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Damage assessment of composite plate structures with material and measurement uncertainty

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ABSTRACT

Composite materials are very useful in structural engineering particularly in weight sensitive applications. Two different test models of the same structure made from composite materials can display very different dynamic behavior due to large uncertainties associated with composite material properties. Also, composite structures can suffer from pre-existing imperfections like delaminations, voids or cracks during fabrication. In this paper, we show that modeling and material uncertainties in composite structures can cause considerable problem in damage assessment. A recently developed C^0 shear deformable locking free refined composite plate element is employed in the numerical simulations to alleviate modeling uncertainty. A qualitative estimate of the impact of modeling uncertainty on the damage detection problem is made. A robust Fuzzy Logic System (FLS) with sliding window defuzzifier is used for delamination damage detection in composite plate type structures. The FLS is designed using variations in modal frequencies due to randomness in material properties. Probabilistic analysis is performed using Monte Carlo Simulation (MCS) on a composite plate finite element model. It is demonstrated that the FLS shows excellent robustness in delamination detection at very high levels of randomness in input data.

1. Introduction

Composite materials created an impact on structural engineering whether from aerospace, automobile, civil or mechanical industry, due to their superior fatigue characteristics and very high specific structural properties as compared to that of metals. But they are also very susceptible to damages caused by low or high velocity impacts which can result in delamination between composite layers. This can adversely affect structural life and safety aspects. Delamination damage is one of the very common damage modes observed in composite structures.

The main objective of developing a structural health monitoring (SHM) system is to increase mission safety and integrity [1]. However, SHM also helps in better planning and reduction in maintenance cost, which can be of the order of 24 percent of the direct operating cost in some applications [2]. To identify that damage has occurred based on the changes in patterns of structural signatures and relate these changes to physical changes in the structure is a very difficult problem. The need of detecting damage in complex structures led to the development of a vast range of techniques; many of them are based on

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analyzing structural vibration signatures. Vibration-based diagnosis involves detecting and estimating the size of a damage from the dynamic properties of the structure. Modal analysis is one of the few non-destructive methods that are technically mature enough to be used as structure integrated damage monitoring system [3].

Several other non-destructive techniques (acoustic emission, dye penetrant, stereo X-ray radiography, ultrasonics) with different sensitivity levels are also used for damage detection in structures. Advantages and disadvantages of different available techniques depend on the type of damage to be detected and on the test conditions in which sophisticated laboratory techniques can give highly accurate results. For example, penetrant-enhanced X-radiography, which utilizes a radio-opaque liquid to infiltrate the examined area, can be used to detect matrix cracks and delaminations. The main drawback of this technique is that it can resolve only damage connected to the surface, while internal defects impossible to fill with the dye may remain undetected [4]. Ultrasonic techniques rely on the use of high-frequency mechanical oscillations for damage detection by evaluating the signal amplitude and/or the time-of-flight of the ultrasonic signal. On the contrary, matrix cracks, lying perpendicular to the surface, and fiber fracture paths are difficult to detect because they do not offer the wide enough reflecting surface which delaminations present [4]. Due to the complex features of damage mechanisms, more than one method is usually required for a complete non-destructive evaluation of induced damages. The modal based methods are global in nature and can be used as a complement to local non-destructive techniques.

Boller [5] mentions that there is no practical need to locate damage to within a few millimeters. The cost and efforts involved in predicting damage to a high level accuracy can be prohibitive. In addition, because of measurement, model and signal processing inaccuracies, systems that endeavor to predict damage with great accuracy are likely to give false alarms. Hence, a better approach is to roughly locate damage in the structure and then use standard NDT methods such as acoustic emission and ultrasound for closer analysis of the damaged area. Modal analysis methods are useful in roughly locating the damage.

Modal based methods have been extensively researched [6–11] and a comprehensive review is given by Doebling et al. [12] and Montalvao et al. [13]. The modal characteristics used to detect structural damage include frequency response functions (FRF), natural frequencies, mode shapes, mode shape curvatures, modal flexibility, and modal strain energy [12]. Among various modal parameters, natural frequency is widely used as it can be measured most conveniently and accurately [14]. Limitation on frequency based methods is due to their relatively low sensitivity to damage. However, resonant frequencies show much less statistical variation from random error sources than do other modal parameters [15,16]. While many of the works in this area have looked at the effect of measurement noise in data, most have ignored the important effect of uncertainty in the model.

Composite structures show considerable scatter in their structural response due to large uncertainties associated with their material properties [17]. Therefore, structural damage detection in composite structures is relatively more difficult. Further to that, composite materials can experience many different modes of structural damage such as delamination, fiber matrix debonding, fiber breakage, fiber pull-out and matrix cracking [18]. This further complicates the damage detection problem. Also, huge variation in structural response can be observed when using different mathematical models for composite structures when compared with metallic structures. This necessitates an investigation addressing uncertainty effects in model based damage detection system for composite structures.

Inter- or intra-delamination is one of the common failure modes, which can be caused by pre-existing imperfections or can occur during the structures service life due to high interlaminar stresses or low/high velocity impact. Extensive research is available on model based delamination detection in composite structures using vibration signatures. Recently, delamination detection in composite beams using three different nonlinear inverse algorithms based on frequency changes was performed by Zhang et al. [19]. The three inverse algorithms used were graphical method, artificial neural network (ANN) and surrogate based optimization. It was reported by them that the ANN was more sensitive to measurement errors. Ihesiulor et al. [20] applied ANN for the solution of inverse problem of delamination detection in composite beams using frequency shifts. Yeum et al. [21] proposed delamination detection algorithm by comparing pitch-catch Lamb wave signal obtained from a piezoelectric (PZT) transducer network. Most of the literature addresses uncertainty in measured data by only ignoring the important aspect of high uncertainties in composite structure itself.

Model-based damage detection methods are quite useful for accurate damage prediction using inverse methods, even with noisy data. The accuracy of damage prediction is based on the accurate damage modeling and accurate structural modeling. There is always some difference between predictions by mathematical models and test results due to associated uncertainties. Uncertainties associated with the mathematical characterization of a structure can lead to unreliable damage detection [22]. A comprehensive review in the area of uncertainties involved in flight vehicle structural damage monitoring, diagnosis, prognosis and control is given by Lopez and Nesrin [23]. According to Lapez et al. [23], uncertainty is a state of limited knowledge where it is impossible to exactly describe the existing or future state of a system.

In general, there are two types of uncertainty in structural dynamics. The first one called aleatory or random uncertainty is caused due to inherent variabilities or randomness in the system like uncertainty in material properties and geometric properties. This type of uncertainty is sometimes referred to as irreducible uncertainty. The second type of uncertainty is called epistemic uncertainty and it is also referred to as reducible uncertainty which covers un-modeled physics [24].

Structural uncertainties are generally incorporated using probabilistic analysis by describing the uncertain parameters as random variables. Collins et al. [25] addressed uncertainty in the structural model by treating the initial structural parameters as normally distributed random variables. Conventional Monte Carlo simulation (MCS) is the most common and

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