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Assessment of sensor debonding failure in system identification of smart composite laminates

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ABSTRACT

System identification is an inverse algorithm of developing/improving mathematical representation of a physical system from input-output responses. This paper assessed a mathematical model of smart composite laminate identified with spurious output data due to sensor debonding failure. Improved layerwise theory and higher-order electric potential field were incorporated to develop electromechanically coupled finite element based mathematical model of the smart composite laminate with or without sensor debonding failure. The input-output data of the developed model were fed into the direct system identification algorithm to identify the state-space model of the smart structure. The developed theory was numerically implemented on a 16-layer cross-ply laminate with surface bonded piezoelectric sensor and actuator. Results showed that system identification algorithm misapprehended the true dynamic behavior of the smart structure in the presence of sensor debonding failure. In addition, principal component analysis was used to detect the presence and severity of partial sensor debonding in the identified state-space model.

1. Introduction

Inverse algorithm of system identification for developing/improving mathematical representation of a physical system from input-output data is a promising way to faithfully represent the dynamics of complex structures. The key requirement of the system identification process is the identification of the input-output behavior of the targeted system [1–3]. Fast response, high stiffness, light weight, and large force output of piezoelectric materials make them suitable as sensors and actuators. Laminated composite materials have the favorable properties of strength-to-weight and stiffness-to-weight ratios, design flexibility, and anti-corrosion property. Smart composite laminate is the integration of piezoelectric sensor/actuator and laminated composites and has become an excellent candidate in smart structure applications [4,5]. In smart applications of composite laminates, input signal is applied to the PZT actuator for attenuation of vibration amplitude or active shape control while system response is measured through the PZT sensor in time or frequency domain.

Literature review shows that piezoelectric sensors and actuators have been widely used for experimental and theoretical identification of dynamic behavior of smart structures. Yang and Lee [2] have developed a backpropagation neural network with an adaptive learning rate to identify structural dynamics of glass fiber composite laminated beam embedded with two piezoelectric actuators. All simulations have been verified by experiments. Their results have shown that a neural network with six input neurons, seven hidden layer neurons, and two output neurons is capable of representing system dynamics both in time and frequency domains. Okugawa and Sasaki [6] have proposed system identification and vibration control of a cantilever fabricated from piezoelectric materials and shown that both system identification and state estimation can be used to achieve self-maintenance of a self-sensing system. Si and Wang [7] have developed Hilbert spectral analysis-based multi-damage identification technique with piezoelectric wafer sensor arrays to monitor and identify the presence, location, and severity of the damage in carbon fiber composite structures via wave reflection from damage in the structure. Nestorovic et al. [8] have presented a subspace-based identification procedure for obtaining state-space model of a smart beam from its input-output measurement data.

Various approaches have been used to model a composite laminate with surface bonded or embedded piezoelectric sensor/actuator. Santos et al. [9] have developed a finite element model based on 3D linear elasticity theory for the bending and free vibration of a 3D axisymmetric laminated shell with piezoelectric sensors and actuators. Della and Shu [10] have presented a mathematical model for the vibration of beams with embedded arrays of piezoelectric sensors and actuators using Eshelby's equivalent inclusion method, Rayleigh-Ritz approximation

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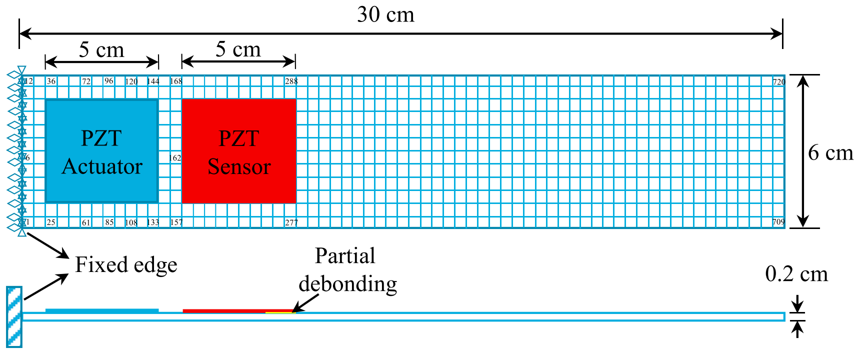

Fig. 1. Physical configuration of smart laminated plate for numerical simulation.

Table 1
Material properties of a single lamina of host laminate and piezoelectric patches.

Property	Host Laminae	PZT-5H
Young's Modulus (GPa)	$E_1 = 372$ $E_2 = E_3 = 4.12$	$E = 62$
Shear Modulus (GPa)	$G_{12} = G_{13} = 3.99$ $G_{23} = 3.6$	$G = 23.67$
Poisson Ratio	$\nu_{12} = \nu_{13} = 0.275$ $\nu_{23} = 0.42$	$\nu = 0.31$
Density (kg/m^3)	1788.5	7500
Piezoelectric Constant (m/V)		$d_{31} = d_{32} = -274 \times 10^{-12}$ $d_{24} = d_{15} = 741 \times 10^{-12}$
Permittivity (nF/m)		$b_{11} = b_{22} = b_{33} = 14.41$
Length (m)	0.3	0.05
Width (m)	0.06	0.04
Thickness (m)	0.125×10^{-3}	0.25×10^{-3}

technique, and Euler-Bernoulli beam theory. Qu [11] has presented a finite element formulation for modeling of a laminated composite plate with distributed piezoelectric sensors/actuators using first-order shear deformation laminated plate theory. Chrysochoidis and Saravanos [12] have presented a layerwise mechanics for analyzing coupled electromechanical response of delaminated composite beams with embedded passive or active piezoelectric layers. Kim et al. [13] have developed a framework for studying the time response of a laminated composite plate with embedded discrete and continuous piezoelectric sensors for structural health monitoring. The smart structure with delaminations in the host composite laminate was modeled and implemented using improved layerwise theory and finite element scheme, respectively.

From literature review of modeling of smart composite laminates, it is evident that the development of a detailed mathematical model of smart composite laminates is often difficult, if not impossible. On the other hand, modeling of system dynamics from input/output data through system identification algorithms is relatively easy and efficient. However, in the process of system identification, the sensor and actuator are assumed to be perfectly bonded to host structures during the input-output data extraction [14,15]. Whereas, in practice, the piezoelectric sensor/actuator may partially debond from the host structure due to high peeling stress at the bonding edge. The presence of debonding will degrade input/output capabilities of the sensor/actuator in smart structures [16] and lead to spurious input/output data. Hence, a system identified with spurious input/output data may deviate significantly from the dynamic behavior of the actual system. Therefore, a thorough investigation of the debonding effect of smart elements on system identification algorithms is of noble interest, particularly in structural vibration control.

In this work, the performance of direct system identification algorithm [17] was investigated in the presence of partial sensor debonding. Improved layerwise theory [13] was employed to model smart composite laminate with perfectly bonded and partially debonded piezoelectric sensor. Higher order electric potential field [18] was chosen to describe the potential variation through the thickness of piezoelectric patches. Extended Hamilton's principle and finite element method were adopted to obtain the governing equation of electromechanically coupled system. At first, the system was identified in state space form from the data of perfectly bonded sensor. The identified model was validated by comparing the impulse and sinusoidal responses of the identified state-space model to the responses of the finite element based analytical model. In the next step, the models identified with various cases of sensor debonding failure were assessed. Finally, statistical procedure of principal component analysis (PCA) was used to investigate sensor debonding failure, its severity, and location from the identified parameters of the system.

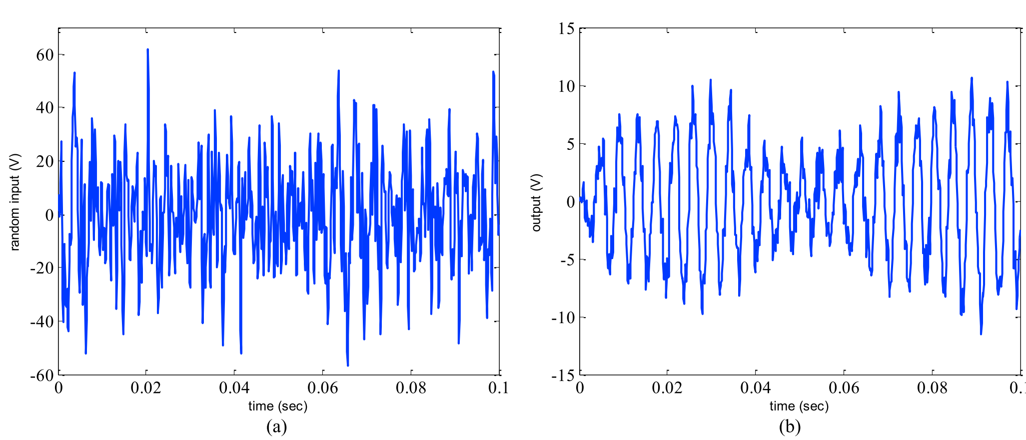

Fig. 2. (a) Random input signal applied through PZT actuator, (b) response of the system obtained through PZT sensor.