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An efficient computational approach for control of nonlinear transient responses of smart piezoelectric composite plates

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ABSTRACT

An efficient computational approach based on a generalized unconstrained approach in conjunction with isogeometric analysis (IGA) are proposed for dynamic control of smart piezoelectric composite plates. In composite plates, the mechanical displacement field is approximated according to the proposal model using isogeometric elements and the nonlinear transient formulation for plates is formed in the total Lagrange approach based on the von Kármán strains and solved by Newmark time integration. Through the thickness of each piezoelectric layer, the electric potential is assumed linearly. For active control of the piezoelectric composite plates, a close-loop system is used. An optimization procedure using genetic algorithm (GA) is considered to search optimal design for actuator input voltages. Various numerical examples are investigated to show high accuracy and reliability of the proposed method.

1. Introduction

Piezoelectric materials belong to a smart material class that expresses electromechanical coupling. The development of smart structures integrated with sensors and actuators offers a considerable interest in many engineering applications: structural health monitoring, automotive sensors, actuators, vibration and noise suppression, shape control and precision positioning, etc. The main feature of smart materials is transformation between mechanical energy and electric energy. When the application of electric field to piezoelectric structures is considered, the mechanical deformation is generated. This is known as the converse phenomenon of piezoelectric effect [1,2].

With the advantages of piezoelectric materials, various numerical methods have been devised. Mitchell and Reddy [3] presented the classical plate theory (CPT) using the third order shear deformation theory (TSDT) to obtain the Navier solution for composite laminates with piezoelectric lamina. Suleman and Venkayya [4] used the classical laminate theory (CLT) with four-node finite element to investigate static and vibration analyses of a laminated composite with piezoelectric layer based on hourglass stabilization and reduced numerical integration Victor et al. [5] developed the higher order finite formulations based on an analytical solution to investigate the mechanics of composite structures integrated with actuators and sensors. Liew et al. [6] studied post-bucking of FGM plates integrated with piezoelectric under thermo-electro-mechanical loadings using a semi-analytical solution with Galerkin differential quadrature integration algorithm based on the higher-order shear deformation theory (HSDT). The radial point interpolation method (RPIM) combined with the first order shear deformation theory (FSDT) and the CPT with rectangular plate bending element were investigated by Liu et al. [7,8] to compute and simulate the static deformation and responses of smart plates. In addition, Hwang and Park [9] studied piezoelectric plates using the discrete Kirchhoff quadrilateral (DKQ) element and the Newmark β -method to analyze the direct time responses of the plate subjected to negative velocity feedback control. A HSDT-layerwise generalized finite element formulation [10] and the layerwise based on analytical formulation [11] were investigated to study piezoelectric composite plates. Finite element (FE) formulations based on HSDT for analysis of smart

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laminated plates was studied in [12]. Ray and Mallik [13] used FEM to study smart structures containing piezoelectric fiber-reinforced composite actuator. Nonlinear analysis for composite structures using some finite element methods (FEMs) were reported in Refs. [14–16]. It was proved in [17] that free vibration analysis using FEM leads to less accurate solution for high frequencies. Such shortcomings become more challenges in coupled-field problems as piezoelectric structures.

For vibration control, Bailey et al. [18] and Shen [19] investigated smart beams integrated with layers using analytical solutions. Tzou and Tseng [20] used a thin hexahedron solid element to examine dynamic control of piezoelectric plates and shells. The meshfree model based on FSDT was presented by Liew et al. [21] to simulate shape control of piezoelectric composite plates with different boundary conditions. Wang et al. [22] used FEM to investigate dynamic stability of piezoelectric composite plates, where the governing equations of motion using Lyapunov's energy [23] with active damping was used. Active control of geometrically nonlinear of composite structures was examined in Refs. [24,25]. Recently, isogeometric analysis (IGA) has been developed to investigate the piezoelectric composite plates by Phung-Van et al. [26]. However, nonlinear transient analysis has not considered in their previous work.

For optimal control, Kumar et al. [27] and Rao et al. [28] used GA to study the optimization problems for finding optimal piezo location on a cantilever plate and a two-bay truss. Chang-Qing et al. [29] investigated optimal control of piezoelectric structures using independent modal space control (IMSC). Optimal location of piezoelectric using GA for vibration control of structures was investigated by Bruant et al. [30]. In their work, two variables for each piezoelectric device in an optimization problem, the location of its center and its orientation, are considered. A closed-form solution based on the linear quadratic regulators (LQR) for the optimal control of piezoelectric composite plates was reported in [31].

It is known that FSDT requires the shear correction factors to ensure stability of solutions, but high accuracy of stresses is not guaranteed. HSDTs have then been developed to overcome the shortcomings of FSDT without any shear correction factors. Among HSDTs, the unconstrained third order shear deformation theory (UTSDT) [32] showed an alternative and effective approach for laminated plate structures. In addition, UTSDT allows us to relax traction-free boundary condition at the bottom and the top surfaces of plates, which is commonly required in HSDTs. The appearence of the unconstrained theory opens future applications of the UTSDT to the problems considering flow field in which the boundary layer of stresses is significant. The differential equations for UTSDT are of similar complexity to those of TSDT. This approach produces more accurate solutions [33]. Responses of the laminated plates using UTSDT were also investigated in [33]. Static and free vibration analyses of composite plates using radial point interpolation method (RPIM) combined with UTSDT were reported in [34]. In UTSDT, the displacement field includes seven displacement components. More importantly, we here propose a generalized unconstrained HSDT that also uses seven displacement components like UTSDT, but higher order rotations depend on an arbitrary function $f(z)$ through the plate thickness.

Hughes et al. [35,36] developed isogeometric analysis (IGA) with the original objective of integrating Computer Aided Design (CAD) and FE analysis. The basic functions of IGA are the same with those of CAD (most notably NURBS or T-Splines). One of features of IGA is that it can easily achieve any desired degree of basic functions through the choice of the interpolation order, as opposed to traditional FEM where C^0 inter-element continuity is normally achieved. In the past few years, IGA has been successfully applied to various fields. Particular relevancy to this paper is the study of structural vibrations and the development of shell and plate isogeometric elements [37–45]. So far, there are few papers related to nonlinear analysis using IGA for composite plates based on FSDT [46,47], Euler–Bernoulli beams [48], shells [49] and so on. Apparently, there are no researches on geometrically nonlinear transient based on isogeometric analysis for the piezoelectric composite plates. Hence, we propose an efficient approach to fill this research gap via a generalized UHSDT and IGA. For reference, it is termed as IGA-UHSDT. The method will be applied for active control of geometrically nonlinear transient responses and optimization of smart piezoelectric composite plate structures. The IGA-UHSDT is used to approximate the displacement field of smart plates. Through the thickness of each piezoelectric layer, the electric potential is assumed linearly. The nonlinear transient formulation for plates is formed in the total Lagrange approach based on the von Kármán strains and solved by Newmark time integration. An optimization procedure based on GA is considered to find optimal input voltages. The reliability and accuracy of the method are confirmed by numerical examples.

2. A brief of NURBS basis functions

A knot vector $\Xi = \left\{\xi_1, \xi_2, ..., \xi_{n+p+1}\right\}$ is defined by a sequence of parameter values $\xi_i \in \mathbb{R}$, $i = 1, ..., n+p$. The knot vector is called open knot if the first and the last knots are repeated $p+1$ times. A B-spline basis function is C^∞ continuous inside a knot span and C^{p-1} continuous at a single knot. The associated B-spline basis functions are defined recursively starting with the zeroth order basis function ($p=0$) and a polynomial order $p \geq 1$,

$$N_{i,p}(\xi) = \frac{\xi - \xi_i}{\xi_{i+p} - \xi_i} N_{i,p-1}(\xi) + \frac{\xi_{i+p+1} - \xi}{\xi_{i+p+1} - \xi_{i+1}} N_{i+1,p-1}(\xi)$$
$$\text{as } p=0,\ N_{i,0}(\xi) = \left\{ \begin{array}{ll} 1 & \text{if } \xi_i \leq \xi < \xi_{i+1} \\ 0 & \text{otherwise} \end{array} \right\} \quad (1)$$

From the tensor product of basis functions with two knot vectors $\mathbf{H} = \left\{\eta_1, \eta_2, ..., \eta_{m+q+1}\right\}$ and $\Xi = \left\{\xi_1, \xi_2, ..., \xi_{n+p+1}\right\}$ the B-spline basis functions can be obtained as

$$N_A(\xi, \eta) = N_{i,p}(\xi) M_{j,q}(\eta) \quad (2)$$

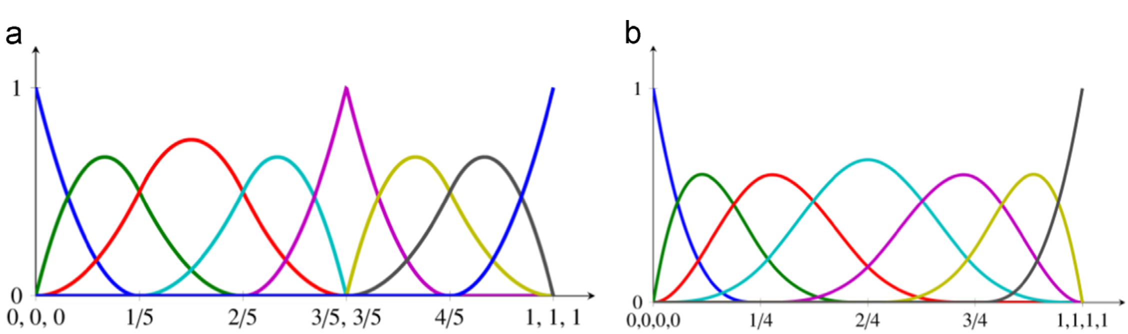

Fig. 1. B-splines basic functions: (a) univariate quadratic and (b) univariate cubic.