DIGITAL SIGNAL PROCESSING SYSTEM OF ULTRASONIC SIGNALS

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Abstract

In general the ultrasonic testing is used for flaw detection and localization in tested materials. Flaws in materials are commonly characterized in measured ultrasonic signals by faults echoes. Ultrasonic signals measured on materials with coarse grained structure contain relative high level of noise. This undesirable part of ultrasonic signal should be reduced to make the fault echo detection process more accurate. The different method for the noise reduction have been proposed but implementation to the full ultrasonic system is still missing. This paper presents the implementation of the proposed digital signal processing (DSP) methods for ultrasonic noise reduction based on wavelet transform and Wiener filter. The presented system can be described as full automated ultrasonic system that offers the measurement and processing of ultrasonic signals with consequent visualization of flaws in 3D volume representation. The basic characteristics as Fourier transform, power spectral density and time segmentation of measured signals are also considered. The system is implemented in graphical user interface (GUI) in Matlab. The ultrasonic signal based on the equation considered the physical properties of measured material can be simulated and the proposed DSP algorithms are evaluated in terms of signal-to-noise ration enhancement. The DSP ultrasonic system consists of two main windows, one for the measurement and processing of signals and another for the simulation. The different representation of ultrasonic signal in A-scan, B-scan and C-scan can be displayed in the graphical window.

1   Introduction

The ultrasonic testing is commonly used for flaw detection in materials. The ultrasonic signal characterizes structure of the tested material and displayed signal typically consists of many scatterers caused by reflections of ultrasonic waves from the structure, flaw or crack, and a material surface. This reflections are in ultrasonic called echoes, especially fault echo (flaw), back-wall echo (surface) and the noise (grains). In general, two sources of noise are considered in case of ultrasonic signals. The first source is caused by scattering of ultrasonic waves from the grains contained in coarse grained materials. In ultrasonic testing area this source of noise is called backscattering noise. The larger grains relates to the higher noise level and they can masks the fault echo. This case is undesirable and efficient method [1], [2] for the backscattering noise reduction have to be used. Another source of noise is caused by the electronic circuitry. The electronic noise doesn't have the same effect as the backscattering noise and the level is lower than backscattering noise. But in noise consideration both sources should be used.

In this paper, full system [4] for ultrasonic signal generation, measurement and signal processing is presented. The system is implemented in graphical user interface (GUI) in Matlab environment and can be used as standalone system. The system consists of two windows, first for the ultrasonic signal simulation and another for the signal measurement and processing. The ultrasonic signal simulation is based on the material properties as number of grains, attenuation, size, and particle volume. The basic parameters of ultrasonic transducer are also considered and the physical parameters as near field and angle beam are calculated automatically. The window for the measurement and signal processing contains the main requirements for the surface scanning (size) and user can choose the displaying of signal in A-scan, B-scan or C-scan [5]. The signal processing feature contains the basic characteristics of signal as frequency analysis (Fourier transform). The main emphasis is focused on de-noising methods. The system has implemented

de-noising methods based on Wiener filter and wavelet transform. Considered Wiener filter is based on group delay characteristics as moving autocorrelation, standard deviation and entropy. In wavelet transform the de-noising algorithms based on discrete, stationary and wavelet packets are used.

This paper is organized as follows. In first section the GUI window for the ultrasonic signal simulation is presented. The signal generation based on the material and ultrasonic transducer characteristics is described. Next section elaborates the de-noising methods based on Wiener filter and wavelet transform algorithms. The third section describes the fully automated system of ultrasonic signals. Some theoretical and experimental results are presented. At the end in conclusion the discursion about the system improvement is discussed.
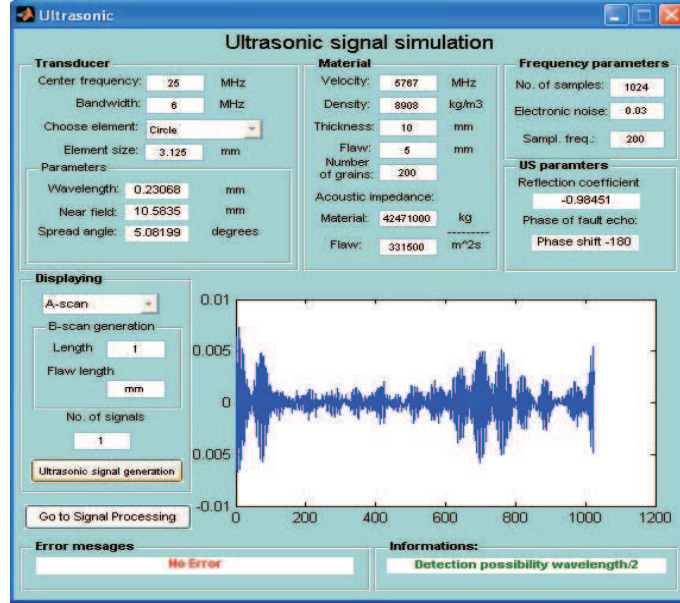

Figure 1: Ultrasonic signal simulation window

2   Ultrasonic signal simulation

The received ultrasonic signal contains echoes caused by scattering from grains in materials with a non-homogeneous structure. These echoes are commonly called as backscattering noise. A second source of noise in the ultrasonic signals is noise from electronic circuitry. The backscattering noise generation used in this work is based on the simple clutter model presented in [?]. We consider the noise as the superimposition of signals coming from grains in the material. The frequency response of the material can be expressed [1] by

$$H_{mat}(\omega) = \sum_{k=1}^{K_{tot}} \beta_k \frac{\omega^2}{x_k} exp(-\alpha_s 2x_k \omega^4) exp(-i\omega \frac{2x_k}{c_l}) \tag{1}$$

where α_s is material attenuation coefficient, c_l is velocity of the longitudinal waves, x_k is the grain positions of $k = 1 K_{tot}$ number of grains and β_k is a random vector depending on the grain volume. The signal of the backscattering noise in the frequency domain can be expressed [1] by

$$H_b(\omega) = H_t(\omega)H_t(\omega)H_{mat}(\omega) \tag{2}$$

The H_t occurs twice since the ultrasonic transducer is used as a transmitter and as a receiver in our case. This model was used for backscattering noise generation. To construct an ultrasonic signal in a pulse-echo testing setup, we can add the back-wall echo and fault echo to the ultrasonic

noise. Noise caused by electronic circuitry was simulated in considering as white noise i.e. noise with Gaussian distribution. This electronic noise was added to simulated ultrasonic signal.

The simulation of ultrasonic signal is contained in window "Ultrasonic Signal Simulation" (see Fig. 1.). Based on equations presented above, it is possible to simulate ultrasonic signal in one or more realizations, based on user requirements. Both sources of noise are considered. The electronic noise can be set as percentage level. The backscattering noise is simulated in relation of the material characteristics. The basic characteristics of measured material and used ultrasonic transducer are considered. For the appropriate simulation, the user should set the transducer frequency, bandwidth, sampling frequency, size of material, flaw localization, number of grains, attenuation and velocity. The signal is simulated and the basic characteristics as wavelength, near field and spread angle are automatically calculated. For the signal propagation, reflection coefficient is calculated. The simulated signals can be used for the evaluation of the proposed signal processing methods.

3 Ultrasonic signal processing

3.1 Wavelet transform

3.1.1 Discrete wavelet transform

The discrete wavelet transform [2] can be used as an efficient filtering method for families of signals that have a few nonzero wavelet coefficients for a given wavelet family. Filtering procedure is based on a decomposition of signal using DWT in N levels using band pass filtering and decimation to obtain the approximation and detailed coefficients. Next step is thresholding of detailed coefficients and reconstruction of signal from detailed and approximation coefficients using inverse transform (IDWT). One of the most important properties is to choose the suitable mother wavelet and propose threshold level.

3.1.2 Wavelet packets

The WP method is a generalization of wavelet decomposition that offers a larger range of possibilities for signal analysis. In wavelet analysis, a signal is split into an approximation and detail coefficients. The approximation is then itself split into a second-level approximation and detail, and the process is repeated. In WP analysis, the detail coefficients as well as the approximation coefficients can be splited.

3.1.3 Stationary wavelet transform

The discrete stationary wavelet transform (SWT) is an undecimated version of DWT. The main idea is to average several detailed coefficients which are obtained by decomposition of the input signal without downsampling. This approach can be interpreted as a repeated application of the standard DWT method for different time shifts.

3.2 Wiener Filter Based Group Delay Statistics Estimation

The Wiener filter [3] is a global filter and produces an estimate of the uncorrupted signal by minimizing the mean square error between the estimate and the uncorrupted signal in a statistical sense. Process representing the received signal consists of signal and noise, both uncorrelated zero-mean wide-sense-stationary random process.

$$y(t) = s(t) + n(t). \tag{3}$$

By filtering $y(t)$ we estimate $s(t)$ using time-invariant linear system with transfer function $H(f)$. Resulting mean-square error then will be

$$e = \int_{-\infty}^{\infty} |1 - H(f)|^2 S(f) df + \int_{-\infty}^{\infty} |H(f)|^2 N(f) df \tag{4}$$

where $N(f)$ and $S(f)$ are power spectral densities of noise and signal. Where e is minimized over $H(f)$ for fixed $S(f)$ and $N(f)$. Reason for using the group delay spectrum is that the target signal is a constant over the working frequency. The following techniques is based on using the discrete group delay. It can be calculated by

$$T(k) = -\frac{N}{2\pi}[\phi(k+1) - \phi(k)] \tag{5}$$

where $\phi(k)$ is the phase component of the discrete Fourier transform, k is the frequency index and N is the total number of points. For minimizing the edge effect different windows for received time sequence are applied. To obviate discontinuity in the group delay phase unwrapping techniques are used. The techniques based on the group delay statistics are group delay moving autocorrelation, group delay moving standard deviation and group delay moving entropy. All techniques are computed within a moving window. The window is set to a small compared data length, and reflects a trade off between resolution and estimation error. The frequency step between the window is set to 1, and reflects a trade off between resolution and computational efficiency.

3.2.1 Group Delay Moving Autocorrelation

To obtain the final effect, the following steps are used. First calculate the group delay within a moving window with center frequency and bandwidth. Next step calculates with increment frequency until the desired frequency was covered.

$$\overline{R}_k(m) = \frac{1}{M-m} \sum_{n=k}^{M-m+k-1} \Delta T(n+m)\Delta Tn \tag{6}$$

The result is autocorrelation function forming a surface with frequency index and correlation lag.

3.2.2 Group Delay Moving Standard Deviation

The same effect can also be evaluated by computing its standard deviation within a moving window. While the group delay of the target is constant then the standard deviation is very small. In this case, the standard deviation for the group delay of the noise is larger. In this possibility it is necessary to calculate the standard deviation of the group delay within a moving window with center frequency and bandwidth for each frequency until the desired frequency is covered. The standard deviation group delay statistic can be expressed as

$$\sigma_k = [\frac{1}{M-1} \sum_{m=k}^{M+k} \{\Delta T(m) - \Delta \overline{T}_k\}^2 \}^{\frac{1}{2}}] \tag{7}$$

where $\Delta \overline{T}_k$ is the mean

$$\Delta \overline{T}_k = \frac{1}{M} \sum_{m=k}^{M+k} \sigma T(m) \tag{8}$$

3.2.3 Group Delay Moving Entropy

Another method is to calculate entropy with information measure

$$b = log_2 M \tag{9}$$

at frequency k can then be obtained from $f(T)$

$$H_k = - \sum_{j=k+1}^{M+k} f(T_j) log_2[f(T_j)]. \qquad (10)$$

until the desired frequency has been covered. The target signal has small entropy, while the frequency range containing the noise having large entropy.

4 Ultrasonic Measurement and Signal Processing System

The main part of GUI is the window called "Ultrasonic Measurement and Signal Processing System" (see Fig. 2.). It is possible to measure and process the signals. The first part is the measurement, where the data are acquired using ultrasonic system DIO-2000 developed by Starmans electronic. System DIO-2000 is connected to the device for the material scanning. All devices can be controlled with our system and measured signals can be displayed in different manners. The user can acquire data in both, one measurement or in scanning process. By one measurement only the A-scan is displayed. If the surface of material is scanned in two directions, B-scan or 3D volume visualization can be displayed. The measured signals can be saved or used for the signal processing techniques performance.
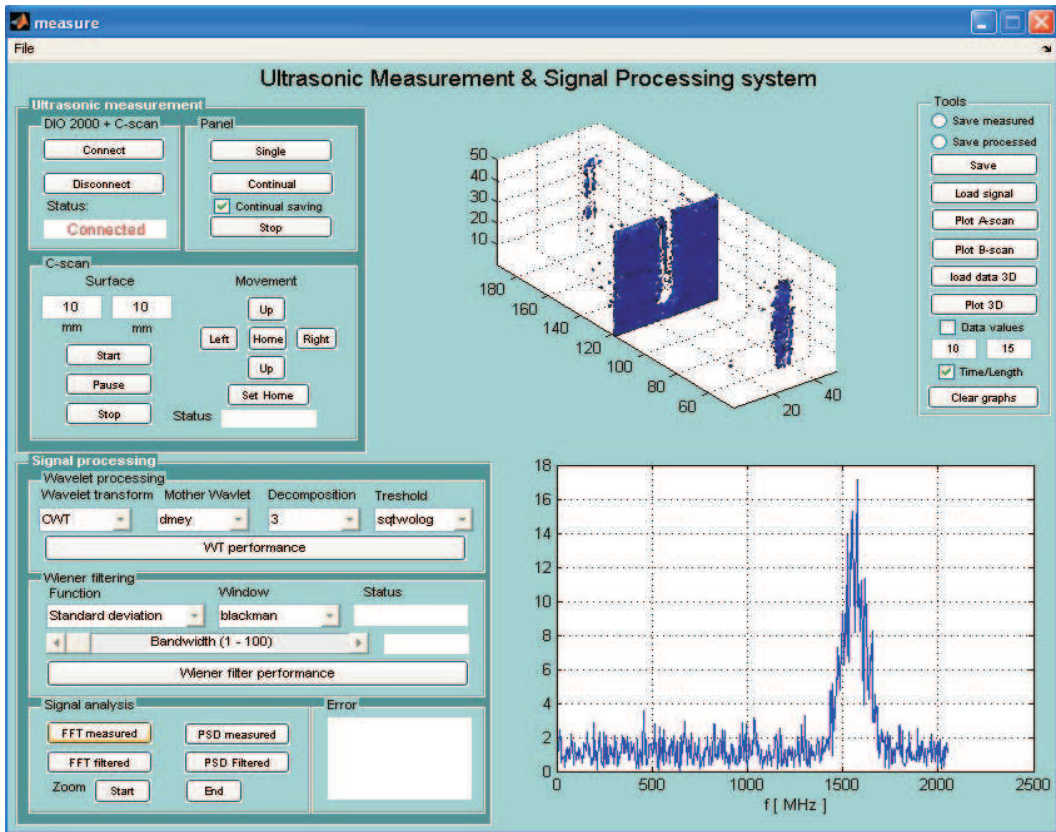

Figure 2: GUI window for ultrasonic signal processing

The window contains two graphs (see Fig. 2.), one for the measured signals displaying and another for the processed signals displaying. The basic processing as spectral analysis and power spectral density analysis are implemented. The main problem in the ultrasonic testing is the noise reduction. Our system has implemented two methods for the de-noising of the signals. First method is based on wavelet transform. The DWT, SWT and WP algorithms can be performed for the signal de-noising. Main problem in wavelet analysis is to choose the proper mother wavelet, appropriate threshold rule and decomposition level. All mother

wavelets and threshold rules implemented in Matlab can be used for the signal de-noising. We also implemented our own threshold rule based on standard deviation of detailed coefficients. The local thresholding and hard threshold are preset. Another method is Wiener filter based on group delay statistics. User also can choose the group delay algorithm and set the window type. Based on our experience, both methods are good alternative for the ultrasonic signal de-noising. The proposed GUI with signal processing method is very useful tool for the detail analysis and de-noising of ultrasonic signals.

5 Conclusion

In this paper the system for simulation, measurement and processing in graphical user interface implementation is presented. The system consists of two windows, one for the ultrasonic signal simulation and another for measurement and signal processing. The processing window contains the standard spectral analysis of the signal and the de-noising methods based on Wiener filter and wavelet transform filtering. In this window the measurement of the signal is also possible and useful for the scanning of the material. The different displaying in A-scan, B-scan and 3D volume visualization of the material is included. In future, the system will be improved by adding the window for evaluation of de-noising methods.

6 Acknowledgement

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