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Multiobjective design optimization of laminated composite plates with piezoelectric layers

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ABSTRACT

A methodology of multiobjective design optimization of laminated composite plates with piezoelectric layers is presented in this paper. Constrained optimization is conducted for different behaviour objectives, like the maximization of buckling load or natural frequencies of specific vibration modes or prescribed displacements for example. Weight minimization can also be considered or the minimization of the electric voltages applied in the piezoelectric actuators. The optimization problems are constrained by stress based failure criteria and other structural response constraints like limits imposed on certain displacements, buckling characteristics and natural frequency constraints. The design variables considered in the present work are the fiber reinforcement orientations in the composite layers, thicknesses of individual layers and the electric potentials applied to the actuators.

The optimization problems are solved with two direct search derivative-free algorithms: GLODS (Global and Local Optimization using Direct Search) and DMS (Direct MultiSearch). DMS, the multiobjective optimization solver, is started from a set of local minimizers which are initially determined by the global optimizer algorithm GLODS for each one of the objective functions.

1. Introduction

Developments in smart composite structures incorporating integrated piezoelectric sensors and actuators offer potential benefits in a certain range of engineering applications such as structural health monitoring, vibration and noise suppression, shape control and precision positioning. Accurate and efficient numerical tools able to support the structural design process of these structures are very important.

It has been demonstrated that classical laminate theory and also first order shear deformation theory can lead to substantial errors in the prediction of stresses of highly anisotropic and/or thick to moderately thick composite plates in general and also when the case of embedded or surface bonded piezoelectric layers are incorporated [1–3]. Refined and complex numerical models of laminated composite structures using three-dimensional finite elements can give accurate results by setting computationally expensive refined meshes, but a good compromise could be obtained with alternative less expensive equivalent single layer models based on higher order shear deformation theories involving higher order expansions of the displacement field in powers of the thickness coordinate. It has been shown that these models can accurately account for the effects of transverse shear deformation yielding quadratic variation of out-of-plane strains, not requiring the use of artificial shear correction factors, and could be suitable for the analysis of highly anisotropic laminated plates ranging from high to low length-to-thickness ratios. In what concerns sandwich plates with very soft cores and stiff skins these equivalent single layer models, even based on more sophisticated higher order shear deformation theories do not perform so well and special attention has to be given to those cases, as recently shown by Moita et al. [4].

It is important to adopt sufficiently accurate but also computationally efficient finite element models, based in appropriately selected shear deformation theories, to be used in the optimization of composite laminated plates. This is especially important when the optimization techniques could involve a high number of objective function evaluations.

The Direct MultiSearch (DMS) [5] solver for multiobjective optimization problems do not use any derivatives of the objective functions. It is based on a novel technique called Direct MultiSearch, developed by extending direct search from single to multiobjective optimization. It has been recently applied to find the

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optimal positioning of surface bonded sensors and actuators for damping maximization in a given frequency range [6] and also to solve the problem of minimum weight and maximum damping of a viscoelastic sandwich plate [7,8], among several other applications.

In the present work, a previously developed equivalent single layer finite element model based on a higher-order shear deformation theory, which has been successfully applied to composite laminated plates and sandwiches with adaptive capabilities achieved through the use of piezoelectric layers working as sensors and actuators [1–3,9], has been used with the DMS solver for multiobjective design problems [5,10]. A very brief description of the finite element displacement field and equilibrium equations are presented and the reader is addressed to previous works for further development details. The GLODS [11] method for single objective optimization and the DMS [5] method for multi-objective optimization are both described. Two illustrative cases of multiobjective optimization problems are presented: one involving the maximization of buckling load and natural frequencies of a skew plate, with the stacking orientation angles of the fibers in the reinforced layers as design variables; and the second involving the minimization of the weight, the maximization of the actuation effect and the minimization of the electric potentials applied to the actuators, in a classical cantilever plate/actuator specimen used by Crawley and Lazarus [12], with the thicknesses of the substrate layers and the electric voltages at the actuators considered as design variables, subject to stress based failure criteria constraints both in the brittle piezoceramic actuators and in the substrate layers.

From the published works related with this area it should be mentioned the recent paper from Honda et al. [13] who proposed a multi-objective optimization approach for fibrous composite plates with curvilinear fibers using the non-dominated sorting genetic algorithm (NSGA-II) to obtain Pareto optimum solutions, by establishing a trade-off relation between the mechanical performance and the curvatures of the reinforcing fibers and studied the strength around a circular hole in a plate using the Tsai-Wu failure criteria or the fundamental frequency for the objective function, while the average value of fiber curvatures was used as the conflicting objective function.

Also, very recently, Kalantari et al. [14] have presented a so-called multi-objective robust optimization, based on a modification of an elitist non-dominated sorting genetic algorithm (NSGA-II), of hybrid composites with carbon and glass fiber-reinforced layers, respectively placed at the tensile side and compressive side of the laminate subject to bending. In their work the conflicting objectives for optimization were to minimize the cost and weight of the composite subject to a constraint related with a minimum flexural strength of the laminate and the design variables were the fiber angles and the thickness of the laminas.

Ghiasi et al. [15] have stated that to solve multi-objective design problems it is required an efficient multi-objective optimization algorithm and the evolutionary algorithms were popular for this purpose, due to its simplicity and minimum involvement of the user. However they are slow in convergence and these authors have presented a NSGA-II hybridized with a local search algorithm based on the Nelder-Mead simplex method to improve its convergence rate and quality of the solutions. The constrained-domination was used to handle the inequality constraints in constrained optimization problems.

Narita [16] has proposed a layerwise optimization approach based on the physical observation that the outer layer has more stiffening effect than the inner layer in bending of laminated plates, and therefore the outer layer was considered to be a more influential factor in determining the maximum natural frequency of the plate. Related work has been done by Honda and Narita [17] combining a layerwise optimization and a genetic algorithm in studies aiming the improvement of natural frequencies in plates with local anisotropy induced by short fibers and curvilinear fibers.

Campen et al. [18] have studied the optimal fiber angle distribution, for variable stiffness laminates, using a two-step approach, where first the composite is designed in terms of the lamination parameters and secondly the lamination parameters are converted into fiber orientation angles for each layer in the laminate, exploiting the advent of advanced fiber placement technology which has made possible the fiber steering through the laminate.

Ijsselmuiden et al. [19] proposed a multi-step framework for design of composite panel assemblies and subsequent blending of the designs to ensure laminate continuity across multi-panel configurations, where the structure was first optimized using panel thickness and lamination parameters as continuous design variables and in a second step the authors obtained the discrete blended stacking sequences using a genetic algorithm.

Two review papers have been published by Ghiasi et al. [20,21] addressing the optimum stacking sequence of laminated composite materials with constant stiffness and variable stiffness designs, respectively. The challenges of this problem which can be expressed by both discrete and continuous variables were discussed, the main optimization methods were described, namely gradient-based methods, direct search and heuristic methods, specialized techniques, and hybrid methods, their features were compared, and the potential areas requiring more investigation were highlighted. As pointed out by these authors, for optimum stacking sequence problem, gradient-based methods were found to be generally faster than other techniques and normally are able to find a local minimum in a small number of iterations, however they are limited to problems with continuous design variables and first or second derivatives (either exact or approximate) and when a local optimum is reached the final solution depends on the initial point. This is well known as an important limitation of those methods. In contrast, direct search methods are popular because no derivatives need to be calculated and due to their capabilities of handling a mixture of continuous and discrete variables, finding the global optimum of a multi-modal objective function and working with a population of solutions.

Concerning the studies involving the optimal placement of piezoelectric actuators in composite structures, Chhabra et al. [22] have studied the optimal placement of piezoelectric actuators on a thin plate using the modified control matrix and singular value decomposition approach and the maximization by using a modified heuristic genetic algorithm. Honda et al. [23] have proposed a multidisciplinary design process considering the placement of piezoelectric actuators in composite plates and the lay-up configurations for optimum vibration suppression by using a genetic algorithm.

Concerning the studies related with the electric voltage distribution at the actuators, Kang et al. [24] have investigated the combined optimization of a two-phase material layout controlled by a power-law and the actuation voltage distribution applied to structures with embedded in-plane piezoelectric actuators. The optimization problem was solved by the Method of Moving Asymptotes and the derivatives of the objective function were obtained by sensitivity analysis using the adjoint variable method, not guaranteeing that the global optimum was obtained for the final solutions.

Mehrabian and Yousefi-Koma [25] presented an approach for optimizing the location of piezoelectric actuators for vibration suppression on a flexible fin with bonded piezoelectric actuators by recording the frequency response function (FRF) of the system and the maximization of the FRF peaks was considered as the objective function to find the optimal placement of the piezoelectric actuators. Neural networks were employed to perform surface