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Signal Processing of Ultrasonic Data by Frequency Domain Deconvolution

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Abstract

Digital deconvolution of ultrasonic echo signals improves resolution and quality of ultrasonic images. The signal is modeled as resulting from convolution of the Ultrasonic pulse with the reflectivity function with additive noise. A deconvolution in the frequency domain is used to estimate the reflectivity function. An approach to minimize the effects of the transducer is developed. The simulation of pulse echo operating into a medium of interest is deconvolved with the simulation of pulse echo transducers with different values of dynamic range. The technique has been successfully employed to an ultrasonic data model for reconstruction of reflectivity function and the final result shows an improved signal to nose ratio with better axial resolution.

Keywords: Deconvolution, frequency domain, reflectivity function, signal processing, FFT

Introduction

The use of deconvolution techniques for both range and later resolution enhancement in ultrasonic application has been subject to widespread investigation and is well documented in the literature [1-4]. Wei [5] used a sparse deconvolution method for deconvolving ultrasonic signals to obtain the transducer pulse echo wavelet. The main sparse deconvolution methods and algorithms, with a view to applying them to ultrasonic non-destructive testing, have been investigated [6]. Herrera *et al.* [7] used Wiener filters to obtain the ultrasonic reflectivity function through wavelet-based models. The practical applications and limitations of different signal processing methods in ultrasonic NDE of multilayered structures have been analyzed [8]. A signal processing technique is developed in the present paper to minimize the transducer's effect on the range resolution of an ultrasonic pulse-echo system. The processing scheme utilizes a deconvolution filter that is based upon the standard frequency domain techniques. The problem of determining the ultrasonic reflectivity function resulting from density changes in a material is posed as an image restoration problem. The received time-domain signal is modeled as resulting from convolution of the acoustic pulse with the reflectivity function with additive noise. A frequency domain deconvolution method is used to estimate the reflectivity function. The convolution of two time sequences is equivalent to the product of their Fourier transforms, and a popular form of deconvolution, therefore, is simply the division of the Fourier transform of the simulation of pulse-echo signal with the Fourier transform of the pulse-echo transducer. The inverse Fourier transform of the result should then leave the deconvolution data. The Fast Fourier transform (FFT) deconvolution algorithm is easy to implement but suffers from the division-by-zero problem. As a result, a parameter is used to control the deconvolution performance. In the present work we examined FFT deconvolution for ultrasonic data, and proposed an algorithm to determine the cutoff frequency by using a different denominator dynamic range (dB). It was clearly observed that the reflectivity function improved after deconvolution with the proposed algorithm.

Deconvolution technique

In practice, it is well accepted that one scan line of the received pulse-echo signal y(*t*) at time *t* can be represented as [9]

$$y(t) = w(t) * u(t) = \int_{-\infty}^{+\infty} w(\tau).u(t-\tau)d\tau \qquad (1)$$

where u*(t)* is the medium response or the reflectivity function [10], *w*(*t*) is the ultrasound system response [11], and * represents convolution. Deconvolution attempts to remove the effect of the input function w(t) from the output y(t) to achieve some close approximation to the original medium impulse response u(t). In the frequency domain, Eq. (1) is represented as

$$Y(j\omega) = W(j\omega) \bullet U(j\omega) \qquad (2)$$

where Y(j ω), W(j ω) and U(j ω) are the frequency domain representation of y(t), w(t) and u(t) respectively. The process of obtaining u(t) knowing both y(t) and w(t) is called deconvolution. Ideally, deconvolution can also be performed in the frequency domain using the Fourier transform. Eq. (2) can be written as

$$U(j\omega) = \frac{Y(j\omega)}{W(j\omega)} \qquad (3)$$

Due to measurements and signal processing limitation, simple division will result in noise-like error around the zeros of W(j ω). Filtering should be used to improve the estimation of the reflectivity function response. A filter that demonstrated quality performance is given by [12,13]

$$U(j\omega) = \frac{Y(j\omega)}{W(j\omega) + Q} \qquad (4)$$

Q is the regularization parameter, or noise desensitizing factor [14], which is properly selected to control the noise content. The simulation of Pulse-echo Ultrasonic signal propagation in an inhomogeneous medium is deconvolved with output voltage from the same transducer when an echo is received without consideration of any other field effects.

Simulation results

The results are derived for a representative range of simulated ultrasonic data, obtained using the modeling of ultrasonic piezoelectric transducers described in reference [15]. The simulation was applied using typical data for a transducer constructed with medium damping materials applied to the back face. The transmitter response was applied for 10 mm diameter pulse-echo transducer of 5 MHz center frequency. The simulation was carried out at an effective sampling time of 5 ns. **Figure 1** shows the simulation of a 5 MHz pulse-echo transducer. The resulting frequency spectrum is shown in **Figure 1**. The artificial reflector sequence of material is shown in **Figure 3**, corresponding to seven point targets in the material which were distributed randomly in position and amplitude. **Figure 3** shows an example of the simulated data based on the parameters presented in **Table 1**, which reflect an example of the potential variations in the time properties of multiple targets in non-homogeneous materials. The pulse-echo response of the transducer is combined with the reflector sequence. Under this situation, Gaussian noise can be used to model the noise present in an A-scan. Consequently, an uncorrelated Gaussian noise can be simply added to the overall time-domain response [16]. The simulation signal-to-noise ratio values presented here use the average power values for signal and noise in which the average values are obtained by averaging over the time range of interest. **Figure 4** shows the overall time-domain response at the receiver terminal at a signal-to-noise level of 25 dB. The frequency domain of the overall time domain response is divided by the frequency domain of the pulse-echo reference response as shown in **Figure 2** and then, finally, the inverse Fourier transform is taken. The deconvolution results for A-scan ultrasonic data at different denominator dynamic ranges are shown in **Figure 5**. From this figure, it can be seen that the location of targets are very close to the true reflectivity sequence for different denominator dynamic ranges, while their heights fall approximately proportionally as the denominator dynamic range is decreased. **Figure 6** is a repeat of the simulation of **Figure 4** but with a signal to noise ratio equal to 15 dB. The deconvolution result is shown in **Figure 7**. It is clear from all of these results that simulation using the deconvolution technique proposed in this paper yields an accurate determination of target position. The amplitudes of the responses of the reconstructed function are not equal to the initial amplitudes and these amplitudes are dependent on the dynamic range of the denominator. Amplitudes of the responses are not equal to the initial amplitudes, and their locations look like real locations only qualitatively. Also, the duration of target pulses increased at 20 dB (denominator dynamic range). The deconvolution results presented are in good agreement with the published results [7,17].

Table 1 Simulated target parameters.

Target	Location (μs)	Amplitude
1	0.6	0.89
2	1.0	–0.96
3	1.9	0.51
4	2.9	0.74
5	3.55	–0.56
6	4.25	–0.45
7	4.5	0.35

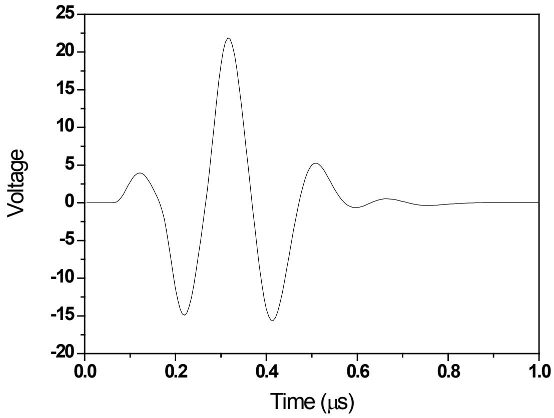


Figure 1 Time domain pulse-echo response of 5 MHz transducer.

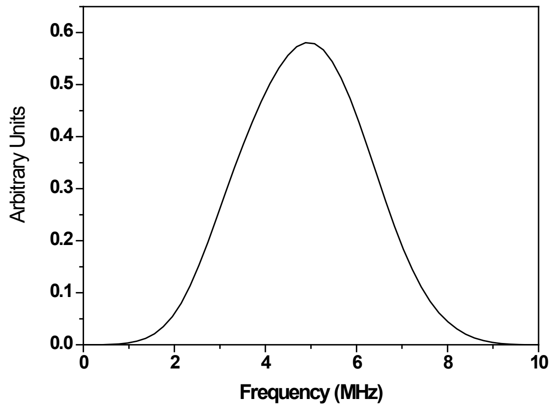


Figure 2 The frequency domain spectrum of **Figure 1**.

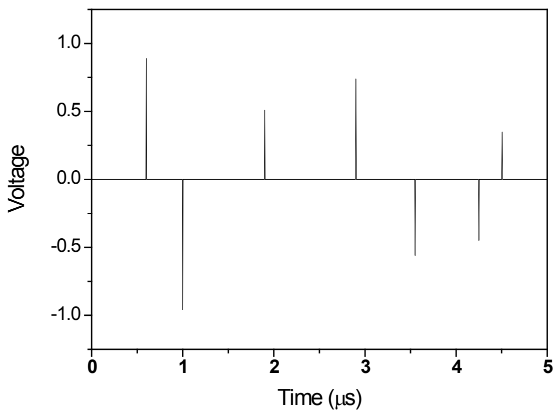


Figure 3 The impulse reflector series of material.

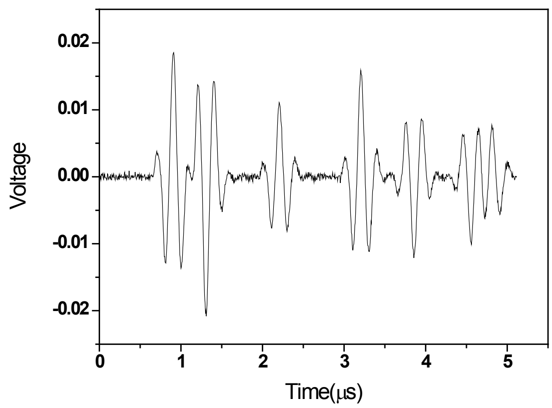


Figure 4 The overall simulation of pulse-echo 5 MHz with signal to noise level 25 dB.

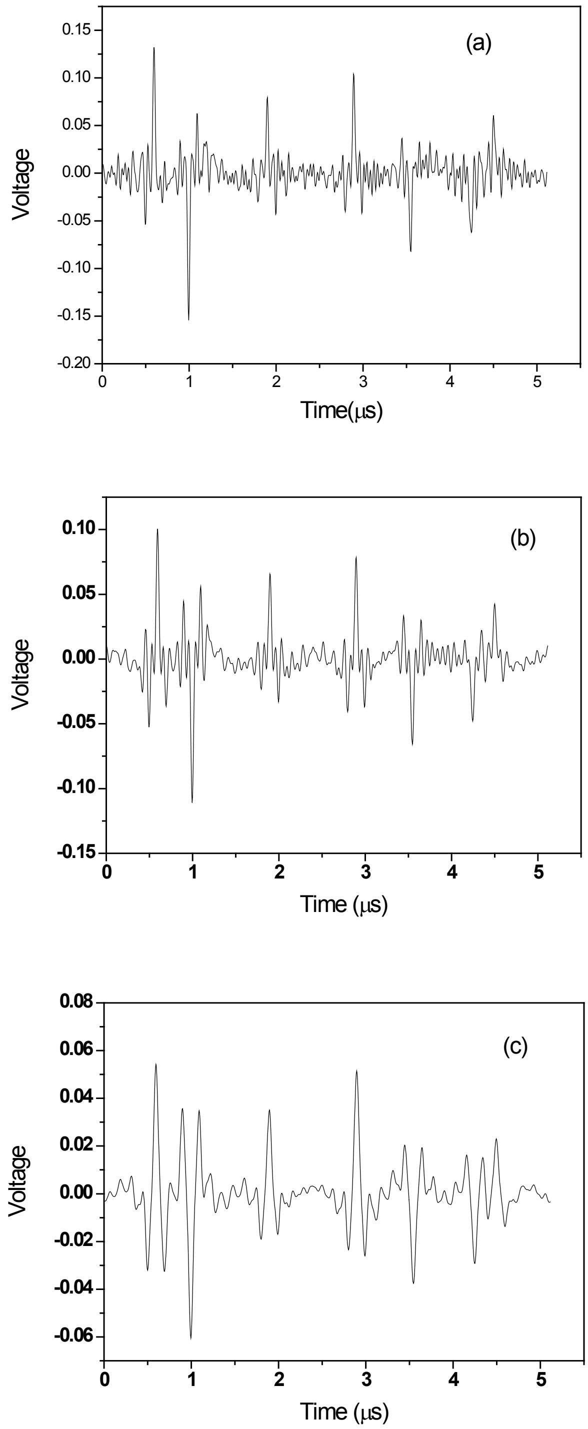


Figure 5 Deconvolution processor output with different denominator dynamic ranges (a) 40 dB (b) 30 dB (c) 20 dB.

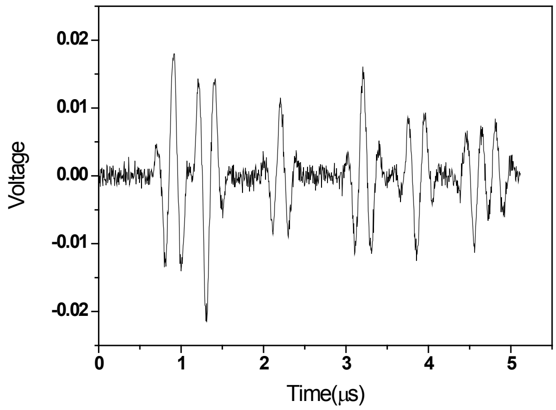
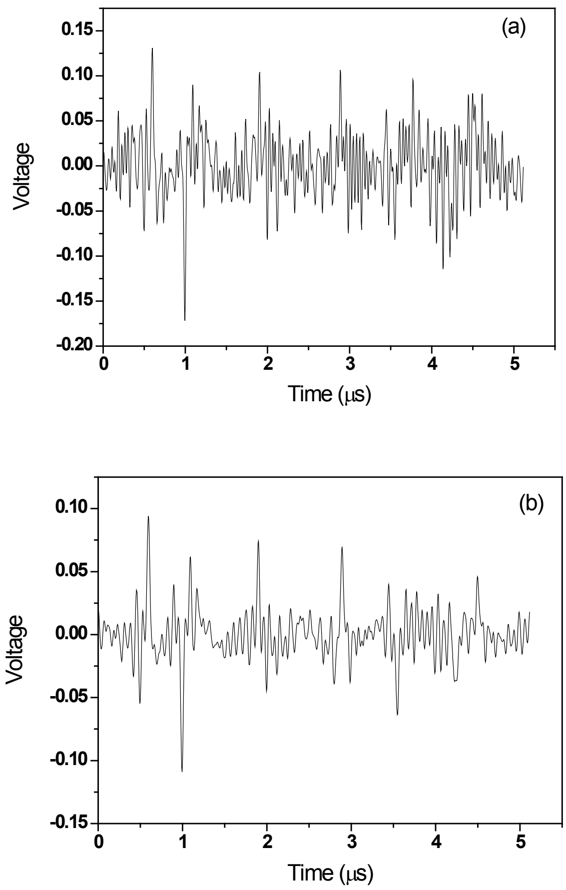


Figure 6 The overall simulation of pulse-echo 5 MHz with signal to noise level 15 dB.



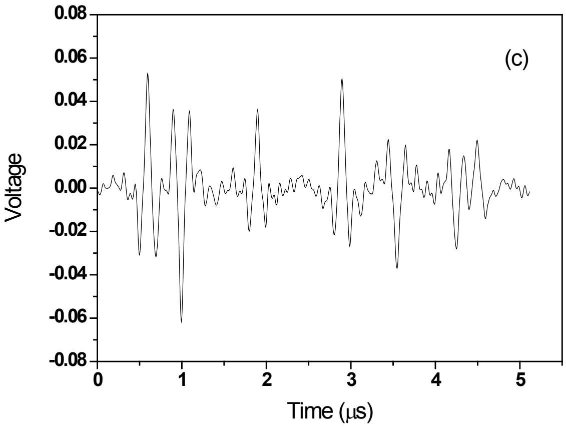


Figure 7 Deconvolution processor output for **Figure 6** with different denominator dynamic ranges (a) 40 dB (b) 30 dB (c) 20 dB.

Conclusions

This paper has described a method for ultrasound deconvolution based on frequency domain. We have presented a frequency domain deconvolution technique to process ultrasound echo signals in order to obtain a better estimation of the reflectivity function. The success of this technique is dependent on the denominator dynamic range. The locations of the reflectors, as provided by the deconvolution, agree with the true reflectivity function. The deconvolution results presented are in good agreement with the true reflectivity functions of the constructed materials.

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