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ON THE USE OF THE NON-STATIONARITY OF THE STRUCTURAL NOISE FOR DEFECT VISIBILITY ENHNACEMENT IN ULTRASONIC INSPECTIONS

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ABSTRACT

Structural noise is an important distortion source in ultrasonic images of highly dispersive materials. This noise can considerably mask the flaw signals and cannot be eliminated using standard techniques for noise cancelling like band-pass filtering or temporal averaging. Fortunately, this noise has several characteristics that may help to an algorithm designer to develop methods that improve the defect visibility.

In the literature there exist many techniques for flaw visibility enhancement in the presence of structural noise. However, many of the proposed algorithms do not systematic exploit the above mentioned characteristics. In this work we analyze the structural noise from a point of view of an algorithm developer that seeks parameters that may help to eliminate the noise enhancing the defect visibility. Also, we present several algorithms examples that, using this information, dramatically improve the visibility of the flaw echoes.

INTRODUCTION

In UT non-destructive evaluation of highly scattering materials (stainless and austenitic steel, titanium, composite materials) little flaw signals are usually masked by the so called structural noise also referred as speckle, scattering, coherent noise. Due to the spectral coherence of this noise with the flaw signal, this noise cannot be eliminated by conventional techniques like classical filtering or temporal averages.

In the literature, several techniques have been proposed for enhancing the signal to noise ratio (SNR) of signals coming from scattering materials. Spatial and spectral diversity techniques [1] compose several A-scan traces for obtaining a unique trace with enhanced SNR. On the other hand, a more interesting approach is to use only one trace for enhancing the defect visibility, like Split Spectrum Processing (SSP)[2], maximum likelihood estimation (MLE) [3], group delay moving entropy [4,5] noise suppression with low-frequencies band pass filtering [6,7] or adaptive filtering techniques [8,9].

However, the vast majority of the proposed techniques assume stationarity of the structural noise as an initial hypothesis in order to validate the proposed algorithms. However, received echo has a nature that can dramatically differ from stationarity.

This work is organized as follows. First part present several characteristics of the structural noise that may help to an algorithm developer to eliminate this kind of noise and so enhance the defect visibility. These characteristics are divided in spectral based or unidimensional information and time-frequency based or bidimensional information. In the second part, several algorithm examples that exploit these features are presented. These methods have been developed by the authors of this work.

SIGNAL PROCESSING STRUCTURAL NOISE CHARACTERISTICS

When a transducer is excited by an electrical pulse and generates an ultrasonic wave, this wave travels through the grained and scattering structure of the material as is shown in figure 1. When the reflectors of the structure has a dimension comparable to the wavelength of the ultrasonic signal, the structure changes the shape and the spectral content of the front wave.

Dominant physical phenomena is the attenuation due to dispersion that produce that high frequencies are more severely attenuated than low frequencies.

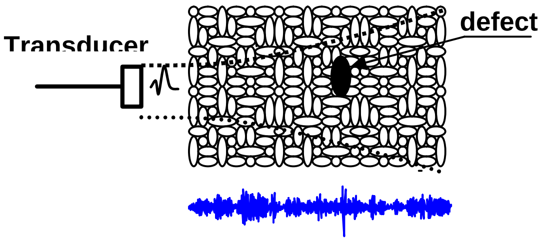

Figure 1. Structural noise masking a defect

A useful linear time-variant model of the received signal coming from a scattering material was proposed by [10] and has the following general expression:

$$y(t,z) = n(t,z) + s(t,z) = x(t) * a^2(t,z) * (h_{mat}(t) + h_d(t)) \qquad \text{(Eq.1)}$$

where the received signal $y(t)$ is the sum of two terms: the structural noise reflected by the scatterers, $n(t,z)$, and the signal coming form the defects $s(t,z)$; $x(t)$ is the signal generated by the transducer, $a^2(t,z)$ is the scattering material attenuation and $h_{mat}(t)$ and $h_d(t)$ are the impulse responses of the material and the defect respectively.

Transforming $n(t,z)$ and $s(t,z)$ into the time-frequency domain yields:

$$\begin{aligned} N(w,z) &= X(w)\cdot\sum_{k=1}^{k_s} b_k \frac{w^2}{z_k} \exp(-a_R 2 z_k w^4)\cdot\exp(-jw2z_k/c) \\ S(w,z) &= X(w)\cdot\sum_{k=1}^{k_d} r_k \exp(-a_R 2 z_k w^4)\cdot\exp(-jw2z_k/c) \end{aligned} \qquad \text{(Eq.2)}$$

where bw^2/z is the reflectivity of the scatterers, r is the reflectivity of the defects and $\exp(-a_R\cdot 2z\cdot w^4)$ is the attenuation into the Rayleigh zone where a_R is a constant and material dependent.

We have considered a time-frequency model for the generation of the structural noise, however, processing tools can be chosen to analyze de UT signals in a one dimension frequency information or in a time frequency plane.

Frequency information.

As is shown above, structural noise can be modeled as a non-stationary process and indeed a time-frequency processing tool is the more natural way to represent it. However, using only one dimension and obtaining frequency representations can be a very suitable tool for developing very efficient methods for coherent noise elimination. This part shows the characteristics of the spectral analysis when a defect echo is contaminated with grain noise.

In figures 2 and 3 se present simulated and experimental results. Figure 2 shows the normalized linear spectra of the reflected signals coming from defects located at different deeps. It can be observed that the spectra of these defects have a low-frequencies shift with depth. Figure 3 shows the spectrum of an only structural noise signal (blue line) and a signal that contains a defect masked by structural noise (red line). It can be observed that in the region located at 2MHz a higher signal to noise ratio exist. This fact is exploited by the classical low frequencies band pass filtering is based on this spectrum analysis.

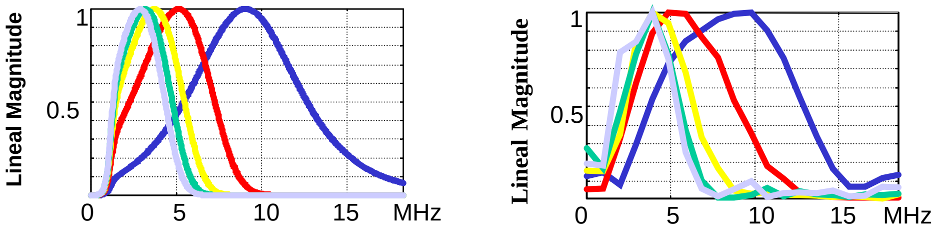

Figure 2. Simulated (left) and experimental (right) signals frequency responses of the interface echo (blue line) and of the defects located at 10 mm. (red line), 30 mm. (yellow line), 50 mm. (green line) and 70 mm.(gray line)

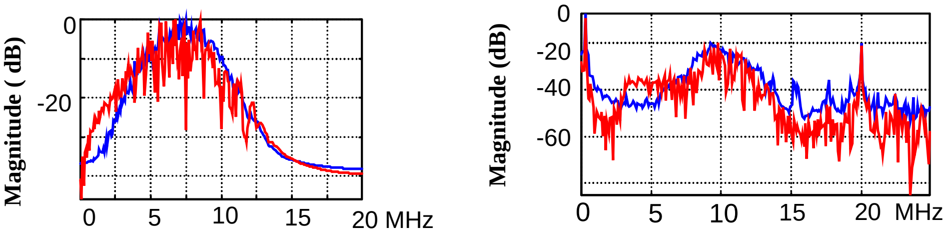

Figure 3. Simulated and experimental spectral difference between an only structural noise signal (blue line), and a flaw signal masked by structural noise (red line).

Time-frequency information

As we have yet mentioned, the structural noise is non-stationary. So, the processing tools that best fit this characteristic are those based in the time- frequency plane. This fact is shown in figure 4. In this figure we can see the evolution with time (depth) of the energetic spectral content of an only structural noise trace. Figure 4(a) shows the spectrogram with a synthetic structural noise trace. This fact allow us to observe that higher spectral contents are highly attenuated at the beginning of the trace. This is an observation that we can not do with experimental signals due to the interface echo that mask the behaviour of the structural noise at the beginning. So, Figure 4(b) shows the experimental result. We can see an only structural noise trace spectrogram between 6 and 14 μsec. Due to the above mentioned fact related with the interface echo.

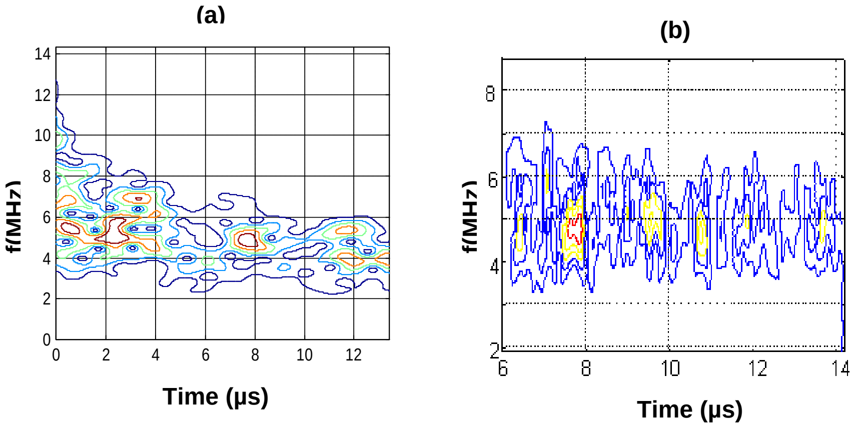

Figure 4. Simulated and experimental spectrogram of the structural noise

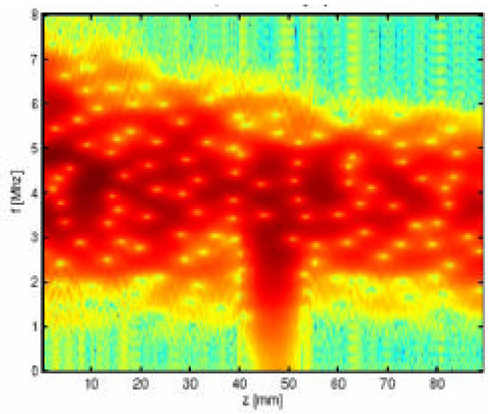

Figure 5. Spectrogram of a simulated trace that contains a defect located at 45 mm deep contaminated with structural noise

Figure 5 shows the spectrogram of a simulated trace that contains a defect corrupted with structural noise. Again is observed that the defect has a higher SNR at low frequencies. It is interesting to compare this figure with figure 3. Figure 3 is the projection of the entire time axis onto the frequency axis.

ALGORITHM EXAMPLES

This part of this work present several algorithms, proposed by the authors, that systematically exploit the structural noise features of eliminate it.

Energy time-frequency filtering

The first method we are going to present is the energy time-frequency filtering [7]. In this method, block-processing autoregressive techniques are used to estimate the instantaneous center frequency of the travelling wave. From this information, a time-frequency filter is designed tuned at half the estimated instantaneous center frequency. Figure 6 shows the time frequency filter designed with this method. It is interesting to note two things: (a) Defect energy occupies the lower frequencies, (b) a low-frequencies band pass filtering (a band-pass filter tuned to the center frequency of the interfaz echo) do not eliminate most of the middle to high deep structural noise energy.

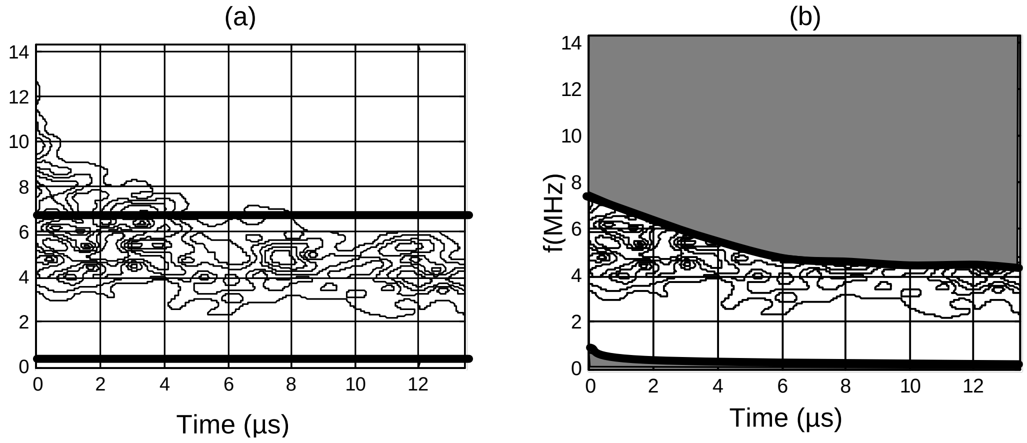

Figure 6. Comparison of the time-frequency behaviour of (a) the classical low-frequencies band pass filtering and (b) the proposed energy time-frequency filtering

Time-varying prediction filter

Many of the techniques that eliminate the structural noise assume that in the ultrasonic inspection we have access to several parts of the material that are free of defect in order to estimate the structural noise features. However, not always this is the case, or simply we do not want a calibration process of the algorithm. In these circumstances, a adaptive algorithm may be useful. Proposed technique is based on the prediction error obtained with a linear and time-varying parametric model of the noise [9]. By this method, when the analyzed UT echo has only structural noise, the prediction error is low, however, if it contains a flaw, high prediction error occurs because a flaw is a non-predictable alteration of the material structure.

Structural Noise Reduction Using Multiresolution-Based Spectral Subtraction

Methods that use the time-frequency information are potentially the best methods for enhance the defect visibility in coherent noise. In [11], a multiresolution-based spectral subtraction method for enhancing the flaw signal to structural noise ratio (SNR) is proposed. This method, using the wavelet transform, exploits the non-stationary characteristics of the structural noise. First step of this algorithm is the time-scale estimation of several statistics of the structural noise. On the second step, non-linear over-subtraction of the raw signal wavelet transform is applied. This strategy produces improved results in SNR compared with linear and non-over-subtraction techniques. Next, a post-processing based on exploiting additional information from the physical knowledge of the structural noise is applied and finally the inverse Wavelet Transform obtains the output processed signal.

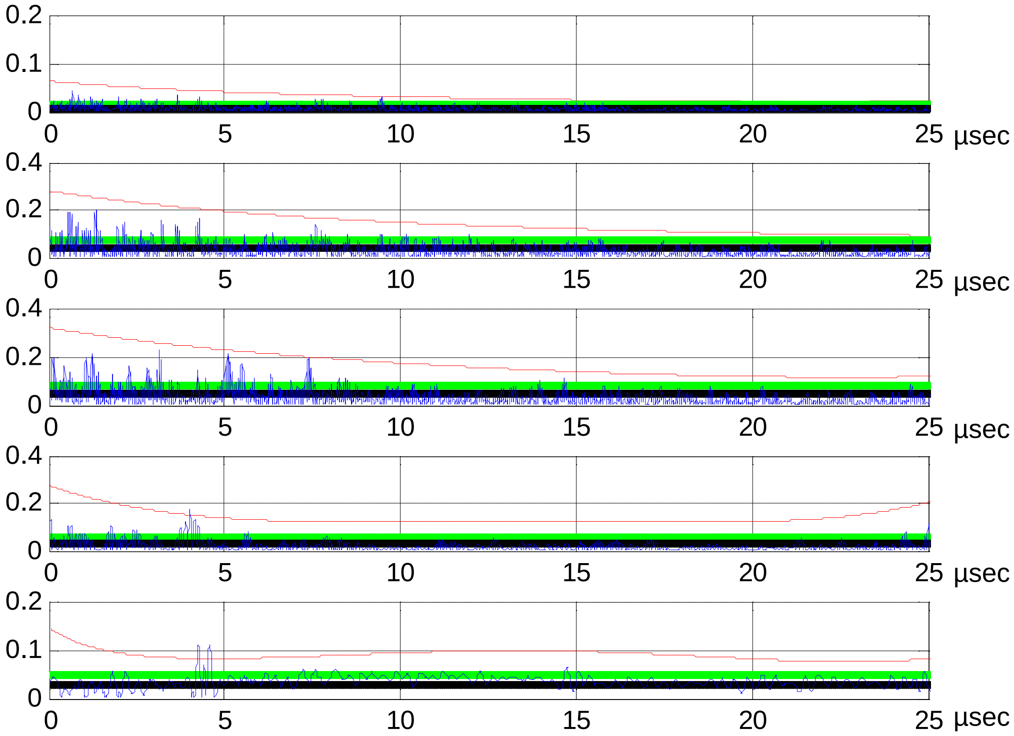

Figure 7. Comparison of the different threshold levels applied to a wavelet decomposition. Minimax (black line), Universal (green line) and the proposed threshold based on spectral substraction (red line)

From the figure 7, we can infer that the threshold of the different scales are a function of depth. Classical methods for selecting the threshold (Minimax, Universal Threshold) are based on the analysis of stationary white noise and apply the same threshold to the scale. The proposed method based spectral subtraction is more adequated for the non-stationary characteristics of the structural noise.

CONCLUSIONS

This work has presented several characteristics of the structural noise that may help to an algorithm designer to develop methods that improve the defect visibility. The most important of them is that this noise has a non-stationary nature. These features are shown in the spectral analysis based representation and in time-frequency representation.

In the literature there exist many techniques for flaw visibility enhancement in the presence of structural noise. However, many of the proposed algorithms do not systematic exploit the above mentioned characteristics. In this work we analyze the structural noise from a point of view of an algorithm developer that seeks parameters that may help to eliminate the noise enhancing the defect visibility. Also, we have presented several algorithms examples that, using this information, can dramatically improve the visibility of the flaw echoes.

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