Ultrasonic Signal Processing in the Detection of Defect in Composite

Redouane DRAI, Abdesselem BENAMMAR, Image and signal processing laboratory.
Welding and NDT Centre, Chéraga, Algérie

Abstract. Because of their good mechanical strength and light weight, fibre-reinforced composites are increasingly used in industrial fields. However, during the fabrication of polymer materials, various flaws may occur which have negative impact on polymer composite quality.
Usually in this type of materials, the received signals consist of components and additive structural noise. This noise often masks the signal of the defect and creates an embarrassment in its detection. Also, in thin samples the reflected signals are overlapping thus making detection of defects in the sample and accurate measurements impossible. It is thus necessary to enhance the visibility and resolution of the defect echo by signal processing techniques. In this context, we develop signal processing tools based on Split Spectrum Processing (SSP) with Q constant method allowing to detect and locate the imperfections present in these materials. This work answers to the selected ultrasonics NDT problems of composite like sensitivity and resolution of defects detection.

Introduction

The new methods of Non Destructive Testing by ultrasounds of materials have much developed for a few years. They are based on the fact that the received ultrasonic signal of a defect contains a sum of information forsaken by the traditional techniques. These last consider that information essential to take into account is the maximum amplitude of the ultrasonic echo. The possibility of acquiring information making it possible to characterize the defects in type, in size and in orientation required the development of more advanced techniques which are gathered under the general term of **ultrasonic signal processing.**
Because of their good mechanical strength and light weight, fibre-reinforced composites are increasingly used in industrial fields. However, during the fabrication of polymer materials, various flaws may occur which have negative impact on polymer composite quality.
Usually in this type of materials, the received signals consist of components and additive structural noise. So the detection of imperfections is often difficult because one cannot distinguish between the signal from the imperfections and the noise. This noise often masks the signal of the defect and creates an embarrassment in its detection. Also, in thin samples the reflected signals are overlapping thus making detection of defects in the sample and accurate measurements impossible. It is thus necessary to enhance the visibility of the defect echo by signal processing techniques. In this context, we develop signal processing tools based on Split Spectrum Processing (SSP) with Q constant method [1] allowing to detect and locate the imperfections present in these materials. This work answers to the selected ultrasonics NDT problems of composite like sensitivity and resolution of defects detection.

1. Closely spaced defect echoes problem

In general, the received signal with two defect echoes is expressed as:

$$y(t)=x(t-t_0)+ax(t-t_1)+n(t) \qquad (1)$$

Where a : constant ; $n(t)$: structural noise signal ; t_0 and t_1 are temporal locations of these defect echoes. The problem of closely spaced defect echoes is encountered when separation t_1-t_0 becomes very small from where an interference phenomenon between these two echoes appears.

The Fourier Transform of the received signal (1) with no structural noise:

$$Y(j\omega)=\sqrt{1+a^2+2a\cos\left[\omega(t_1-t_0)\right]}\,|X(j\omega)|\exp j\left[\Phi-tang^{-1}\left(\frac{\sin(\omega t_0)+a\sin(\omega t_1)}{\cos(\omega t_0)+a\cos(\omega t_1)}\right)\right] \qquad (2)$$

If the two echoes have the same amplitude i.e. a=1, equation (2) becomes:

$$Y(j\omega)=2\cos\left(\frac{\omega(t_1-t_0)}{2}\right)|X(j\omega)|\exp j\left[\Phi-\left(\frac{\omega(t_1-t_0)}{2}\right)\right] \qquad (3)$$

The output magnitude of Y(jω) is the product of magnitude spectrum $|X(j\omega)|$ and cosine function which contains the echo separation information, where its period is related to the separation between the defect echoes. The zeros of this function (or minima) determine these echoes separation. The detection of these zeros is strongly influenced by the bandwidth of $X(j\omega)$.

In the case of the infinite bandwidth signals, i.e. $|X(j\omega)|=1$, the equation (3) becomes:

$$Y(j\omega)=2\cos\left(\frac{\omega(t_1-t_0)}{2}\right)\exp-j\left[\left(\frac{\omega(t_1-t_0)}{2}\right)\right] \qquad (4)$$

The layout of this function shows that the minima are localised in $\omega=\frac{(2k+1)\pi}{t_1-t_0}$ while the maxima ones are localised in $\omega=\frac{2k\pi}{t_1-t_0}$

2. Used noise

The noise signal used in this work, is based on the simple clutter model presented in [2]. We applied this model in order to simulate an ultrasonic signal containing defect echoes with additive structure noise. The simulated temporal and frequential responses of this noise are illustrated respectively by figure 1a and 1b. Then, we added to simulated noise signal, a real defect signal of 1mm diameter located at 4μs with the same amplitude of noise (100%). It can be noticed that it is very difficult to detect manually this defect. Works were achieved in order to enhance the visibility of this kind of defect echo [3]. Figure 1c shows this input signal. Tests have been undertaken with different levels of noise in order to enhance this signal to noise ratio.

3. Split Spectrum Processing (SSP) Technique

This technique [1] splits the received wideband signal into a group of frequency-diverse narrow band signals exhibiting different SNR, and subsequently recombines those using non linear techniques in order to increase this SNR. The behavior principle of this technique is schematized by figure 2a. 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).

Works [4] showed that this algorithm gives better results when the decomposition is achieved by constant bandwidth filters but by filters whose bandwidth b_i increase with the frequency centre f_i, more precisely, with Q constant. Where Q is the quality factor defined as $Q = \frac{f_i}{bi}$.

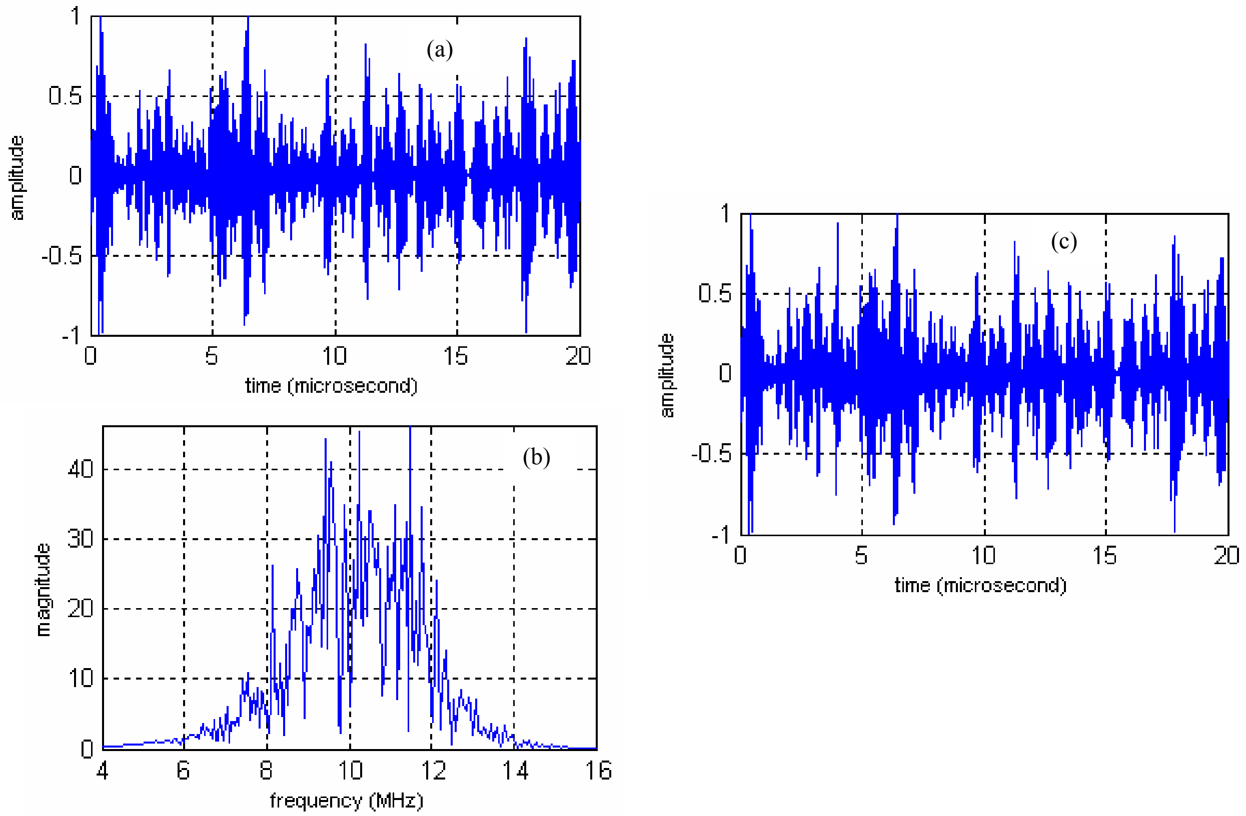

Fig.1.(a) Modelled noise, (b) Noise spectrum
(c) Input signal with defect echo at 4 µs.

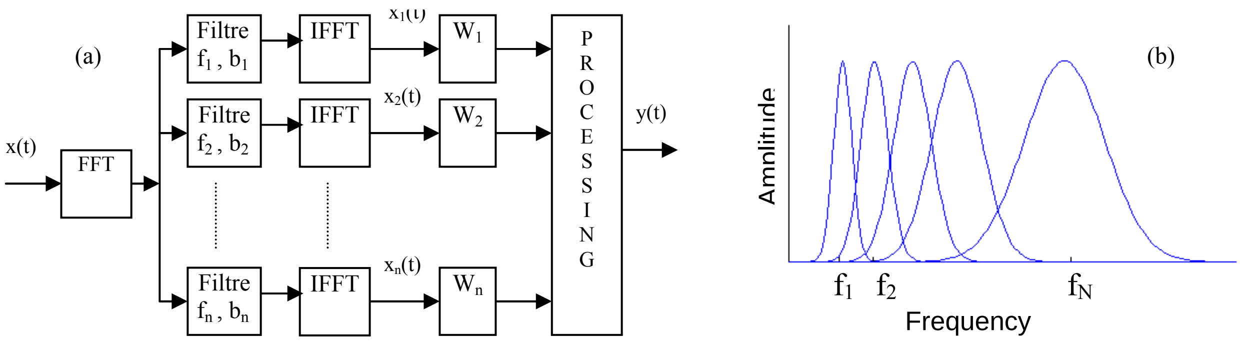

Fig.2. (a) Filter bank of SSP. (b) Q constant bandwidth of filters

The reconstruction stage of output signal is achieved by several non linear algorithms [5], in this work geometric mean and absolute minimisation are used. The geometric mean algorithm consists of taking the geometric mean of narrow band, frequency diverse signals [6]. The output signal is calculated mathematically by:

$$y(t) = \sqrt[N]{\prod_{i=1}^{N} \left[\left| w_i x_i(t) \right| \right]} \qquad (5)$$

The output of absolute minimisation algorithm for each time instant is expressed as:

$$y(t) = \min \left[\left| w_i \; x_i(t) \right|^2 : \; i=1,2,...N \right] \qquad (6)$$

These algorithms are applied in order to detect and enhance closely spaced defect echoes with additive structural noise.

4. Simulation study

The limited bandwidth echo signal used in this work, is expressed by:

$$x(t)=A.b.exp(-2(\pi bt)^2).cos(2\pi f_c t)$$

with f_c : the center frequency of ultrasonic transducer, 2b : its bandwidth at –6dB and A : constant.

Let us take as example two echoes with linear phases separated by $\Delta t=0.1\mu sec$ (figure 3a).

f_c=9.5 MHz, b=2.5 MHz , t_0=4 µsec et t_1=4.1 µsec.

The spectrum of two closely spaced defect echoes presents two minima with 5 MHz and 15 MHz (figure 3b). The difference of these two values, equal to 10 MHz, gives us the temporal separation between the two echoes: $\Delta t = 1 / 10 = 0{,}1$ µsec

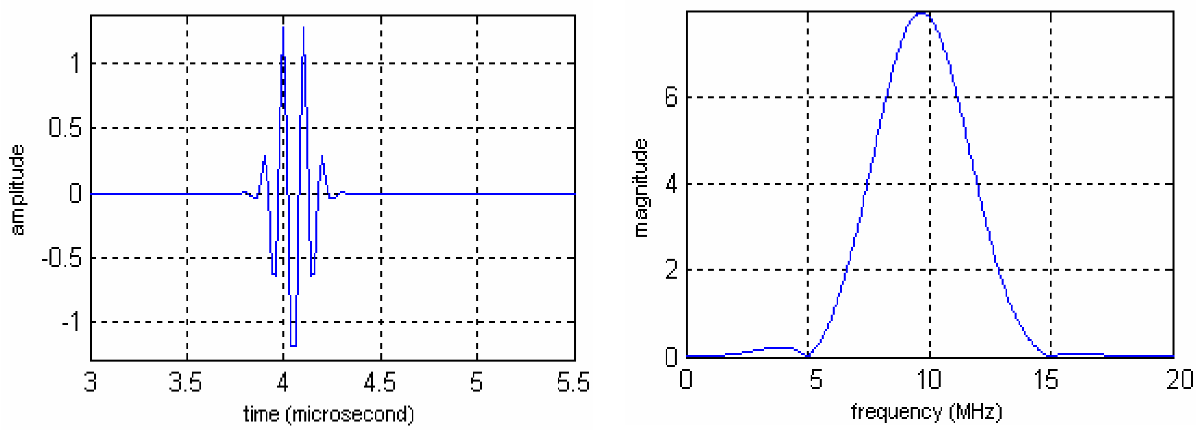

Figure 3. (a) Free noise input signal with two echoes separated by $\Delta t=0.1\mu sec$.
(b) Its spectrum

Other minima could appear on this spectrum if the ultrasonic transducer used, had a larger bandwidth. The simulation study showed that separation between these two echoes is possible so at least one minima is located inside the band-width of filter. It should be noted that the resolution of the system is equal to 3db the bandwidth of the ultrasonic transducer [7].

To the signal illustrated by figure 3a, we added structural noise signal modelled in section 2. Various levels of noise were added, we present in figure 4a, the noise level equal to 60% of the amplitude of defect echoes. Figure 4b represents the spectrum of this signal. Figures 4c and 4d illustrate output signal obtained by SSP with Q constant using respectively the

geometric mean and minimization. In the same way, figures 5c and 5d illustrate algorithm results for a noise level equal to defect echoes amplitude (100%).
We note that for a bandwidth 2b=5MHz and $\Delta t = 0.1 \mu sec$, the developed algorithm gives very satisfactory results. Other tests were carried out for b=2MHz and b=1MHz, we noticed that this algorithm loses its robustness with respect to the added noise. Thus, more the bandwidth of the ultrasonic transducers decreases and more the detection probability of the defects decreases. Table 1 summarises this result. Note that " X " symbolizes "detected" and " 0 " symbolizes "not detected".

5. Experimental study

The first experiment that we carried out in this work, was achieved on a sample in composite of thickness equal to 1.2mm with an ultrasonic transducer of frequency centre f_c= 10 MHz and bandwidth at –6dB, $2b$= 7.5 MHz.
The resolution of this ultrasonic system is equal to $\Delta x = \frac{V}{2b}$, where V is the celerity of longitudinal wave in this material. For V = 2500 m/s and 2b = 7.5 MHz, it results Δx = 0.3mm. In temporal separation, Δt = 0.25 µsec. This value represents the minimal temporal separation that this system can detect using this ultrasonic transducer.
A groove was detected at 0.3 µsec from the bottom of the sample. This is illustrated by input signal representation (fig.6a) and zoom of defect echo and back wall echo part illustrated by the figure 6.b. It should be noticed that these two echoes are very close and this defect can not be detected. Figures 6.c and 6d show results obtained by SSP with Q constant using respectively geometric mean and minimisation. The minimisation algorithm give us a better result.

Table 1. Simulation results.
X :detected and 0 : not detected

	Δt = 0.4 µsec			**Δt = 0.3 µsec**			**Δt = 0.2 µsec**			**Δt = 0.1 µsec**		
Noise level ↓	**Bandwidth 2b in MHz**			**Bandwidth 2b in MHz**			**Bandwidth 2b in MHz**			**Bandwidth 2b in MHz**		
	5	**4**	**2**	**5**	**4**	**2**	**5**	**4**	**2**	**5**	**4**	**2**
0%	X	X	X	X	X	X	X	X	X	X	X	0
20%	X	X	0	X	X	0	X	0	0	X	0	0
40%	X	X	0	X	X	0	X	0	0	X	0	0
60%	X	X	0	X	X	0	X	0	0	X	0	0
80%	X	X	0	X	X	0	X	0	0	X	0	0
100%	X	X	0	X	X	0	X	0	0	X	0	0

The result of second experiment which we developed, is shown by figure 7. It achieved on composite material of 0.6mm thickness. The transducer frequency centre is f_c=15 MHz. Figure 7.a shows the input signal with front echo closed to back wall echo. Figure 7.b shows the result obtained using SSP with Q constant and minimisation. (Q = 5, 1st filter location= 3 MHz, Last filter location= = 11Mhz, Number of filters = 12). We note that the developed algorithm permits the detecting of the back wall echo.

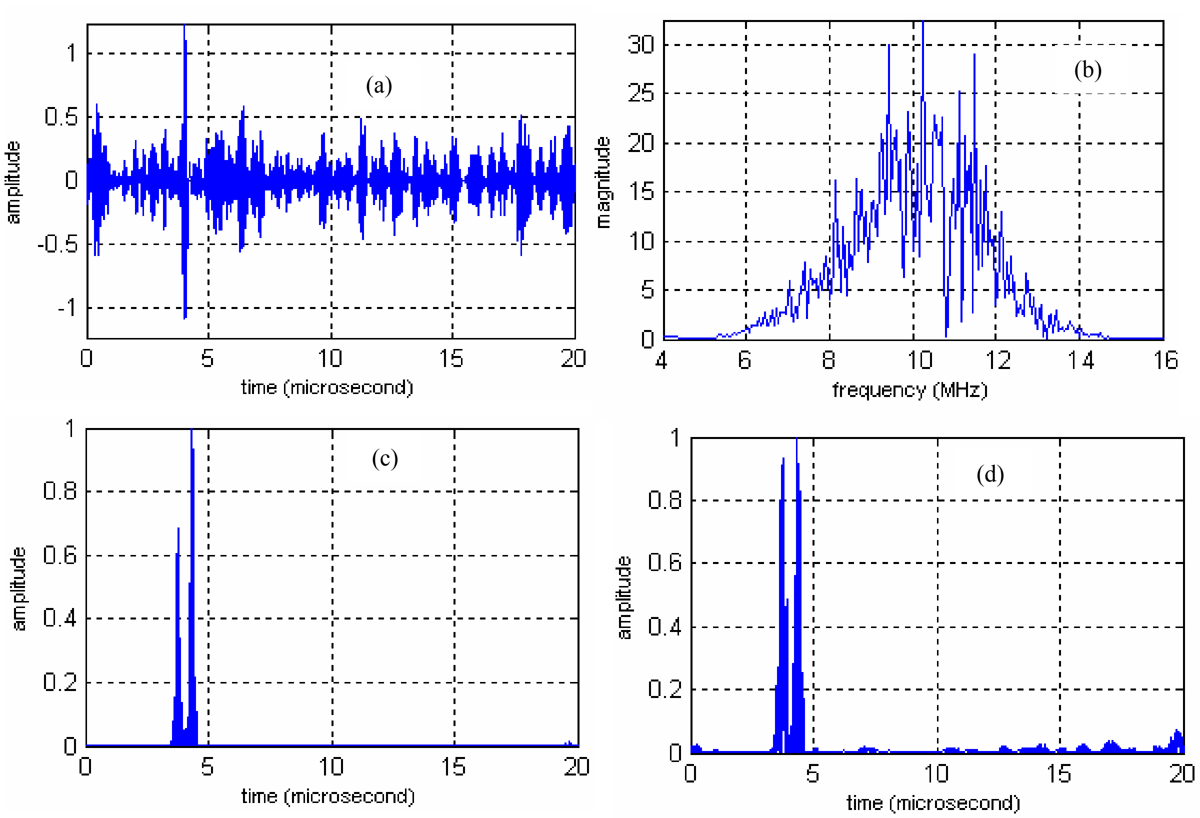

Figure 4. 2b=5MHz (a) input signal with structural noise (60%) – (b) its spectrum –
(c) output signal using SSP with Q-constant algorithm. Geometric mean –
(d) output signal using SSP with Q-constant algorithm. Minimisation

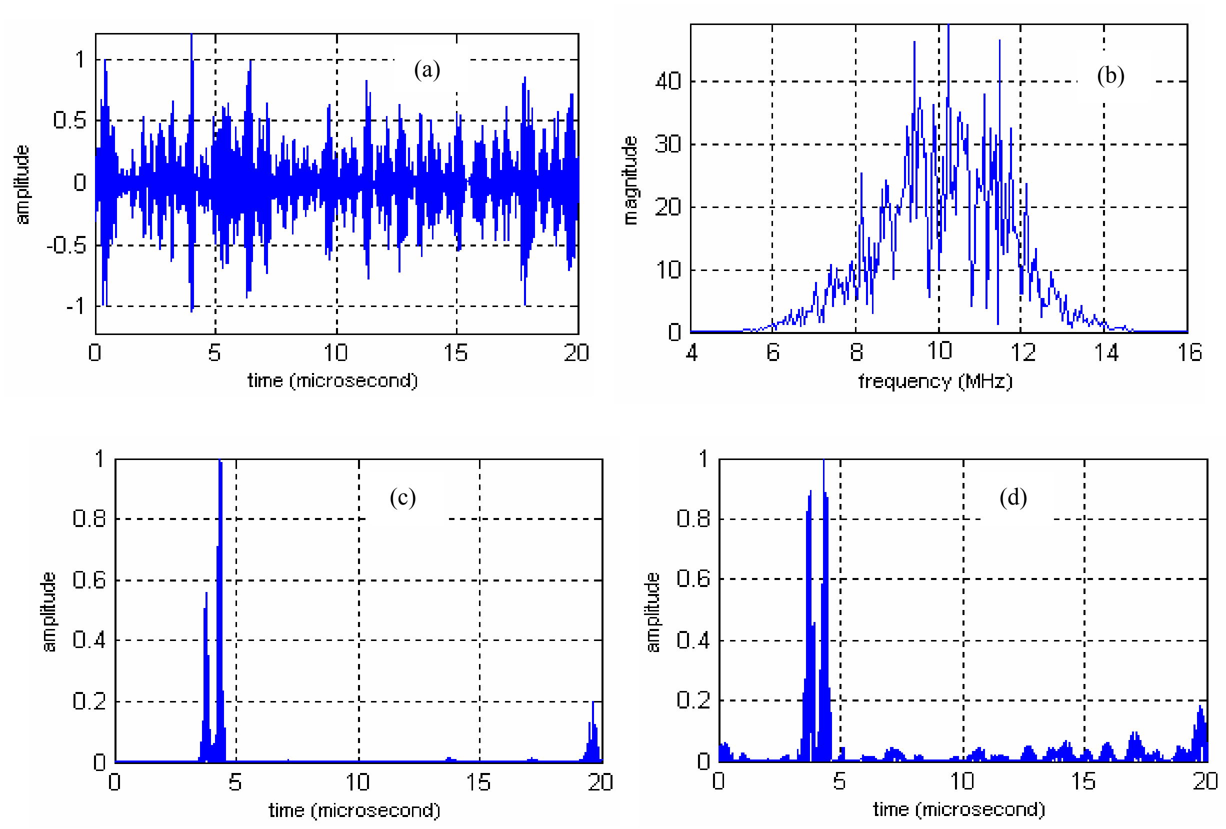

Figure 5. b=2.5MHz (a) input signal with structural noise (100%) – (b) its spectrum – (c) output signal using SSP with Q-constant algorithm. Geometric mean – (d) output signal using SSP with Q-constant algorithm. Minimisation

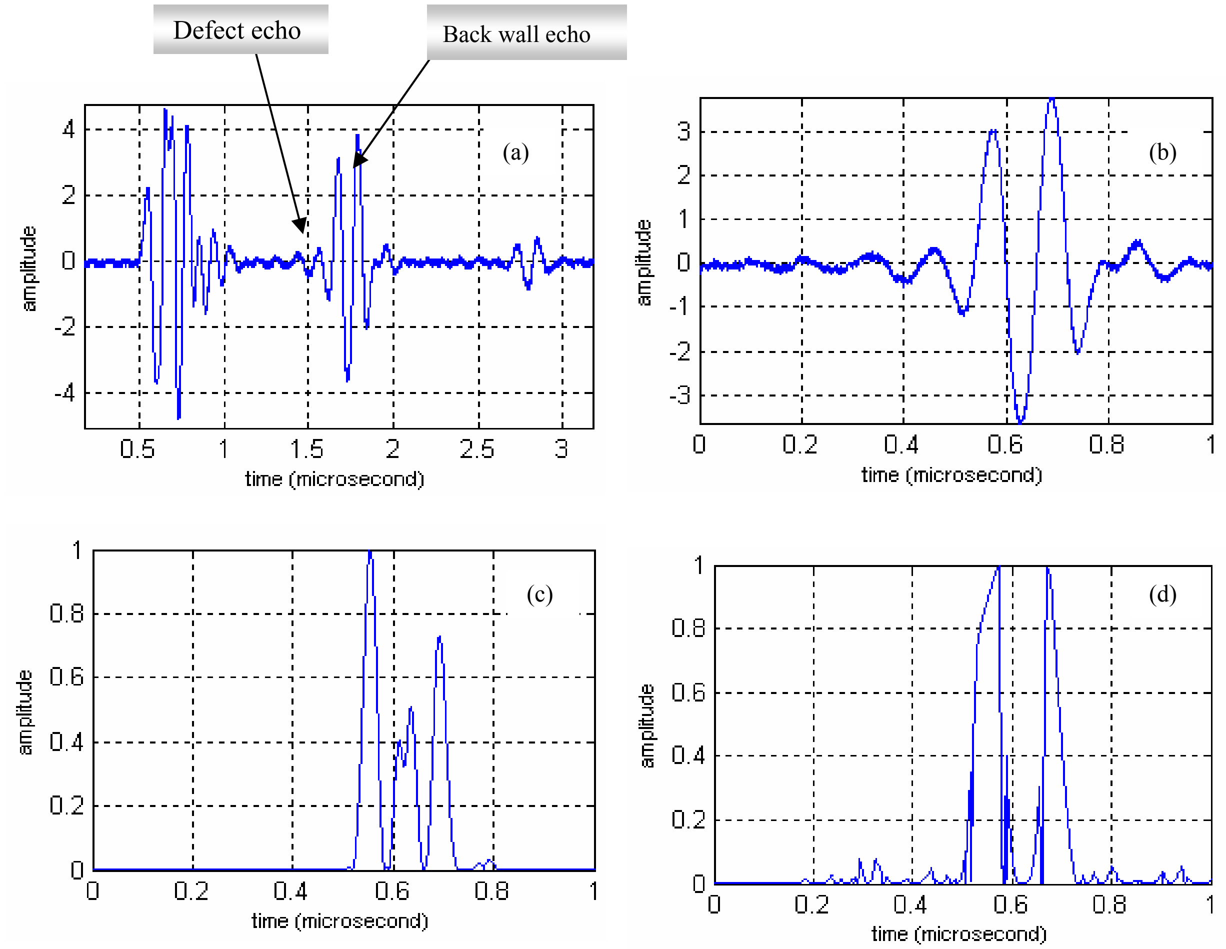

Figure 6. Experimental results. (a) input signal with defect echo closed to back wall echo. (b) defect echo and back wall echo zoomed. (c) result obtained using SSP Q constant and geometric mean. (d) result obtained using SSP Q constant and minimisation

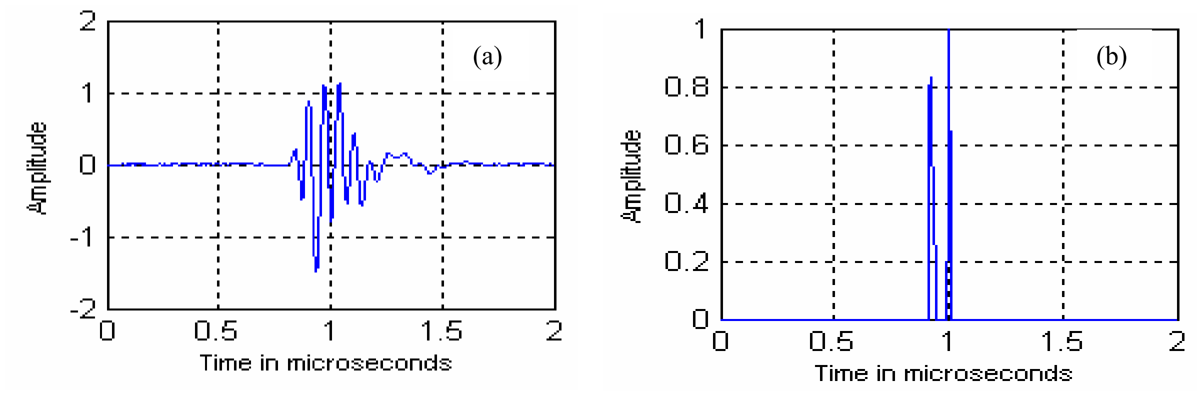

Figure 7. Experimental results of composite material. Thickness=0.6mm. f_c=15 MHz (a) input signal with front echo closed to back wall echo. (b) result obtained using SSP Q constant and minimisation (Q = 5, 1st filter location= 3 MHz, last filter location= = 11Mhz, Number of filters = 12).

Conclusion

The work which was described in this paper, shows the possibility of detecting two defects drowned in a structure noise. Firstly, we modeled and simulated this noise signal by a simple clutter model. Then, we added to this noise signal, two closely spaced defect echoes. We supposed that these echoes have same centre frequencies. In [8], we presented the nonstationary problem of the ultrasonic echo. This is due to the nonuniform propagation medium which contains discontinuities, and causes the frequency variation of received wave compared to emitted wave.

By applying non linear SSP algorithm with Q constant such geometric mean and absolute minimisation, it can permit the detection of two distinct defect echoes. The minimisation algorithm give us a better experimental result. We noticed that this algorithm loses its robustness with respect to the added noise. We conclude also, more the bandwidth of the ultrasonic transducers decreases and more the detection probability of the defects decreases.

According to the obtained results, we can note that the developed and implemented algorithm, could emphasize echoes and consequently the diagnosis shall be righter but the disadvantage of this algorithm is the bad echoes localization.

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