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Delamination detection with error and noise polluted natural frequencies using computational intelligence concepts

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A B S T R A C T

Delaminations are one of the most prevalent defects noticed in laminated composite structures. The existence of delaminations changes the vibration characteristics of laminates and hence such indicators can be used to quantify the health characteristics of laminates and detect potential risk of catastrophic failures. An approach for online health monitoring of in-service composite laminates is presented in this paper that relies on methods based on computational intelligence. Typical changes in the observed vibration characteristics (i.e. change in natural frequencies) are considered as inputs to identify the existence, location and magnitude of delaminations. The performance of the proposed approach is demonstrated using both numerical models and experimental studies of composite laminates. Since this identification problem essentially involves the solution of an optimization problem, the use of finite element (FE) methods as the underlying tool for analysis turns out to be computationally expensive. A surrogate assisted optimization approach is hence introduced to contain the computational time within affordable limits. An artificial neural network (ANN) model with Bayesian regularization is used as the underlying approximation scheme while an improved rate of convergence is achieved using a memetic algorithm. However, building of ANN surrogate models usually requires large training datasets. *K*-means clustering is effectively employed to reduce the size of datasets. ANN is also used for the solution of the inverse problem to determine the interface, size and location of delaminations using changes in measured natural frequencies before and after damage. The algorithms successfully performed delamination detection given limited amount of training datasets. Since in all practical problems, noise and error are inherently present, the performance of the proposed approach is also evaluated under varying levels of noise and error. The results clearly highlight the efficiency and the robustness of the approach. Hence, a delamination prediction strategy via *K*-means clustering, ANN and optimization algorithms integrated with surrogate models based on ANN for computational enhancement have been successfully developed and found efficient for detection of the interface of delamination, its size and location in FRP composite laminates using variations in natural frequencies. The developed algorithms are applied to composite beams. Results clearly indicate the delamination detection capability of the algorithms. The results demonstrate that the proposed techniques provide remarkable accurate detection of delamination damage with error and noise corrupted natural frequency validation data. The algorithms are quite promising, successful, flexible and practical with significant increase in terms of efficiency and effectiveness for SHM.

1. Introduction

Composite structures have become the most preferred choice in recent years in engineering applications where weight and cost savings are of great significance. Fiber reinforced laminated composites are one of the most favored kinds of composite configurations due to their high specific strength and stiffness ratio, resistance to fatigue and corrosion, negligible thermal expansion characteristics and ease of tailoring its strength properties. Such composite structures in service can suffer from a number of failure mechanisms, such as ply/fiber breakage, matrix cracking and delaminations, due to static overload, impact, fatigue, design/manufacturing errors, overheating, and lightning strikes [1]. Ultimately, delamination is the greatest weakness of composite laminates due to their susceptibility to transverse impacts and fatigue. Delamination or inter-lamina damage is the separation of the laminate plies as a result of low shear strength (lack of reinforcement) at the through-the-thickness direction leading to loss of structural integrity [2]. Delaminations are early indicators of the onset of in-service failures and can easily spread throughout the whole laminate upon repeated loading resulting in costly

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and/or disastrous failures if undetected. Online vibration based monitoring using shifts in natural frequencies can provide early warning of occurrence of delamination.

Nowadays, non-destructive testing (NDT) techniques such as ultrasonic inspection, thermography, optical holography and mechanical impedance have been employed for delamination assessment in composite laminates [3–5], however, they cannot be used for real time and online damage detection [6]. To overcome these drawbacks, vibration based techniques as a structural health monitoring (SHM) tool to identify and assess delamination damage are employed. The key purpose of SHM is to ensure rapid assessment of the health condition of a structure in terms of reliability and safety, as well as optimizing the economic impacts of structural failure before degradation hampers the target objectives of in-service structures. SHM exploiting vibration measurements are global methods based on the principle that degradation due to damage in a structure changes its vibration parameters, namely, natural frequencies, mode shapes and damping characteristics. It is hence feasible to use any one of measured vibration quantities to characterize and identify the presence of damage via an inverse modeling. Natural frequencies are one of the vibration parameters commonly used because they can be determined easily [7].

An approach for online SHM hence exploits the variation in vibration measurements i.e. shifts in natural frequencies of healthy and damaged specimens due to degradations to detect the nature and quantum of damage. A review of vibration based health monitoring methods utilizing neural networks and optimization algorithms appears in previous works [8,6,9–14,2,15,16]. Although previous works have demonstrated the feasibility of artificial neural networks and optimization algorithms for delamination damage detection, some significant hurdles still exist. Almost all the works deal with one or at most two variables i.e predicting either delamination size or location at mid-planes. Secondly, most of the damage detection methods that have been reviewed attempt to identify delamination by solving an inverse problem, which often requires the construction of numerical models. This dependency on firsthand numerical models, which are computationally expensive makes these approaches unpromising for SHM. Thirdly, while neural network based approaches have been found successful due to their adequate generalizing capabilities, they require a large number of training cases. Finally, most of the works validate their results against numerical data without considering experimental uncertainties. To the best of our knowledge, there are no reports of any SHM approach that investigates the effects of noise and error on its behavior.

Damage detection methods of structural systems based on changes in their vibration characteristics have been widely and extensively employed over the years. Doebling et al. [6] detailed an intensive review of vibration-based damage identification methods. ANN and optimization of structural parameters using gradient based local search and genetic algorithms (GAs) have found their applications in delamination identification mostly in composite laminated beams. Harrison and Butler [9] employed two numerical optimizers (gradient-based local search and genetic algorithm techniques) to locate delaminations in composite beams. In most of their validation cases, it was seen that the interface position of the delamination was not identified perfectly well and the delamination size was under-predicted. However, their adopted GA predicted better solutions than the gradient-based method as evident by a lower value in objective function at the expense of high computational cost. Nag et al. [10] identified only mid-plane delaminations in composite beams by using genetic algorithm. Valoor and Chandrashekhara [11] investigated the feasibility of neural networks in determining only mid-plane delaminations in laminated composite beams. They essentially modified the analytical model developed by Okafor et al. [12] by taking into account the Poisson effect and the transverse shear deformation to obtain the natural frequencies. They trained a back-propagation neural network to predict the delamination size and location from the natural frequencies of the beam with a maximum average error of 15%. They found that errors were excessive for delaminations located near the beam end as a result of insufficient number of training data. Islam and Craig [13] combined neural network and embedded piezoceramic sensors to detect the presence of damage in composite structures. They predicted delamination with maximum error of 27% and 10% in location and size respectively. Okafor et al. [12] demonstrated strategies based on ANN technique with 850 simulated datasets using natural frequencies as network input to predict only delamination size at the mid-plane. Their results using experimental data show a prediction error between 0.25% and 19% for the delamination size. Watkins et al. [14] employed 1066 datasets generated from analytical model for feed-forward back propagation neural network training, delamination size and location at midplane were predicted with an average error of 5.9% and 4.7% respectively. Zheng et al. [2] employed a finite element analysis to obtain simulated modal frequencies and applied a new neural network learning procedure, called genetic fuzzy hybrid learning algorithm (GFHLA) with 283 training datasets to predict delamination size and location at mid-planes with an average error of 4.7% and 4.3%, respectively. All their validation cases were based on simulation results. Chen et al. [15] developed an approach that combines genetic algorithm and neural network technique for delamination detection in composite laminates using numerical analysis. They used ANN to train a back propagation neural network using 1624 datasets with a network architecture of 3-70-70-10 and validated their trained neural network using 1104 datasets. The three inputs to the network are the thickness location, lengthwise location and delamination size and the outputs to the network are the first ten natural frequencies. The trained ANN model provides an encapusulation/approximation of the numerical model. They customized GA using ANN approximations of the numerical model to detect delaminations in laminated composite beams and plates over 9600 function calls. Their approach failed to predict accurately small delamination sizes and near surface delaminations. Furthermore, they did not however validate their methodology with experimental results. Su et al. [16] solved a 3-variable problem (interlaminar position, delamination size and location) by exploring GA and ANN to evaluate delaminations in clamped composite beams. Their GA method required 2000 function evaluations and large population size. Using experimental data, their model reported a maximum error of 26.5%. Most recently, other researchers [17–20] have carried significant research to detect delaminations in composite structures.

As mentioned earlier, the reviews above highlight the need to develop more accurate algorithms for delamination detection. This work proposes a solution strategy for detecting delaminations in composite beam laminates. Assessment of delamination damage is effectively the solution to the inverse problem. However, it may be necessary in many cases to solve the forward problem to generate data for the solution to the inverse problem. Generation of data is usually computationally expensive and surrogate models are created to limit the computational expense. Therefore, in practice, extensive data characterizing the delamination damage as well as an inverse solver must be included in any delamination detection method. The principal components of the proposed methodology include; the use of *K*-means clustering for identification of training data with adequate spread, ANN based models for building of surrogates used for approximations, direct application of the ANN based models for delamination prediction and optimization techniques (gradient-based and global search strategies) with surrogates (surrogate assisted optimization) and without