Abstract

Fibre-reinforced composite laminates are increasingly used in high performance structures such as aircraft, automobiles, spacecraft, propellers, spaceships, wind turbine blades, bridges, sports and medical equipments. However, their significant anisotropic and inhomogeneous characteristics make them prone to a rather serious mode of invisible sub-surface damage, namely delamination at ply interfaces. Thus, a structural health monitoring (SHM) strategy becomes imperative for ensuring the integrity and reliability of such laminated composite structures. Lamb waves are often used for both off-line non-destructive evaluation (NDE) and online SHM for identifying the sub-surface defects in thin-walled structures. Piezoelectric wafer active sensors (PWAS) transducer patches, surface-bonded or embedded in the laminate, provide a very low cost and convenient option for actuation and sensing of high-frequency guided waves. Both model-assisted and physics-informed data-driven strategies for SHM require solving the inverse problem involving solutions of a large number of forward wave propagation problems. Thus, there is a need to develop computational models that can predict guided wave propagation in smart laminated structures accurately and at the same time efficiently.

In this thesis, a novel computationally efficient multiphysics time-domain spectral element (TDSE) model is presented for simulating Lamb waves in smart composite strips (beams and panels) integrated with surface-bonded or embedded patch or full layers of PWAS transducers, featuring delaminations in the host laminate. The delaminations are modelled using the region approach based on the free mode assumption. A new C^1-continuous spectral interpolation using the Gauss–Lobatto–Legendre basis is proposed, which is shown to eliminate the Runge phenomenon observed in the conventional higher-order Hermite interpolation. This interpolation function is used in an efficient layerwise zigzag theory (ZIGT) for kinematics, which combines with a piecewise quadratic variation for the electric potential field to develop an electromechanically coupled formulation for modelling intact host laminate, patch transducer-bonded laminates, and sub-laminates between adjacent delamination. The normal deformation

caused by the electric field is incorporated in the deflection without introducing additional displacement variables beyond the smeared third-order theory (TOT). The high-order multifield TDSE based on this coupled ZIGT has n physical nodes containing mechanical and electric degrees of freedom (DOFs) and a separate virtual electric node for modelling the transducers' equipotential surfaces with significantly reduced DOFs. The recently proposed hybrid point-least squares continuity (HPLSC) method is adapted for the spectral strip element to satisfy the continuity of the nonlinear in-plane displacement field across the laminate thickness at the delamination fronts. These conditions are imposed using a transformation matrix that relates the nodal DOFs of the sub-laminate at the delamination front to those of the intact laminate. In addition, the segment integrated with PWAS is connected to the host segment via the patch fronts at which the continuity is maintained using the same advanced HPLSC model. The methodology offers a general framework for modelling multiple delaminations and surface-bonded or embedded transducer patches at arbitrary interfacial or longitudinal locations. The coupled semi-discrete governing equations of motion for the piezolaminated system are derived using the Hamilton's principle.

The developed spectral element is validated and critically assessed on the basis of accuracy, efficiency, and convergence through a comprehensive numerical study for static, free vibration, and wave propagation analyses of elastic and piezoelectric smart composite strips, with and without delaminations. The Lamb wave propagation examples are selected so as to represent actual SHM applications. The present results are validated using experiments on the actuation and sensing of guided waves and compared to the previously published data, analytical ZIGT solutions, continuum-based finite element solutions from ABAQUS, and different laminate theory-based solutions. It is shown that the present element yields excellent accuracy with much faster convergence, higher computational efficiency and many-fold reduction in computational time than its conventional finite element counterpart for narrowband high frequency guided wave propagation problems in both undamaged and damaged strips. The role of the slope discontinuities in the in-plane displacement approximation is delineated by comparing it with the smeared TOT-based SE solution with the same number of DOFs. The effect of imposing continuity at the patch fronts is investigated for free vibration and wave propagation responses of the smart strips. The developed model is used to study the interaction of Lamb waves with notch-type damages. Finally, the effect of delamination on sensor signal due to Lamb wave propagation in smart composite strips is also studied to explore the identification of interfacial location and sizing of delamination damage. This development will directly benefit the model-based and physics-informed data-driven SHM of composite structures.