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Modeling and assessment of partially debonded piezoelectric sensor in smart composite laminates

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ABSTRACT

As substantive components of intelligent structures, piezoelectric sensors need to perform their intended function without any spuriousness. In this work, a mathematical model has been developed to characterize the performance degradation of a piezoelectric sensor due to its debonding from a smart composite laminate. The electromechanically coupled governing equation of motion is developed by incorporating improved layerwise theory and higher electric potential field along with the finite element method and Extended Hamilton's principle. The problem governing equation is solved by Newmark time-integration algorithm to assess the performance of a piezoelectric sensor in the presence of partial debonding at the edge and inner side of the sensor. The partially debonded piezoelectric sensor is investigated in frequency domain via power spectral density of the sensor output. The degradative performance of the partially debonded sensor is generalized for random loadings via basic signal statistics. The numerical results show that the developed model recover the presence and extent of partial debonding between the piezoelectric sensor and the host laminate.

1. Introduction

Laminated composite structures that are integrated with an embedded or surface-mounted piezoelectric actuator and sensor for the introduction of actuation and self-sensing capabilities have garnered attention because they are simple and easy to implement and produce high performances in real applications. In smart composite laminates, the applications of the piezoelectric sensor include structural health monitoring (SHM) [1], non-destructive evaluation (NDE) [2,3], non-destructive inspection (NDI) [4–6], system identification [7], active vibration control [8,9], and energy harvesting [10,11]. In the above applications, it is assumed that the piezoelectric sensor is perfectly bonded to the host structure; however, the sensor could debond from the host structure due to impact loading, bonding defects, environmental effects, fatigue loading, or high free-edge stresses [12,13]; here, the defective sensor could significantly mispredict the actual dynamic behavior of the smart structures. When a sensor debonds from the host structure, it is crucial to assess its effect on the overall characteristics of the smart structure.

To date, a variety of mathematical models regarding smart composite laminates with perfectly bonded/embedded piezoelectric components have been developed and applied, such as second-order shear-deformation plate theory [14]; the multi-layer higher-order finite-element approach [15]; first-order shear-deformation theory [8,16]; refined hybrid-plate theory [17]; layerwise mechanics [18]; and an improved layerwise theory [19]. Analytical techniques have also been used to model smart composite laminates with defects such as delamination, debonded piezoelectric sensor/actuators and matrix crack; here, the identified cases include a formulation that is based on a refined higher-order theory for the dynamic analysis of delaminated smart composite structures [20,21], a third-order refined displacement field for the modeling and detection of delamination in a smart composite plate [22], a lamb-wave-based technique for damage detection in smart composite laminates [4,23], the use of the layerwise laminate theory for the static and modal responses of delaminated smart composite beams [24], an improved layerwise theory for the analysis of delaminated smart composite laminates and time and frequency domains [3,25], a first-order shear deformation and the midline-plate theory for the assessment of partially debonded piezoelectric actuator in active vibration control [26], a higher-order theory for the detection of delamination and matrix crack in smart composite laminates [27,28], segmentation of electrodes and voltage relations for the detection of debonding of PZT sensor [29], modal flexibility curvature matrix for delamination detection [30], auto regressive models for the detection of low velocity impact-induced delaminations in composite laminates [31], ultrasonic guided waves for disbond identification in a honeycomb composite sandwich [32].

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The debonding of a piezoelectric sensor/actuator from the host structure decreases the control efficiency of the vibration suppression and reduces the actuation ability of the actuator [33]. The presence of debonding between the host structure and the piezoelectric actuator results in a reduced load-carrying ability, a reduced control ability, and the instability of the closed-loop control system [26]; moreover, the debonding at the edge of the actuator is typically more severe than that at the middle area [34,35].

In the past decade, various methods have been proposed for detecting sensor failure in smart systems. Friswell and Inman [36] employed the approaches of modal participation factors and the response subspace for the identification of faulty sensor. Park et al. [37] proposed a self-diagnostic procedure for the in situ monitoring of the operational status of PZT sensors and actuators using electrical admittance measurements. Lee et al. [38] presented a diagnostic technique for the detection of defects in PZT transducers on the basis of linear reciprocity of guided waves. Abdelghani and Friswell [39] used modal filtering approach and Parity Space approach for the detection of faults in a single sensor. Arun et al. [40] employed a pattern recognition approach for the identification of partially deboned PZT transducers. Lee and Sohn [41] presented a self-diagnostic technique for a PZT transducer on the basis of time-reversal process. They proposed two indices for self-diagnostic of PZT that identified and distinguished debonded and cracked PZT conditions from changing environmental and structural conditions.

In this work, a new mathematical model is proposed for smart composite laminates that comprise a partially debonded sensor; here, the patches of the piezoelectric sensor and actuator are considered as additional layers of the composite structure. Improved layerwise theory [42] is used to account for the possible in-plane slippage and out-of-plane jumps in the displacement field at the debonded interface between a thick/thin laminated composite of arbitrary stacking sequence and a piezoelectric sensor. A higher-order electric-potential field is used for the electric potential of the piezoelectric patches, and a governing equation is obtained through the use of a finite element method and the Extended Hamilton's principle. The system is then solved in the time domain to elicit the effects of the sensor debonding in smart composite laminates. The presence of partial debonding in the sensor is investigated in frequency domain via power spectral density analysis. Temporal energy values are used to generalize the effects of partially debonded sensor for random loading conditions.

2. Mathematical formulation

2.1. Layerwise displacement field

To formulate the electromechanically coupled governing equation of the smart plate, one needs to choose the displacement and electric potential fields. Based on nature of the problem at hand, we select improved layerwise theory to model the displacement field. According to improved layerwise theory, the displacement of a point *P(x, y, z)* on a N-layered laminated composite plate is described by the superposition of the first-order shear deformation theory, layerwise functions, and a Heaviside-unit step function. A first-order shear-deformation-based displacement field is used to encode the overall response of the laminate, while the layerwise functions are employed to address the complexity of the zigzag-like in-plane deformation through the thickness of the laminate and simultaneously satisfy the shear-deformation-continuity condition at the ply interface. The discontinuity of the displacement field at the delaminated interface is addressed through the Heaviside-unit step function, along with the corresponding coefficients. As shown by Eq. (1a), the three parts of the improved layerwise theory comprise the displacement field with the delamination/debonding, as follows:

$$\begin{aligned} U_x^k(x,\ y,\ z,\ t) &= u_0 + A_1^k\psi_x + B_1^k\psi_y + C_1^k w_{0,x} + D_1^k w_{0,y} + E_1^k\left\{\bar{w}^j_{,x}\right\} \\ &\quad + F_1^k\left\{\bar{w}^j_{,y}\right\} + \sum_{j=1}^{N-1}\bar{u}_x^j(x,y,t)H(z-z_j) \\ U_y^k(x,\ y,\ z,\ t) &= v_0 + A_2^k\psi_x + B_2^k\psi_y + C_2^k w_{0,x} + D_2^k w_{0,y} + E_2^k\left\{\bar{w}^j_{,x}\right\} \\ &\quad + F_2^k\left\{\bar{w}^j_{,y}\right\} + \sum_{j=1}^{N-1}\bar{u}_y^j(x,y,t)H(z-z_j) \\ U_z^k(x,y,z,t) &= w_0(x,y,t) + \sum_{j=1}^{N-1}\bar{w}^j(x,y,t)H(z-z_j) \end{aligned} \tag{1a}$$

with

$$\begin{aligned} &A_1^k = z + a_1^k g(z) + e_1^k h(z),\ \ A_2^k = a_2^k g(z) + e_2^k h(z) \\ &B_1^k = b_1^k g(z) + f_1^k h(z),\ \ B_2^k = z + b_2^k g(z) + f_2^k h(z) \\ &C_1^k = b_1^k g(z) + e_1^k h(z),\ \ C_2^k = b_2^k g(z) + e_2^k h(z) \\ &D_1^k = b_1^k g(z) + f_1^k h(z),\ \ D_2^k = b_2^k g(z) + f_2^k h(z) \\ &\bar{E}_1^j = \bar{c}_1^j g(z) + \bar{g}_1^j h(z),\ \ \bar{E}_2^j = \bar{c}_2^j g(z) + \bar{g}_2^j h(z) \\ &\bar{F}_1^j = \bar{d}_1^j g(z) + \bar{h}_1^j h(z),\ \ \bar{F}_2^j = \bar{d}_2^j g(z) + \bar{h}_2^j h(z) \end{aligned} \tag{1b}$$

where U_x^k, U_y^k, and U_z^k denote the displacement of k-th layer along the x, y, and z axes, respectively. The quantities u_0, v_0, and w_0 are the displacements of the reference plane. The terms ψ_x and ψ_y denote the rotations of the normal-to-reference plane about the x and y axes, respectively and account for the shear deformation along the thickness of the laminate. The quantities $\bar{u}_x^j$, $\bar{u}_y^j$, and $\bar{w}^j$ represent the discontinuity in the displacement that is due to in-plane slipping and an out-of-plane separation in the delaminated regions. $H(z-z_j)$ is a Heaviside-unit step function with z_j referring to the delaminated interface. The layerwise coefficients of A_i^k, B_i^k, C_i^k, D_i^k, $\bar{E}_i^j$ and $\bar{F}_i^j$ (i=1, 2) are obtained from the geometric and material properties of the laminate, detail can be found in the reference [42]. The terms a_i^k, b_i^k, e_i^k and f_i^k (i=1, 2) are scalar coefficients at each layer, whereas $\bar{c}_i^j$, $\bar{d}_i^j$, $\bar{g}_i^j$ and $\bar{h}_i^j$ (i=1, 2) are $1\times D$ row vectors describing the slipping and opening effect due to delamination (D) at each layer. The functions $g(z)$ and $h(z)$ encode the in-plane zigzag-like deformation through the thickness. In this formulation it is assumed that the delamination exists at all of the interfaces between the layers of the laminate. A laminate with perfectly bonded laminae can be simulated by setting $\bar{u}_x^j$, $\bar{u}_y^j$, and $\bar{w}^j$ as equal to zero. The mathematical forms of $g(z)$ and $h(z)$ are as follows:

$$\begin{aligned} g(z) &= \sinh(z/h) \\ h(z) &= \cosh(z/h) \end{aligned} \tag{2}$$

The displacement field of Eq. (1a) for an N-layered composite laminate is now expressed in terms of the variables u_0, v_0, w_0, ψ_x, ψ_y, $\bar{u}_x^j$, $\bar{u}_y^j$, and $\bar{w}^j$.

2.2. Piezoelectric constitutive relations

Without a consideration of the thermal effects, the total free energy of an elastic system with piezoelectric materials can be expressed in the following form with the use of the function of the electric-enthalpy density [43]:

$$H(\varepsilon_{ij}, E_i) = \frac{1}{2}c_{ijkl}\varepsilon_{ij}\varepsilon_{kl} - e_{ijk}E_i\varepsilon_{jk} - \frac{1}{2}k_{ij}E_iE_j, \tag{3}$$

where ε_{ij} denote the components of the strain tensor, E_i represents the electric-field vector, and c_{ijkl}, e_{ijk}, and k_{ij} are the elastic-, piezoelectric-, and dielectric-permittivity constants, respectively. It is assumed that all of the material constants are measured at a constant electric field. The dielectric displacement and stress for the piezoelectric materials are obtained as follows:

$$\begin{aligned} D_i &= -\frac{\partial H}{\partial E_i} = e_{ij}\varepsilon_j + k_{ik}E_k \qquad i = 1,2,3 \\ \sigma_i &= \frac{\partial H}{\partial \varepsilon_{ij}} = c_{ij}\varepsilon_j - e_{ki}E_k \qquad i = 1,2,\ldots\ldots\ldots,6 \end{aligned} \tag{4}$$