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Simultaneous optimization of photostrictive actuator locations, numbers and light intensities for structural shape control using hierarchical genetic algorithm

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ABSTRACT

The present paper introduces an investigation into simultaneous optimization of the PbLaZrTi-based actuator configuration and corresponding applied light intensity for morphing beam structural shapes. A finite element formulation for multiphysics analysis of coupled opto-electro-thermo-mechanical fields in PbLaZrTi ceramics is derived and verified with the theoretical solution and the commercial software ANSYS. This element is then used to simulate beam bending shape control using the orthotropic PbLaZrTi actuators and the simultaneous optimization. In this procedure, the controlling and geometrical variables are simultaneously optimized via a hierarchical genetic algorithm. A bi-coded chromosome is proposed in a hierarchical mode, which consists of some control genes (i.e. actuator location and number) and parametric genes (i.e. applied light intensity). Whether the parametric gene is activated or not is managed by the value of the first-grade control genes. The numerical results demonstrate that the achieved beam bending shapes correlate remarkably well with the expected ones and the simultaneous optimization of photostrictive actuator locations, numbers and light intensities can result in optimal actuator layout with less PbLaZrTi actuators and irradiated light energy. The simulation results also show that the hierarchical genetic algorithm has more superior performance over the conventional real-coded genetic algorithm.

1. Introduction

Static structural shape control is one key application of smart structures with embedded or surface mounted actuators and/or sensors using intelligent materials, such as piezoelectric (PZT) actuators and shape memory alloys (SMA). In this application, it is required that the intelligent structure is able to morph its shape to fulfill evolutionary structural property demands in response to alterations in circumstances and operating situations. At present, the research on the application of piezoelectric actuator concentrates mainly on two parts. One is active shape control for beam, plate and shell structures. The other is vibration reduction.

For static shape and vibration control, the allocation of piezoelectric actuators and associated electrical voltage distribution are crucial design parameters for performing an expected structural property. Considerable investigations have been dedicated to explore the optimized allocation of the PZT actuators in active vibration or sound radiation control [1]. Some essential problems in the optimizing issues originating from static shape and vibration control applications are mutual. However, most of the existing works on quasi-static shape control concentrates on optimizing the applied voltage distribution for performing the expected structural shape. To the authors' knowledge, the investigation on simultaneous optimization of both the shape and location of an actuator are limited. Liu et al. [2] presented a two-level algorithm for simultaneous optimization of geometrical magnitudes of an actuator and its correlative optimal control variables. In level one, the optimal control variables are confirmed for a pre-defined actuator allocation, while in the second-level of the procedure, the scales of actuators can be optimized for a given control parameters. Nguyen and Tong [3] presented an iterative alternative voltage and evolutionary piezoelectric actuator design optimization method to synchronously optimize the piezoelectric actuator allocation and the associated voltage. A combined optimization algorithm of the topologies of both host and actuation layers with spatial layout of applied voltage had been introduced, see [4–6]. However, in some cases, the host structure is, if not impossible,

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too difficult to alter. Thus, optimizing the locations and voltages of piezoelectric actuators is the primary solution.

Compared with usual piezoelectric transducers, the emerging photostrictive ceramics can induce actuation strain due to the irradiation from ultraviolet light, thus removing the requirements for electric wires and circuits. Hence, PbLaZrTi (PLZT) actuators are comparatively free from electrical disturbance and also prospective to be acted as a “electro-magnetic-noise free” driving component for wireless shape and vibration control [7–12]. With respect to piezoelectric shape control, the investigation on wireless shape control via photostrictive actuators is relatively rare. Shih et al. [13] presented an analytical approach to study the effect of photostrictive actuators locations on the deflection of various beams with different boundary conditions. Rahman and Nawaz [14] established a finite element method for multiphysics analysis of coupled optoelectro-thermo-mechanical fields in PbLaZrTi (PLZT) ceramics and studied how the location, size of a photostrictive actuator affect the transverse deflection of a beam. Sun and Tong [15] optimized the light intensities applied to PLZT actuators at a given actuator configuration. Luo et al. [16] used topology optimization to find the best topological distributions for both the photostrictive layers and the host elastic material layers, as well as the best actuating light intensities. To the authors’ knowledge, most of the available investigations for piezoelectric or photoelectric shape control focus on the simultaneous optimization of spatial distribution of matrix structure and actuator configuration. An investigation into simultaneous optimization of actuator locations, numbers and applied inputs was presented in this paper.

The rest of this paper is organized as follows. In Section 2, an optimal shape control method via hierarchical genetic algorithm is established. Section 3 derives a solid-shell element for multiphysics analysis of coupled optoelectro-thermo-mechanical fields in PbLaZrTi (PLZT) ceramics. Then, numerical simulations were carried out, and results were shown in Section 4. Finally, some conclusions are made in Section 5.

2. Polarization and performance of photostrictive material wafers

There are usually two schemes [17] used to polarize PLZT materials: 0–1 and 0–3 polarization. The former is to electrically pole the material along length direction, and the 2–3 planes are the planes of the electrodes. The latter is to pole the material through thickness direction and the electrodes are located in the 1–2 planes. This paper is only limited to 0–1 polarized PLZT actuators.

PLZT actuators possess both the photovoltaic and converse piezoelectric effects. The UV light gives rise to not only the photovoltaic voltage (E_l) and mechanical strain but also temperature rises, which in turn generate an extra voltage due to the pyroelectric effect. Thus, the total induced strains in PLZT actuators can be defined as following:

$$\varepsilon_{ii} = \varepsilon_{ii}^{c} + \varepsilon_{ii}^{p} + \varepsilon_{ii}^{t} \tag{1}$$

where ε_{ii}^{c} and ε_{ii}^{p} are respectively the strains related to converse piezoelectric and pyroelectric effects, and the thermal strain ε_{ii}^{t} is a result of body temperature variations.

When UV light is used to irradiate the surface of a 0–1 polarized PLZT wafer, an electric field E_l opposite to the polarization direction is generated due to the photovoltaic effect. The electric field produces a photovoltaic voltage between the two metalized electrodes which induces tensile strain ε_{11} because of the converse piezoelectric effect. The photo-induced electrical field and mechanical strain are uniform across the thickness because of the same electrical potential happened between two electrodes on left and right sides, which causes a wafer to deform in extension. The 0–1 polarized PLZT actuators have been studied by many researchers. The strain for a 0–1 polarized PLZT wafer is given as follows [18]:

$$\begin{aligned}\varepsilon_{ii}^{c} = d_{11}E_l(t) = E_l(t_{j-1}) + \left[E_s - E_l(t_{j-1})\right]\frac{\alpha}{\alpha_s}I(t_j)e^{-(\alpha/\alpha_s)I(t_j)\Delta t}\Delta t\\ - E_l(t_{j-1})\beta e^{-\beta\Delta t}\Delta t(i = 1)\end{aligned} \tag{2}$$

$$\varepsilon_{ii}^{p} = d_{11}E_{\theta}(t) = d_{11}\frac{P_n}{\varsigma}\theta(t) \tag{3}$$

$$\varepsilon_{ii}^{t} = \alpha_T\theta(t) \tag{4}$$

Where the induced electric field $E_l(t)$ and the body temperature $\theta(t)$ at the time instant t_j can be estimated by Eqs. (5) and (6)

$$\begin{aligned}E_l(t_j) = \frac{V(t_j)}{a} = E_l(t_{j-1}) + \left[E_s - E_l(t_{j-1})\right]\frac{\alpha}{\alpha_s}I(t_j)e^{-(\alpha/\alpha_s)I(t_j)\Delta t}\Delta t\\ - E_l(t_{j-1})\beta e^{-\beta\Delta t}\Delta t\end{aligned} \tag{5}$$

$$\theta(t_j) = \theta(t_{j-1}) + \left\{\left[I(t_j)P - \gamma\theta(t_{j-1})\right]\Delta t\right\}/(H + \gamma\Delta t) \tag{6}$$

in which E_s is the saturated photovoltaic field, α is the opto-electromechanical actuator constant, β is the voltage leakage constant, Δt is the time step, P is the power of the absorbed heat, H is the heat capacity of the opto-electromechanical actuator, $I(t_j)$ is the light intensity at time t_j, and $\alpha_s = a/b$ (length/width) is the aspect ratio, P_n is the pyroelectric constant and ς is the permittivity.

3. Optimal shape control

The wireless shape control problem is regarded as best meeting the expected shape of elastic structures by appropriately optimizing the actuator configuration and designing the illuminated light intensity. For the shape control problem, there are usually two kinds of design parameters: one is the location and number of the actuators and the other is the illuminated light intensity. Thus, the shape control problem falls into three categories. The first kind called light intensity problem, merely uses light intensity as design variable, and the second one (topology optimization problem) optimizes the topology distribution of actuators, as well as the last one simultaneously optimizes light intensity, location and number of actuators.

3.1. Fitness function

In nature, shape control is an inverse problem with a pre-defined desired shape as the output and actuation parameters to be resolved as the input. Solving this kind of inverse problem frequently demands nonlinear optimization of an objective function representing the differences between the gained and expected (pre-defined) shape. One primary purpose of wireless shape control is to find some control variables (e.g., the layout of the PLZT actuators, as well as the illuminated light intensities, etc.) so that the deviations are minimized. Genetic algorithm (GA) have been usually employed as optimization methods in a wide variety of fields, and have also demonstrated their superior performance in resolving complicate, non-linear, discrete and barely known optimization problems [19]. This is the main reason why we choose GA to resolve the present wireless shape control problem.

In this problem, the layout of photostrictive actuators and the corresponding illuminated light intensities are tuned automatically by minimizing an error function about the achieved and the pre-defined shapes. The shape of the structure is represented by normal deflections of the finite element nodes. Most literatures took a weighted sum of the squared error between the actuated and the desired shapes as the objective function, but this paper