STATISTICAL ANALYSIS OF SPLIT SPECTRUM PROCESSING

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Abstract
This work provides a statistical analysis of Split Spectrum Processing (SSP) performance in detecting multiple targets. The investigation is performed under two conditions: (i) known a priori target spectra (i.e., center frequency and bandwidth) which, in turn, identifies the optimal spectral range for processing, and (ii) adaptively obtaining the processing frequencies using group delay moving entropy. The group delay moving entropy (GDME) method was introduced to select the optimal frequency regions for SSP when detecting multiple targets. The effectiveness of this technique is statistically demonstrated in this paper. The performance is measured in terms of Normalized Signal-to-Noise Ratio and probability of target detection. SSP with known target information yields a slightly higher probability of detection compared to SSP using GDME, while both cases achieve comparable SNR enhancement. SSP results were compared to the optimal bandpass filter performance and shown to be superior.

Introduction
A major limitation facing the ultrasonic evaluation of materials is the high level of background noise from unresolvable grain boundaries that often mask the reflections from the target of interest in the measured signal. A realization of the frequency diversity principle known as Split Spectrum Processing (SSP) that first decomposes the received broadband signal into a narrowband ensemble exhibiting different signal-to-noise ratios (SNR) and subsequently recombines them non-linearly has been shown to enhance flaw visibility [1-3]. Earlier work has demonstrated that SSP is an effective method of discriminating between target echoes and microstructure scattering, based on differences in power and phase spectra [4-5].

A multi-step procedure was developed that successfully extended the application of SSP to the detection of multiple targets having different spectral characteristics [5]. Simulations were presented to demonstrate the potential of this technique for detecting multiple targets in complex environments. In the current work, extensive statistical analysis is performed to evaluate the performance of conventional and adaptive SSP using group delay moving entropy (GDME). An expanded version of this work has been submitted to IEEE Transactions on UFFC [6].

Multi-Step SSP using Group Delay Moving Entropy
As detailed in [4-5] the target signal exhibits relatively small group delay variations compared to noise. Therefore, the frequency range containing the target signals will yield significantly smaller group delay entropy values compared to the frequency ranges containing noise only. When multiple targets are present, the group delay entropy technique permits the selection of the ideal SSP spectral ranges for the individual targets as long as the moving window is small enough to sense the spectral variations between the targets.

When multiple targets are present in the received signal, the frequencies centered around the minimum value of the GDME (i.e., the high SNR region in the spectrum) are likely to correspond to the optimal frequency range for the most dominant target. Consequently, when SSP is applied to this spectral region, the target signals concentrated in these frequencies will be enhanced. Though conventional SSP is generally capable of detecting multiple targets, application over a single spectral range is less likely to detect multiple targets located in different regions. Therefore, a multi-step SSP technique was designed to iteratively detect the most dominant target present in the received signal. After a target has been identified, it is suppressed using a time domain window centered at the target location prior to detecting the remaining targets.

Signal and Noise Models
The data processed consists of simulated targets embedded in experimentally collected background grain noise. The number of targets in the simulated data is fixed at 3. The absolute-minimization algorithm, which selects the minimum magnitude of the normalized narrowband signals at each time instant, is used in this work.

It is clear that the relative performance of the multi-step GDME technique will be more pronounced in non-homogeneous materials (i.e., when targets occupy different spectral regions). The simulations here are based on all three targets having the same center frequency and bandwidth but different locations and amplitudes. Such a situation is likely to represent the worst-case scenario in terms of relative performance for SSP. The targets are randomly distributed over the total data length (N=512). Only one distinct target is permitted per range cell in the simulation. The amplitude of the background grain noise is
normalized to unity and the amplitude of the targets is uniformly distributed between 0.3-0.9. Target amplitude of less than 0.3 was considered too weak to be detected, whereas amplitudes larger than 0.9 can generally be identified without processing. The target with the highest amplitude is labeled as target #1, the next highest amplitude target is labeled target #2 and so on. The background grain noise is obtained from a stainless steel sample with average grain size of 160 µm using a 5 MHz transducer [2]. The center frequency and 3-dB bandwidth of the grain noise are approximately 5 MHz and 2.1 MHz, respectively. The simulated target signals are added to the background noise to create hybrid data. A typical hybrid data signal containing three targets is shown in Fig. 1. The unprocessed data is seen to have extremely low SNR and the three targets are completely indistinguishable from the backscattered grain noise.

This work presents the statistical evaluation of multi-step SSP under two conditions: (i) known a priori target spectra (i.e., center frequency and bandwidth) which, in turn, identifies the optimal spectral range for processing and (ii) adaptively obtaining the processing frequencies using GDME. The performances are also compared to the performance of conventional bandpass filter (BPF) over the frequency range used by SSP. For notational convenience, SSP using the frequencies indicated by the GDME is abbreviated as SSP-GDME, while SSP with a priori knowledge of target spectra (i.e., optimal spectral range for processing) is denoted as SSP-KN, and similarly, the optimal BPF as BPF-KN.

Statistical Analysis

One hundred independent hybrid A-scans with randomly selected target amplitudes and locations are used to generate the statistical data for each target center frequency. The center frequency of the targets was varied up to the center frequency of the grain noise while the bandwidth was fixed at 1.36 MHz. Figure 2 shows the probability of detection of all three targets for SSP-GDME, SSP-KN and BPF-KN. SSP with known target information is seen to yield a slightly higher probability of detection than SSP-GDME. Although this is an adaptive process which does not require any a priori target information, it still achieves remarkably high probability of detection (i.e., of all three targets). As the center frequency of the targets approaches the frequencies where the noise energy is concentrated, i.e., low SNR regions, the probability of correct detection of all three targets becomes extremely low for both cases.

SNR enhancement for individual targets is evaluated next. The Normalized Signal-to-Noise (NSNR) for a single target present in the time sequence y(n) is defined as:

$$\text{NSNR} = \frac{\sum_{n=T-P/2}^{T+P/2} y^2(n)}{\sum_{n=1}^{N} y^2(n)}$$  \hspace{1cm} (1)

where T is the target location and P is the target pulse-width. Note that this definition results in SNR values ranging from 0 to 1. This is now extended for the multiple target case, where the NSNR for the jth target is defined as:

$$\text{(NSNR)}_j = \frac{\sum_{n=T_j-P/2}^{T_j+P/2} y^2(n)}{\sum_{n=1}^{N} y^2(n) - \sum_{i=1}^{T_j-P/2} y^2(n)}$$  \hspace{1cm} (2)

Figure 3 shows the NSNR vs. target center frequency for target 1 as the target center frequency is increased. The input SNR of target 1 is also plotted for reference. Note that the legend given in Fig. 2 applies for Figs. 3 through 8. Both SSP-GDME and SSP-KN are seen to achieve significant SNR enhancement over a wide range of target frequencies. In the extreme case of grain noise completely overwhelming the targets, i.e., when the signal and noise spectra completely overlap, the probability of detection is very low leading to statistically insignificant SNR values. The SNR is set to zero for such frequencies. Symmetrical values were obtained for higher target center frequencies.

Figure 4 shows the probability of detection of target 1 only, for SSP-GDME, SSP-KN and BPF-KN. The probabilities in the 'no-processing' plot refers to the likelihood of picking the highest amplitude in the raw data signal as target 1, the next highest amplitude outside range cell 1 as target 2, and the third highest amplitude outside cells 1 and 2 as target 3. The SNR and probability of detection for targets 2 and 3 are shown in Figs. 5, 6, 7, 8 respectively. Similar results are seen as those obtained in Figs. 3 and 4.

Figures 9 and 10 show the input and output SNRs for the three targets using SSP-GDME and SSP-KN respectively. It can be inferred that higher input SNR generally results in higher output SNR.

Evaluation of the BPF performance shows that the NSNR drop off with frequency is more rapid for BPF indicating that bandpass filtering is less robust compared to SSP. However, the probability of detection performances for the two cases are similar. Therefore, it verifies that in a statistical sense (i) SSP achieves substantially more SNR enhancement than bandpass filtering alone, and (ii) SSP is robust over a wider frequency range than bandpass filtering and is, therefore, more reliable.

In practical applications, the parameters for the bandpass filter and SSP must be determined without a priori information about the signal or noise. Thus the GDME provides a reliable procedure by which the optimal parameters can be determined from the received signal itself which is the major advantage of this technique.

Similar results are obtained by changing the target 3-dB bandwidth from 1.36 to 1.02 MHz.

710 — 1996 IEEE ULTRASONICS SYMPOSIUM
Figure 1 Unprocessed data with three targets

Figure 2 Prob. Detection of all three targets

Figure 3 NSNR for Target 1

Figure 4 Prob. Detection for Target 1

Figure 5 NSNR for Target 2

Figure 6 Prob. Detection for Target 2
Conclusions

Statistical analysis of SSP shows that the technique based on the GDME provides the optimal spectral regions for processing and is effective in multiple target detection. The performance of the various methods is measured in terms of the Normalized SNR and probability of detection. SSP with known target information yields a slightly higher probability of detection compared to SSP using GDME, while both cases achieve comparable SNR enhancement. The results were compared to the corresponding bandpass filter outputs which demonstrate the superior grain noise suppression capabilities of SSP.

Acknowledgments

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References:


