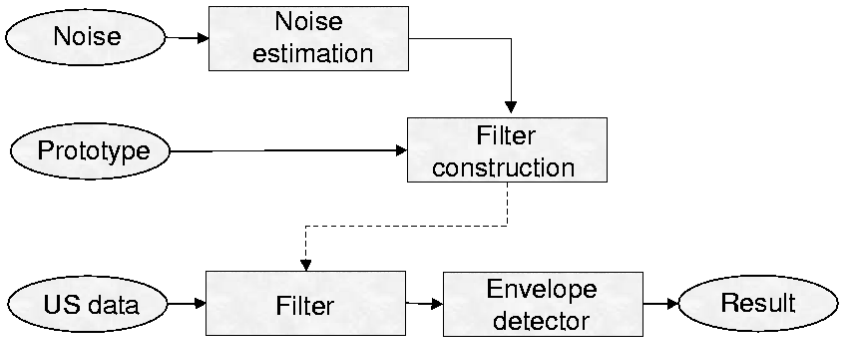

Fig. 1. Structure of the noncoherent detection algorithm.

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. This method will be utilized in the evaluation below.

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 [3], 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.

Regardless of the performance measure used during the filter construction procedure the basic idea is the same: the prototype parameters (f_{lower} and f_{upper}) are varied in a systematic manner and the performance of the resulting filter are evaluated by applying it to the selected ultrasonic data. When a known test block is available, the set of data would typically be a B-scan containing one defect echo surrounded by grain noise. The coordinates of the defect and noise regions are then supplied to the filter construction algorithm so that the SNR enhancement (SNRE) can be automatically calculated for each set of prototype parameters. By plotting the SNRE as a function of the parameters a “map” is obtained which shows how the performance of the resulting filter varies, see Fig. 2 for an example.

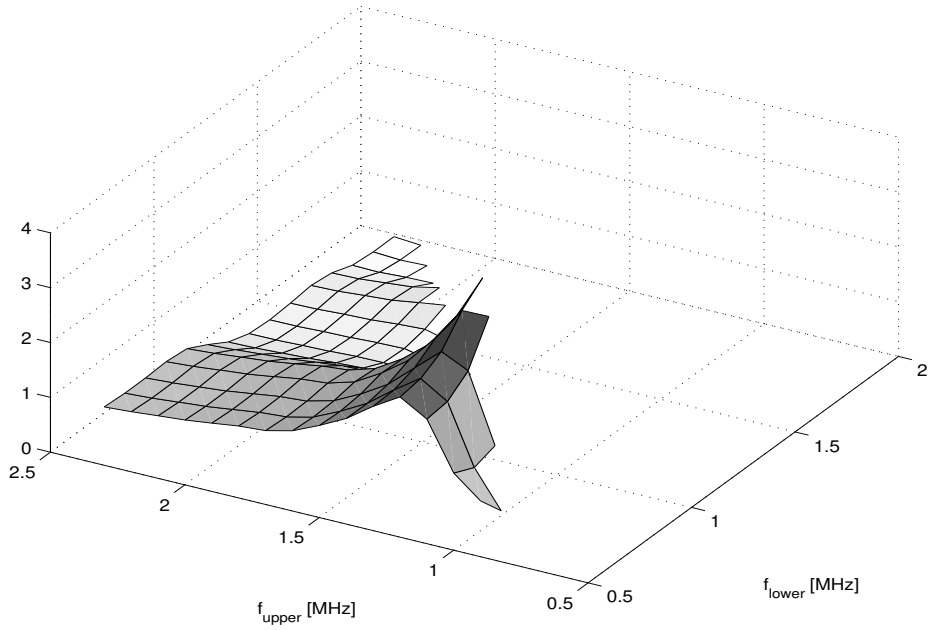

Fig. 2. Signal-to-noise ratio enhancement as a function of prototype parameters.

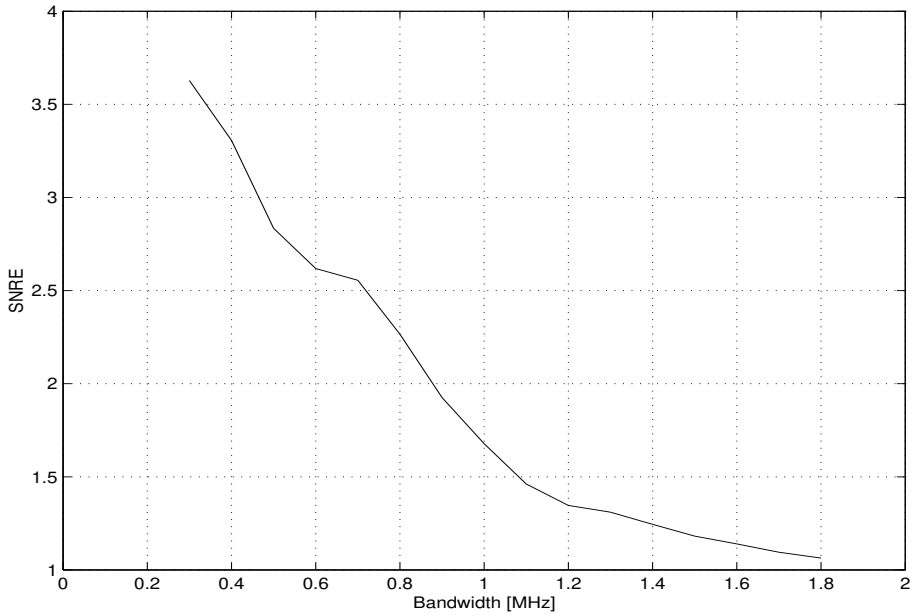

Fig. 3. Signal-to-noise ratio enhancement as a function of prototype bandwidth.

From the map obtained during the filter construction process the filter providing the best possible SNRE for a given prototype bandwidth, i.e., temporal resolution, can be found. Fig. 3, which was constructed from the map in Fig. 2, shows the SNRE as a function of prototype bandwidth. The curve clearly shows that a trade-off has to be made between grain noise suppression capability and temporal resolution. However, by storing the filters corresponding to the different prototype bandwidths in the computer, it is possible to change the bandwidth in real-time while watching the result. Consequently, the same B-scan data may be used both for detection and defect sizing by merely turning a knob to change the trade-off between SNRE and temporal resolution.

3 EXPERIMENTAL RESULTS

The NCD technique, as described above, was evaluated using ultrasonic signals acquired from samples made of cast stainless steel and large grained copper. The data acquisitions were performed with computerized ultrasonic instruments with an amplitude resolution of 8 bits. The acquired B-scans were then transferred to a PC running MATLAB™ for off-line processing.

3.1 Results from cast stainless steel

Ultrasonic signals utilized for the evaluation were acquired from a test block made of two pieces of cast stainless steel welded together. The structure of the block was similar to what can be found in certain parts of nuclear power plants. Two wide-band transducers, both with two crystals, emitting P-waves and an angle of 45° were used for inspection of a machined notch, located close to the welding area, in the test block. One transducer operated at a center frequency of 2.25 MHz, and the other one at 0.5 MHz.

Ultrasonic B-scans acquired from the test sample by the two transducers are shown in Fig. 4-5. The notch is located at transducer position 40 mm, at a sound path of 80 mm. As expected the 2.25 MHz B-scan exhibits a much higher grain noise level than the 0.5 MHz B-scan. From Fig. 5 it is also obvious that the temporal resolution provided by the 0.5 MHz transducer is to low for resolving the upper and lower edge of the notch.

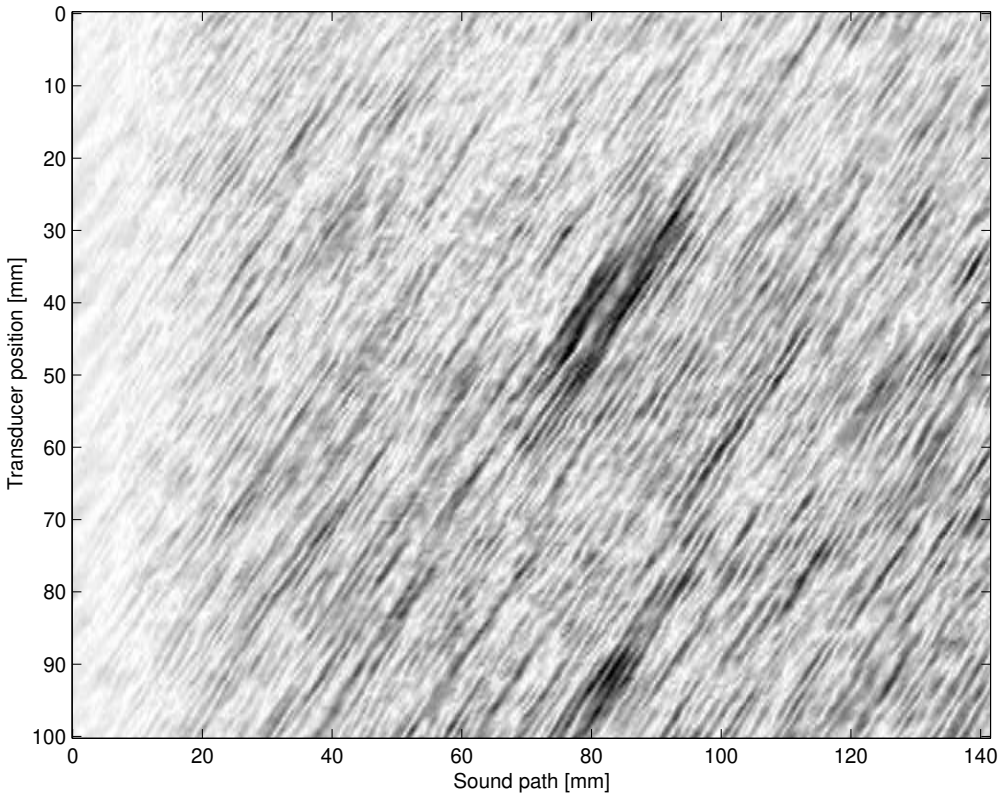

Fig. 4. Artificial notch in cast stainless steel, located close to welding zone, inspected by 2.25 MHz P-wave transducer at 45°.

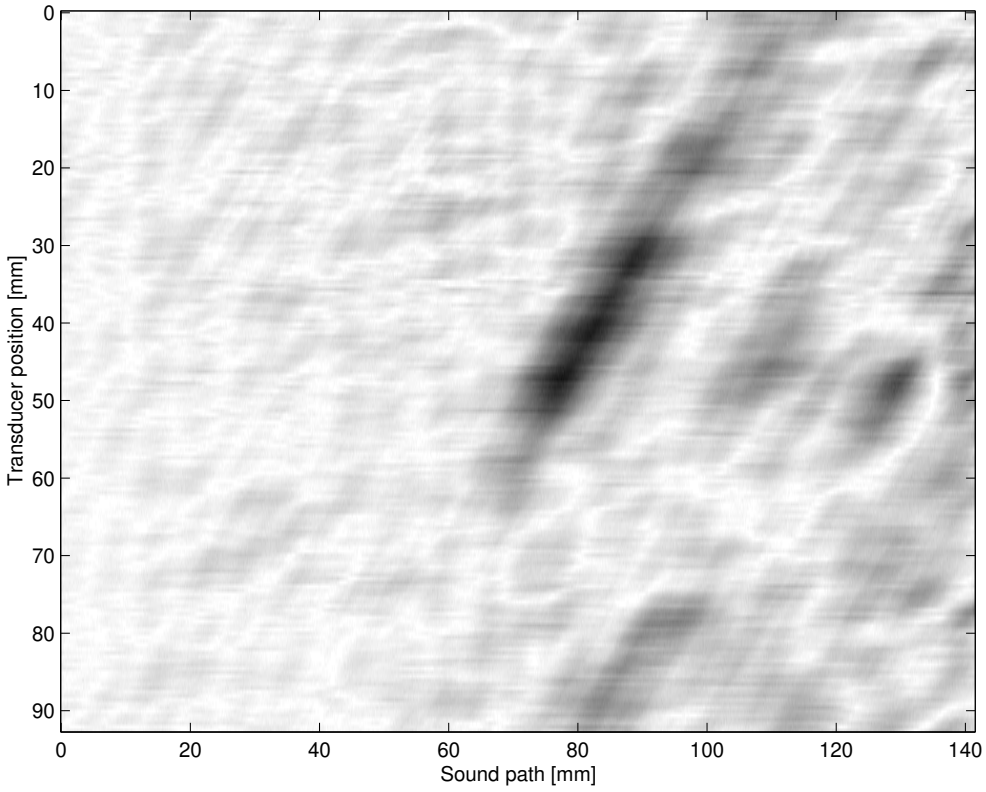

Fig. 5. Artificial notch in cast stainless steel, located close to welding zone, inspected by 0.5 MHz P-wave transducer at 45°.

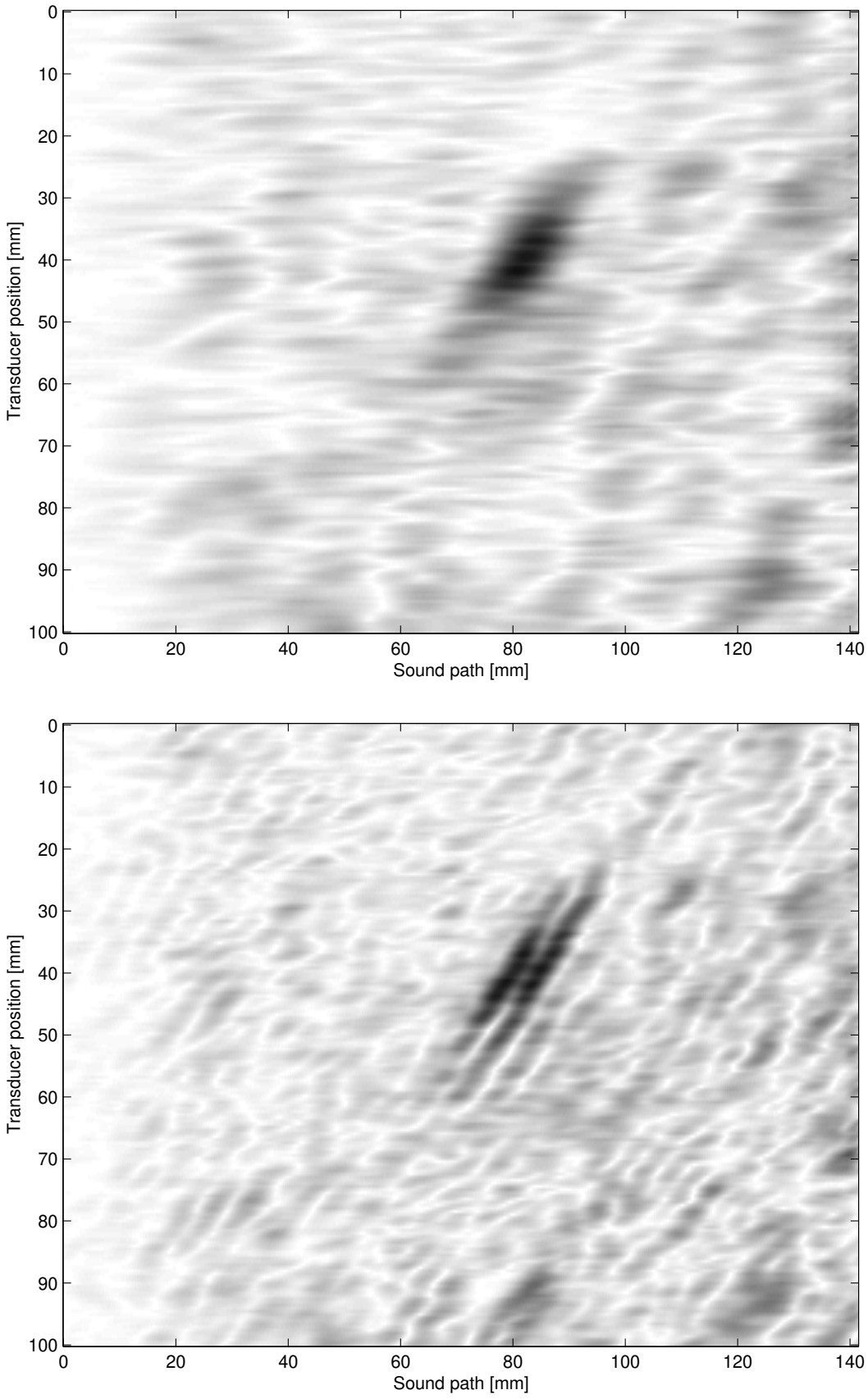

Fig. 6. The B-scan from Fig. 4, after processing by NCD. The upper figure shows the result obtained by setting the prototype bandwidth to 0.3 MHz, and the lower figure the result with the parameter set to 0.7 MHz.

In order to evaluate the capabilities of the NCD approach, the B-scan acquired by the 2.25 MHz transducer was used as input data. The SNRE map, resulting from the filter construction procedure, is shown in Fig. 2. The filters yielding the highest SNRE for each bandwidth, as shown in Fig. 3, were stored during the adaptation process for subsequent application to the ultrasonic data.

The results of the processing, using two different prototype bandwidths, 0.3 MHz and 0.7 MHz, are shown in Fig. 6. Evidently, by utilizing a low bandwidth the processed B-scan exhibits a SNR as least as high as could be obtained by the 0.5 MHz transducer. Additionally, by increasing the bandwidth the temporal resolution can be made high enough to resolve the upper and lower edges of the notch. In the latter case, the SNR is still substantially higher than in the original data.

3.2 Results from copper

The NCD approach has also been tried on ultrasonic data acquired from test blocks made of copper with large grains, a material expected to be used for making canisters intended for long-time storage of nuclear waste. The sample was inspected using a linear ultrasonic array, operating at a frequency of 3 MHz. The array had 64 elements, of which 16 were used simultaneously to form the ultrasonic beam. By employing a combination of electronic and mechanical scanning a three dimensional array of data was obtained.

The 3-D data were then used to form a C-scan, see Fig. 7. The temporal gate used for creating the C-scan was wide enough to comprise the entire block. The intention was to get a quick overview of the block and detect two bottom-drilled holes, located at x=197 mm and x=216 mm. Evidently, the grain noise accumulated by the wide gate made defect detection virtually impossible.

In order to apply the NCD technique to the data, the B-scan obtained by making an intersection at x=197 mm was used for filter construction. The resulting filter was then applied to the entire data set and a new C-scan was created in the same way as above, see Fig. 8. The bottom-drilled holes are now easily detected and also the ends of a number of side-drilled holes are clearly visible.

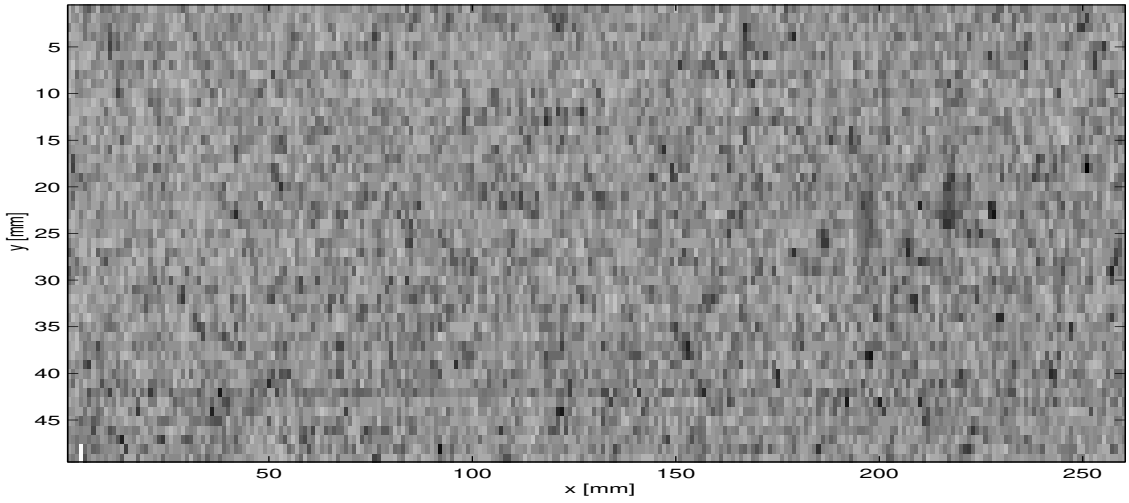

Fig. 7. C-scan showing two bottom-drilled holes in large grained copper, inspected by a 3 MHz ultrasonic array at 0°.

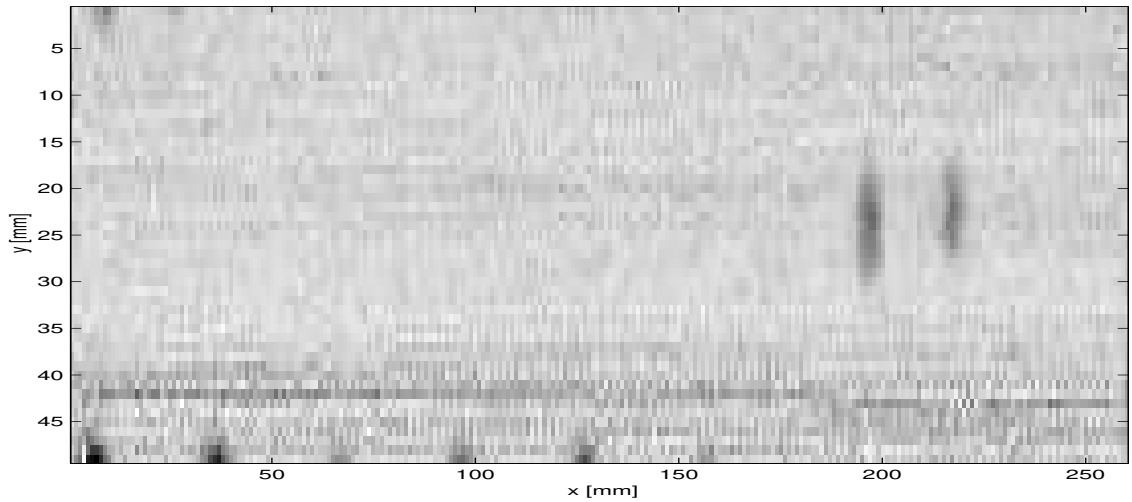

Fig. 8. The C-scan from Fig. 7, after processing by NCD.

4 SUMMARY AND FUTURE DEVELOPMENTS

A recently introduced approach for suppression of grain noise in ultrasonic signals, based on noncoherent detector statistics, has been presented. Experimental evaluation of the technique, using ultrasonic images from test blocks made of cast stainless steel and large grained copper, has proven its high performance.

By employing this technique, the frequency range best suited for a particular material can be automatically estimated and utilized for inspection, without the need to employ a tailor-made transducer. Consequently, a single wide-band transducer can be used to get near-optimal inspection results for a wide range of materials. Furthermore, the effective bandwidth of the filter can be changed interactively in order to maximize either the noise suppression or the temporal resolution. This feature makes it possible to use the same set of ultrasonic data both for detection and defect sizing.

In the near future the technique will be further evaluated using ultrasonic signals from natural defects, e.g., fatigue cracks. It will then be especially interesting to investigate whether a filter constructed using an artificial defect in a test block can be used efficiently when inspecting other objects with the same material composition.

ACKNOWLEDGEMENTS

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