Available online at www.sciencedirect.com

SCIENCE DIRECT®

Comput. Methods Appl. Mech. Engrg. 193 (2004) 4475–4492

Computer methods in applied mechanics and engineering

www.elsevier.com/locate/cma

On the use of computational intelligence in the optimal shape control of functionally graded smart plates

K.M. Liew [a,b,*], X.Q. He [b], Tapabrata Ray [c]

[a] *School of Mechanical and Production Engineering, Nanyang Technological University, Nanyang Avenue, 639798, Singapore*
[b] *Nanyang Centre for Supercomputing and Visualisation, Nanyang Technological University, Nanyang Avenue, 639798, Singapore*
[c] *Temasek Laboratories, National University of Singapore, 5 Sports Drive 2, 117508, Singapore*

Received 15 July 2003; received in revised form 5 November 2003; accepted 19 February 2004

Abstract

Functionally graded material (FGM) plates are an essential component for most advanced integrated systems in terms of vibration and acoustic controls or condition monitoring. In general, these FGM plates are designed with embedded piezoelectric sensors and actuators to achieve their shape control. This optimal control problem is normally required to find appropriate actuator voltage and displacement control gains that will generate the desired shape. Such an optimal control problem is known to be highly non-linear and often posses slope and functional discontinuity that will limit the efficiency of the gradient based methods. Stochastic, zero-order, population-based optimization methods are ideal for solving this class of problems. In this paper, we introduce a stochastic, zero-order optimization algorithm based on the principles of learning. This algorithm is embedded with three key learning strategies that control *who to learn from* (i.e. leader identification and leader selection) and *what to learn* (i.e. information acquisition) to reach a common goal. The leader identification mechanism partitions the individuals into a set of leaders and a set of followers. The followers interact with the leaders and move toward the better performing leaders in searching for better solutions. The parameter-free algorithm provides the designer with the true flexibility that is necessary to handle various forms of design problem effectively and at a computational cost that is comparable to existing stochastic optimization methods. In this study, numerical results are presented for the shape control of the FGM plates under a temperature gradient by optimizing (i) the voltage distribution for the open loop control, and (ii) the displacement control gain values for the closed loop feedback control. We also examine the effect of the constituent volume fractions of zirconia, through the varying of volume fraction exponent n, on the optimal voltages and gain values.

Keywords: FGM; Optimal shape control; Computational intelligence; FEM; Smart plates

---

[*] Corresponding author. Address: Nanyang Centre for Supercomputing and Visualisation, School of Mechanical and Production Engineering, Nanyang Technological University, Nanyang Avenue, 639798, Singapore. Tel.: +65-6790-4076; fax: +65-6793-6763.
E-mail address: mkmliew@ntu.edu.sg (K.M. Liew).

0045-7825/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.cma.2004.02.016

1. Introduction

A smart functionally graded (FG) structure is constructed by integrating intelligent and active materials, such as piezoceramics, in a host structure within which material properties vary continuously and inhomogeneously. FG structures contain different compositional concentrations of a desirable second phase material leading to smooth and continuous spatial variations of the properties across its thickness. They were first developed by the Japanese in the late 1980s, and since then this class of materials have attracted a number of investigators (see [1–4]). In general, functionally graded materials (FGMs) are made from a mixture of ceramics and metals. The ceramic constituents of the FGMs are able to withstand high temperature environments due to their better thermal resistance characteristics, while the metal constituents provide stronger mechanical performance and reduce the possibility of catastrophic fracture.

Embedding a network of piezoceramic actuators and sensors within the FG structure creates a self-controlling and self-monitoring smart system. This newly engineered class of materials has resulted in significant improvements in the performance of integrated systems, actuation technologies, shape control, vibration and acoustic control, and condition monitoring.

Many researchers have recently focused their attention on the use of piezoelectric materials as sensors and actuators for the active control of structures. Most of the effort, however, has been directed toward the vibration control of structures. Examples of these include the exact analytical solution provided by Rivory et al. [5] for the dynamic response of a simply-supported beam excited by a pair of out of phase piezoelectric actuators, by Chen et al. [6] for laminated cylindrical shells with piezoelectric layers, by Reddy [7] for the Navier solution of laminated composite plates with integrated sensors and actuators, and by Liew et al. [8] for the mesh-free solution of the active control of composite beams and plates with piezoelectric layers under different dynamic loading conditions. Finite element models have been proposed by Allik and Hughes [9], Lammering [10], Hwang et al. [11], Liew et al. [12–15], and He et al. [16,17] for the dynamic analysis and control of more complicated structures, such as laminate beams, plates and shells with piezoelectric patches, and functionally graded plates and shells that are subjected to thermal loading. In these studies, the third-order theory of Reddy, the classical laminate plate theory (CLPT), first-order shear deformation theory (FSDT), and layerwise laminate theory have been presented for thin and moderately thick plates and shells. Various control algorithms, based on the direct feedback of displacement, velocity, and acceleration, have been applied, and various controllers, such as the Linear Quadratic Gaussian with Loop Transfer Recovery (LQG/LTR), the Independent Modal Space Control (IMSC), and the neural network controllers, were designed for the effective control of vibration.

In contrast to vibration control, less work has been carried out on the shape control of structures. Koconis et al. [18] first investigated the shape control of composite plates and shells with embedded actuators. They carried out the bending analysis of composite beams, plates, and shells using the Rayleigh–Ritz method to determine the voltages that are needed to achieve a specified desired shape. Their method was formulated on the basis of mathematical models using two-dimensional, linear, shallow shell theory including transverse shear effects. Chandrashekhara and Varadarajan [19] developed finite element model for the adaptive shape control of composite beams. They based the finite element model on a higher-order shear deformation theory and accounts for lateral strains, and implemented a constrained optimization algorithm to obtain the desired shape of beams. Wang et al. [20] derived analytical expressions and optimality conditions for determining the input voltages to be applied to the piezoelectric actuators to bend the beam to the desired shape. The obtained optimal voltages for various beam problems serve as benchmarks for the validity, convergence, and accuracy of numerical results from other numerical methods. Tong et al. [21] presented analytical models and solutions for the shape control of composite thin plates with piezoelectric actuators. Ribeiro et al. [22] applied the Genetic Algorithm (GA) for the optimal design and control of beams and plates. The finite element method was used for the analysis of the bending and vibration analysis of beams and plates. Only input voltages were considered as variables. Feedback control gains