AN ITERATIVE SPECTRAL METHOD FOR MULTIPLE TARGET DETECTION

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Abstract
Although split spectrum processing (SSP) is an effective method for suppressing grain noise in ultrasonic non-destructive testing, its application has been mainly limited to the detection of single targets or multiple targets having similar spectral characteristics. In this paper, the group delay moving entropy technique is introduced to enhance the performance of SSP in detecting multiple targets which exhibit different spectral characteristics. This is likely to occur in complex, dispersive and non-homogeneous media such as composites, layered and clad materials, etc. It is shown that the group delay moving entropy can be used to select the optimal frequency region for SSP when detecting such targets. An iterative procedure that combines group delay moving entropy and SSP is proposed whereby the multiple targets are identified one at a time. The dominant target is subsequently eliminated using time domain windows which improves the detection of the remaining weaker targets. Simulation results are presented which demonstrate the feasibility of the multi-step SSP for detecting multiple targets.

Introduction and Background
Ultrasonic detection and identification of flaws embedded in coarse-grained materials is often limited by the presence of high amplitude interfering echoes from unresolvable grain boundaries. A frequency diversity technique known as split spectrum processing (SSP) that first splits the received wideband signal into a frequency diverse narrowband ensemble exhibiting different signal-to-noise ratios (SNR) and subsequently recombines them non-linearly is known to enhance flaw visibility [1-2]. Previous work has shown that the performance of SSP is fairly sensitive to the frequency region used for processing [3]. Based on the observation that the target (i.e., flaw) has a fairly constant group delay while the noise has random group delay, the group delay moving standard deviation technique was developed for selecting the ideal frequency region for SSP [4].

So far these techniques have been mainly applied for detecting single targets or multiple targets with similar spectral characteristics. However, in many applications it is possible to simultaneously insconspicuous multiple targets with distinct geometrical features located at different regions of the material, which results in signals with significantly different temporal and spectral characteristics. This situation can be further complicated if the material is non-homogeneous such as composites, centrifugally cast stainless steel, layered materials, etc. In such cases, the variations in the location and orientation of the defects, as well as their geometry and size can profoundly affect the spectral characteristics of the corresponding backscattered ultrasonic signals.

Hence, the conventional application of the SSP algorithms using a single spectral range may not be sufficiently sensitive to the variations in the spectral characteristics of the different targets to permit their detection simultaneously. Consequently, it is desirable to develop new techniques that address the complex multiple target detection problem tailored for composites and other non-homogeneous materials.

In this paper, a multi-step method which combines the group delay moving entropy and the SSP techniques is presented for improved detection of complex multiple targets in ultrasonic applications. The theoretical model and analytical aspects are considered in a previous paper [5].

Selection of the Optimal Frequencies Using Group Delay Moving Entropy
As detailed in [4] the group delay moving standard deviation technique was used effectively in the problem of single target detection. This method is based on the observation that the target signal exhibits relatively small group delay variations compared to the frequencies containing noise only. The randomness of the group delay is measured by its standard deviation, which is estimated using a moving window along the frequency axis. In other words, the standard deviation of the group delay is inversely related to the frequency domain SNR and may be used to identify the optimal frequency region for the application of SSP. However, this method is not effective in detecting multiple targets which exhibit spectral variations and cannot be extended for this purpose. Entropy, which is a more sensitive measure of randomness is used instead to identify the optimal frequency region(s).

The discrete group delay of the signal is defined as the derivative of the phase spectrum, $\phi(k)$:

$$\nu(k) = \frac{N}{2\pi} [\phi(k+1) - \phi(k)], \quad 1 \leq k \leq N/2$$

(1)

where $k$ is the frequency index, $\phi(k)$ is the phase component and $N$ is the total number of data points in the discrete Fourier transform (as well as the total time duration of the signal). Equation (1) will yield discrete group delay values in the range $\nu(k)\in [0, \pi]$ for $1 \leq k \leq N/2$.

In order to determine the entropy it is necessary to first estimate the pdf of the group delay, $f_{\nu}(\nu)$. As described in [5], this is done by normalizing the area of the group delay histogram to unity. Next, the group delay moving entropy at frequency $k$ is obtained using the formula:
where $M$ is the width of the moving window as well as the number of quantization levels for the group delay values (i.e., quantization step size = $\frac{N}{M}$). In practice the center frequency $k$ is incremented by an integer value $\pm 1$, which should be selected based on the trade-off between the desired accuracy for $I_k$ and the computation time. In general, $r$ is chosen to be small compared to $M$.

As mentioned earlier, the frequency range containing the target signal will exhibit significantly smaller group delay variation compared to the frequency range containing noise only. If the moving window is small enough to sense the spectral variations between the targets i.e., when multiple targets exhibit spectral differences, the group delay entropy will permit the selection of the ideal SSP spectral ranges for the individual targets. This suggests that the selection of the window size $M$ is critical to the performance of the proposed technique resulting in a trade-off between the sensitivity to detecting the spectral differences between the target signals and the accuracy of the estimation of the group delay pdf. Large value of $M$ provides a larger number of quantization levels for the group delay values (i.e., lower quantization error) and a larger number of data points for the estimation of the group delay pdf, $f_k(m)$, resulting in a more accurate estimate of $f_k(m)$ and $I_k$. Conversely, a small window size $M$ will provide a greater accuracy in locating the high SNR regions (i.e., target frequencies), and greater sensitivity to detecting the spectral differences between the targets. Furthermore, since the maximum number of points available for estimating the group delay moving entropy $I_k$ is limited to $1+(N/2-M)/r$, smaller $M$ values will provide a more accurate estimate of $I_k$. Based on these trade-offs and the simulation results examined, a general rule recommended for selecting the $M$ value is $M=N/M$ or $M \ll N$.

### Multi-Step Split Spectrum Processing

Multi-step Split Spectrum Processing (SSP) is generally capable of detecting them as long as these targets exhibit similar spectral characteristics. In such cases, the frequencies centered around the minimum value of the group delay moving entropy (i.e., the high SNR region in the spectrum) are likely to correspond to the optimal frequency range for the most dominant target. Thus when SSP is applied to this spectral region, the target signals concentrated in these frequencies will be enhanced. However, in non-homogeneous media, SSP applied over a single spectral range is less likely to detect multiple targets located in different regions. Therefore, a multi-step method is developed which consists of iteratively identifying the separate frequency regions (i.e., multiple targets) one at a time. The dominant target is then eliminated using a time-domain window centered at the target location, which improves the detection of the remaining weaker targets. This procedure is repeated until all the targets are detected. In summary:

(i) Compute the group delay moving entropy for the unprocessed data and locate the high SNR frequencies as indicated by the entropy minima.

(ii) Apply SSP over the spectral range indicated by Step (i). This will result in the identification of one or more targets.

(iii) Suppress the dominant target using a target elimination window with pulse width equivalent to the system impulse response yielding semi-processed data.

(iv) Return to Step (i) and iterate until all the targets have been identified.

This procedure will now be illustrated using hybrid data that has been created by adding simulated target signals to grain noise data obtained from a stainless steel sample with average grain size of 160 $\mu$m. Figure 1 shows an example of the simulated data based on the parameters presented in Table 1, which reflects an example of the potential variations in the spectral properties of multiple targets in non-homogeneous materials. The group delay spectrum of the data in Fig. 1 is shown in Fig. 2.

<table>
<thead>
<tr>
<th>Target</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>5.1 $\mu$s</td>
<td>14.6 $\mu$s</td>
<td>10.9 $\mu$s</td>
<td>8.4 $\mu$s</td>
</tr>
<tr>
<td>Amplt.</td>
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<td>0.44</td>
<td>0.67</td>
<td>1.2</td>
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<tr>
<td>Center</td>
<td>2.0 MHz</td>
<td>2.6 MHz</td>
<td>2.9 MHz</td>
<td>3.9 MHz</td>
</tr>
<tr>
<td>Freq.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 dB BW</td>
<td>1.05 MHz</td>
<td>0.92 MHz</td>
<td>1.4 MHz</td>
<td>1.4 MHz</td>
</tr>
</tbody>
</table>

Table 1 Simulated target parameters

To begin, the group delay moving entropy is computed using processing parameters $r=4$ (i.e., 0.196 MHz), $M=32$ to determine the optimal frequency region for the initial application of SSP. From plot 1 of Figure 3a, it is seen that a minimum entropy value occurs at approximately 1.23 MHz. The data (Fig. 1) is processed using SSP over the frequency range which falls within 90% of the minimum group delay moving entropy value. The SSP window parameters are selected based on past experimental results with metal samples [2] (i.e., window spacing $\Delta f=49$ KHz; window bandwidth of 409 KHz). The resulting output shown in Figure 2 clearly extracts the first target from the background grain noise. However, the process is unable to identify the remaining targets which are suppressed along with the grain noise. It should be pointed out here that application of SSP in the conventional manner using a single wide spectral region, such as 1.0-4.5 MHz, also fails to recover all four targets.
Fig. 2: Group Delay of the Simulated Data

Fig. 3 (a) (b): Group Delay moving entropy at various iterations

Fig. 4: Split spectrum processing output at step 1

Fig. 5: Target Elimination window

Fig. 6: Split spectrum processing output at step 2

Fig. 7: Split spectrum processing output at step 3

Fig. 8: Split spectrum processing output at step 4
In order to detect the remaining targets using the multi-step approach, target 1 is eliminated by multiplying the original signal in Figure 1 with a time window of width 0.52 μs centered at t₀ = 5.1 μs (Fig. 5). The group delay moving entropy is then computed for the modified data yielding plot 2 in Figure 3a. For this iteration, the minimum value of the group delay moving entropy is at 2 MHz. The modified data is processed using SSP over the new frequency range (1.8-2.53 MHz). The resulting output is shown in Figure 6, where the dominant signal corresponds to target 2 located at 14.6 μs. It is seen that this step has also enhanced target 3 located at 10.9 μs, due to the similarities in the spectral locations of targets 2 and 3 (see Table 1). The dominant target (i.e., target 2) located at 14.6 μs is eliminated next from the modified signal and the new group delay moving entropy (Fig. 3b-plot 3) with minimum value at approximately 2.1 MHz is obtained. The SSP output at step 3 is shown in Figure 7. The process is repeated one more time to detect the last target as seen in Fig. 8.

At this point, all the simulated targets have been detected using multi-step SSP. The frequency increment, Δf, and bandwidth of the narrowband windows were unchanged while the spectral range was varied as indicated by the group delay moving entropy. In order to terminate the multi-step detection process, the above technique is applied one more time to the modified data with target 4 removed. In this case, the SSP frequency range suggested by the group delay moving entropy (Figure 9) is 8.17 - 8.70 MHz, which is much higher than in the previous steps where targets were present. In addition, the entropy plot has a noticeably different pattern compared to those with targets (i.e., Fig. 5). Figure 10 shows the SSP output which exhibits greater number of high amplitude echoes than previously observed but no single dominant target. These observations indicate that it is unlikely that other targets remain in the data and the process is terminated.

The simulation parameters for the targets were varied randomly (i.e., target position, amplitude, bandwidth and center frequency) to further assess the performance of the multi-step approach. The results show that the technique is able to consistently detect with reasonably high reliability the target signals which were originally completely masked by grain noise as in the above example. However, it is expected that as the spectral differences between the targets become negligible, the advantage of the multi-step approach over the conventional SSP application will begin to diminish. We would like to point out that the geometry and spectral variations of actual targets are often more complicated than can be accounted for in a simulation. Therefore, the future goal is to obtain test samples with actual targets that exhibit spectral variations, to further assess the practical implications of this method.

Conclusions
The split spectrum processing technique has been shown to be effective in ultrasonic flaw enhancement, particularly in the detection of single targets or multiple targets with similar spectral characteristics. A multi-step SSP technique was demonstrated here, which extends the application of SSP to the detection of multiple targets having different spectral characteristics resulting from inhomogeneities in the material. The proposed technique combines the group delay moving entropy method, which identifies the optimal frequency region for processing, with the multi-step split spectrum processing technique. The results presented here show the potential of the proposed technique for detecting multiple targets in complex environments.

Acknowledgments
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References