Composite Structures 130 (2015) 155–162

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Vibration-based delamination diagnosis and modelling for composite laminate plates

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ARTICLE INFO

Article history:
Available online 29 April 2015

Keywords:
Delamination detection
VSHM
Composite plates
SSA

ABSTRACT

This study suggests a methodology for damage diagnosis in structures, which is based on a multivariate statistical procedure and uses the measured time domain structural vibration response. In this paper the methodology is developed for the purposes of delamination assessment in free vibrating composite laminate plates. It applies singular spectrum analysis to the measured strains in order to decompose and compress the information contained in these responses into a smaller number of independent variables. The method works on the principle of clusterization between healthy and delaminated plates with different delamination sizes and locations. The developed methodology is then applied and verified on numerically simulated and experimentally obtained results for composite laminate plates. The results demonstrate a good capability for clusterization between different delamination scenarios in composite laminate plates.

1. Introduction

Composite laminates are composite materials made by stacking composite layers in a sequence depending on the final usage of the laminate. Delamination is the most common failure mode for laminates, and it can be due to different reasons including impacts, fatigue loading and excessive strain [1]. Delamination is a particularly dangerous failure mode, because it takes place and grows under the surface without being visible from the outside, causing matrix breakage and leading to changes in physical properties of the whole laminate such as reduction in stiffness and strength.

This study suggests the use of the vibration response of a laminate to monitor its health. Structural Health Monitoring (SHM) techniques use non-destructive procedures to derive conclusions for the health and the condition of a structure. Vibration-based SHM (VSHM) methods present a very attractive possibility since they are global non-destructive methods and do not require any a priori information for the damage location, type or size. There exists a number of VSHM methods that have been developed, some of which are based on the modal parameters of a structure, including its natural frequencies [2] and/or mode shapes [3], others use its Frequency Response Functions (FRFs) and/or its time or frequency domain vibration response [4]. In general VSHM methods can be divided into two big categories: model-based and non-model based methods. The model-based methods are generally based on the comparison between the measured and the modelled vibration response. Eventually the damage identification is made minimizing the difference between the measured and the modelled structural vibration responses. Different distances can be used to measure this difference and different updating techniques have been used to bring the model as close as possible to the measured response and thus find the parameters that characterize the delamination like e.g location, extent or more precise dimensions or coordinates [5]. Composite laminates and structures made of composites in general demonstrate nonlinear dynamic behaviour in the sense of time series nonlinearity and in the sense of nonlinearities with respect to different parameters. In such a sense, modelling the vibratory response of such structures is difficult especially if precise prediction is required since the traditional modelling techniques cannot be used. There are some studies that target model-based VSHM methods as applied to composite structures but it should be stressed that these are developed for specific applications in the sense of material and structures and they are generally not applicable to other cases. FEM has been used by several authors for the purposes of modelling the response of

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http://dx.doi.org/10.1016/j.compstruct.2015.04.021
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structures made of laminates, especially beams and a few of them are focused on plates [6–13]. A number of works can be found dealing with modelling the vibratory response of delaminated composite laminate structures [6–10]. Even though some methods can relatively precisely model the presence of delamination, little research is available on the topic of delamination detection, which involves dynamic modelling of laminate structures [11–13]. Thus it should be noted that VSHM methods developed for structures made of composites and or composite laminates tend to be non-model based [14]. The non-model based VSHM methods do not use any model and they do not assume any linearity for the vibratory behavior of a structure. They are solely based on the analysis of its vibration response in terms of e.g. natural frequencies, time series analysis and/or pure data analysis procedures. A previous paper by some of the authors of this work [15] treats the first six modal frequencies of composite beams and their changes due to the presence of delamination. Authors showed that to a certain extent natural frequencies can be successfully used to investigate the presence, the location and the dimensions of the delamination in a composite beam. But the problem with using the natural frequencies for structures made of composites can be a rather difficult job because of their well-expressed nonlinear vibratory behaviour which results in e.g. double or very close natural frequencies which cannot be found using the spectrum of the vibration response. Moreover it is generally the higher frequencies that contain information about the presence and the parameters of localized damage which are still more difficult to identify from experiment.

Thus a lot of authors suggest the application of purely data driven statistical and data analysis methods for the purposes of extracting information for the delamination from the measured vibration response. In [16] the application of signal cross correlation is considered for similar purposes of delamination detection and localization. The data driven methods are targeting different characteristics of the signals recorded, they are in principle data analysis methods and thus can be applied for any signals, including deterministic and random ones. There are several papers that suggest the use of multivariate data analysis methods, specifically principal component analysis (PCA) for the purposes of VSHM [17–20] because they reveal correlation between the measured vibration characteristics. PCA has been applied for delamination detection and classification with results that prove its potential for damage detection [17]. Tibaduiza et al. [18] present PCA as a tool for damage classification with the extension of self-organizing maps. Yan et al. [19] detail in two papers the use of PCA as a linear tool for correlating the vibration characteristics and environmental conditions in order to detect damage in structures. Subsequently, they present an extension for non-linear cases [20] where PCA is applied firstly to cluster the data and secondly locally for each set of data. These methodologies apply PCA on certain values or characteristics of the vibration responses of the structure like e.g. amplitude, frequency and impedance. However, applied in this manner PCA will only be able to uncover information contained at these particular time or frequency data points. In contrast the methodology proposed here is able to uncover information and particularly rotational patterns at any frequency throughout the whole frequency range of the measured signal. In turn this results in a very precise reconstruction of the original signal.

It should be noted that PCA possesses several favourable properties as applied for damage/delamination assessment purposes. It first reduces the dimension of the measured data, in our case this reduces the dimension of the measured vibration signals. Furthermore it possesses clustering or categorization properties in the sense that the new components tend to make clusters corresponding to the different categories of data: in our case signals from intact structures and those from structures with different sizes and locations of delamination. This is achieved by reducing the distance between data vectors from the same category while in the same time increasing the distance between data vectors from different categories. It also preserves the information contained in the original signals in terms of variability.

The method suggested here is based on PCA which is a data analysis method and thus it uses solely the measured vibration response in order to extract information about the structural vibratory behavior and its health. Singular Spectrum Analysis (SSA) is a natural extension of PCA which is specifically developed for time series [21] and it possesses properties which are beneficial and make it appropriate for the analysis of dynamic/vibratory behavior. SSA is able to uncover the rotational patterns of the measured response and it is especially appropriate for non-linear and non-harmonic rotations and periodicities since in contrast to spectrum analysis it is capable to uncover periodicities at any frequency. This is why it was initially developed for applications in climatology, meteorology and social sciences [22], but the first development of SSA for structural vibration analysis and for the purposes of VSHM belongs to some of the authors of this study [21]. In addition SSA as an alternative of PCA features properties that are favorable for damage assessment and for the analysis of data from different categories. It first reduces the dimension of the measured data, in our case this significantly reduces the dimension of the measured vibration signals. Furthermore it possesses clustering or categorization properties in the sense that the new components tend to make clusters corresponding to the different categories of data in our case signals from intact structures and those from structures with different sizes and locations of delamination. This is achieved by reducing the distance between data vectors from the same category while in the same time increasing the distance between data vectors from different categories. It also preserves the information contained in the original signals in terms of variability.

There is only one other application of SSA that the authors are aware of, for the purposes of bridges monitoring [23]. SSA is principally a data analysis method which can be applied in the time and/or the frequency domain. This study looks at the application of SSA in the frequency domain. The frequency domain strain signals measured on a structure are subjected to SSA in order to extract useful information and features that can be used for delamination assessment. Only few of the first principal components containing most of variance of the initial signals are used to approximate each vibration signal.

The rest of the paper is organized as follows. The next paragraph introduces the delamination assessment methodology. Section 3 is dedicated to the case study of a laminate plate: its free vibratory behaviour without delamination and in the presence of several delamination scenarios is simulated by using FE modelling. An experimental study is also performed to obtain the free decay responses of a laminate plate with the same dimensions and characteristics as the simulated one under the same delamination scenarios (including the healthy plate). Section 4 presents the results from the application of the methodology for delamination diagnosis, which are further discussed from view point of their application to the experimentally and the FE simulated vibratory responses. The results validate the delamination assessment capabilities of the methodology. The paper finishes with some conclusions regarding the methodology and this specific application.

2. The SSA-based methodology as applied to composite laminate plates

In this paragraph the SSA-based methodology is applied for composite laminate plates.