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# Inspection problem of composite materials using an ultrasonic signal processing

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In this paper, signal processing techniques associated to ultrasonic instrumentation are tested for their ability to resolve echoes reflected by delaminations in carbon fiber reinforced polymer multi-layered composite materials (CFRP). These techniques include the $L^2$ norm deconvolution and the expectation–maximization (EM) algorithm. A simulation study on defect detection was performed, and results were validated experimentally on CFRP with and without delamination defects taken from aircraft. Comparative study of the methods for their ability to resolve echoes is made. Theoretical and experimental results indicate resolution enhancement in detecting and locating delamination defects.

# 1 Introduction

Fiber-reinforced laminated composite materials are widely used in aircraft, modern vehicles and light-weight structures. Composite structures can be damaged under mechanical and thermal loadings. The typical damage behaviour in the laminated composites is transverse microcracking, fiber-breakage and delamination [1]. Typically, the transverse microcracking through the thickness of the ply occurs as the first-ply failure, and the delamination damage follows. The fiber-breakage usually happens at the last stage of the failure. So, a catastrophic failure can occur only with the microcracking and delamination damage [1]. The failure behaviour in the laminated composites is usually complicated and highly dependent on the properties of the constituent materials, fiber orientation, stacking sequence, nature of loading, etc.[1,2]. These materials like CFRP are inspected by non destructive evaluation (NDE) methods. The ultrasonic flaw detection is an important problem in the NDE of composite materials. In order to successfully detect and classify flaw echoes from high absorption materials, an efficient and robust method is required.

In this work, we use ultrasonic technique associated to electronic instrumentation and signal processing. The ultrasonic testing is based on the detection and the interpretation of the ultrasonic waves reflected by defects. Several methods of signal processing have been proposed like the wavelet transform [3] and split spectrum processing (SSP) were introduced [4]. They are based on time and frequency analysis and used in order to increase the detection and to improve the localization of these defects. Other algorithms based on the functions of intercorrelation, the energy cepstrum or the Hilbert transform [5] have also been proposed in order to solve the problem of closer echoes separation in time. This problem occurs in ultrasonic inspection for thin layers measurement. These algorithms do not provide satisfactory results since they are very sensitive to signals drowned in noise, especially experimental signals [6].

In this paper, we propose two methods permitting delamination defect echoes detection and estimation. The first method is a deconvolution algorithm based on $L^2$ norm minimization. The second method is a defect echo signal estimation by expectation–maximization (EM) algorithm [7,8]. We present both the deconvolution of backscattered echoes using the model of signal and the reflectivity estimation. We then analyse the results for simulated ultrasonic signals. Finally, we present the experimental results when using a CFRP block which has been carried out in order to assess the good performance of the proposed approach. Flaw echoes are detected even when they correspond to small defects close to the surface.

# 2 Echo detection schemes

Delaminations in thin composite laminates are usually detectable by an immersion transducer operating in pulse-echo mode. Figure.1a shows a typical ultrasonic setup. The sample used is a carbon fiber-reinforced polymer multi-layered composite material (CFRP) achieved with two delamination defects located at front surface and back wall. Multiple waves are reflected from the surfaces of the specimen as well as from delaminations, as shown in Figure.1b. Typical waveforms represented by A-scan signals are digitized and recorded by an oscilloscope.

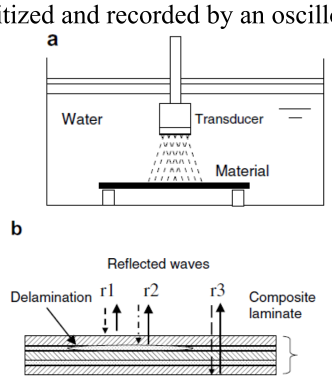


Figure. 1. Experimental setup for immersion pulse-echo testing and a schematic of reflected echoes.

# 3 Proposed methods

## 3.1 $L^2$ Norm Deconvolution Algorithm

The received ultrasonic signal is modelled as a convolution between a function that represents the waveform emitted by the transducer $h(t)$ and a function that is abusively called the "defect impulse response" $r(t)$ . The model can be written as (Figure. 2):

$$y(t) = h(t) * r(t) + n(t) \tag{1}$$

Where $n(t)$ corresponds to measurement noise that is assumed random and uncorrelated. Convolution is denoted by the asterisk symbol.

Deconvolution provides an estimate of $r(t)$ that satisfies a well defined optimality criterion based on the measurements of $y(t)$ and knowledge of the system $h(t)$. Thus, deconvolution requires a priori information of the system, which presents the main difficulty in its implementation.

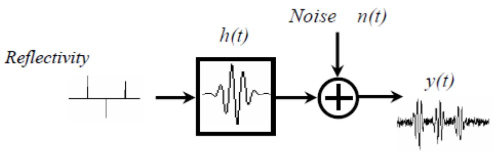


Figure. 2. System model for deconvolution

A widely used optimality function in the déconvolution process is the minimization of the norm of the estimation error. The *Lp* norm is defined as:

$$\|J\|_p = \left[ \int_0^{\infty} J^p(t)dt \right]^{1/p} \tag{2}$$

Where $J(t)$ is the error function given by:

$$J(t) = |y(t) - h(t) * r(t)| \tag{3}$$

Thus, the deconvolution problem consists of finding $r(t)$ to minimize the error $||J||_P$ for a given $h(t)$ .

One way that this can be done is to minimize an objective function $J_P(x)$, which is a weighted sum of the $L^P$ norms of the estimated solution $x(t)$ and the "error" $(y-Hx)$ which corrupts the measured output $y(t)$ :

$$\min_{x \in R^n} J_p(x) = \|y - Hx\|_p^p + \eta \|x\|_p^p \tag{4}$$

The parameter η, is a relative weighting or damping factor selected to balance the conflicting priorities of data accountability, i.e., minimizing $(y-Hx)$, and addressing the *a priori* assumption that the true solution $h(t)$ is sparse. The common choice of $p = 2$ in the application of (4) has the advantage of computational convenience [9,10]. This $L^2$ norm minimization algorithm can be summarized in following steps:

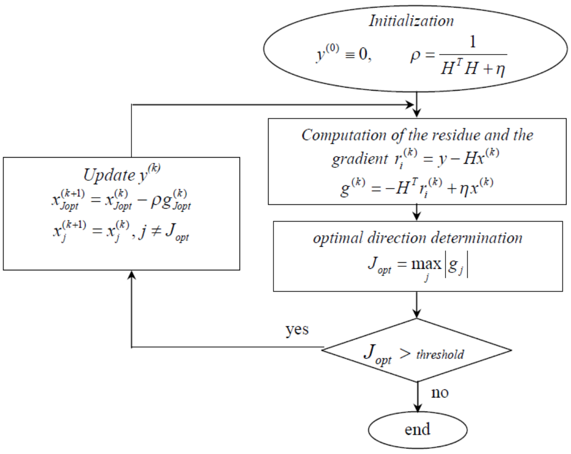


Figure.3. $L^2$ norm minimization algorithm

## 3.2 Deconvolution of backscattered echoes

In this section, we tackle the problem of deconvolution by considering a model-based approach. A similar approach was used for the deconvolution of the seismic signals [11]. Actually, suggesting a parametric expression for the system response significantly simplifies the problem. However, this parametric expression should be in agreement with the physical characteristics of the system. For example, if the impulse response of the system is expected to be a spike train, the solution to be found should be spikes with unknown time locations and amplitudes.

Then, the deconvolution problem can be treated as a parameter estimation problem, which offers a high resolution solution [12].

1) *Ultrasonic backscattered echo model*: The ultrasonic backscattered noiseless signal y(t), made of a single echo reflected by a flat surface can be modeled as [13]

$$x(t) = s(\theta; t) \tag{5}$$

Here, $s(\theta; t)$ is a gaussian echo,

$$s(\theta;t) = \beta\, e^{-\alpha(t-\tau)^2} \cos(2\pi f_c (t-\tau) + \phi) \tag{6}$$

where the parameter vector $\theta = [\alpha \;\; \tau \;\; f_c \;\; \phi \;\; \beta]$ contains all the unknown parameters of the problem, the bandwidth α, the arrival time τ, the center frequency $f_c$, the phase $\phi$ and the amplitude β. As a generalization of Eq. (5) for describing multiple echoes from a reflector, we write $y(t) = \sum_{m=1}^{M} s(\theta_m; t)$

where $\theta_m = [\alpha_m \;\; \tau_m \;\; f_m \;\; \phi_m \;\; \beta_m]$ and where M denotes the number of superimposed gaussian echoes.

2) *Estimation of unknown parameters of the pulse-echo wavelet by EM algorithm:* The transducer pulse-echo wavelet can be represented by using Eq. (5) with a number of M superimposed Gaussian echo wavelets [12],

$$x(t) = y(t) + n(t) = \sum_{m=1}^{M} s(\theta_m; t) + n(t) \tag{7}$$

$$y(t) = \sum_{m=1}^{M} \beta_m e^{-\alpha_m (t-\tau_m)^2} \cos(2\pi f_{c_m}(t - \tau_m) + \phi_m + n(t) \tag{8}$$

In this equation, $x(t)$ represents the noisy pulse-echo wavelet (or observed signal), $y(t)$ is the model-based noiseless signal and n(t) is the added white gaussian noise (WGN).

The parameter vector $\theta_m$ is defined as $\theta_m = [\alpha_m \;\; \tau_m \;\; f_m \;\; \phi_m \;\; \beta_m]$ which contains all the unknown parameters of the problem, the bandwidth $\alpha_m$, the arrival time $\tau_m$, the center frequency $fc_m$, the phase $\phi_m$ and the amplitude $\beta_m$.

# 4 Simulation study

In order to apply the proposed algorithm, a numerical experiment is set up simulating a real case of ultrasonic test material. The signal results from the convolution between a reflectivity function made up of five reflectors and a wavelet of frequency center equal to 2.25Mhz. The sampling rate is of 50MHz (Figure. 4). The described method relates to the $L^2$ norm deconvolution known as of signature. We consider a signature supposed near to the signature real. This leads us to measure the quality of the results obtained according to the errors made on the choice of this signature (wavelet used). For that, we generated three wavelets modified starting from the reference wavelet, of frequency 2.25MHz, in the following way: (Figure. 5)

- Wave-1 : Wavelet with a larger bandwidth;
- Wave-2 : Wavelet with a center frequency *fc*=2Mhz;
- Wave-3 : wavelet drowned in the noise;

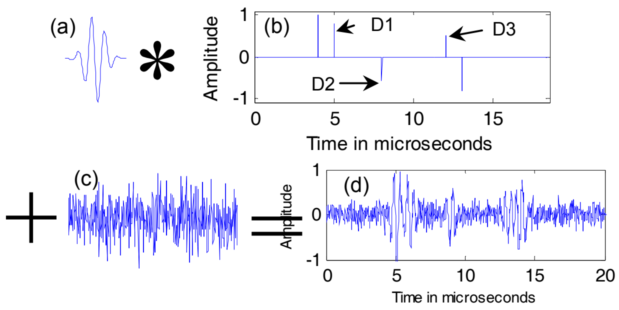


Figure. 4. a) Reference wavelet, b) Reflectivity, c) Noise, d) Signal drowned in the noise.

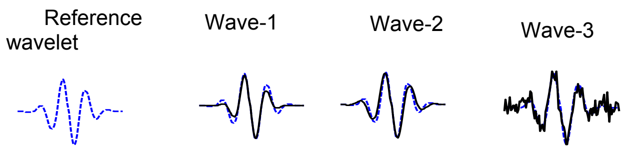


Figure. 5. Wavelets used for the $L^2$ norm deconvolution.

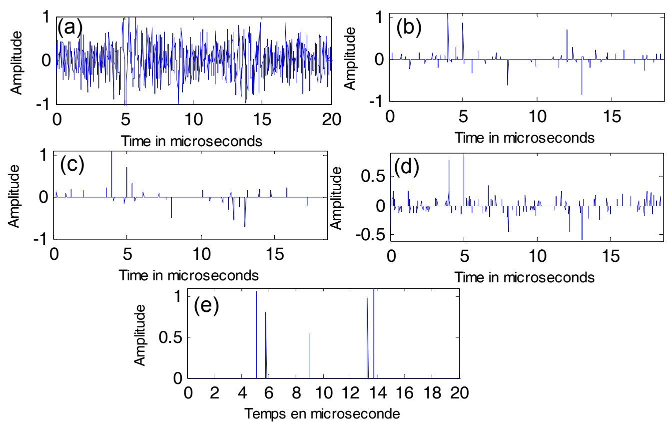


Figure. 6. Results obtained by $L^2$ norm deconvolution, a) Input signal (synthetic trace drowned in 50% and 100% of the noise), b) wave-1, c) wave-2, d) wave-3, e) EM deconvolution.

Table 1. Depth of defect in µs with error in %

| | | | Time of flight in µs and error in % | | |
|---|---|---|---|---|---|
| | | | Defect | | |
| | | | D1 | D2 | D3 |
| Real value (µs) | | | 1 | 4 | 8 |
| *$L^2$ norm* | *Wave 1* | 50% | 1<br>0% | 4<br>0% | 8<br>0% |
| | | 100% | 1<br>0% | 4<br>0% | 8<br>0% |
| | *Wave 2* | 50% | 1<br>0% | 4<br>0% | 8<br>0% |
| | | 100% | 1<br>0% | 4<br>0% | 8.22<br>2.7% |
| | *Wave 3* | 50% | 0.98<br>2% | 4<br>0% | 8.2<br>2.5% |
| | | 100% | 0.98<br>2% | 4<br>0% | 8.2<br>2.5% |
| EM | | 50% | 0.9<br>10% | 3.88<br>3% | 8.18<br>2.2% |
| | | 100% | 0.85<br>15% | 3.9<br>2.5% | 8.24<br>3% |

From the results obtained by the $L^2$ norm, we notice that we have a good echoes detection using the three waves, but when the noise level increases we have an undesirable appearance of the peaks.

Table 1 presents the resultants of absolute measures of goodness according to the rate of the noise injected with the useful signal.

# 5 Experimental results

The experimental data studied in this section (see Figures 7, 8 and 9; and Table 2) are obtained using a transducer centered at 2.25MHz. A carbon fiber-reinforced polymer (CFRP) of 2.67 mm thickness is used, provided by an aircraft manufacturer company. It is achieved as follows: the unidirectional layers are sticked with epoxy, one layer on the other altering the orientation from (0°, 45°, 0°).

This sample is made of 0.45 mm each layer, shared into three parts as follows:

– 1st part with no defect.

– 2nd part with a delamination defect past at the end of the first layer.

– 3rd part with a delamination defect before the end of the last layer.

Longitudinal waves are used and we recall that the sound velocity in this material is $V_{sample} = 2830$ m/s.

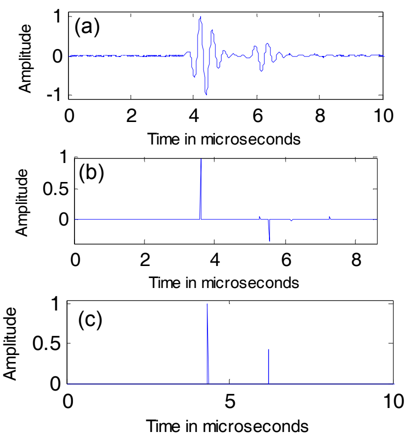


Figure. 7. a) Experimental signal, front face echo and back face echo, b) results obtained by $L^2$ Norm Deconvolution, c) results obtained by EM deconvolution.

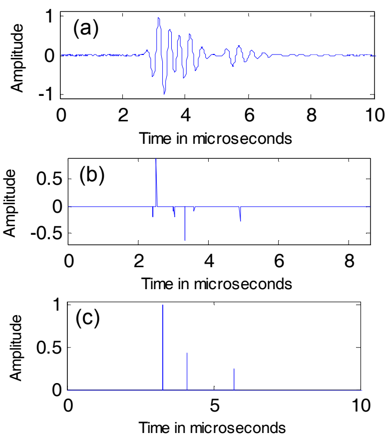


Figure. 8. a) Experimental signal, closely-spaced echoes in front face zone, b) results obtained by $L^2$ norm Deconvolution c) results obtained by EM deconvolution.

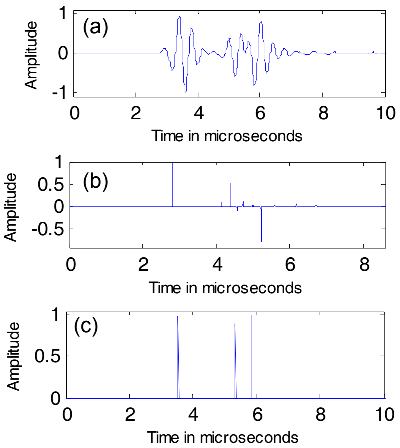


Figure. 9. a) Experimental signal, closely-spaced echoes in back wall zone, b) results obtained by $L^2$ norm Deconvolution c) results obtained by EM deconvolution.

Table 2. Thickness of the part and depth of defect with precision in %.

| | ***$L^2$ norm* deconvolution** | **EM deconvolution** | **Real value (mm)** |
|---|---|---|---|
| *Thickness of the part* | 2.75mm $\Delta x/x$=2.99% | 2.66mm $\Delta x/x$=0.3% | 2.67mm |
| *Position of the delamination close to the front surface* | 1.16mm $\Delta x/x$=84% | 0.66mm $\Delta x/x$=6% | 0.63mm |
| *Position of the delamination close to the back wall* | 2.24mm $\Delta x/x$=0.9% | 2.5mm $\Delta x/x$=12.6% | 2.22mm |

## 5 Conclusion

In this study, we have used two methods allowing the detection and estimation of delamination defect echoes. These methods are based on signal processing techniques. The first method is based on a deconvolution algorithm realised by $L^2$ norm. The second method is based on the EM algorithm. In the case of thickness measurement of experimental data, we have obtained a precision lower than *0.3%* for the deconvolution by algorithm EM and *3%* for $L^2$ norm. According to the localization of the defect (close to the front surface or close to the back wall respectively), we have obtained a precision for the detection of echoes of 84% and 0.9% respectively for the $L^2$ norm algorithm, and a precision of 6% and 12.6% respectively for the EM algorithm. According to the obtained results, we can note that both proposed algorithms can locate accurately the delaminations defect.

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