DATA COMPRESSION AND NOISE SUPPRESSION OF ULTRASONIC NDE SIGNALS USING WAVELETS

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Abstract - Ultrasonic imaging of materials often requires a large amount of data collection. Therefore, it is desirable to use data compression techniques to facilitate the analysis and remote access of ultrasonic information. The correct data representation is paramount to the accurate analysis of the geometric shape, size, and orientation of the ultrasonic reflector, as well as to the determination of the properties of the propagation path. In this study, we analyze a successive parameter estimation technique (based on the continuous wavelet transform) to deal with the compression and denoising of ultrasonic signals. The algorithm is applied to both simulated and experimental ultrasonic signals for data compression and material characterization. This technique achieves data compression ratios of up to 95% and signal-to-noise ratios improvement beyond 30dB.

I. INTRODUCTION

Signal modeling and parameter estimation has been recognized as a practical method for ultrasonic non-destructive evaluation [1,2]. The successive parameter estimation algorithm presented in this paper relies on the assumption that any ultrasonic signal, no matter how complex it is, can be decomposed into the superposition of multiple single echoes. The goal is then to estimate the parameters (correlating to physical properties of materials) of each echo, and then by superposition, reconstruct the original signal. This model has been shown to be able to reproduce the real ultrasonic signal with satisfactory fidelity [2]. The parameter estimation method presented in this paper uses continuous wavelet transform (CWT) to perform the correlation of a mother wavelet with the ultrasonic signal. A modified version of the Morlet wavelet is used to estimate the echo parameters (amplitude, bandwidth, phase, time of arrival, and center frequency). Since this is a successive approach, the parameter estimation algorithm keeps searching until the error criteria is satisfied. The parameter estimation algorithm is applied to both simulated and experimental data, and the results are presented in this paper.

II. MODIFIED MORLET WAVELET

The backscattered echo from a flat surface reflector is given by

$$s(n) = \beta . \exp\left(-\alpha (n-\tau)^2\right) . \cos\left(w_c . (n-\tau) + \phi\right) \qquad (1)$$

The parameters of this model are independent and closely related to the physical behavior of the ultrasonic signal inside the material. The time of arrival (τ) determines the distance between the transducer and the reflector. The attenuation of the original signal and the size of the reflector relative to the beam field are defined by β. The parameters w_c and α are the center frequency and bandwidth factor modified by the propagation path. The difference in the phase of the signal ϕ is sensitive to the orientation of the reflector [3].

The similarity between wavelet kernel and signal brings many advantages in the decomposition of the signal [4]; hence the Morlet is the wavelet of choice for ultrasonic signals. Once the CWT is applied to this kernel, the time × scale representation of the signal is given by

$$WT(a,b) = \frac{1}{\sqrt{a}} \int f(t) . \psi^* \left(\frac{t-b}{a} \right) dt \qquad (2)$$

The Morlet wavelet kernel is therefore shifted in time and frequency as shown in the following equation. The parameter a tracks the changes in frequency and b the arrival time of the echo.

$$\psi\left(\frac{t-b}{a}\right) = \exp\left[i \left(\frac{t-b}{a} \right) \right] \exp\left[\frac{1}{2} \left(\frac{t-b}{a} \right)^2 \right] \qquad (3)$$

The ultrasonic echo model can have variations not only in frequency and time, but also in phase and bandwidth. For this reason a modified Morlet wavelet kernel is developed to address these two parameters. This kernel includes two additional parameters: θ (phase) and γ (bandwidth).

$$\psi(t) = \exp\left[i\left(\frac{t-b}{a}\right) + i\theta\right]\exp\left[\gamma\left(\frac{t-b}{a}\right)^2\right] \tag{4}$$

III. SENSITIVITY ANALYSIS

The goal of sensitivity analysis is to determine the dependency of the ultrasonic signal model to the estimated parameters [5]. The gradient of a function gives the sensitivity of the estimation to small changes in the model parameters. The gradient of $s(\beta,\alpha,\tau,w,\phi)$ is given by

$$\nabla s(\beta,\alpha,\tau,w,\phi) = \left[\frac{\partial s}{\partial \beta},\frac{\partial s}{\partial \alpha},\frac{\partial s}{\partial \tau},\frac{\partial s}{\partial w},\frac{\partial s}{\partial \phi},\right]^t \tag{5}$$

where

$$\frac{\partial s}{\partial \beta} = \sum_{j=0}^{N-1} \exp\left(-\alpha_j (n-\tau_j)^2\right)\cos\left(w_{cj}.(n-\tau_j)+\phi_j\right) \tag{6}$$

$$\frac{\partial s}{\partial \alpha} = \sum_{j=0}^{N-1} -\beta_j (n-\tau_j)^2 \exp\left(-\alpha_j (n-\tau_j)^2\right)\cos\left(w_{cj}.(n-\tau_j)+\phi_j\right) \tag{7}$$

$$\frac{\partial s}{\partial \tau} = \sum_{j=0}^{N-1} \beta_j w_{cj} \exp\left(-\alpha_j (n-\tau_j)^2\right)\sin\left(w_{cj}.(n-\tau_j)+\phi_j\right) + \tag{8}$$
$$\beta_j\left(2\alpha_j n - 2\tau_j\alpha_j\right)\exp\left(-\alpha_j (n-\tau_j)^2\right)\cos\left(w_{cj}.(n-\tau_j)+\phi_j\right)$$

$$\frac{\partial s}{\partial w} = \sum_{j=0}^{N-1} \beta_j \tau_j \exp\left(-\alpha_j (n-\tau_j)^2\right)\sin\left(w_{cj}.(n-\tau_j)+\phi_j\right) \tag{9}$$

$$\frac{\partial s}{\partial \phi} = \sum_{j=0}^{N-1} -\beta_j \exp\left(-\alpha_j (n-\tau_j)^2\right)\sin\left(w_{cj}.(n-\tau_j)+\phi_j\right) \tag{10}$$

Figure 1 shows how the reconstruction error (*Er*) behaves as each of the estimated parameters varies from –10% to 10% around its correct value (while the other parameters are assumed to be correctly estimated). From this plot the time of arrival (τ) is the most critical parameter to be estimated, followed by w_c, β, ϕ, and α. For this reason the parameter estimation method uses the CWT for the estimation of τ and w_c, but is not refined enough to estimate the other parameters (β, ϕ, and α).

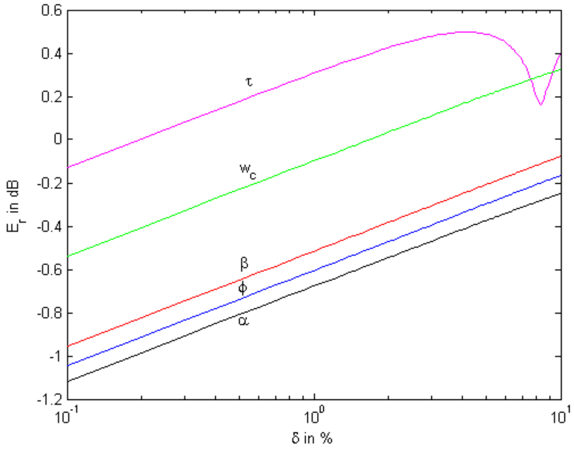

Figure 1: Effect of parameters on reconstruction error (*Er*) for –10% < δ < 10%

IV. PARAMETER ESTIMATION ALGORITHM

The successive ultrasonic parameter estimation algorithm is a recursive method that starts with a continuous wavelet transform (CWT) representation of the input signal. A block diagram of the algorithm is shown in Figure 2. The first step of the algorithm is to localize the candidate echoes in the time × scale representation of the ultrasonic signal. Based on this representation a window scheme separates one echo from the others. The decision rule to separate multiple echoes can be a function of one or more of the following factors: energy, location, amplitude, and frequency of the estimated echo. The choice of which decision rule to use is application specific. Once the individual echoes are identified, the following steps of the algorithm will deal of the windowed data only. After the frequency and time of arrival of the echo are estimated, the next step is the estimation of the echo's bandwidth and phase. These two parameters are obtained by correlating the mother wavelet with the ultrasonic echo and representing the results in the phase × bandwidth domain. The peaks of the correlation reveal the optimal values of the phase and bandwidth.

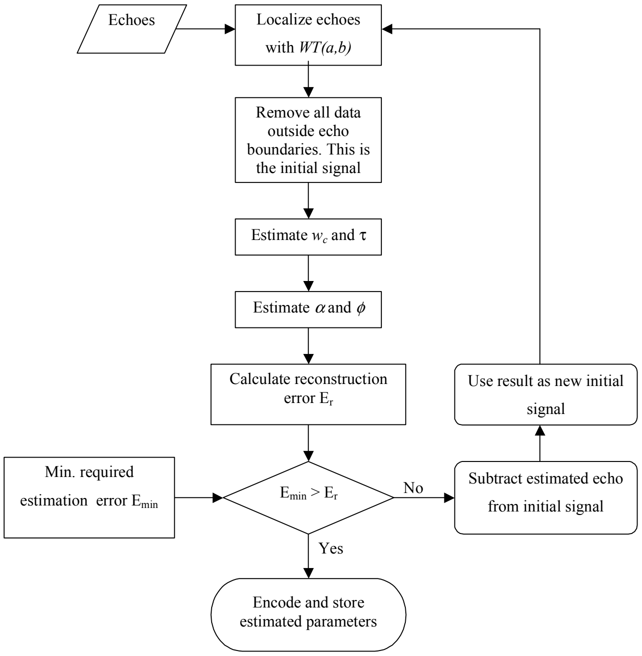

Figure 2: Parameter estimation block diagram

If the ultrasonic signal contains multiple interfering echoes this approach becomes sub optimal. To search for an optimal result this method is iterated until the reconstruction error Er is below an acceptable value (E_{min}). If the error is not acceptable, the estimated signal is subtracted from the original signal, and the whole estimation process is repeated until the error is within the acceptance level. Each echo has its frequency, time of arrival, bandwidth, amplitude, and phase estimated individually. After all echoes are estimated ($E_{min} > Er$), they are added to form the reconstructed signal. Note that if the original signal is too noisy, this process, at some interaction, will start to track the noise instead of the ultrasonic signal. For this reason in a noisy environment the number of estimation steps should be limited.

V. PERFORMANCE EVALUATION WITH SIMULATED AND EXPERIMENTAL ULTRASONIC ECHOES

In this section we analyze the performance of the parameter estimation method using simulated and experimental echoes. Figure 3 shows a simulated ultrasonic signal with 10 interfering echoes in the time domain. The signal to noise ratio (SNR) of the noisy signal (Figure 3b) is 1.5dB. Upon determination of the signal parameters using the parameter estimation algorithm the SNR of the estimated signal is 30dB, showing an improvement of almost 30dB. The SNR between the noisy signal and the reconstructed signal is 5dB. The algorithm also introduces a great deal of data compression (approximately 90%). The original signal has 512 16-bit coefficients, while the estimated signal can be reconstructed with 50 16bit coefficients. Further compression can be achieved by encoding the resulting parameters using lossless compression encoders [6].

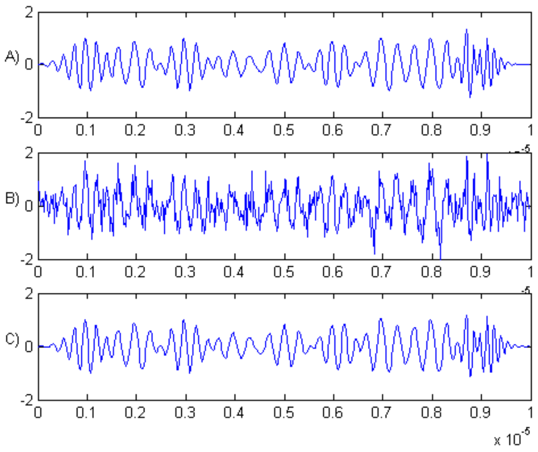

Figure 3: Simulated ultrasonic echo: A) Noiseless signal, B) Noisy signal, C) Reconstructed signal using estimated parameters

The parameter estimation algorithm was also tested with an experimental signal. This data represents multiple backscattered echoes from a thin metal sample. The SNR figures presented are relative to the experimental data. The experimental signal is shown in Figure 4a, while Figure 4b shows the estimated signal. Since this is a successive parameter estimation algorithm, the echoes with the highest energy in the time × scale domain are estimated first. The single estimated echoes are presented in order of energy (starting with the highest energy) in Figure 5. The figure shows that the first estimated echo *A)* is about 4 times more energetic than echo *B)*. This result suggests that the signal has a predominant echo, and one could have used this outcome as a criterion to stop the estimation algorithm.

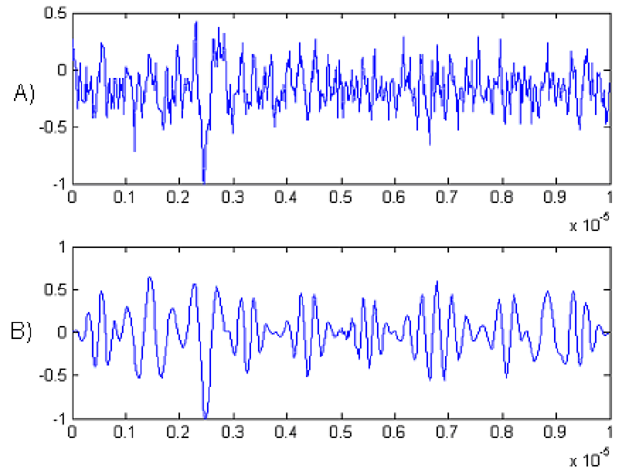

Figure 4: A) Experimental signal, B) Estimated signal

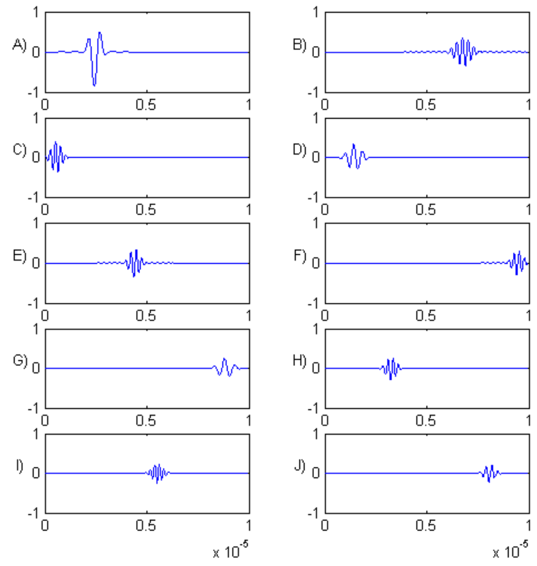

Figure 5: Sequence of single echo estimations (highest energy echo in *A*, lowest energy echo in *J*)

VI. CONCLUSIONS

The correct ultrasonic data representation is paramount to the accurate analysis of the geometric shape, size, and orientation of the ultrasonic reflector, as well as to the determination of the properties of the propagation path. In this paper we have analyzed a successive parameter estimation technique to deal with the compression and denoising of ultrasonic signals. This method uses continuous wavelet transform (CWT) to perform the correlation of a mother wavelet with the ultrasonic signal. A modified version of the Morlet wavelet is used to estimate the echo parameters (amplitude, bandwidth, phase, time of arrival, and center frequency).

The parameters of the ultrasonic echo have different physical meaning, so the error in the estimation of each of the parameters affects the overall estimation error differently. Thus, we have analyzed the sensitivity of the reconstruction error to the variation of the estimated parameters. Analytical and simulation results are presented which show that center frequency and time of arrival are the most critical parameters in the estimation of ultrasonic echoes. The algorithm has been applied to both simulated and experimental ultrasonic signals for data compression and material characterization. This technique achieves data compression ratio of up to 95% and a signal-to-noise ratio improvement beyond 30dB.

VII. REFERENCES

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