SPECTRAL HISTOGRAM AND ITS APPLICATION TO FLAW DETECTION

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Abstract

The split-spectrum processing technique (SSP), introduced a decade ago, has been used in conjunction with linear and nonlinear signal processing methods to enhance target detection. This technique creates a frequency diverse ensemble of decorrelated narrowband signals by windowing the spectrum of the received wideband signal. In the past, considerable success has been reported in signal-to-noise ratio (SNR) enhancement using these methods. The SSP technique is fairly sensitive to the processing parameters viz. the spectral region to be selected for processing, the frequency increment between adjacent windows, and the bandwidth of each window. Previously, schemes have been suggested for choosing the optimal frequency increment and bandwidth. However, the choice of the spectral region has been made in the past by trial and error, and depends on the skill and experience of the operator. In this paper, a new method is presented for determining the optimal spectral region, based on the statistical distribution of the spectral windows selected by the SSP-minimization algorithm. Experimental data obtained by ultrasonic non-destructive testing show that this technique yields performance comparable to those obtained by a trained operator using trial and error approach, indicating its feasibility in the automation of the SSP-minimization algorithm.

Frequency response of SSP-minimization algorithm

The block diagram of the SSP-minimization algorithm is shown in Fig.1. The wideband input sequence x(t), which in general consists of both the flaw and noise terms is first transformed into the frequency domain using the fast Fourier transform. The spectrum is then split into N narrowband signals in the frequency domain using N bandpass filters in parallel. The resulting spectra are transformed back to the time domain using inverse Fourier transform and weighted by factors w_1 to w_N, where the weighting factors w_i are chosen such that the amplitude of each narrowband signal is normalized to unity. The N narrowband signals $w_1x_1(t),\ldots,w_Nx_N(t)$ are then processed to produce the output signal y(t) using the absolute-minimization algorithm which can be expressed as:

$$y(t)=\min(|w_1x_1(t)|, |w_2x_2(t)|, \ldots |w_Nx_N(t)|) \qquad (1)$$

It has been reported that significant SNR enhancement can be obtained using this technique when the processing parameters have been carefully chosen[1-8]. The SSP processing parameters are basically the frequency region, the frequency increment and the bandwidth of each window. It has been found that the most critical parameter is the frequency region over which SSP is performed. However, the choice of this region has been made in the past by trial and error, and depends on the skill and experience of the operator.

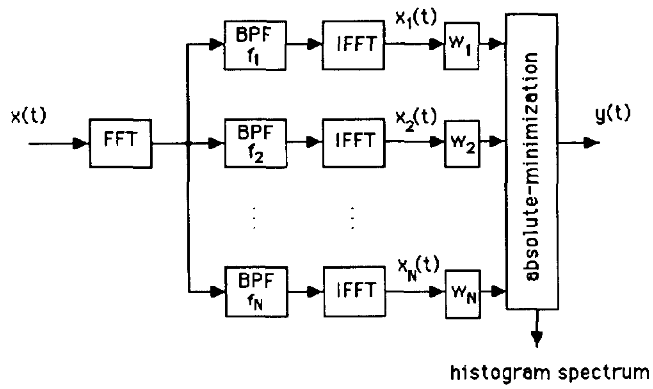

Fig. 1 The block diagram of SSP-minimization algorithm

In order to find a more reliable way of determining the optimal frequency region for the SSP-minimization algorithm, its frequency response has been studied and compared with the response of an optimal linear system. It is well known that the frequency response of a linear, time-invariant system can be expressed as:

$$H(f)=\frac{Y(f)}{X(f)} \qquad (2)$$

where X(f) and Y(f) are the input and output spectra, respectively. Furthermore, we assume that the input consists of flaw signal and additive noise, represented by

$$x(t) = s(t) + n(t) \qquad (3)$$

According to Wiener filter theory, for optimal SNR enhancement, the system transfer function H(f) should be

$$H(f)=\frac{S_{ss}(f)}{S_{ss}(f)+S_{nn}(f)} \qquad (4)$$

where s(t) and n(t) are assumed to be orthogonal[9-12].

Based on Eq.(4) it is clear that the frequency components of the input sequence with high SNR make a greater contribution to the output than those with low SNR. Since the SSP-minimization algorithm consists of a nonlinear operator - i.e. the absolute-minimization process described by Eq.(1), the above analysis is not valid. However, the SSP-minimization algorithm achieves significant SNR enhancement by selecting the high SNR frequency components in the input sequence. Therefore, the frequency response of the SSP-minimization algorithm may be characterized by examining the number of times each window is selected by the minimization algorithm.

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For example, if there are N narrowband signals $x_1(t),...,x_N(t)$, then only one of these narrowband signals $x_i(t)$ will be selected at each time instant t and the corresponding value will be recorded as the process output y(t). In a time interval of length $(M-1)\Delta T$, (ΔT is the sampling interval) the total number of selections made by the SSP-minimization algorithm will be M, and the number of times $x_i(t)$ (i.e. *i*th window output) is selected is m_i. Since each narrowband window corresponds to a specific center frequency, the statistical distribution of the narrowband windows selected within a given signal interval can be used to characterize the frequency response of the SSP-minimization algorithm in the statistical sense, termed the *spectral histogram*. Thus, the spectral histogram is defined as the distribution (histogram) of each frequency component (i.e. window or frequency band) of the input time sequence selected to form the output time series and may be considered analogous to the Wiener filter transfer function. For a stationary input time sequence, if the processing time is long enough, the spectral histogram of the SSP-minimization algorithm should, in general, converge to a mean histogram.

Optimal spectral region selection based on spectral histogram

The concept of the spectral histogram as described above will now be applied to the SSP-minimization algorithm. As an example, Fig.2 shows an input time sequence x(t) from a cylindrical shaped heat treated stainless steel sample of average grain size 160 μm and Fig.3 is the corresponding power spectrum $|X(f)|^2$. It is clear from Fig.2 that the target echo is completely masked by grain noise (clutter). The application of the SSP-minimization algorithm to the time sequence within the 3 dB frequency region of the received power spectrum (4.0 to 7.0 MHz in Fig. 3) using frequency increment $\Delta f = 49$ KHz and bandwidth 0.29 MHz results in the output time sequence y(t) shown in Fig.4. Note that the flaw echo cannot be distinguished from the grain echoes. The results obtained are not very surprising since it was previously observed that the flaw information is mainly concentrated in the lower regions of the input spectrum, while the higher spectral regions chiefly contain grain noise[6]. Therefore, there is clearly a need to develop a technique to select the optimal spectral range for SSP. This can be achieved based on the spectral histogram concept introduced here, which is a measure of the relative SNR of the signal spectral components.

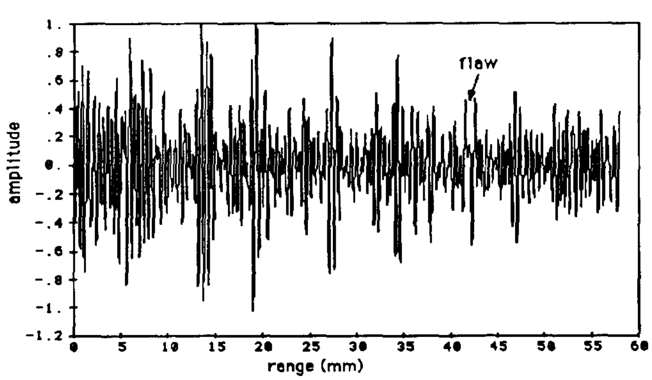

Fig.2 Received signal from a stainless steel sample (SST87)

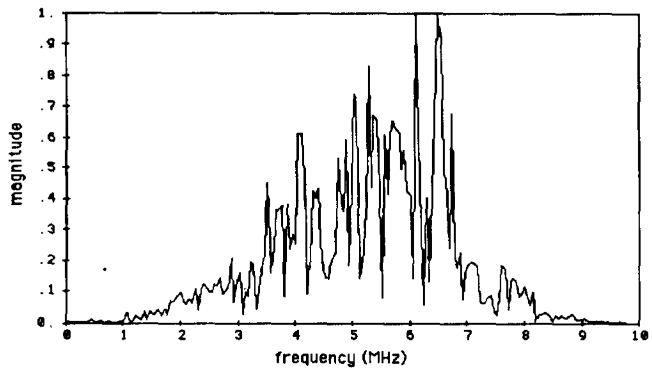

Fig.3 Power spectrum of the received signal

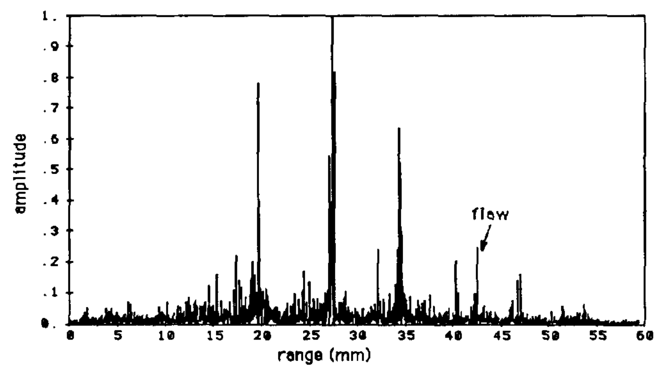

Fig.4 Absolute-minimization output for the received signal using the 3dB spectral range
frequency range: 4.0-7.0 MHz
frequency increment: 49 KHz
bandwidth: 0.29 MHz

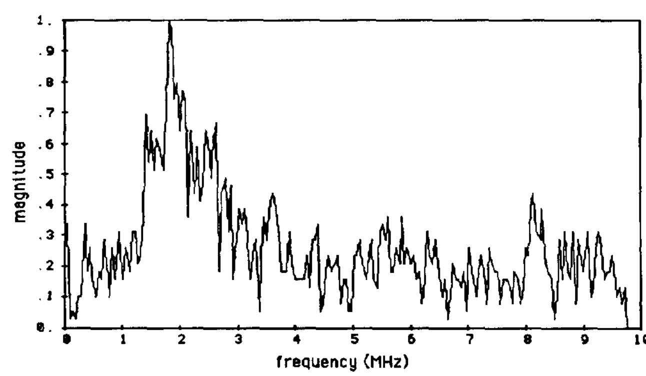

Fig.5 Spectral histogram
frequency range: 0.0-9.8 MHz,
frequency increment: 49 KHz,
bandwidth: 0.29 MHz

In order to determine the optimal frequency region based on the spectral histogram , the input time sequence is processed over the entire frequency region from 0.0 to 9.8 MHz, with a frequency increment $\Delta f \approx$ 49 KHz and bandwidth 0.29 MHz. The corresponding spectral histogram plotted in Fig.5 shows a clear peak at about 2 MHz. The spectral region about this peak corresponds to the high SNR frequencies in the input time sequence. This can be demonstrated by examining three normalized narrowband signals with bandwidths 0.29 MHz and center frequencies 0.98, 1.95 and 5.85 MHz, plotted in Fig. 6. It is clear that the narrowband signal with center frequency 1.95 MHz in Fig. 6b has the highest SNR, since the flaw can be identified easily and the grain echoes are relatively small. If the absolute-minimization algorithm is applied to these three normalized narrowband signals, the signal in Fig.6b will be selected more often than the others, since it generally has lower values except at the flaw location. Therefore, if the input sequence is reprocessed using the SSP-minimization algorithm within the region suggested by the spectral histogram shown in Fig.5 (i.e. 1.5 to 2.5 MHz) while maintaining the frequency increment $\Delta f \approx$ 49 KHz and bandwidth 0.29 MHz, the output SNR can be improved significantly as shown in Fig.7, where the target is clearly visible and the grain noise is dramatically reduced. This clearly demonstrates the SNR enhancement capabilities of the SSP-minimization algorithm (compared to the unprocessed sequence shown in Fig. 2) when the optimal spectral range is used. Furthermore, this technique yields similar performance compared to the trial and error approach for determining the optimal SSP frequency region. Alternatively, the input sequence can be processed by a linear bandpass filter, analogous to the Wiener filter, in the frequency region suggested by the spectral histogram (1.5 to 2.5 MHz), to obtain significant SNR enhancement as shown in Fig.8. However, in both cases a reduction in resolution is observed due to the lower signal bandwidth compared to the input signal in Fig.2.

The results presented here demonstrate that the spectral histogram technique allows the SSP-minimization process to achieve optimal target detection automatically by a two-step process: i) the input time sequence is first processed over the entire frequency range, using the SSP-minimization algorithm to obtain the spectral histogram and, ii) based on the peak of spectral histogram, the input sequence is reprocessed in the high SNR region using the SSP-minimization algorithm.

Conclusions

The flaw detection capabilities of an ultrasonic non-destructive testing system is limited by the presence of high amplitude background grain noise in the measured signal. The SSP-minimization algorithm has been successfully used to enhance flaw detection. However, this technique is fairly sensitive to the processing parameters, especially the frequency region selected for processing. In the past, the optimal region could be obtained only by trial and error. In this paper, the concept of the spectral histogram has been introduced to achieve this automatically. In addition, it has been shown that the spectral histogram for the SSP-minimization algorithm can be used to approximate the frequency response of this nonlinear system in the statistical sense, which can be utilized for obtaining a linear filter analogous to the Wiener filter.

Acknowledgements

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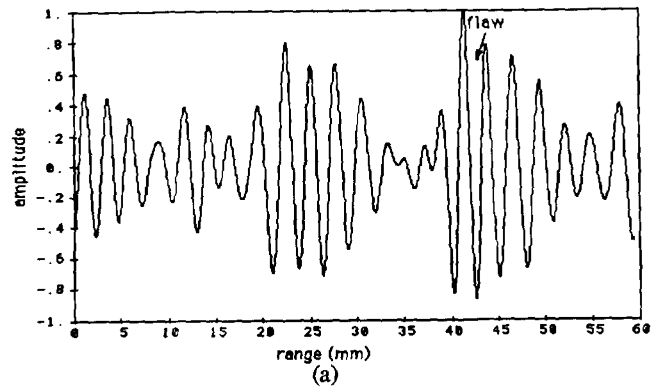
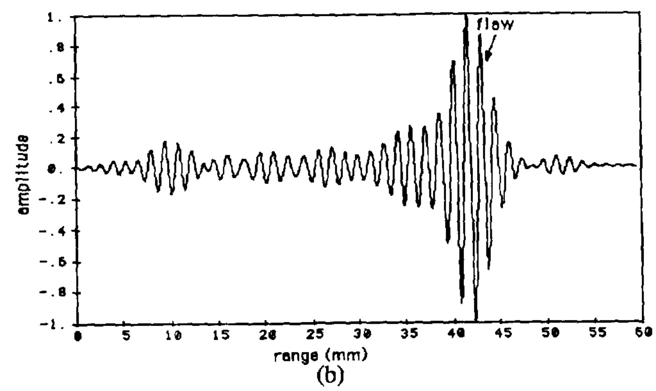
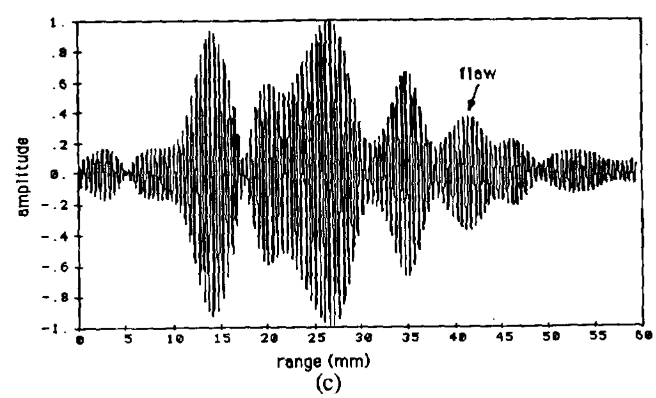


(a)



(b)



(c)

Fig.6 Narrowband signals corresponding to different SSP windows
(a) f_0=0.98 MHz, b=0.29 MHz
(b) f_0=1.95 MHz, b=0.29 MHz
(c) f_0=5.85 MHz, b=0.29 MHz

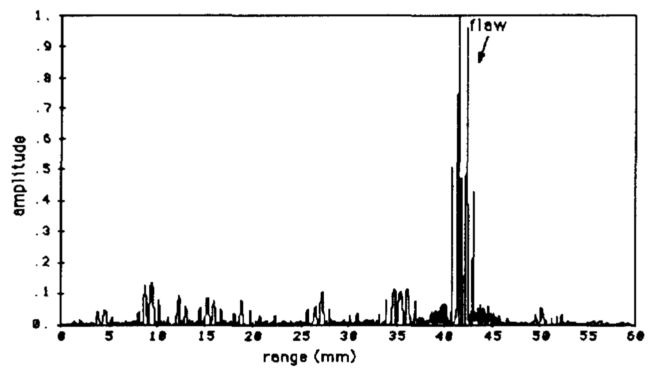


Fig.7 Absolute-minimization output using the spectral histogram result
frequency range: 1.5-2.5 MHz
frequency increment: 49 KHz
bandwidth: 0.29 MHz

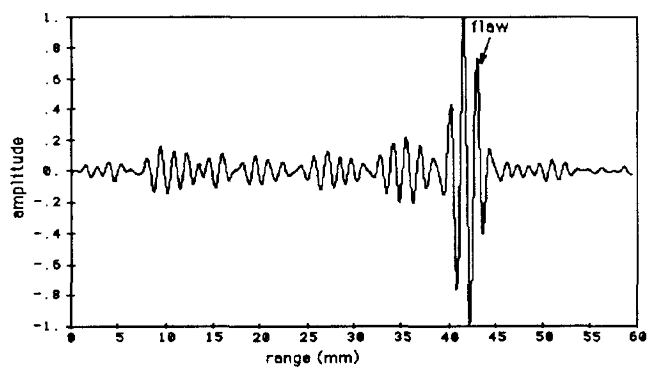


Fig.8 Bandpass filter output using the spectral histogram result
center frequency: 2.0 MHz
bandwidth: 1.0 MHz

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