ROBUSTNESS STUDY OF DETECTION ALGORITHMS OF MULTIPLE IMPERFECTIONS IN COARSE GRAINS MATERIALS.

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Abstract

In this work, we propose to develop algorithms based on the Split Spectrum Processing (SSP) method associated with the multi-steps method based on "Group delay moving entropy" (GDME) allowing detecting and locating multiple imperfection echoes drowned in the structural noise of materials. In fact, GDME is based on the fact that defect echoes have a constant group delay while the noise has a random group delay. The investigation is performed with 4 known defect echoes with different characteristics (position, center frequency and bandwidth). The defect echo frequency is varied around the frequency of the input signal in order to evaluate, by SNR calculation, the robustness of the detection method. The grain noise signal is generated first, by a simple clutter model which consider the noise, in the time domain, as the superimposed of signal coming from backscaterers in the medium and second, experimentally by a material with coarse grains.

Key words: Ultrasonic NDE, Split Spectrum Processing, signal to noise ratio, structure noise.

Introduction

In practical applications of ultrasonics NDE, it is possible to find simultaneously multiple with complex geometrical forms, defects located at various areas of the material, having as result signal echoes with different temporal and spectral characteristics. This situation can be still complicated if the material is nonhomogeneous or has a coarse grains. In such materials, signal energy is lost due to scattering so the detection of imperfections by ultrasounds is often difficult.

Moreover, the Split Spectrum Processing (SSP) comprises some non-linear operations, which can improve the visibility of the great defect echo than the smaller one. For these reasons, the conventional application of SSP employing a simple spectral range can not be sufficiently sensitive to the variations of the spectral and temporal characteristics of the various targets to allow their detection simultaneously[1,2]. Consequently, it is desirable to develop new techniques [3] which resolve the complex problem of multiple targets detection, in particular, for materials with coarse grains.

In this work, we propose to develop algorithms based on the Q constant SSP method associated with the multi-steps method based on "Group delay moving entropy" (GDME) allowing detecting and locating multiple imperfections echoes drowned in the structural noise of materials. In fact, GDME is based on the fact that defect echo has a constant group delay while the noise has a random group delay.

The investigation is performed with 4 known defects echoes with different characteristics (position, amplitude, center frequency and bandwidth). The defect echoes frequency is varied around the frequency of the input signal in order to evaluate, by Signal to Noise Ratio (SNR) calculation, the robustness of the detection method. The grain noise signal is generated first, by a simple clutter model which consider the noise, in the time domain, as the superimposed of signal coming from backscatterers in the medium and second, experimentally by a material with a coarse grains.

1. Noise modelling

The noise generation used in this work is based on the simple clutter model presented in [4]. We consider the noise as the superimposed of signals coming from backscatterers (grains) in the material.

If the ultrasonic transducer has the frequency response $H_t(\omega)$ and the material viewed as a single system with its frequency response $H_{mat}(\omega)$, the frequency response of structure noise is given by :

$$N(\omega)=H_t(\omega).H_t(\omega).H_{mat}(\omega) \quad (1)$$

$H_t(\omega)$ occurs twice since the transducer is used as transmitter and receiver. $H_t(\omega)$ is modelled as a band pass Gaussian shaped spectrum, in practice, it can be measured using a flat surface reflector positioned at the far field of the transducer. In this work, we have used a transducer of 5.2 MHz as central frequency.

In the Rayleigh region ($\lambda >> D$, where λ is the wavelength and D is the average diameter of material grain), where the attenuation is proportional to ω^4 and omitting multiple reflections, $H_{mat}(\omega)$ is expressed by

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

where α_s is a material scattering coefficient (constant), c_l is the velocity of longitudinal waves, x_k is the particle positions, k=1,…,K_{tot} (K_{tot} is the particle number). Since β_k and x_k are random variables, then H_{mat} is also a random variable. The frequency response of structure noise became :

$$N(\omega) = H_t(\omega)H_t(\omega)\sum_{k=1}^{K_{tot}} \beta_k \frac{\omega^2}{x_k} \exp(-\alpha_s 2\ x_k\ \omega^4) \exp(-j\omega 2\ x_k / c_l) \qquad (3)$$

We applied this model in order to simulate an ultrasonic signal containing defect echoes with additive structure noise. Simultaneously to this simulation work, we carried out experiments concerning the measurement of the structural noise of a material with coarse grains giving a very strong diffusion.

Using several simulated values of α_s [5], we have simulated several defect signals in noise. We have studied the shifting of the central frequency in the spectrum of the defect echo signals; we have noted that this shifting reached to the maximum of 1 MHz towards the low frequencies. For that, we decided to take as central frequency values of four defects, close to the transducer central frequency as described in table 1.

Table 1. The simulated target characteristics

Defects	# 1	# 2	# 3	# 4
Position Amplitude	3.8µs 1.2	8.9 µs 0.8	13.2 µs 0.6	18.2 µs 0.3
Central Frequency	5.2 Mhz	4.8 Mhz	4.6 Mhz	4Mhz
Bandwidth at -3 dB	1.4 Mhz	1.4 Mhz	1.3 Mhz	1.3 Mhz

2. SSP technique

This technique splits the received wideband signal into a group of frequency-diverse narrow band signals exhibiting different SNR, and subsequently recombines them using non linear techniques in order to increase this SNR[3]. The performance of the SSP is sensitive to four parameters which are the number of filters used for splitting spectrum, the filters bandwidth, the step frequency between filters and the position of pass-band filter (the frequency center of the first and the last filter).

3. Mathematical model of multiple targets

The problem of multiple targets can be formulated by $y_P(t) = \sum_{i=1}^{P} A_i\ f(t - T_i)$ where P is the total number of targets; A_i and Ti are respectively the amplitude and the position of the i[th] target. Ai and Ti are statistically independent random variables. The Fourier transform of the multi targets signal is given by $Y_P(f) = \sum_{i=1}^{P} A_i\ F(f)\ \exp(-j2\pi f T_i)$

The phase is expressed by

$$\Phi_P(f) = -\left\{\tan^{-1}\frac{\sum_{i=1}^{P} A_i\ F(f)\ \sin 2\pi f\ T_i}{\sum_{i=1}^{P} A_i\ F(f)\ \cos 2\pi f\ T_i}\right\} \qquad (4)$$

The discrete group delay is expressed by

$$\Delta T_P(k) = -\frac{N}{2\pi}[\phi_P(k+1) - \phi_P(k)] \qquad 1 \le k \le N/2 \qquad (5)$$

where k is the frequency index and N is the total number of points. It can be noted that its group delay is not a constant.

4. Analysis

In order to improve multiple targets detection with various spectral and temporal characteristics using the SSP, two principal stages must be followed:

1. Optimal frequency range Selection;
2. Iterative utilisation of SSP

4.1. Selection of the optimal frequency range

To improve the results of the SSP in the detection of multi-targets, it is efficient to develop an adaptive algorithm, which can detect the spectral variations of targets signals. The received ultrasonic signal can be modelled by $y(t) = s(t)*h(t) + n(t)$ where s(t) is a flaw signal and h(t) is the impulse response of ultrasonic system. The frequential representation of the received signal (for a single target) is expressed by:

$$Y_l(f) = A_l\ H(f)\ \exp(-j2\pi f T_l) + |N(f)|\ \exp(j\theta(f)) \qquad (6)$$

Where H(f) is the Fourier transform of h(t). Consequently, the group delay corresponding to only one target becomes:

$$\Delta T(f) = -\frac{1}{2\pi}\frac{d}{df}\left\{\tan^{-1}\frac{\frac{A\ H(f)}{|N(f)|}\sin 2\pi f T_l - \sin\theta(f)}{\frac{AH(f)}{|N(f)|}\cos 2\pi f T_l - \cos\theta(f)}\right\} \qquad (7)$$

This expression describes the characteristics of the group delay of the received signal. AH(f)/|N(f)|

function is the signal to noise ratio. It is clear that if AH(f) / |N(f)| > > 1, then it results a group delay constant T_0. If AH(f) / |N(f)| < < 1, It results a random group delay.

Since the entropy is an adequate measurement for the random aspect, we propose an iterative technique which estimates the randomness of the group delay by entropy using a moving window of M width along the frequency axis. The steps of this algorithm are described in [3].

The calculation result of the entropy gives a frequency function of k. Since the target signal results in a group delay with a relatively small variations compared to the noise, the frequency band containing the target signals only gives values of entropy appreciably smaller than the values compared in the frequency bands containing the noise. From where, the GDME application will allow the determination of the optimal spectral region for the application of the multi steps algorithm based on SSP.

4.2. Multi steps algorithm

The algorithm that we propose consists of several stages, it acts to detect in an iterative way, the most dominant target in the received signal, and then to eliminate it by applying a window filter, in the temporal field, positioned in the place of the target. The elimination window of this target has a width equivalent to the impulse response of the system. This process is repeated until all the remaining targets are detected.

4.3 Simulation results and discussion

We have applied the SSP-GDME algorithm on a signal containing 4 targets (fig.1) having the characteristics given by table 1. Initially, we have proceeded by the calculation of the entropy by a moving window on the group delay.

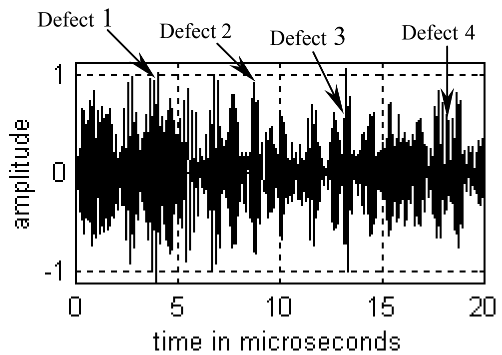

Fig.1. Signal with 4 defects. 1024 samples

It is to be noted that the group delay is characterized by small variations in the frequency band between 3MHz-4MHz, which corresponds to the frequency band where the SNR is the highest. Figure 2 shows the resulting entropy using the following parameters M= 32, and B = 5.

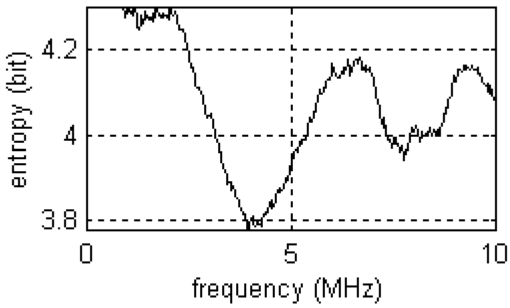

Fig.2. Measured entropy

Note that the minimal value of the entropy is located around 4 MHz. Then, the SSP was applied with Q constant filters and absolute minimisation as output signal processing [3], the SSP parameters are described in table 2.

Table 2. SSP parameters with Q constant

Targets	#1	#2	#3	#4
Values of Q	24	22	22	22
Number of filters	12	12	12	12
Frequency range (in MHz)	3.5-4.5	3.6-4.7	3.9-5	3.9-5.4

In order to detect targets, we have used the multi steps approach which consists of detecting the first target and then, eliminating it by multiplying the original signal by a temporal window filter. Then, we proceed in the same way, detecting the 2nd target, then eliminating it and so on. As example, the output signal illustrated by figure 3 shows clearly the detection of the fourth target located at t_0= 18.2 µs. After having detected and eliminated all targets, the central frequency estimated by entropy is 6.7 MHz. This frequency is much higher than the transducer central frequency. It should be noted that application of the SSP in this frequency band, gives in output a great number of echoes of high amplitude. This indicates that no other targets are remaining in the data. Consequently, the process is finished.

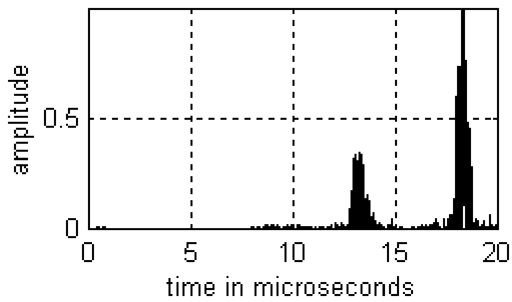

Fig.3. Detection of target #4 located at t_0= 18.2 µs.

5. Statistical study and conclusion

The SNR for multi-target signals (time sequence) y(n) is calculated as the energy within the range containing the target j divided by the total signal energy with all targets suppressed except target j [5]. It is expressed as:

$$SNR = \frac{\sum_{n=T_j-W/2}^{T_j+W/2} y^2(n)}{\sum_{n=0}^{N-1} y^2(n) - \sum_{\substack{i=1 \\ i\neq j}}^{P} \sum_{n=T_i-W/2}^{T_i+W/2} y^2(n)} \qquad (8)$$

where T_i is the i^{th} target location and W, its pulse-width.

The robustness is measured by SNR and the detection probability of 100 signals containing 3 targets [6]. Simulations are carried out on each of the three targets having the same central frequency and bandwidth but various positions and amplitudes. The three target positions are distributed randomly between 1 and N, where N is the number of samples equal to 1024. The amplitude of the noise is normalized to unity and the amplitude of the targets is uniformly distributed between 0.2-0.9. The target amplitudes lower than 0.2 is regarded as very weak being detected, while the amplitudes greater than 0.9 can be generally identified without processing. The central frequency of noise is more or less equal to 5.6 MHz. The simulated targets have Gaussian spectra and 1.2MHz bandwidths at -3dB. The central frequency of the targets is changed between 3 MHz and 8MHz.

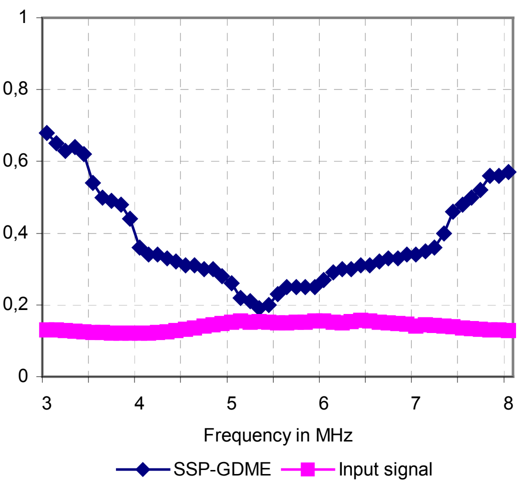

Fig.4. SNR values according to frequency

Figure 4 and 5 respectively show the results of the SNR calculation of the target having the highest amplitude and the 3 targets detection probability according to the frequency. We can note that the SNR reaches very appreciable values apart around the central frequency of the noise. At 5.6 MHz, the algorithm becomes ineffective.

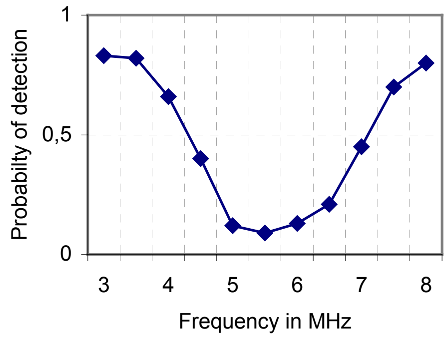

Fig.5. Probability of detection of targets

Nevertheless, it was shown that in experiments, the central frequencies of defects do not reach this frequency. In the same way, the defects detection probability is around 0.5 when the central frequency of the targets is around 4 MHz. It passes by a minimum at the noise frequency.

In conclusion, the results confirm that GDME is optimal for determining spectral regions for processing. SSP with Q-constant is applied for detecting defects and it can be noted that it is an effective method.

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