International Journal of Solids and Structures 000 (2017) 1–16

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

A cubic spline layerwise time domain spectral FE for guided wave simulation in laminated composite plate structures with physically modeled active piezoelectric sensors

Christoforos S. Rekatsinas, Dimitris A. Saravanos*

Department of Mechanical Engineering & Aeronautics, University of Patras, University Campus, 16504, Greece

ARTICLE INFO

Article history:
Received 31 January 2017
Revised 13 June 2017
Available online xxx

Keywords:
Time domain spectral finite elements
Explicit integration scheme
Composite laminates
Layerwise mechanics
Piezoceramics
Mode conversion

ABSTRACT

A novel theoretical framework is presented enabling enhanced simulation of guided waves generated by piezoelectric actuators in laminated composite plates. A new multi-field multi-physics layerwise theory is formulated for laminated plates with piezoelectric actuators and sensors which captures symmetric and anti-symmetric stress waves. Third-order Hermite splines are employed in the approximation of displacements and electric potential through the thickness. The piezoelectric actuators and sensors are physically modeled though coupled electromechanical governing equations. An explicit time-domain spectral finite element is formulated entailing displacement and electric degrees of freedom at the nodes which are further collocated with Gauss–Lobatto–Legendre integration points. The stiffness, consistent semi-diagonal mass, piezoelectric and electric permittivity matrices are calculated. Furthermore, an explicit time integration scheme is presented for the calculation of the coupled transient electromechanical response including the free sensor response. Numerical guided wave predictions of the developed multi-node time domain spectral finite elements are correlated with well established numerical tools and with experiments conducted on laminated carbon/epoxy plates with active piezoceramic sensor networks. Important effects introduced by the physical presence of the active actuator/sensor system on guided wave propagation, such as wave reflections, mode conversions and sensor signal attenuation, are successfully captured by the developed finite element and correlated and evaluated with numerical and experimental results.

1. Introduction

In recent years, there is an increasing awareness regarding the damage diagnosis and prognosis systems in mechanical, aeronautical and civil structures. It is envisaged that passive and active damage prognosis systems can be developed which would appraise structural health, inform the user about incipient damage and provide an estimation of its remaining lifetime. Active structural health monitoring (SHM) relying on propagating waves is a prevailing approach for damage diagnosis, as it can interrogate the structure over a controlled spectrum of frequencies and wavenumbers and provide repeatable information leading to damage detection. The development of effective SHM approaches for composite structures is also urgent but more challenging. The latter cannot be a direct extension of SHM systems developed for metallic structures. Moreover, the inherent complexity of composite structures which typically span from the microstructure (~μm) to the structural scale (~m) and the likelihood of many physically different types of intralaminar damage (voids, resin cracking, broken fibers) and interlaminar damage (delaminations, joint disbonds) which may coexist in a composite structure, hidden or barely visible, set severe challenges in the development of effective and robust SHM systems.

Piezoelectric materials are the most popular choice for transducers in active guided wave (GW) SHM systems. Damage detection through built-in piezoelectrics was initially investigated by Keilers and Chang (1995) for delamination identification in composite plates, while Liang et al. (1996) developed an impedance method for dynamic analysis of active material systems. De Vera and Guemes (1998) used embedded self-sensing piezoelectrics for damage detection of small composite specimens. Wilcox et al. (2000) investigated the use of circular and linear arrays using piezo-ceramic disk actuators and linear arrays using square shear piezoceramics for long-range GW SHM in isotropic plate structures. Valdes and Soutis (2000) have experimentally and theoretically studied the propagation of low-frequency guided waves in fiber composite laminates for real-time non-destructive evaluation. Chrysochoidis and Saravanos (2004) demonstrated both ex-

---

* Corresponding author.
E-mail addresses: xrek@mech.upatras.gr (C.S. Rekatsinas), saravanos@mech.upatras.gr (D.A. Saravanos).

http://dx.doi.org/10.1016/j.ijsolstr.2017.06.031
0020-7683/© 2017 Elsevier Ltd. All rights reserved.

Please cite this article as: C.S. Rekatsinas, D.A. Saravanos, A cubic spline layerwise time domain spectral FE for guided wave simulation in laminated composite plate structures with physically modeled active piezoelectric sensors, International Journal of Solids and Structures (2017), http://dx.doi.org/10.1016/j.ijsolstr.2017.06.031

perimentally and analytically the capability of piezoelectric actuator and sensor pairs to generate vibrations and antisymmetric waves in composite strips to detect delaminations.

The previous studies suggested that the small size and complexity of damage, favor the implementation of active SHM systems relying on small wavelength ultrasonic waves. Hence, current promising and highly efficient SHM methods for composite structures tend to exploit very high-frequency linear and nonlinear vibrations and Lamb waves induced and monitored by piezoelectric actuators and sensors (Osmont et al. (2001); Kessler et al. (2002); Valdeś and Soutis (2002); Kehlenbach and Das (2002); Diamanti et al. (2007); Chrysochoidis et al. (2011); Pavlopoulou et al. (2013); Bhuiyan et al. (2016); Zhu and Lanza di Scalea (2016); Shen and Cesnik (2016)).

However, the development of active Lamb wave based SHM systems requires the improvement of available analytical and/or traditional numerical (finite element and finite difference) methods which can conduct direct and inverse analyses of associated complex wave propagation phenomena in healthy and damaged composite structures with permanently attached piezoelectric actuators and sensors. The pioneer works, by Crawley and dE Luis (1987); Jia and Rogers (1990) and Crawley and Lazarus (1991), introduce the induced -stress and -strain approach to represent the piezoelectric actuators and sensors. The aforementioned works were initially upgraded by Giurgiutiu (2005) where the force is frequency wave number dependent, by Raghavan and Cesnik (2005, 2007) with the semi analytical FE method (SAFE) and by numerous other researchers (Yu et al. (2010); Banerjee and Pol (2012); Santoni-Bottai and Giurgiutiu (2012); Shen and Giurgiutiu (2014); Dugnani and Chang (2017); Kalkowski et al. (2016)). The previous models, have undoubtedly captured many of the important effects related to the generation, propagation and detection of ultrasonic waves, but neglected the effects of actuator and sensor stiffness, mass, and so forth, which can be detrimental to the prediction of the generation, propagation and sensing of ultrasonic waves.

A large variety of advanced electromechanical models have been already reported for the static and vibrational analysis of composite structures which physically model piezoelectric actuators and sensors, including layerwise approaches and finite elements for laminated beams, plates and shells with piezoelectric devices starting with the works of Lammering (1991), Ha et al. (1992), Saravanos and Heyliger (1995), Saravanos (1997), Chen et al. (1997), Saravanos and Heyliger (1999), Varadan and Varadan (2000), Benjeddou et al. (2000), Lee et al. (2013) and Kalkowski et al. (2016), which are outlined in comprehensive reviews. The previous models manage to provide physical representations of the composite structure and the piezoelectric elements providing adequate results for static, modal and frequency response analysis, by using the traditional FEs, frequency spectral FEs and SAFE methods. However, the previous models have not been fully utilized in the modeling of active guided waves and high-frequency transient dynamic simulations.

Most of the commercially available piezoelectric finite elements implement implicit time integration formulations which require very fine spatial and temporal discretizations for the simulation of small wavelengths and ultrasonic frequencies involved in transient dynamic phenomena, leading to time-consuming intractable computations. In order to remedy the numerical shortcomings, the so-called spectral element (SE) method was equipped, which was introduced by Patera (1984) for fluid dynamics and renamed to time-domain spectral finite element (TDSFE) method for structural dynamics (Ostachowicz et al., 2012).

The TDSFE method combines high order polynomial interpolation functions and nodes collocated at Gauss–Lobatto–Legendre (GLL) quadrature points; among other advantages, TDSFEs provide diagonal consistent mass matrices which make them ideal choice for the implementation of explicit time integration methods into various applications of practical interest. For example, Komatitsch and Vilotte (1998) and Komatitsch et al. (1999) applied the TDSFE method to simulate the seismic response of two dimensional (2D) and three dimensional (3D) geological structures, respectively. A 2D membrane TDSFE was introduced for wave propagation in composite panels by Zak et al. (2006), while Kudela et al. (2007) presented several aspects of 1D elastic wave propagation, concerning the detection of small damage, illustrating the capability of TDSFE to simulate very small wavelengths with coarser spatial discretization. Peng et al. (2009) introduced a 3D TDSFE for the analysis of wave propagation in aluminum plate structures, by comparing signals from pristine and damaged specimens, in order to identify the presence of a transverse crack.

In addition, Hennings and Lammering (2012) explored the TDSFE method for the simulation of the high frequency excitation of a CFRP composite plate in order to reveal hidden delaminations between joint layers and also demonstrated the superiority of the TDSFE method versus commercial finite element analysis formulations. Furthermore, Li et al. (2012), expanded their previous work (Peng et al., 2009) for isotropic materials to composite materials, by presenting a 3D TDSFE for the identification of an artificially modeled crack. Pahlavan et al. (2012, 2013) described the development of a 2D and a 3D TDSFE, respectively, were the temporal discretization is implemented in the wavelet domain. Successful layerwise TDSFEs have been developed for the simulation of Lamb waves in laminated composite strips by Rekatsinas et al. (2015) and in thick composite sandwich plates by Rekatsinas and Saravanos (2017a).

To our best knowledge, few works have been reported thus far, on the development of explicit TDSFE methods for laminated composite structures with permanently surface bonded piezoelectric actuators and/or sensors. Kim et al. (2008) presented a 3D solid spectral element for wave propagation analysis in isotropic media with capability to model piezoelectric actuators and sensors, which was later optimized by Ha and Chang (2010). Ostachowicz et al. (2012) extended the use of piezoelectric 3D FEs for cylindrical structures, while Lonkar and Chang (2013) updated the work of Ha and Chang (2010) by introducing a 3D PZT spectral element for composite laminates, while, Ashwin et al. (2014) used layerwise kinematics, by applying compatibility conditions between consequent layers, to predict the coupled electromechanical system. Finally, to reduce the high number of degrees of freedom (DOFs) resulting from the implementation of multiple solid TDSFEs through a multi-layer piezocomposite structure, Rekatsinas and Saravanos (2017a) presented a layerwise TDSFE for thick laminated composite strips with piezoelectric actuators and sensors.

Consequently, the present paper moves a step forward and describes the development of a new 3D layerwise high-order piezolaminate theory and an associated explicit time domain spectral finite element with the aim to provide robust, accurate and fast simulations of the transient coupled electromechanical wave response in laminated composite plates with networks of piezoelectric actuators and sensors. The new finite element is founded on a recast high-order (coupled) piezoelectric laminate theory (HOPLT) which substantially extends the capabilities and flexibility of previous reported models (Saravanos et al., 1995; Plagianakos and Saravanos, 2005). Layerwise kinematic hypotheses regarding the in-plane and transverse displacements and the electric potential are implemented through the thickness of the laminate, using Hermite spline basis functions with focus on the efficient modelling of symmetric and anti-symmetric wave modes. The combination of the HOPL model with a plate TDSFE, provides the capability to decouple the order of approximation along the thickness and the plane of the laminate. Innovative features of the presented high-order piezoelectric laminate model and TDSFE, include the direct

Please cite this article as: C.S. Rekatsinas, D.A. Saravanos, A cubic spline layerwise time domain spectral FE for guided wave simulation in laminated composite plate structures with physically modeled active piezoelectric sensors, International Journal of Solids and Structures (2017), http://dx.doi.org/10.1016/j.ijsolstr.2017.06.031