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FLAW DETECTION ON HIGHLY SCATTERING MATERIALS USING MULTIRESOLUTION ANALYSIS WITH TIME-FREQUENCY THRESHOLDING

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ABSTRACT

In ultrasonic non-destructive evaluation of highly scattering materials, detection of flaw echoes is difficult due to the masking effects of the structural noise. This paper presents a method for the reduction of the structural noise on highly scattering materials. The method consists of a multi-resolution analysis using wavelets and a time-frequency thresholding applied to the approximation coefficients. This threshold is estimated by considering the mean and the standard deviation of the time-frequency energy representation. This method exploits spectral properties of the structural noise and the incoming flaw signal, resulting in a processed signal that maintains the defect pulse shape. In order to validate this strategy, synthetic and experimental signals have been evaluated. The performance of this method is compared with known selection rules as Minimax and Universal threshold.

INTRODUCTION

Ultrasonic flaw detection has been widely used in non-destructive evaluation (NDE) of materials. When materials are non-homogenous, these are considered as a scattering medium. Due to scattering effects, ultrasonic signals supply structure information as structural noise, but this coherent noise mask possible flaws in the inspected materials. The non-stationary nature of structural noise entails to use time-frequency filtering and detecting methods. So, these techniques try to enhance the signal to noise ratio (SNR) of signals coming from scattering materials.

Several techniques as Split Spectrum Processing (SSP) [1], group delay entropy [2] or noise suppression with low-frequencies band pass filtering [3] have been proposed for enhancing the SNR assuming stationarity of the structural noise. However, few works have presented techniques that exploit the structural noise and their non-stationary nature. Rodriguez et al [4] proposed to use of time–frequency and time-scale transforms to detect ultrasonic flaws. Izquierdo et al [5] consider the time-varying spectral content of the received echoes using a method that assumes a time-varying autoregressive model of the structural noise. So, the structural noise reduction and flaw detection are still fields in continuous research.

This work presents a technique for detecting flaws on highly scattering materials using multi-resolution de-noising (wavelet transform) with a proposed selection rule (thresholding) in the time-frequency space. The performance of this method is compared with known selection rules as Minimax and Universal threshold. Synthetic traces and experimental signals from a stainless steel block have been employed in order to validate the proposed technique.

MULTI-RESOLUTION DENOISING

The noisy signals x is assumed to consist of possible free-noise flaws s, and coherent noise (structural noise) η as

$$x(n) = s(n,z) + \eta(n,z) \qquad \text{(Eq. 1)}$$

where n is the temporal index and z represents the distance.

In order to recover *s*, a de-noising procedure is carried out by wavelet decomposition. The general scheme of this procedure is as follow:

1. Signal decomposition into *M* resolution levels related with a specific mother wavelet φ is carried out. The decomposition process can be iterated, with successive approximations being decomposed in turn, so that one signal is broken down into many lower resolution components, resulting the detail coefficients $W_{1,n}$, $W_{2,n}$, …, $W_{M,n}$ and the approximation coefficient $V_{M,n}$, where *n* is the temporal index. This is called the wavelet decomposition tree and implemented as a filter bank as is depicted in Figure 1.

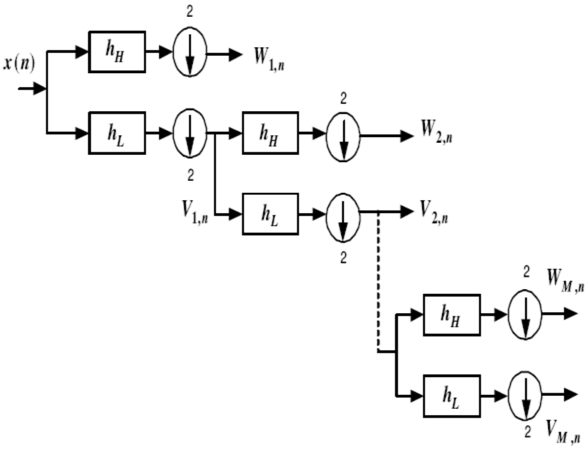

Figure 1.- Implementation of Wavelet decomposition by filter bank.

2. A thresholding process $\Lambda\{\cdot\}$ is applied to the detail coefficients and also the *M*-approximation coefficients. This process is defined in order to exclude terms or samples in function of a threshold λ . So, thresholding process is performed as

$$\widetilde{W}_{M,n} = \Lambda\{W_{j,n}\} \qquad (\text{Eq.}2)$$

$$= \begin{cases} sign\{W_{j,n}\}[|W_{j,n}| - \lambda] & ,|W_{j,n}| > \lambda \\ 0 & ,|W_{j,n}| < \lambda \end{cases} \qquad (\text{Eq.}3)$$

Besides, the details coefficients $\{W_{m,n}\}$ are processed according to the rule [6]

$$\widetilde{W}_{m,n} = \begin{cases} W_{j,n} & ,j < L \\ 0 & ,j \geq L \end{cases} \qquad (\text{Eq. }4)$$

where *L* represents the levels which want to be excluded in the signal reconstruction.

3. After performing the thresholding, a reconstruction of the signals is made by means of the modified coefficients $\{\widetilde{W}_{m,n}\}$ and $\widetilde{V}_{M,n}$. The reconstruction is carried out to apply the inverse process as shown in Figure 1.

Therefore, the previous scheme provide a general de-noising process where will be necessary to define the number of the *M* decomposition levels, the mother wavelet φ and also the threshold estimation λ .

Threshold Estimation

In this paper, flaw detection is carried out by a multi-resolution de-noising scheme. We present a threshold estimation (explained in the next section) which will be compared with two well-known thresholding methods (selection rules): Minimax [7] and Universal thereshold [8], defined respectively as

$$\lambda^{mm} = \begin{cases} \sigma\,(0.3936 + 0.1829\log_2(N)) & ,N > 32 \\ 0 & ,N \leq 32 \end{cases} \qquad (\text{Eq.}\,5)$$

$$\lambda^{uni} = \sigma\,\sqrt{2\log(N)} \qquad (\text{Eq.}\,6)$$

where *N* is the signal length and σ is the noise standard deviation.

Calculus of the proposed threshold

We propose a threshold λ_j^{tf} taking as start point research in [4]. This threshold is calculated from statistical values of the detail coefficients at *j* levels and the approximation coefficients at *M* level as

$$\lambda_j^{tf} = \sqrt{\mu_j + \sigma_j} \qquad (\text{Eq.}\,7)$$

Where *j* means the decomposition level, μ_j and σ_j are the mean and the standard deviation, respectively, of energy signals $\tilde{E}_j$ which have been obtained by a time-frequency processing. This processing produces a detection of high energy concentration in time-frequency space. So, $\tilde{E}_j$ is determined as follow

$$\tilde{E}_j = \int D_j d\omega \qquad (\text{Eq.}\,8)$$

$$D_j = \begin{cases} C_j & C_j > 0 \\ 0 & C_j < 0 \end{cases} \qquad (\text{Eq.}\,9)$$

$$C_j = \int \hat{W}_{j,n}\left(t + \frac{\tau}{2}\right)\hat{W}^*_{j,n}\left(t - \frac{\tau}{2}\right)e^{-i\omega\tau} \qquad (\text{Eq.}\,10)$$

Where C_j is the Wigner-Ville distribution. Note that time-frequency distributions are generally calculated by means of analytical signals, therefore $\hat{W}_{j,n}(\cdot)$ is the analytical signals of the detail coefficients at *j* level and those expressions are also valid in order to find the threshold for $V_{M,n}$.

SIMULATION RESULTS

Several synthetic traces have been generated using a simple clutter model [9]. This model emulates the impulse response both of a scattering material and the transducer response for separated. The frequency response of the synthetic signals is given by

$$X(\omega) = P(\omega)[R(\omega,z) + F(\omega,z)] \qquad (\text{Eq.}\,11)$$

where $P(\omega)$ is the frequency response of an ultrasonic pulse, and also $R(\omega,z)$ (structural noise response) and $F(\omega,z)$ (flaw response) are defined as

$$R(\omega,z) = \sum_{k=1}^{K_d} \beta_k \omega^2 e^{-2\alpha z_k \omega^4} e^{-i2\omega z_k/c} \qquad (\text{Eq.}\,12)$$

$$F(\omega,z) = \sum_{\text{k}=1}^{\text{K}_f} \rho_k e^{-2\alpha d_k \omega^4} e^{-i2\omega z_k/c} \qquad (\text{Eq.}\,13)$$

where K_d and K_f are the scattering number and flaw number, respectively. The value of β_k is a Gaussian random variable corresponding to the grain size, ρ_k is the reflectivity coefficient. The values of z_k represent uniform random variables which determine the scatters positions, whereas the flaw positions are determined by d_k. The attenuation coefficient and wave speed are considered as constant values defined by α and c, respectively. So, from $X(\omega)$, a synthetic signal *x* is generated by the inverse Fourier transform.

The next simulation considers a 20 MHZ and 83% bandwidth transducer. The synthetic signal has been generated considering the following values: $\alpha = 1\mathrm{x}10^{-15}$ dB/cm, $c = 5700$ m/s, K_d = 300 (scatters) distributed in a distance of 29.18 mm. Only one flaw is adding in the synthetic signal. Figure 2 shows the synthetic signal with the flaw and their spectra. Figure 3 shows the results of the de-noising processing using synthetics signals from the simple clutter model.

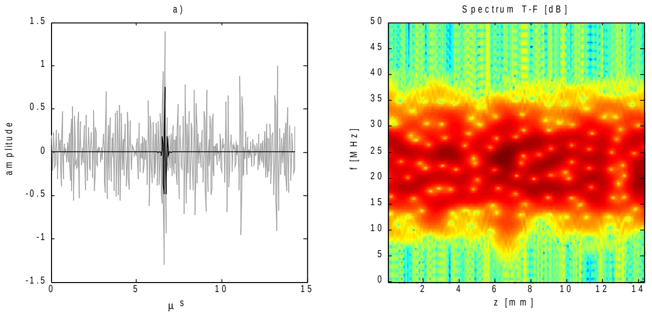

Figure 2.- Synthetic signal. a) Time-domain and b) Spectrum.

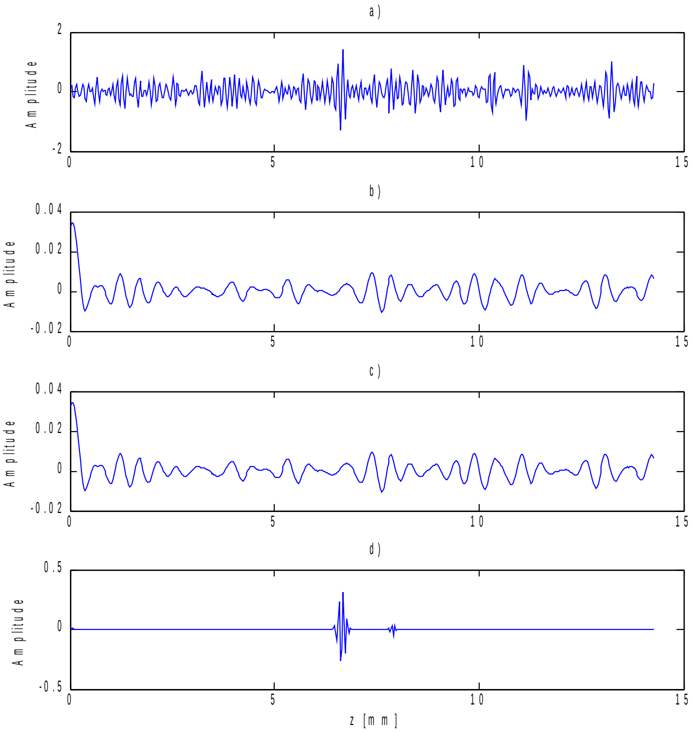

Figure 3.- De-noising results from synthetic signal. a) Structural noisy signal; de-noising by selection rule: b) Minimax, c) Universal threshold and d) proposed time-frequency threshold with *M*=3, *L*=2 and using a mother wavelet, *φ*= *dB7*.

Note that using the proposed threshold is able to detect the flaw in compare with the Minimax and Universal threshold. Thus, we can enhance the flaw visibility and detect it without making a deformation in the pulse shape. So, we can infer from Fig. 3b and 3c that using this selection rules is not possible the detection of the flaw pulse.

EXPERIMENTAL RESULTS

A rectangular shaped 80x120x110 mm^3 stainless steel block has been employed for the experimentation. It has been inspected with a 20 MHz and 83% bandwidth transducer. Several transversal holes with ϕ2 mm. and deeps at 50 and 70 mm. have been made. From the top view, holes are located each 2 cm, a distance less than the beam width. Signals have been digitised at 100 MHz and 256 averages have been applied in order to have only structural noise.

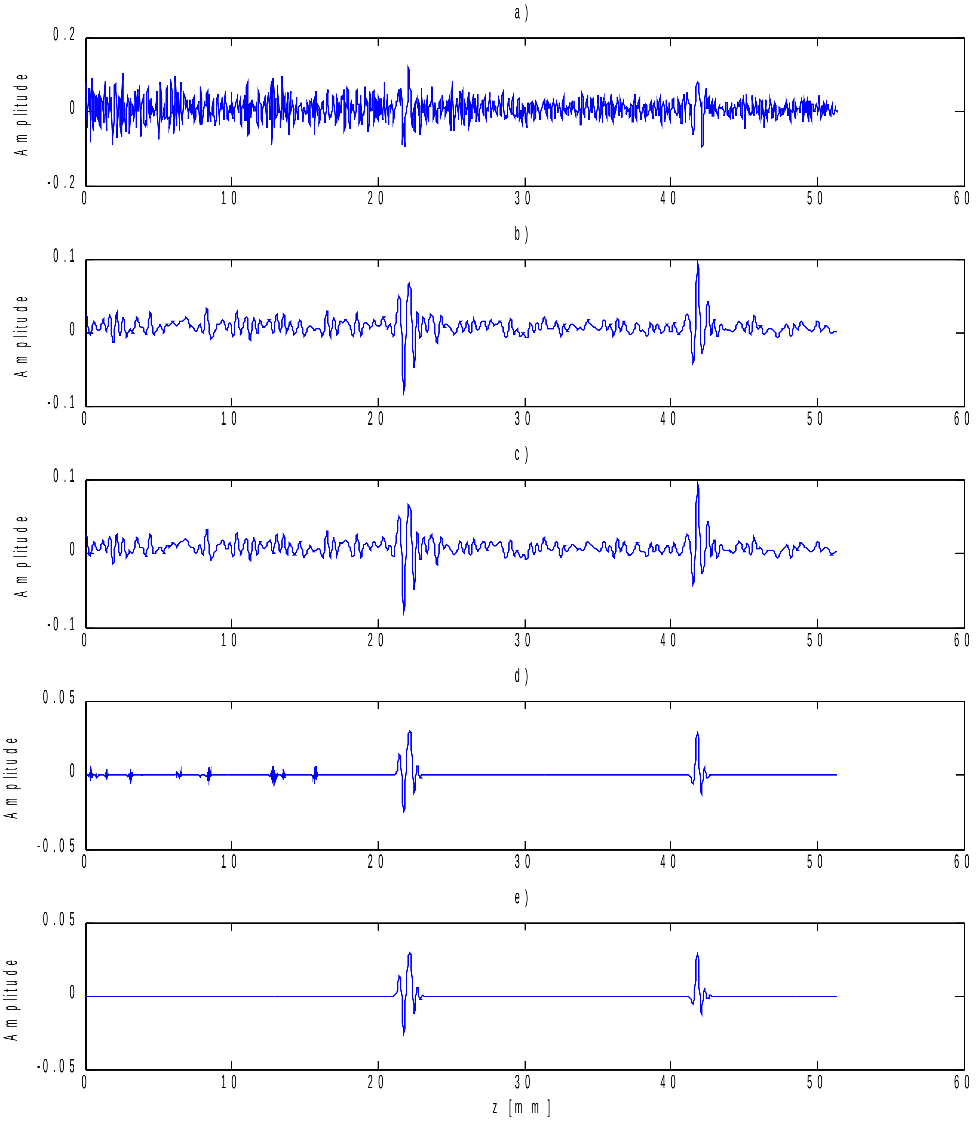

Figure 4.- De-noising results from experimental signal. a) Structural noisy signal; de-noising by selection rule: b) Minimax, c) Universal threshold, d) proposed time-frequency threshold with *M*=3, *L*=2 with φ= *dB7*, and e) proposed time-frequency threshold with *M*=3 and *L*=1 with φ= *dB7*.

Figure 4 shows several results of the de-noising process using different selection rules. From Figure 4b (Minimax threshold) and 4c (Universal threshold), we can observe a low SNR in the signal. For this reason, we propose a time-frequency threshold in order to increase the SNR. Figure 4d shows a considerable enhancement of the flaw visibility, but noisy terms still appear. However, changing the levels which want to be excluded in the signal reconstruction, (i.e. L=1) therefore we have dramatically obtained a free-noise signal (Fig. 4e).

CONCLUSIONS

A new selection rule for structural noise reduction has been presented in this work. This threshold is based on the statistical values from energy signal in time-frequency space. Therefore, this estimation considers the non-stationary nature of the structural noise. The proposed technique exploits the performance of time-scale (wavelet de-noising) and time-frequency (thresholding via Wigner-Ville) for detecting flaws. Simulated and experimental results have shown that the proposed technique is effective in order to enhance the defect visibility from highly scattering materials.

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