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Detection of low-velocity impact-induced delaminations in composite laminates using Auto-Regressive models

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ABSTRACT

In this paper, the detection of delaminations in carbon-fiber-reinforced-plastic (CFRP) laminate plates induced by low-velocity impacts (LVI) is investigated by means of Auto-Regressive (AR) models obtained from the time histories of the acquired responses of the composite specimens. A couple of piezoelectric patches for actuation and sensing purposes are employed. The proposed structural health monitoring (SHM) routine begins with the selection of the suitable locations of the piezoelectric transducers via the numerical analysis of the curvature mode shapes of the CFRP plates. The normalized data recorded for the undamaged plate configuration are then analyzed to obtain the most suitable AR model using five techniques based on the Akaike Information Criterion (AIC), the Akaike Final Prediction Error (FPE), the Partial Autocorrelation Function (PAF), the Root Mean Squared (RMS) of the AR residuals for different order p, and the Singular Value Decomposition (SVD). Linear Discriminant Analysis (LDA) is then applied on the AR model parameters to enhance the performance of the proposed delamination identification routine. Results show the effectiveness of the developed procedure when a reduced number of sensors is available.

1. Introduction

Carbon-fiber-reinforced plastic (CFRP) structures have been developed and extensively implemented in the aeronautic and space industries over the last years. The major benefits of composites over other conventional materials are manifold: higher stiffness-to-weight or strength-to-weight ratio, higher resistance in harsh environments, lighter in weights Nevertheless, CFRP components can be affected by delaminations induced by low-velocity impact (LVI) inducing a breakdown of structural performances throughout their service life [1].

LVI are impacts characterized by an impact velocity smaller than 10 m/s [2] that can produce a combination of matrix cracking, delamination and fiber breakage, among which delaminations lead to a severe stiffness and strength decrement [3]. The monitoring of structural changes can be based on changes in dynamic response. In fact, any change in the physical properties, such as reduction in stiffness resulting from the onset of cracks, produces changes in the measured dynamic response of the structure [4].

The time history response of a structure can be acquired by various sensors, e.g. accelerometers, fiber optic strain gauges etc., and such measures can then be evaluated in the frequency domain using Fourier transform. Further analysis of the frequency domain data is subsequently performed to extract modal parameters of the system [5]. Modal data, however, e.g. resonance frequency, reflects the global properties of the system, whilst damage is typically a local phenomenon.

A typical structural health monitoring process requires (i) the observation of the system over time by means of sampled dynamic response measurements from sensors, (ii) the extraction of proper damage-sensitive features from such measures, and (iii) the statistical analysis of the selected features to assess the state of the system [6]. It is then apparent that the setup of an optimally-placed transducer network and the data acquisition from the structure play a crucial role. In this context, the use of piezoelectric transducers has showed to lead to prominent results. A detailed description of the mathematical modeling of piezoelectric laminated composite plates can be found in [7,8].

In this article, the detection of delaminations in CFRP composite laminates subjected to LVI is accomplished.

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Table 1
Composite laminate model.

Geometrical features	
Length (b) [cm]	15
Width (a) [cm]	10
Thickness (t) [cm]	0.4
Number of plies	16
Stacking sequence	$[45^\circ/0^\circ/-45^\circ/90^\circ]_{2s}$

The essential parts of the proposed technique are (i) the piezo devices placement and data acquisition, (ii) the data fitting via AR model, (iii) the pattern recognition procedure, based on the separation of the measured vibration data in the reference and the comparison datasets, (iv) the classification operation and (v) the discussion of the obtained results.

This SHM routine is based on previous damage pattern recognition studies performed on composite beam [9] and plates [10] via wavelet-based approach. The novelty here reported is the use of AR parameters as damage sensitive features. Such layout represents a practical solution for an in situ monitoring procedure of the state of integrity of the structure.

2. Piezo devices placement and data acquisition

Three laminated composite plates are used for the impact tests. The prepreg used to manufacture the specimens is a $M10.1/38\%/UD300/CHS$, which consists of a thermosetting epoxide matrix with unidirectional carbon fibers. Cutting, laminating and curing are the three main phases referred to such process. Although the three composite plates are manufactured with standard geometrical dimensions and with the same materials, any physical changes are ascribable to these phases.

The active structural sensing diagnostic of the composite structure is achieved by means of a piezoelectric sensors couple that are employed for the generation of known and controlled inputs signals to excite the structure and then record its response.

The selected optimal placement of the piezo devices is the high strain region obtained via twofold differentiation of the mode shapes [11].

The geometrical parameters and stacking sequence of the laminates are reported in Table 1. The curvature of the mode shapes is obtained by implementing a finite element model of the unidirectional Carbon/Epoxy plate. The material mechanical properties adopted in the numerical model and its description can be found in [10]. The proposed work is limited to the first three resonance modes.

Due to its accurate experimental reproducibility, a free edge configuration layout is chosen for the specimen boundary conditions. Elastic bands are used to hang the laminates on a steel rigid frame.

It results that, for the first three considered modes, the z component of the displacements is about ten orders of magnitude larger than x and y components. Therefore only the out-of-plane behavior is regarded to maximize the strain field.

A numerical interpolation through 2D polynomial functions of properly selected rank is carried out to extract the modal curvatures. The average surface curvature [12] is computed from the second derivatives of the approximated mode shapes with respect to x and y axes:

$$\chi_{average} = \chi_x + \chi_y \tag{1}$$

The average surface curvature of the considered three modes is shown in Fig.1.

The position of the piezo patches is selected so as to avoid low values of the computed average curvature ensuring, at the same time, adequate sensing and actuation conditions.

A compromise solution becomes necessary in order to assure an efficient analysis of the selected modes. In addition, the central region of the laminated plate must be avoided because in this region the impact will occur according to ASTM-D7136, together with the plates edges where impact support fixture must be placed.

The selected optimal placement of the piezo patches is shown in Fig. 2. The piezo devices are square patches of 10 mm length and a thickness of 0.2 mm.

Three plates C1, C2 and C3 have been realized according to the same manufacturing process. The impact energy values considered in this study are equal to 20 J for C1 plate, 8 J for C2 plate and 12 J for C3 plate, which correspond to 2.7 m/s, 1.7 m/s and 2.1 m/s, respectively. For each of the above mentioned plates two configurations (before and after the impact) are considered for a total number of 6 analyzed configurations.

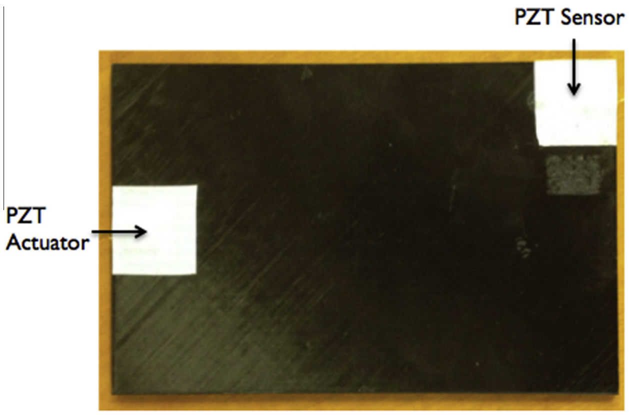

Fig. 2. The composite plate with integrated piezo patches.

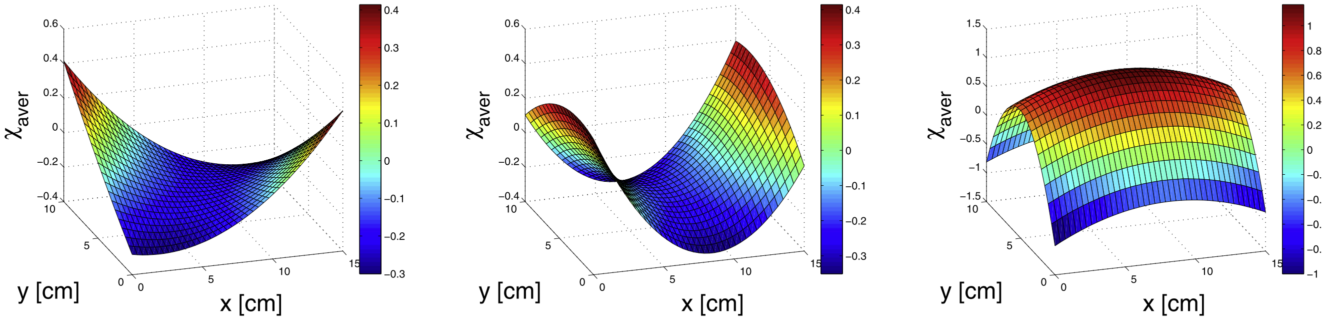

Fig. 1. Mode Shapes average curvature. From left to right: first, second and third mode shape.