Design, Manufacturing and Characterization of Functionally Graded Flextensional Piezoelectric Actuators

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Abstract. Previous works have been shown several advantages in using Functionally Graded Materials (FGMs) for the performance of flextensional devices, such as reduction of stress concentrations and gains in reliability. In this work, the FGM concept is explored in the design of graded devices by using the Topology Optimization Method (TOM), in order to determine optimal topologies and gradations of the coupled structures of piezoactuators. The graded pieces are manufactured by using the Spark Plasma Sintering (SPS) technique and are bonded to piezoelectric ceramics. The graded actuators are then tested by using a modular vibrometer system for measuring output displacements, in order to validate the numerical simulations. The technological path developed here represents the initial step toward the manufacturing of an integral piezoelectric device, constituted by piezoelectric and non-piezoelectric materials without bonding layers.

1. Introduction
Piezoactuators are based on the capability of electromechanical energy conversion presented by some ceramics. To amplify the ceramics displacements, flexible coupling structures are commonly attached to them. This kind of assembly is known as flextensional piezoactuator and it is employed in a wide range of applications, such as ink jet print head [6], compact high-dynamic orientation systems [11] and airplane-wing deformation control [10]. Regarding gains in reliability and performance, flextensional actuators can be designed by considering Functionally Graded Materials (FGMs), which are advanced materials with continuously graded properties due to their spatially graded microstructure. FGMs can be manufactured by using several techniques, among which stands out the Spark Plasma Sintering (SPS), which consists in a powder densification process subjected to pressure and electromagnetic field, simultaneously [4]. During the last years, the Topology Optimization Method (TOM) has been used as an useful tool for designing flextensional devices [9]. Subsequently, this approach has been extended to the design of FGM piezoelectric actuators [3], by introducing the concept of integral piezoactuators, in which the ceramic-metal interfaces are smoothly graded, eliminating the non-linearities and stress concentrations of bonding layers. Therefore, seeking to expand the role of FGMs in piezoelectrets, this work addresses the systematic design and manufacturing of graded flextensional structures.
2. Design Method

2.1. Material Model

The topology optimization method seeks an optimal material distribution inside a fixed domain for given purposes. This is made by defining which points should be solid and which points should be void, assigning pseudo-densities equal to 0 or 1, respectively. However, such problem is ill-posed and the usual way to find a solution is by defining a material model that allows intermediate property values. Although solvable, the relaxed problem produces gray regions, where the presence or absence of material is not clear. To recover the discrete nature of the problem, penalization coefficients are introduced by material models to minimize regions with intermediate densities, as made in the Simple Isotropic Material with Penalization, SIMP [2].

The material model implemented in this work is based on the FGM-SIMP model [7], which has the capability of representing a domain with property changes along certain direction according to a specified law. This model combines the elastic properties of a void material ($c_{\text{void}}$) and two solid isotropic materials ($c_A$ and $c_B$) and it estimates the properties of graded materials by the following formulation:

$$c(x) = (1 - \rho_1(x))c_{\text{void}} + \rho_1(x) \left(1 - \rho_2(x)\right)c_A + \rho_2(x)c_B$$

where, $\rho_1$ and $\rho_2$ are the pseudo-densities regarding topology and gradation, which are penalized by the coefficients $p$ and $q$, respectively.

2.2. Optimization Problem

The goal of this work is to maximize the output displacement $u_1$ of a flextensional actuator when the ceramic is submitted to an electric potential $\varphi_1$. The Figure 1 shows the load case considered, where $\Omega_s$ denotes the design domain and $\Omega_p$ denotes the fixed piezoelectric domain. To ensure the minimum structural stiffness, springs are placed at the actuation regions $\Gamma_t$. Thus, the formulation of the optimization problem is given by Eq. (2), where $\Theta_1$ is the upper-bound volume constraint and $\Theta_2$ defines the gradation proportions of each material in structure.

$$\text{Maximize : } L_1 = \int_{\Gamma_t} u_1(\rho_1, \rho_2) \, d\Gamma$$

subjected to:

$$0 \leq \rho_1, \rho_2 \leq 1$$

$$\int_{\Omega_s} \rho_1 \, d\Omega_s - \Theta_1 \leq 0$$

$$\int_{\Omega_s} \rho_1 \rho_2 \, d\Omega_s - \Theta_2 \int_{\Omega_s} \rho_1 \, d\Omega_s \leq 0$$

(2)

Figure 1. Load case for evaluation of output displacement.

For the numerical implementation the design domain is meshed using four-node bilinear
elements considering plane stress hypothesis and the Sequential Linear Programming (SLP) to solve the optimization problem.

3. Manufacturing and Characterization
By using Spark Plasma Sintering (SPS) process, graded cylinders are sintered. This method has the capability to produce pieces with the desired kind of material gradation, limited by the feasibility of pouring the layers of powder blends as required. Then, this cylinder is machined to achieve pieces with the designed topology, which are bonded to piezoceramics. However, for manufacturing, the gradations must be expressed in terms of mass percentage of each component material, while the property gradation defined by the material model in Eq. (1) is given in terms of stiffness. Thus, in this work, an elastic modulus versus mass percentage curve is approximated by using Hashin-Shtrikman theory [5], in which the moduli of pure Copper and pure Nickel is obtained by characterizing samples sintered in SPS machine by using a non-destructive ultrasonic method [1]. In order to verify the output displacements of prototypes, a OFV-5000 vibrometer [8] is employed. This equipment operates on the Doppler principle, measuring back-scattered laser light from a vibrating structure.

4. Results
4.1. Numerical
Because of manufacturing constraints, the gradation is restricted to 1mm-layers, as presented in the results below. The Table 1 presents the displacement values of each actuator case considered.

| Displacement ($\mu$m) | Homogeneous Cu | Homogeneous Ni | Vertical Layers | Horizontal Layers |
|----------------------|----------------|----------------|-----------------|-------------------|
| Numerical            | 0.1015         | 0.1149         | 0.1210          | 0.1205            |
| Experimental         | -              | -              | 0.155           | -                 |

Table 1. Output displacements for 20V/4kHz excitation.
5. Conclusion
This work demonstrates the contribution of FGM material in optimizing flextensional actuators by the TOM, with slight gains in the studied problem. Therefore, the feasibility of fabricating graded actuators from pieces sintered by SPS is proved. The experimental validation showed up consistency with the numerical results, despite small differences in terms of output displacement values (0.155µm in experimental and 0.121µm in numerical), probably due to the simplifications introduced by the numerical model and imperfections due to bonding process.

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