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Bat-inspired optimization of multilayered adaptive structures

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ABSTRACT

Adaptive structures constituted by composites and smart materials is a remarkable engineering combination that join together the already known composites' advantages and the possibility of actively control the mechanical response of a structure. These versatile structures are able to react and interact with their surrounding environments, continuously, to accomplish specific objectives. In this work, the main objective is to study, model and predict the mechanical behaviour of adaptive structures by programming the finite element method and optimization algorithms based on micro-bats' echolocation capacity. An integrated symbolic-numerical-graphical package devoted to the analysis of plate/beam-type structures and its meta-heuristic optimization is implemented, with capabilities of simulating active multilayered structures, constituted by a variable number of different material models. Graded mixtures of piezoelectric particles and non-active materials are also modelled along the structures' length direction. A set of illustrative case studies are performed, for different types of structures and materials and the results obtained are discussed and conclusions are drawn.

1. Introduction

The combination of different types of materials has been used in a wide range of engineering applications, where composite materials play a crucial role in terms of structural design. In comparison with conventional isotropic metallic structures, composites have a great advantage which is related to the possibility to tailor the material's constituents in order to optimize the contribution of its different constituent phases' properties. Moreover, by incorporating active materials, composite structures may become controllable when required (actively and continuously), to accomplish a set of functional objectives. This synergic combination has been widely studied by the scientific and industrial communities, and promising and innovative features continue to be expectable in the future, throughout numerous engineering fields, e.g. aerospace, automotive, biomedical, etc. This effort is particularly visible in the review works carried out by a few researchers.

Some of these, Sun et al. [1] carried out a relevant state-of-the-art review concerning smart materials and structures on morphing aircraft applications, also showing that shape memory alloys are also being incorporated on structures in this field. These authors concluded that smart materials and structures are not currently suitable for aircraft production, proposing the following five main research challenges, in order to understand the full potential of these devices: *material modification*, *functional additives*, *structure optimization*, *hybrid applications* and *novel smart materials*.

Ferreira et al. [2] developed a state-of-the-art review about multifunctional material systems, including smart ones. The authors enumerated several main fields where the research on Functionally Graded Materials (FGMs) is currently focused on, including thermal and mechanical loading, fracture properties (crack propagation analysis), innovation concerning manufacturing processes, numerical simulation of FGMs and the use of piezoelectric materials/carbon nanotubes mixed with FGMs. One of the major conclusions from this review has to do with manufacturing characteristics: these are still an important issue in terms of costs. In fact, several innovative ideas of material distributions/mixtures included in the present case studies would need further investigation, especially when mixing piezoelectric particles with passive matrices.

On the context of the optimization studies, we may refer a recent work due to Correia et al. [3] which developed a study on the multi-objective design optimization of laminated composite

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plates, incorporating smart materials. Several objectives were considered, namely the maximization of natural frequencies and the weight minimization. As Design Variables (DVs), the authors considered the layers' fibre orientation angles, the thickness and the electric potentials. Two optimization algorithms were used in their study, namely the Direct Search and Direct Multi-Search methods. It may be concluded from the published works that, nature-inspired optimization techniques have been increasingly adopted. According to Kar [4] the optimization trend in terms of algorithms is the following: when the complexity of problems increases, the need to use bio-inspired heuristic algorithms increases too. Among a wide diversity of techniques, and taking into account the one that will be used in the present work, we refer the Bat-Algorithm (BA), an algorithm based on the behaviour of micro-bats. Xin-She Yang developed the traditional version of BA in 2010, which was found to be very efficient [5]. After that, BA has been evolving and several versions of it were created, mixed up with other optimization methods and used in different applications. For instance, the Modified Bat Algorithm by Huang et al. [6] and Fuzzy Logic Bat Algorithm by Khan and Sahai [7]. Still about bat-inspired optimization, focusing on structural optimization, Hasançebi et al. [8] is a relevant example concerning this engineering optimization approach. The authors used BA to evaluate its performance using one benchmark example, as well as three practical truss structures that were sized for minimum weight subject to stress, stability and displacement constraints according to design standard specifications.

In the present work, another BA variation is proposed, in order to improve its original performance, when optimizing multilayered smart structures. This new algorithm version was named Micro-Hybrid-Bat-Agorithm (MHBA). The goal is to use the capabilities already implemented by other authors in both BA and Hybrid-Bat-Algorithm (HBA), this latter including Differential Evolution (DE) perturbation factors, by adding them the micro-Genetic Algorithm (GA) technique to increase the exploration capabilities of the non-linear meta-heuristic approach and avoid local optima. These three optimization algorithms interact directly and automatically with a Finite Element Method (FEM) algorithm developed in this work to simulate multilayered plane elements (beams and plates). Three different optimization case studies, supported by validation studies, were developed to test the performance of this numerical-symbolic programming package.

2. Models and methods

The present section summarizes the most relevant methodologies that support the study carried out. First, the electromechanical constitutive equations are presented. Hence, the material models are assessed, ranging from orthotropic (monoclinic) and piezoelectric materials, towards smart FGMs along a specified structure's direction. Afterwards, the finite element modelling is described, divided into two phases, in order to address the equations of motion, as well as both displacements and strains approximations; this subsection focusing on the electromechanical coupling between both mechanical and electric fields.

2.1. Constitutive equations

Accounting for both mechanical and electrical effects of materials (if they exist) in a generic multilayered structure, the following constitutive relations apply:

$$\begin{aligned} \{\sigma\} &= \left[\overline{Q}(x,y,z)\right]\{\epsilon\} - \left([\overline{e}(x,y,z)]\right)^{\mathrm{T}}\{\mathscr{E}\} \quad \text{(converse effect)} \\ \{\mathscr{D}\} &= [\overline{e}(x,y,z)]\{\epsilon\} + [\overline{\varepsilon}(x,y,z)]\{\mathscr{E}\} \quad \text{(direct effect)} \end{aligned} \tag{1}$$

where T is the transpose operator, vectors $\{\sigma\}, \{\epsilon\}, \{\mathscr{E}\}$ and $\{\mathscr{D}\}$ contain components associated with different directions of, respectively, stresses, strains, electric field and electric displacement. $\left[\overline{Q}(x,y,z)\right], [\overline{e}(x,y,z)]$ and $[\overline{\varepsilon}(x,y,z)]$ are, respectively, the transformed plane stress-reduced elastic, stress-charge piezoelectric and permittivity coefficients matrices. The electromechanical coupling defined through this constitutive equations, may be separated into both *converse* and *direct* effects, associated with the piezoelectric materials. All material coefficients can depend on *x*-, *y*- and *z*-direction, as the present algorithm is able to model FGMs concerning spatial variation in length, width and thickness directions (individually or at the same time, considering different material layers). The electric field is represented as:

$$\{\mathscr{E}\} = -\nabla\phi(x,y,z,t) = -\begin{Bmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{Bmatrix}\phi(x,y,z,t) = \begin{Bmatrix} \mathscr{E}_x \\ \mathscr{E}_y \\ \mathscr{E}_z \end{Bmatrix} \tag{2}$$

this electric field can be related to the electric potential by using the gradient vector ∇, considering the present linear piezoelectric constitutive behaviour. This way, retrieving the methodology from Loja et al. [9] and considering polarization only in the thickness direction, i.e. $\mathscr{E}_x = \mathscr{E}_y = 0$, the electric field component associated with the *z*-direction can be defined according to the following equation:

$$\mathscr{E}_z = -\frac{\phi(x,y,z,t)}{h_k} \tag{3}$$

this way, each electric field associated with each different layer *k* is a function of its thickness h_k.

2.2. Materials

2.2.1. Piezoelectrics and monoclinics

Modelling smart structures and predicting its behaviour generally implies coping with different types of passive and active materials. To this purpose their constitutive equations have to be considered, considering the coupling between different physical fields. In the present work the most general situation is related to the existence of orthotropic layers as passive materials and piezoelectric patches or layers as active elements, which may be polarized along direction 3, i.e. along the beams'/plates' thickness [10]. The elastic mechanical field associated to the composite material is described by the stress–strain relation:

$$\{\sigma\} = [Q]\{\epsilon\} \Longleftrightarrow \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & Q_{13} & 0 & 0 & Q_{16} \\ Q_{12} & Q_{22} & Q_{23} & 0 & 0 & Q_{26} \\ Q_{13} & Q_{23} & Q_{33} & 0 & 0 & Q_{36} \\ 0 & 0 & 0 & Q_{44} & Q_{45} & 0 \\ 0 & 0 & 0 & Q_{45} & Q_{55} & 0 \\ Q_{16} & Q_{26} & Q_{36} & 0 & 0 & Q_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \gamma_4 \\ \gamma_5 \\ \gamma_6 \end{Bmatrix} \tag{4}$$

where $[Q]$ is the elastic coefficients matrix associated with the material of the active layer *k* in question. Since the First-Order Shear Deformation Theory (FSDT) was considered (5 Degrees Of Freedom (DOFs) per node) to implement the FEM procedures, the transformed plane stress-reduced coefficients are described as follows, starting with the elastic ones [11]: