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Damage assessment based on general signal correlation. Application for delamination diagnosis in composite structures

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ABSTRACT

This work presents a Vibration-Based Structural Health Monitoring (VSHM) technique which is developed and applied for delamination assessment in composite laminate structures. It suggests the mutual information as a measure for nonlinear signal cross correlation. The mutual information between two signals measured on a vibrating structure is suggested as a damage metric and its application for the purposes of damage assessment is discussed and compared to the application of the traditional linear signal cross-correlation. The cross correlation is capable to detect linear dependence between two signals and thus can be used for diagnosing damage on linearly vibrating structures. On the other hand the mutual information is a nonlinear metric, and it is shown that it can detect linear as well as nonlinear signal dependence and thus it is particularly appropriate for structures with nonlinear dynamic behavior and for composite structures as such. The application of the mutual information as a damage metric is demonstrated and discussed first for the case of a simple 2 DOF system with a nonlinear stiffness. Eventually the application of the suggested damage metric is developed and demonstrated for the purposes of delamination diagnosis in a composite laminate beam.

1. Introduction

Structures made of composite materials have an increasing importance in many contemporary industrial, civil and military applications and in particular in the aviation field. They are progressively replacing traditional materials due to their better strength and weight, than traditional materials. Composite laminates are probably the widest used composite material, and besides the number of excellent properties laminates present some difficulties, particularly related to their layered nature, which induces the formation of new failure modes. Delamination is probably the most common failure mechanisms for composite materials and it is particularly dangerous because delaminated structures can lose up to 60% of their initial stiffness, and still remain visibly unchanged.

This work focuses on the use of the vibration response of structures made of composite laminate materials for their integrity and health assessment.

Maintenance and operation costs are usually among the largest expenditures for most structures: an aging structure may reduce profits with increased maintenance costs and down time and it can become a hazard for its users. The ability to access the integrity of a structure and discover a fault at a rather early stage can significantly reduce these costs. A large class of Structural Health Monitoring (SHM) methods are vibration-based methods, where the state of the structure is assessed using its vibration response (Yang et al., 2007).

Laminates are very difficult to inspect and almost impossible to repair, thus the evaluation of the health state of such structures is a must for most industrial applications. Vibration-Based Structural Health Monitoring (VSHM) methods are becoming increasingly important for composite and composite laminate structures. VSHM methods can be largely divided into two main categories (Yu and Yang, 2007; Yang et al., 2009): model-and non-model based. The first category uses the vibratory model of the structure in order to assess its health and condition, while the latter does not assume and/or require any modeling. Most of the model-based methods use a linear structural model. The methods used for structures made of composites tend to be non-model based, because of the complexity of material properties which are difficult to model accurately.

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Plenty of VSHM methods targeted for structures made of composites use the structural resonant frequencies as damage/delamination features. Doebling et al. (1998) mention that the presence of delamination in a structure would decrease structure's natural frequencies and increase its modal damping as compared to the intact structures. Adams et al. (1975) tested glass-reinforced plates to attempt to detect damage after both static and fatigue torsional loading. They found damping to be more sensitive than frequencies for detecting the onset of delamination. Cawley and Adams (1979) apply a frequency-shift-based damage detection routine to several damage cases (holes, saw cuts, crushing with a ball bearing, local heating with a flame, and impact) in composite materials (CFRP plates and honeycomb panels with CFRP faces). They were able to locate low levels of damage accurately. Sanders et al. (1992) measured the modal parameters on damaged graphite/epoxy beams. Damage was induced by tensile loading the beams to 60%, 75%, and 85% of the ultimate tensile strength. It was diagnosed using a sensitivity method based on the measured natural frequencies. Results agreed well with independently obtained findings based on static stiffness measurements and crack densities from edge replication. Because this damage was approximately uniform throughout the beam, the ability of the method to localize damage was not demonstrated. Diaz Valdes and Soutis (1999) used a novel method known as resonant ultrasound spectroscopy to determine the modal frequencies of a prepreg carbon/epoxy composite laminate beam. They used commercial, brass backed, piezoceramic transducer and a piezoelectric film element bonded near the beam's fixed end and operated as actuator and sensor respectively. Changes of the modal frequencies after delamination initiation, compared to those of a non-delaminated specimen, gave a good indication of the degree of damage, demonstrating the feasibility of using measured changes in the vibration characteristics to detect damage. In Minak et al. (2010) the authors make use of the resonant frequencies of a composite beam and develop a pattern recognition procedure for the purposes of delamination diagnosis.

But it should be noted that there are a number of examples when these frequencies turn out to be insensitive to a certain kind of damage especially in its initial state when it has not developed enough (Yang et al., 2009; Nichols et al., 2009). It should be also noted that structures made of composites on a lot of occasions demonstrate quite well expressed nonlinear behavior, while most of the above mentioned methods use a linear model. Traditional spectrum analysis and modal analysis are applicable to structures with linear dynamic behavior and thus strictly speaking they cannot be applied to structures made of composites. Moreover on a lot of occasions the measured vibration response signal from structures made of composites is a nonlinear one and thus it is difficult and on some occasions even impossible to extract information, including the natural frequencies, from its frequency domain representation. Thus most of the above mentioned methods might be inapplicable for structures made of composites.

Monitoring methods based on the time-domain vibration signatures represent a relatively new paradigm in SHM (Nichols et al., 2009; Trendafilova, 2006; Trendafilova and Manoach, 2008). These methods are mostly based on non-linear dynamics tools and signal analysis and most of them utilize statistical characteristics. They represent a very attractive alternative, especially for structures made of composites, since they do not assume any model or linearity of the structure under interrogation and they only require the measured structural vibration signals in the current and possibly in a baseline (undamaged) state. The signal cross-correlation was considered for the purposes of damage assessment in (Wang et al., 2010) in a different context where the authors suggest a vector damage measure. The application suggested here is much simpler and straightforward to apply, which will enhance the practical application of the method. The development here is in the extension of the idea of cross correlation for nonlinear signals and for nonlinear signal dependence. The information and the entropy of vibrating structures were first considered by Nichols (2006) and their application for nonlinearity detection purposes was suggested by Overbey and Todd (2009). In Trendafilova et al. (2012) the authors of the present paper consider the application of cross correlation and the mutual information for damage and delamination detection in freely vibrating structures. This paper extends and enhances the application of the mutual information to real structures and especially to composite structures subjected to unknown random excitation. It introduces a simple damage index, which is capable of detecting the presence and the extent of damage and locating it within the structure. The method is further demonstrated on a composite beam, for which it is proven to detect and localize different delamination sizes and scenarios. The study also offers a comparison between the performance of the cross-correlation and the mutual information for cases of detecting linear and nonlinear damage in a simple simulated 2 DOF example. A similar comparison is provided for the case of delamination diagnosis in a composite beam, where the mutual information is shown to have superior performance.

The rest of the paper is organized as follows. The concepts of cross-correlation and mutual information between two signals are introduced in the context of their application for structural damage detection in &2. &3 considers the 2 DOF system example and &4 is dedicated to application of the suggested metrics for delamination detection in a composite beam. Eventually some results are introduced and discussed (&5), and the paper is concluded with a discussion (&6).

2. Background of the method

2.1. Signal cross correlation and its application as a damage metric

Cross-correlation is a measure of similarity of two signals as a function of a time-lag applied to one of them. If $x_i(t)$ and $x_j(t)$ are two signals, their cross correlation is defined as follows (Bendat and Piersol, 2011):

$$R_{x_i x_j}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T [x_i(t) - \mu_i] \cdot [x_j(t+\tau) - \mu_j] \, dt \tag{1}$$

where μ_i and μ_j are the mean values of $x_i(t)$ and $x_j(t)$ respectively. Or for discrete signals:

$$R_{x_i x_j}(m) = \lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} [x_i(n) - \mu_i] \cdot [x_j(n+m) - \mu_j] \tag{2}$$

The cross correlation is a signal as well. It has a maximum when the two signals are aligned. The normalized cross-correlation between two signals is defined as (Bendat and Piersol, 2011):

$$\rho_{x_i x_j}(m) = \frac{R_{x_i x_j}(m)}{\sqrt{R_{x_i x_i}(0) \cdot R_{x_j x_j}(0)}} \tag{3}$$

Where $R_{x_i x_i}$ and $R_{x_j x_j}$ are the autocorrelations of x_i and x_j respectively. It should be noted that $\left|\rho_{x_i x_j}(m)\right| \le 1$ for all m.

If x_j is the same signal as x_i their cross-correlation will have a maximum for $m = 0$. If x_i and x_j are linearly related (x_j is a shifted and amplified/attenuated version of x_i), then their cross-correlation