Detection of delamination defects in carbon fiber using ultrasonic signal processing

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Abstract

In this work, the ultrasonic signals are modelled as a superposition of many Gaussian echoes with unknown parameters. The detection of ultrasonic echoes using Maximum A Posteriori estimation principle, based on the prior knowledge of the spectral characteristic of the ultrasonic transducer, has been used in order to estimate the unknown parameters. A simulation study validated by experimentation shows the possibilities and the robustness of this method in order to detect delamination defects. We apply the developed method to signals acquired from composite materials like carbon fiber with delamination defects.

Keywords: Ultrasonic NDE; Composite materials; Detection flaw; MAP;

1. Introduction

Fiber-reinforced laminated composites have been used in many structural applications such as airplanes, ships and sporting goods because of their superior specific properties compared with metal materials. The composites structures can be damaged under mechanical and thermal loadings. The typical damage behaviour in the laminated composites is transverse microcracking, fiber-breakage and delamination. 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. However, a catastrophic failure can occur only with the microcracking and delamination damage without the fiber breakage [1][2][3]. In this field, ultrasonic testing associated to signal processing must be developed in order to respond to defect detection and evaluation.

Ultrasonic pulse-echo method is a nondestructive method of examining objects. The method is based on transmitting acoustic waves by transducer through the objects and measuring the backscattered echoes. The aim of the method, by inspection of the backscattered echoes, is to characterize the propagation path and/or to determine the physical properties of reflectors along the propagation path, in terms of their location, geometric shape, size, orientation and microstructure. The extraction of the desired information related to object properties requires models that can simulate the formation of echoes. Linear system models have been introduced in literature to analyze ultrasonic echoes. The overall system response is simplified to the convolution of the transducer impulse response, propagation filter response and the target response for which the input of the system is the transducer excitation pulse and the output is the backscattered echoes. The system identification problem is to determine any one of the three responses given the measured backscattered echoes. In particular, some parameters of the backscattered echoes, i.e., time-of-flight (TOF), amplitude, center frequency, and bandwidth are of importance because of their significance in the system response. The TOF and amplitude of the echo can be attributed to the target response in terms of target location, size and orientation. The center frequency and bandwidth of the echo can be attributed to the frequency modification of the propagation path (i.e., frequency characteristics of materials).

In this work, the ultrasonic signals are modelled as a superposition of many Gaussian echoes with unknown parameters. The Maximum A Posteriori (MAP) estimation principle, based on the prior knowledge of the spectral characteristic of ultrasonic transducer has been used in order to estimate the unknown parameters. In the estimation, we first used a MAP [4] coupled with Gauss Newton (MAP-GN) [5] algorithm to estimate the parameters of a single echo in noise. Then, we coupled this algorithm into a space alternating generalized Expectation-Maximization (SAGE) [6] algorithm (MAP-SAGE) to estimate the parameters of a number of overlapping echoes in noise. Thereafter, a simulation study on defect detection was performed, and results were validated experimentally on CFRP with and without delamination defects taken from aircraft.

2. MAP ESTIMATION ALGORITHMS

2.1. MAP-GN Algorithm

Consider that the ultrasonic measured signal consists of a single echo:

$$x(t) = y(t) + n(t) = s(\theta;t) + n(t) \qquad (1)$$

where $x \in \Re^N$ is a vector of observations, $n \in \Re^N$ is a white Gaussian noise (WGN) sequence with variance σ_n^2 , and $s(\theta;t)$ is a Gaussian echo vector obtained by sampling the continuous time model;

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

where the parameters of the model, bandwidth factor, time-of-arrival (TOA), center frequency, phase and amplitude are stored in a vector parameter $\theta = [\alpha \quad \tau \quad f_c \quad \phi \quad \beta]$. We assume θ is a random variable vector with the following statistics:

$$\begin{aligned} E[\theta] &= \bar{\theta} = \mu_\theta \\ E[(\theta-\bar{\theta})(\theta-\bar{\theta})^T] &= C_{\theta\theta} \end{aligned} \qquad (3)$$

Given above prior statistics and the observation model (Equation 1), we find the Maximum A Posteriori (MAP) estimate of the parameter vector θ. This MAP estimator can be implemented using a Gauss Newton (GN) algorithm [5] (hence called MAP-GN) in the following computational steps:

Step 1. Start with an initial guess $\theta = \theta^{(0)}$ *and prior statistics,* μ_θ *and* $C_{\theta\theta}$

Step 2. Compute the model $s(\theta^{(k)})$ *and the gradients* $H(\theta) = \left[\frac{\partial s}{\partial \alpha} \frac{\partial s}{\partial \tau} \frac{\partial s}{\partial f_c} \frac{\partial s}{\partial \phi} \frac{\partial s}{\partial \beta}\right]_{\theta=\theta^{(k)}}$

Step 3. Iterate the parameter vector by computing the followings:

$$\hat{x}^{(k)} = x - s(\theta^{(k)}) + H(\theta^{(k)})\theta^{(k)}$$

$$\theta^{(k+1)} = \mu_\theta + \left[\left(C_{\theta\theta}^{-1} + \frac{1}{\sigma_v^2} H^T(\theta^{(k)})H(\theta^{(k)})\right)^{-1} H^T(\theta^{(k)}) \frac{1}{\sigma_v^2}\left(\hat{x}^{(k)} - H(\theta^{(k)})\mu_\theta\right)\right]$$

Step 4. Check convergence: if $\left\|\theta_m^{(k+1)} - \theta_m^{(k)}\right\| \le tolerance$ *, then Stop.*

Step 5. Set $k \to k+1$ *and go to Step 2.*

2.2. MAP-SAGE Algorithm

We consider the discrete version of the M-superimposed Gaussian echo model

$$x(t) = y(t) + n(t) = \sum_{m=1}^{M} s(\theta_m;t) + n(t) \qquad (4)$$

where *s(.)* denotes the Gaussian echo model and *n* denotes a WGN sequence with variance σ_n^2.

Note that each parameter vector θ_m completely defines the shape and location of the corresponding echo. This system is illustrated schematically in figure 1.

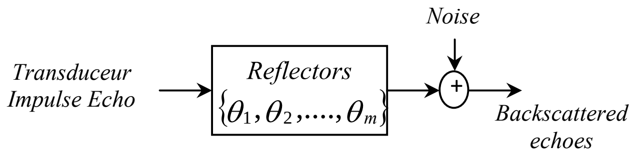

Figure 1**.** Parametric signal rnodel for ultrasonic backscattered echoes.

The parameter estimation problem is to estimate the parameter vectors $\theta_1, \theta_2, \ldots \theta_M$ given the noisy observation of echoes, some of which may be overlapping. Each parameter vector is assumed to be a random vector with prior statistics given in Equation 3. In the MAP parameter estimation of superimposed echoes, one can incorporate the MAP-GN algorithm in a SAGE algorithm [6] to address the multidimensional parameter estimation problem. This MAP-SAGE algorithm can be implemented in the following diagram:

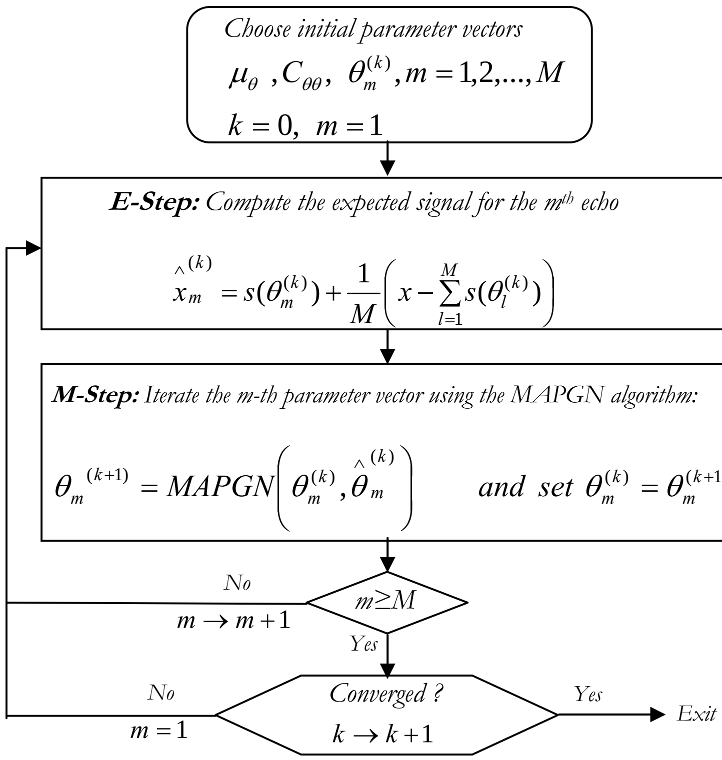

Figure 2: The flow diagram of the MAP- SAGE algorithm.

3. Simulation study

In order to apply the proposed algorithm, we have set up a numerical experiment simulating a material with two defects very close in time with *SNR=5dB*, as illustrated by the A-scan in figure 3.a. The transducer is supposed to be centered at *2.25MHz*, and the time lag between both defects is $\Delta\tau = 0.23\mu s$, equivalent to a distance $\Delta d=0.32mm$. Figure 3.b shows an input signal with a SNR of $5dB$ (blue line) and results obtained by MAP-SAGE (output signal with black line). To evaluate the performances of the implemented algorithm, we have made simulations of a signal with two closely spaced echoes and various levels of SNR. Figure 4 shows a graph with different SNR, we notice that the SNR influences on a good detection of the targets.

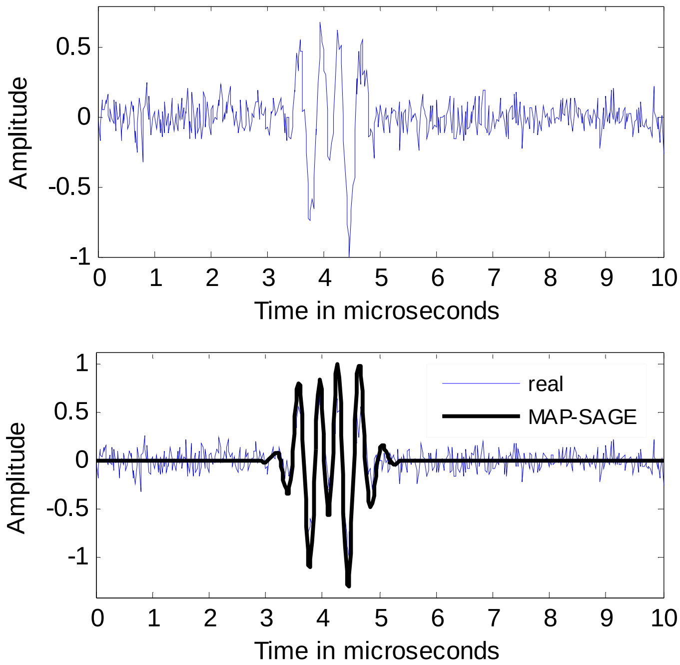

Figure 3: (a) Signal with two echoes with $SNR=5dB$ separated by $\Delta\tau=0.23\mu s$ (equivalent to $0.32mm$), (b) Results obtained by MAP-SAGE in black line. Input signal in blue line.

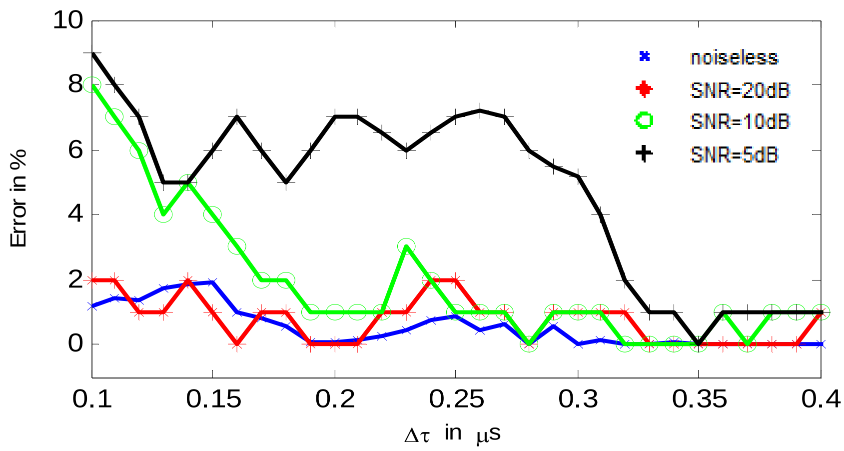

Figure 4: Error $\Delta\tau$ measurement

4. Experimental results

The experimental data examined in this work was obtained using a transducer of 2.25MHz centre frequency from carbon fibre reinforced polymer (CFRP) samples provided by the aircraft manufacturer Company. Thickness of this sample equal *to 3.4mm* in undamaged zone and a little larger in the damaged zone.

The velocity of sound in this material is $V_{sample}=2830\ m/s$.

Figure 5 shows a signal in the undamaged zone, the arrival time of the front surface echo is $\tau_{FS}=3.9\mu s$ and Arrival time of the back wall echo is $\tau_B=6.23\mu s$. $(\tau_B - \tau_{FS})=2.33\mu s$ which is equal to a thickness of *3.29mm*.

Figure 6 shows a delamination defect close to the front surface, after application of MAP-SAGE algorithm. We have a delamination defect detected at a depth of $\tau_d=0.9\mu s$ which is equal to a depth of *1.23mm*.

Figure 7 shows a delamination defect close to the front surface, after application of MAP-SAGE algorithm. We have a delamination defect detected at a depth of $\tau_d=1.28\mu s$ which is equal to a depth of *1.81mm*.

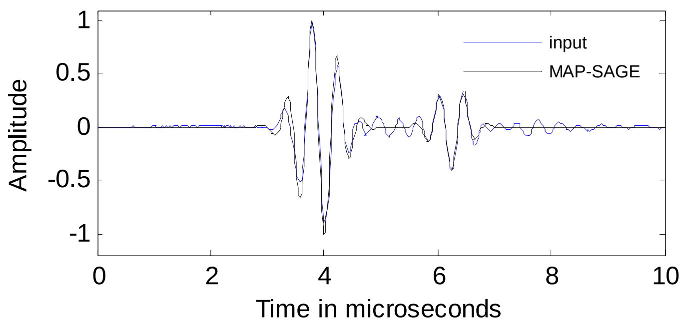

Figure 5: Signal in the undamaged zone (in blue line) and results obtained by MAP-SAGE in black line.

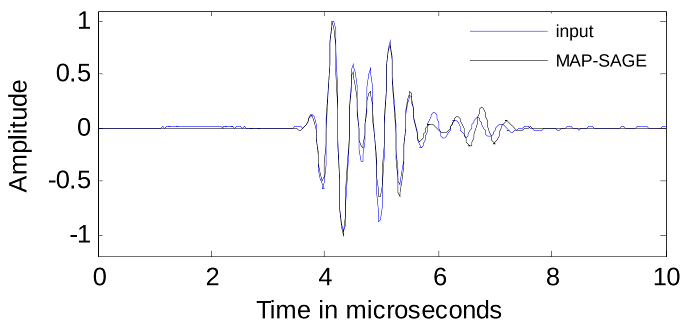

Figure 6: Signal in the damaged zone (in blue line) and results obtained by MAP-SAGE in black line.

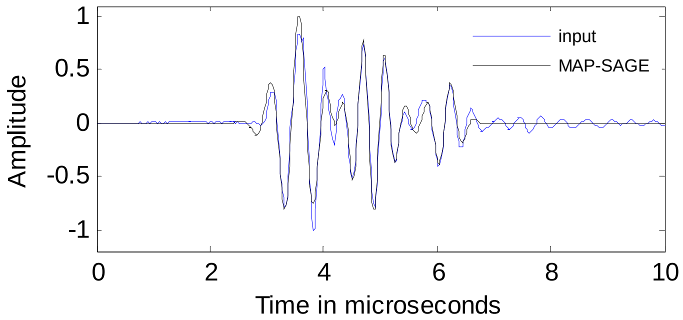

Figure 7: Signal in the damaged zone (in blue line) and results obtained by MAP-SAGE in black line.

According to the obtained results, this algorithm can effectively separate the A-scan echoes corresponding to closely-spaced defects, leading to accurate defect depth estimations within the material.

5. Conclusion

In this study, an iterative MAP estimator is used to estimate the parameters of the signal consisting of many Gaussian echoes. This method is based on signal processing techniques. The experimental part which validated these results enabled us to determine with precision accuracy the position of different delamination defects. We could detect the delamination defect of closer spaced echoes to the front surface at around *1.23mm* and at around *1.81mm*. We can note that thickness measurements on samples were carried out using this algorithm.

According to the obtained results, we can note that the used and implemented algorithm, could emphasize echoes and consequently the NDT results diagnosis shall be righter.

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