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Structural Health Monitoring Algorithm for Composite Plates using Lamb Wave Response Measured by Piezo Transducers

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Abstract. When compared to metals, composite materials exhibit superior structural performance due to their higher Stiffness-to-weight ratio and corrosion resistance, becoming attractive for aerospace structures. However, the economic impact of their rigorous preventive maintenance, required due to their complex damage mechanics, hinders a more extensive use of these materials. In this regard, Structural Health Monitoring (SHM) schemes using Lamb waves is a solution proposal and a hot research topic nowadays. In this paper, a SHM algorithm using lamb waves excited and sensed by piezoelectric transducers is presented. Also, a numerical example with a unidirectional Carbon Fiber plate is used to show its application. The model detects stiffness discontinuities (or damages) along a straight line of three transducers by comparing the Lamb wave response in pristine and damaged states, by estimating an amplitude Mean-Decay Ratio (MDR) and acoustic impedance ratios which are used to locate and quantify the extent of the damage.
Keywords: Lamb waves, Damage Detection, Composite materials, Simulation

INTRODUCTION

Today's aircraft operations deal with the economic challenges imposed by an ever-increasing aging fleet. By the time an aircraft ages, its preventive maintenance frequencies rise. This rise demands operational downtime for the aircraft, increasing direct costs. In the other hand, a way to turn operation more affordable has been by the introduction of composite materials in airframe structures. Designing with them allows to achieve lighter aircrafts that can carry more payload per traveled distance (Alleyne and Cawley, 1992). However, their complex damage mechanics call for highly conservative design approaches.

Is in those scenarios that Structural Health Monitoring have attracted attention since the last two decades. In such a scheme, first, a damage is detected (DD) by actively or passively monitoring a component from its pristine, or no damage, state until a positive-damage signal appears. Then, this damage is localized (DL) so a precise maintenance task can be scheduled. Later, the damage is quantified (DQ) to determine its extent. Finally, an estimation of the residual life of the component (RLE) can establish the potential threat in the short term. The advantage of the scheme lies in moving from a preventive-based maintenance for a condition-based one (Balageas, 2006) in which the downtimes of an aircraft are reduced. Researchers such as Su et al. (2006) estimated a reduction of 30% in maintenance costs under such scheme.

In this paper, an Acoustic Method using Lamb waves is presented to show the SHM process in a comprehensive way that allows to understand its complexities. First, is given context on Lamb waves and its considerations in feature detection. Second, the damage detection model is presented, and then is tested with a Numerical Simulation done in the CAE software Abaqus using experimentally validated information from Samaratunga et al. (2012). Finally, these results are discussed.

THE USE OF LAMB WAVES FOR DAMAGE DETECTION

Lamb waves are defined as elastic waves propagating in an elastic solid with parallel free boundaries, i.e. a plate. They exhibit an infinite number of modes associated with their propagation. For a given thickness c and frequency f there are many vibration modes, but for small values of the product cf there are mainly two modes propagating through: Symmetric fundamental, S_0, and Antisymmetric fundamental, A_0 (Staszewski et al., 2008). In a active SHM scheme, Lamb waves are excited by an actuator, travel through the component in pristine state, the response is sensed by another transducer and it is saved. During operation, if the waves come across some type of defect, i.e. delamination, they change its response accordingly. The sensor saves the response and a CPU compares it with the pristine state's response. If significant differences are detected, then the system decides an action.

STRUCTURAL HEALTH MONITORING ALGORITHM WITH IN-PLANE LAMB WAVE PROPAGATION

Figure 1 shows a damage detection problem. It consists in detecting a discontinuity of material stiffness along a single line of three transducers, which can be both actuators or sensors. The model considers at least three transducers disposed in line, and a single discontinuity, i.e. damage, between any two of them. The latter implies that the model does not account for damages outside the group of transducers. Inspection zones are defined between transducers, i.e. in Fig. 1 there are 2 inspection zones.

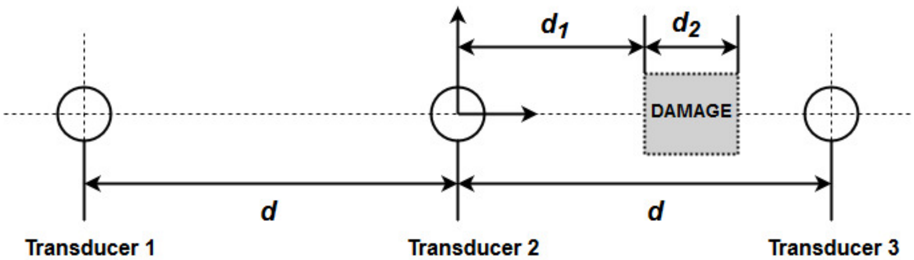

Figure 1 – Structural Health Monitoring model scheme.

First, a Pristine Response Matrix for the three transducers when each one is used as an actuator has to be obtained. The elements of this matrix, $[RM]^P$, which is a three-dimensional array of size N_{pzt} x N_{pzt} x N_t, are:

$$[RM]^P_{ijk} = V^P_{ij}(t) \tag{1}$$

Where N_{pzt} is the total number of piezo transducers aligned, N_t is the total number of discrete time divisions (which are dependent of the measuring equipment's data acquisition frequency), and $V_{ij}(t)$ is the voltage measured at sensor i when the transducer j is actuated at time t. The P superscript means pristine-state measures. Also, the pristine time of flight between two transducers i and j, tof^P, need to be characterized and they can be extracted from the $[RM]^P$.

The last parameters based in Pristine State information are the Mean Decay Ratio (MDR) functions, which are defined as the average voltage amplitude decay ratio per propagated distance among a line of three consecutive sensors (i.e. from transducer 1 to 3, or from 3 to 1 in Fig.1). The objective of these MDR functions is to approximate the maximum voltage value that would be sensed on a theoretical transducer after a signal travels a distance x from the source.

These functions are defined as two exponential approximations of decay ratio. The first exponential is taken from the maximum absolute voltage at source, V_0^{max}, up to the maximum absolute voltage of the first sensor at a distance d, V_d^{max}. That is:

$$\frac{V_x^{max}}{V_0^{max}} = a\exp(bx) = \exp\left(\frac{\ln(V_d^{max}/V_0^{max})}{d}x\right) = \exp(MDR_1 x) \tag{2}$$

The latter relation is used to estimate voltage decay from the source up to a distance x with $x = d$ as maximum; beyond that, it is considered not accurate, regardless of being already a very rough estimate.

The second MDR is used to determine the decay ratio of an already decaying signal, due to the propagation through a distance $x \leq d$, traveling distances such as long as $0 \leq x \leq 2d$. This will be used to determine the amplitude decay of a reflection signal, which use in the detection strategy will be explained in the Damage Quantification (DQ) section. The relation is:

$$\frac{V_x^{max}/V_0^{max}}{V_{2d}^{max}/V_0^{max}} = \exp\left(\left(\frac{\ln(V_d^{max}/V_0^{max})}{d} - \frac{\ln(V_{2d}^{max}/V_0^{max})}{2d}\right)x\right) = \exp(MDR_2 x) \tag{3}$$

Damage Detection (DD)

When the component is put into commission, it is monitored with a certain strategy and frequency. The voltage responses are saved, in the same way like the pristine case, in a Monitored Response Matrix, $[RM]^M$, and are then compared with $[RM]^P$. If for any given time t_0, for a fixed sensor, the absolute difference between responses measured in pristine state and in operation is greater than some tolerance or fulfill some criteria, then a damage is considered to be present in the inspection zone defined between the transducers where the "difference"is found.

Damage Localization (DL)

Damage localization consists in estimating the distance between one transducer in the "faulty"inspection zone, defined in the DD step, up to the discontinuity beginning; that is, to find the distance d_1 in Fig. 1. The model assumes that damage can be modeled as a continuous homogeneous medium in which its mechanical properties suffered a degradation in comparison with the pristine state, this is, the stiffness of this region is a fraction (often 5% or 10%) of its initial value.

In such condition, according to the theory of elastic waves, an incident wave field, $u(x,t)$, will split into reflected, $g(x,t)$, and transmitted, $w(x,t)$, waves when passing through a different medium (Bedford and Drumheller, 2010). Once the wave splits, the reflection $g(x,t)$ moves in the opposite direction, passing through a sensor in the inspection zone where no damage is present. In the voltage history of this latter sensor the time of arrival, tof^R, of this reflected wave can be extracted. By inspection, with $v_P = d/tof^P$ being the pristine state propagation velocity, the relation between the arrival time and the wave's path is:

$$tof^R = \frac{2d_1 + d}{v_P} = tof^P\left(1 + 2\frac{d_1}{d}\right) \tag{4}$$

Now, the flight times must be extracted from the voltage history, and to this purpose the excitation signal choosing is important. An input signal with easy-to-recognize features and a restricted bandwith (which minimizes noise) is the ideal. If a particular feature of this input signal is a unique maximum peak, it can be expected to find a correspondent unique maximum peak in the response. Thus, the time difference between the happening of these maximum peaks can be used to measure flight times and delays. Finally, with the latter information and using Eq. (4), d_1 can be calculated.

Damage Quantification (DQ)

To quantify the damage, the parameter to find is d_2 in Fig. 1. For this purpose, the MDR are used and the theoretical relation between the displacement field of an incident wave and the resulting reflected wave is introduced as (Bedford and Drumheller, 2010):

$$g(x,t) = \frac{1-K}{1+K}u(x,t) \tag{5}$$

Where K is the acoustic impedance ratio defined as, and assuming equal density for the incident and transmitted mediums:

$$K = \frac{\rho_w v_w}{\rho_u v_u} = \frac{v_w}{v_u} \tag{6}$$

Where ρ and v are density and propagation velocity, respectively. The subscript u and w refer to incident (which is equivalent to pristine) and transmitted (equivalent to damaged). In the other hand, the wave's passing through the damaged, or less stiff zone, creates a delay in the arrival of the response to the sensor. The time of flight of the signal in the monitored (with damage) state, tof^M, can be estimated by inspecting the wave's travel path:

$$tof^M = \frac{d_1}{v_P} + \frac{d_2}{v_D} + \frac{d - d_1 - d_2}{v_P} = tof^P + d_2\left(\frac{v_P - v_D}{v_P v_D}\right) \tag{7}$$

Where the last term at the right of Eq. (7) accounts for the latter mentioned time delay. However, the wave's velocity through the damage, v_D, is still unknown and does not allow to solve Eq. (7) for d_2.

Here the MDR is used to move forward. The idea is to say how much would be the measured maximum voltage peak recorded by an hypothetical transducer that is located at d_1, before and after the wave interacts with damage. Before damage, and by traveling a distance d_1, the source peak V_0 will decay as estimated by the first MDR:

$$V_{d_1} = V_0 \exp(MDR_1(d_1)) \tag{8}$$

Now, after damage, the reflected signal's amplitude at d_1, when it starts to propagate in the opposite direction, depends on the unknown acoustical impedance ratio shown in Eq. (5). To solve this, the maximum voltage peak of the reflection measured by the transducer in the healthy inspection zone, V^R, can be also related by means of the second MDR and the reflected wave's propagation path with the reflection signal's amplitude at d_1, $V^R_{d_1}$:

$$V^R_{d_1} = V^R / \exp(MDR_2(d_1 + d)) \tag{9}$$

With this, $V^R_{d_1}$ is calculated, then K with Eq. (6) with V_{d_1} as g and $V^R_{d_1}$ as u; then, v_D with Eq. (5), and finally d_2.

Stiffness Loss Estimation

The stiffness loss in the damaged zone, that can be used to do the Residual Life Estimation (RLE), is estimated using the basic relation for propagation velocity for elastic waves in solids:

$$v_D = \sqrt{\frac{C^D_{1111}}{\rho}} \tag{10}$$

Where C^D_{1111} is the respective "damaged" component of the stiffness matrix associated with the fastest propagating mode, which is the compressional one. Then, the fraction of stiffness lost can be estimated by comparing the pristine and damaged states velocities as:

$$\Delta C_{1111} = 1 - \frac{C^D_{1111}}{C^P_{1111}} = 1 - \left(\frac{v_D}{v_P}\right)^2 = 1 - K^2 \tag{11}$$

NUMERICAL TEST

To test the algorithm, an ABAQUS model of a unidirectional, 8-plies, composite plate was used. The plate in-plane dimensions and piezo localizations are shown in Fig. 2. Three transducers are disposed in line every 200 mm, and a strip (shadowed area in Fig. 2) of 50 mm wide is defined at a fixed distance of 100 mm from the center. First, the strip is modeled with undamaged properties, and the Pristine Characterization is done. Then, mechanical properties are reduced in a 90% in the 4^{th} and 5^{th} plies of the strip zone. The Pristine and Damaged properties used in this study are those used by Samaratunga and Jha (2012) for the 0.202 mm thick AS4 3501-6 CFRP lamina, its values are shown in Tab. 1 and they were experimentally validated. The circular piezo transducers used in this study are 13.5 mm diameter, 0.22 mm thickness. The piezo properties are shown in Tab. 2.

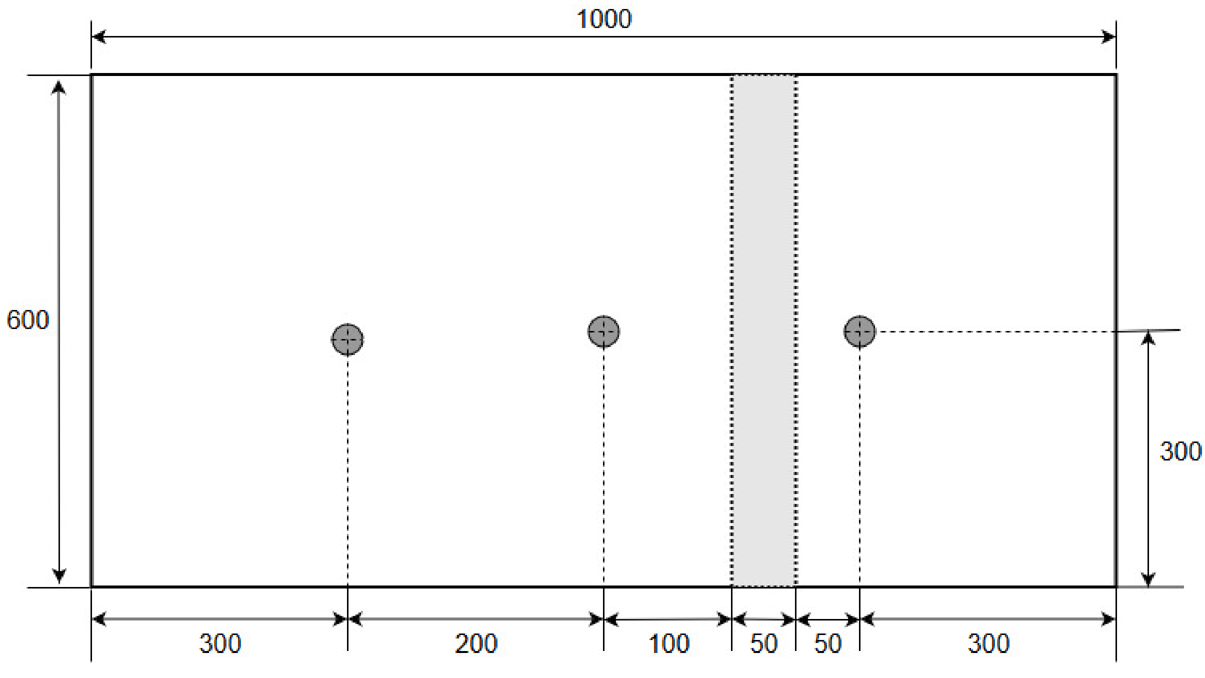

Figure 2 – ABAQUS model (in millimeters) of a composite plate with three piezo transducers in line.

Boundary conditions were defined as fixed in both of the 600 mm edges. Also, voltage on the lower face of transducers, ie. the face in contact with the plate, was fixed at 0V. By this way, all the voltage inputs and outputs are sent and measured at the top of the transducers.

The input voltage profile applied on the transducer's top face was a Modulated Hann window generated by Eq. (12). The signal's parameters used are shown in Tab. 3 (Samaratunga and Jha, 2012) and the final shape is shown in Fig. 3.

$$H(t) = -\tfrac{A}{2}\sin(2\pi F_c t)\left(1 - \cos\left(\tfrac{2\pi F_c t}{N}\right)\right), \quad 0 \le t \le T \tag{12}$$

Where A is the window's maximum value, F_c is the excitation frequency, N is the number of cycles, and T is the time period. The iterations are done for a temporal discretization, of 0.1 μs.

Table 1 – AS4 3501-6 Lamina Properties in Pristine and Damaged states.

Property	Pristine	Damaged
E_{11} (GPa)	147.0	14.7
$E_{22} = E_{33}$ (GPa)	10.3	1.03
$G_{12} = G_{13}$ (GPa)	7.0	0.7
G_{23} (GPa)	3.2	0.32
$\nu_{12} = \nu_{13}$	0.3	0.3
ν_{23}	0.27	0.27
ρ (kg/m^3)	1600	1600
α (damping)	0	0
β (damping)	4E-07	4E-07

Table 2 – Piezo material mechanical and electrical properties.

Mech. Property	Value	Elec. Property	Value
$E_{11} = E_{22}$ (GPa)	60.61	$\varepsilon_{11} = \varepsilon_{22}$ (F/m)	1.505 E-08
E_{33} (GPa)	48.31	ε_{33} (F/m)	1.301 E-08
G_{12} (GPa)	23.5	d_{113} (m/V)	741.0 E-12
$G_{13} = G_{23}$ (GPa)	23.0	d_{333} (m/V)	-274.0 E-12
ν_{12}	0.289	d_{311} (m/V)	593.0 E-12
$\nu_{13} = \nu_{23}$	0.408		
ρ (kg/m^3)	7500		

Table 3 – Hann's window parameters for the present study.

Parameter	Value
A (V)	12
F_c (kHz)	50
N (cycles)	3.5
T (μs)	70
δt (μs)	0.1

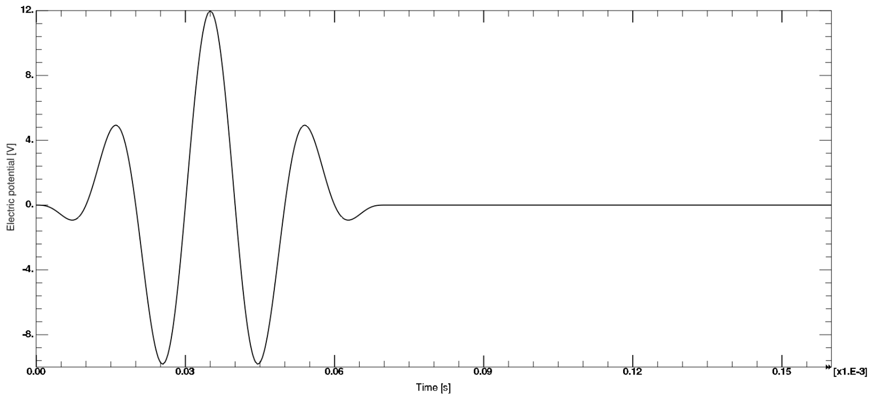

Figure 3 – Voltage actuation signal.

RESULTS

Figure 4 shows the pristine response in transducer 2 and 3 when transducer 1 is actuated. It can be seen how a first package, which is the fastest mode of vibration, i.e. Symmetric fundamental mode, S_0, is followed by a second package, which is the Antisymmetric fundamental mode, A_0, and then border reflections are received. Using the S_0 as reference and by applying Eq. (2), with the maximum peak value at every transducer (5.25 mV for transducer 2 and 2.25 mV for transducer 3), the first and second *MDR* parameters are determined as -38.672 and -17.218. Also, by measuring the time between these maximum peaks, the pristine time of flight between consecutive transducers is determined as 23.125 μs.

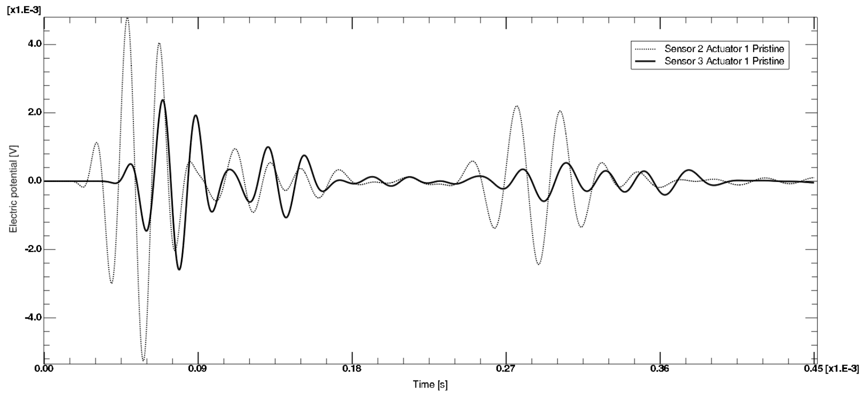

Figure 4 – Pristine responses in transducers 2 and 3 with actuation in 1.

Figure 5 shows the pristine response of transducer 1 and 3 when transducer 2 is actuated. Due to the laminate unidirectionality, parallel to the line of the transducers, and for the transducers to be at the same distance from the source, the responses are equal. Now, Fig.6 shows the same responses when the damaged properties are assigned to the strip area. It can be seen how the damage causes a time delay and an amplitude decay in the response of transducer 3 associated to the S_0 mode due to the propagation velocity drop in the damaged area. This time delay is found to be 0.75 μs.

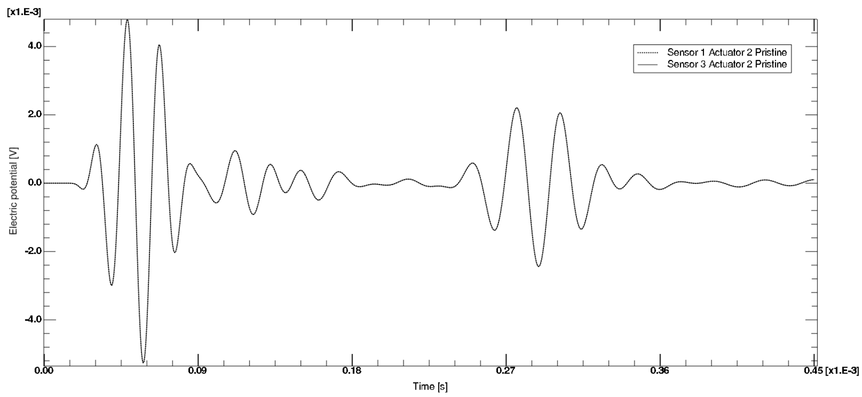

Figure 5 – Pristine responses in transducers 1 and 3 with actuation in 2.

Figure 6 compares the response of transducer 1 for the pristine and damaged states. It can be seen that even founding significant differences between pristine and damage states, the reflection signal is hard to identify. However, the method only asks for its maximum absolute peak and this can be extracted by specifying a time window in which the reflection is to be expected. If the damage is very close to transducer 2, then the signal will take a time of tof_p to get to transducer 1. Now, if the damage is close to transducer 3, the signal will take $2tof_p$ to get to transducer 1. So, all the differences found in the transducer 1 response in damaged state with the response in pristine state, in the time interval $tof_p \leq t \leq 2tof_p$ are due to the reflection signal only. It is assumed that the maximum absolute error in this interval will occur when the reflection's maximum peak passes through the transducer, so the corresponding time can be used to determine the reflection's time of flight, and the corresponding absolute amplitude at that time is used as the reflection's peak voltage. By implementing this, the reflection time of flight is determined as 4.4625 ms, and its maximum peak of 1.125 mV.

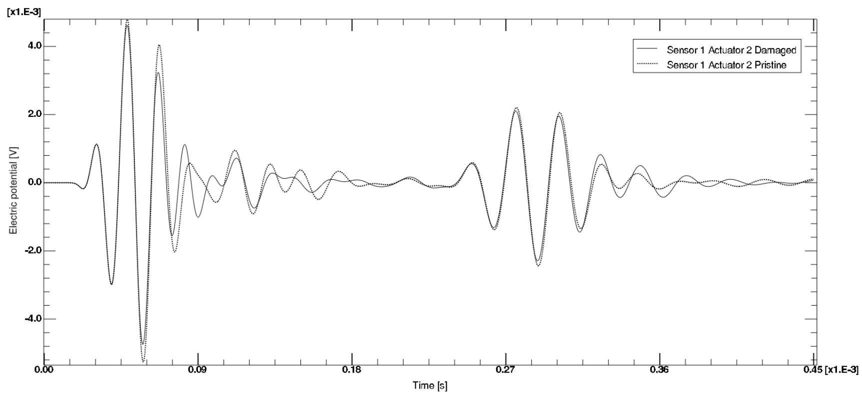

Figure 6 – Pristine and damaged responses in transducer 1 with actuation in 2.

Once all the parameters are extracted from the transducers data, the algorithm can be applied and its results are resumed in Tab. 4. It can be seen that a fair grade of accuracy can be achieved for the d_1 parameter, however the same grade of accuracy could not be achieved for the rest of parameters. The high error in d_2 is associated with the high sensitivity to numeric precision of the exponential function. At first, this error could be interpreted as the damage not being large enough to be alarmed. However, the stiffness loss estimation of almost 50% could trigger a serious warning flag in practice, accomplished the ultimately desired effect of taking the part out of operation only when the threat is big enough.

Table 4 – Algorithm results.

Task	Parameter	Actual	Model	Error
Detection	Error $\geq$ 5%	TRUE	TRUE	NO
Localization	d_1	100 mm	92.97 mm	7%
Quantification	d_2	50 mm	15.338 mm	69%
Stiffness Loss Estimate	ΔC_{1111}	0.9	0.51	43%

However, this method rely heavily in pre-damage characterization, and while in theory this phase could account for the effects of many ply orientations, complex stacking could affect the propagation ways of the reflected wave, making the MDR calculation imprecise and rendering the method extremely inaccurate. To solve this, an accurate model for amplitude decay between transducers should be developed and be used instead of Eq. (2) mean decay. This could be done by means of some data filter. Also, the method depends in how close the real damage can be modeled as a continuous media; this is a practical limitation in the case of fibrous composites. The only type of damage which can be associated as continuous or semi-continuous is delamination; others, as matrix or fiber cracking, are accurately modeled in different ways.

CONCLUSIONS

An SHM model using piezoelectric transducers disposed in a line was introduced and its formulation was discussed. The model employs the *MDR* parameter which relates amplitude decay ratio with propagated distance, and it assumes this decay to be exponential and the decay parameter to remain constant for a given array of sensors, and its value will depend only on mechanical properties of the traveling medium such as, in the case of composites, ply orientation and lamina properties. The model also assumes that the damage can be modeled as a continuous homogeneous medium. The results were found to be good, but their validity is restricted due to assumptions which are somewhat "hard"for practical purposes. However, the idea of modeling damage detection schemes as a line or 1D problem could be useful for expanding it to 2D; that is, to do in-plane detection of features. A 2D detection model could be seen as applying a grid of many 1D detection models, with adding the "coupled"effect of detecting the same damage with different grids (to avoid false positive signals).

The model responded quite well for the detection of damage initiation but the *MDR* parameter fitting still requires revision to correctly estimate damage extension and stiffness loss. Also, important changes in geometry could render the method unpredictably imprecise.

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