Multilayer Perceptron for Classification of Structural delamination and Transducers Debonding in Smart Composite Laminates

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ABSTRACT

This paper investigates the feasibility of multilayer perceptron (MLP) for the classification of structural delamination and transducers debonding in smart composite laminates. Structural vibration response is employed to extract the discriminative features for multiple damages. The dynamic model of the smart structure with inter-ply delaminations and partially debonded piezoelectric sensor and actuator is developed by incorporating improved layerwise theory, higher order electric potential field and finite element method. The developed model is solved in the time domain to obtain the transient response of the healthy and damaged structures through a surface bonded piezoelectric sensor for random input excitations applied through a piezoelectric actuator. The input-output information is fed into a system identification algorithm to identify damage sensitive features for the healthy and damaged state of the smart composite laminate. The discriminative features are classified through MLP in a supervised manner and its classification accuracy is evaluated in terms of true positive (TP) rate, false positive (FP) rate, precision and area under the receiver operating characteristic curve (ROC area).

1. INTRODUCTION

Laminated composite structures with high strength-to-weight ratio, flexible design and high fatigue strength have been extensively used aerospace, civil, robotics, sports goods, and mechanical engineering applications. Piezoelectric transducers are integrated with laminated composite for various smart applications such as shape control, vibration suppression, acoustic analysis, structural health monitoring and others. Smart composite laminates are vulnerable to defects such as structural delamination, matrix crack, voids and debonding of piezoelectric sensor or actuator due to anisotropic nature of the host laminated composite and the presence of high free edge stresses between the host structure and transducers. Detection, quantification and differentiation of multi-damages in smart composite laminates is of essential importance, because the damage is usually not visible and causes substantial loss of structural integrity. Furthermore, the structural damage must be differentiated from the damage in the transducers as the two may have entirely different effects in terms of structural performance. In literature, various approaches have been proposed for the detection of damages in the host laminate and debonding of smart elements (Tan & Tong, 2004). However less effort has been devoted to the multi-damage problem where one could differentiate the structure damage from the defects in the transducers.

In this work, the method of system identification is combined with multilayer perceptron for the identification and differentiation of structural delamination and debonding of piezoelectric sensor and actuator in smart composite laminates.

2. MATHEMATICAL FORMULATION

This section outlines the detail of mathematical formulation of the smart composite laminate with inter-ply delamination and partially debonded PZT sensor and actuator.

Improved layerwise theory (Kim, Chattopadhyay & Ghoshal, 2004) is used to model the displacement field of the smart structure with in-plane and out-of-plane discontinuities at the delaminated/debonded interfaces. The electric potential field of the PZT transducers is modeled by incorporating higher-order electric potential field. The two fields are combined through finite element method and extended Hamilton's principle to form the electromechanically coupled governing equation the problem as shown by Eq. (1)

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F\} \quad (1)$$

where M, C and K are the elemental mass, damping and stiffness matrices, respectively. The term F is the input force vector which accounts for the mechanical and electrical forces.

2.1. System Identification

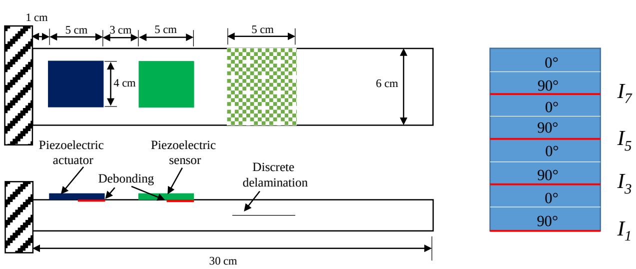
System identification is the inverse algorithm that realizations parameters of the system from the input-output information of the system. In this work, direct system identification method (Phan, Solbeck & Ray, 2004) is employed to extract the system parameters for the healthy and damage cases in the state-space form (A, B, C, D) from the input-output of the PZT actuator and sensor. The normalized value of $A \times B$ was chosen as damage sensitive feature for the delamination in the host laminate and partial debonding of PZT transducers.

2.2. Multilayer Perceptron

A multilayer perceptron (MLP) is a feedforward artificial neural network model that maps sets of input data onto a set of appropriate outputs. MLP has been used for damage detection in smart composite laminates (Sung, Oh, Kim & Hong 2000). In this work, the open source software of Waikato Environment for Knowledge Analysis (WEKA) is used to evaluate the classification performance MLP for multi-damages in smart composite laminates.

3. RESULTS AND DISCUSSION

The developed theory is numerically implemented on a 16-layer cross-ply ($[0/90]_{4s}$) laminated composite with surface bonded piezoelectric actuator and sensor as shown in Fig. (1).



Herein, the right hand side of the figure shows the half thickness of the laminate above the mid plane of the laminate. The possible damages considered in this study are 5 cm delaminations along the thickness (I_1, I_3, I_5, I_7) and length (L_1, L_2, L_3) directions and 10-50% partial debonding of the PZT sensor and actuator. Each case the structural delamination and transducers debonding was subjected to 10 random excitations through the PZT actuator and the corresponding responses were obtained through the PZT sensor. The input-output information was processed through system identification algorithm to realize the parameters of the system in state-space form. Form the realized state-space form, the normalized value of $A \times B$ was chosen for each case to form the discriminative feature space of the problem. The feature space was classified through MLP in a supervised way. Table 1 summarizes the classification performance of MLP

Table 1. Classification performance of MLP

True positive rate	False positive rate	Precision	ROC Area
0.97	0.001	0.972	0.999

Herein, the high values of TP rate, precision, area under the ROC curve and low value of FP rate indicates that MLP can successfully identify and distinguish the delamination damage in host laminate and debonding of the PZT transducers. Furthermore, the confusion matrix provided a further insight into classification performance of the MPL. From the confusion matrix it was observed that none of the structural damage was classified as sensor or actuator debonding. Table 2 summarizes the misclassifications of MLP from the confusion matrix

Table 2. Misclassification of MLP

Number of misclassified instances	True Class	Predicted class
1 out of 10	healthy	10% debonded sensor
1 out of 10	10% debonded sensor	20% debonded sensor
1 out of 10	30% debonded sensor	40% debonded sensor
1 out of 10	10% debonded actuator	20% deboned sensor
1 out of 10	20% debonded actuator	30% debonded actuator
1 out of 10	30% debonded actuator	40% debonded actuator
1 out of 10	40% debonded actuator	50% debonded actuator

The results to Table 2 shows that the classification accuracy of the MLP is consistent with the physical nature of the problem. For example, 10% debonded sensor is very close to healthy case in term of structural response, 20% debonded actuator is close to the characteristics of 30% debonded actuator and so on.

4. CONCLUSION

This paper presents the feasibility of multilayer perceptron (MLP) for the classification of structural delamination damages and debonding of PZT transducers in smart composite laminates. The classification metrics of true positive (TP) rate, false positive (FP) rate, precision and area under the receiver operating characteristic curve (ROC area) showed that MLP can successfully identify and distinguish structural delamination from debonding of PZT transduces. Furthermore, the study of confusion matrix revealed that the misclassifications of the MLP are consistent with the physical nature of the problem.

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REFERENCES

Tan P and Tong L (2004) Identification of delamination in a composite beam using integrated piezoelectric sensor/actuator layer Composite structures. 66 391-8

Kim, H.S., Chattopadhyay, A. and Ghoshal, A., (2004), "Dynamic Analysis of Composite Laminates with Multiple Delamination Using Improved Layerwise Theory," AIAA Journal, Vol. 41, No. 9, pp. 1771~1779

Phan, M.Q., J.A. Solbeck, and L.R. Ray (2004). A direct method for state-space model and observer/Kalman filter gain identification. in AIAA guidance, navigation, and control conference and exhibit, Rhode Island.

Sung D.-U., Oh J.-H., Kim C.-G., Hong C.-S., (2000) Impact monitoring of smart composite laminates using neural network and wavelet analysis, Journal of intelligent material systems and structures, 11 180-190.