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Advanced piezoelectric–ferroelectric stack actuator

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ABSTRACT

A conceptual design and an operational algorithm for an advanced piezoelectric–ferroelectric stack actuator are developed. The actuator takes advantage of the large strains due to the domain-switching phenomenon and utilizes the nonlinear range of response of the ferroelectric material. As a result, the proposed conceptual design allows for deformations that are considerably larger than the ones obtained using conventional piezoelectric actuators and contributes to overcoming the travel range and performance limitations of standard actuators. The shape control algorithm is based on a discrete optimization of the domain state of the active layers and it allows the operation and the shape control of the advanced actuator in spite of the nonlinear and hysteretic material response. The conceptual design of the advanced actuator and the capabilities of the shape control algorithm are demonstrated through numerical examples. The results demonstrate the contribution of the approach to extending the operational range of the actuator through a continuous and controllable response. A summary, conclusions, and directions of future research towards realization of the concept close the paper.

1. Introduction

Piezoelectric stack actuators are a common choice for micro and nano-positioning as well as for many other mechanical and structural applications. Their main advantages are nano-scale positioning accuracy combined with a short rise time. In spite of these advantages and their vast potential, piezoelectric stack actuators are still limited in terms of induced strains and travel range (stroke). The travel range limitation is usually the consequence of the restriction of the electro-mechanical operational range of the material to the linear piezoelectric range.

The limited actuation authority can be overcome by exploiting the ferroelectric nature of the commonly used piezoelectric materials (e.g. PZT, PMN,) and by extending the operational range of the ferroelectric–piezoelectric material into the nonlinear range (Mitrovic et al. [1], Chaplya and Carman [2], Kushnir and Rabinovitch [3], Shilo et al. [4], Burcsu et al. [5]). The ferroelectric range is characterized by the evolution of large strains, mainly due to the domain switching phenomenon (Hwang et al. [6], Kamlah [7]). This phenomenon is characterized by an abrupt change (switch) of the direction of the spontaneous polarization and strain of the unit cells (Kamlah [7]). As a result, the strains and the electrical displacement, as well as the elastic, dielectric, and piezoelectric tensors, become strongly dependent on the switch state (the domain state) of the grain and they may discontinuously vary through the mechanical and/or electrical loading process. Along with potential self-heating, material parameter degradation, and fatigue after millions of cycles (Balke et al. [8,9]), the ferroelectric range of operation is also characterized by severe nonlinear behavior and complex, hysteretic, and non-monotonic relations between the strain, the electric displacement, the stress, and the electrical field (Lynch [10]). This behavior sets an obstacle to the use of the nonlinear effects in practical applications. In particular, it makes the problem of shape control, i.e. the determination of applied electrical voltages necessary to achieve a desired displacement, which is crucial for positioner applications, very complicated and challenging.

Mitrovic et al. [1] experimentally examined the response of commercially available stack actuators under prestress and a sesquipolar electrical loading. The results showed an enhancement of 60% in the actuation capabilities with maximum actuation enhancement at prestress levels of 20–40 MPa. Chaplya and Carman [2], measured the strain response of PZT-5H ceramic to a bipolar, unipolar, and sesquipolar electrical loading cycles, under different levels of compressive stress. Sesquipolar electrical loading combined with a prestress of 40 MPa *enhanced the strain output by a factor of 4*. The enhancement of the strain response is a result of non-180° domain switching. Chaplya et al. [11] investigated the fatigue degredation of commercially available stack actuators under sesquipolar electrical loading and preload. A decrease of only 3% of the strain output after 10^7 sesquipolar electrical cycles under optimum prestress was observed for some actuators. Changes in the order of 10% to the strain output range of PZT after 3×10^7 sesquipolar electric loading cycles with negative electrical field near and

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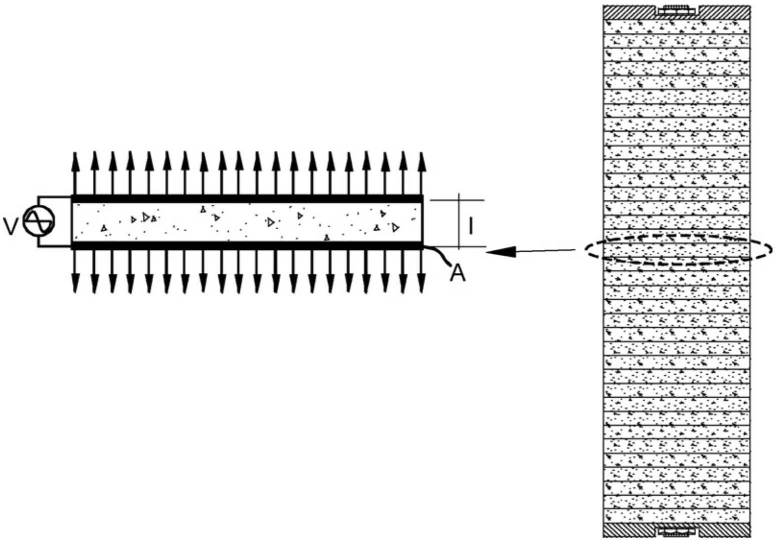

Fig. 1. An active layer in a stack.

beyond the coercive field were also reported by Balke et al. [9]. The experimental results [1,2,9,11] also reflect the ability of the material to withstand cycles of high electrical field that result in domain switching and notable inter-granular stresses at the grain boundaries without notable fracture or cracking. This implies that the material can withstand the tensile stresses at grain boundaries due to switching without notable cracking or fracture.

The experimental and computational results that appear in the literature show that the enhancement of the actuation capabilities by means of the domain switching phenomena is feasible from an engineering point of view. However, the design, operation, and control guidelines for enhanced ferroelectric actuators were not developed. The first objective of this paper is to develop the conceptual design of an advanced stack actuator that aims to overcome the travel range limitation by exploiting the large strains of the ferroelectric effect. The second objective of the paper is to develop an operation procedure for the shape control of the advanced actuator whilst avoiding the potential problems that arise due to the nonlinear and hysteretic behavior of the material. The paper commences with the basic philosophy of the advanced actuator and its concept of operation. Then, design guidelines are drawn. These are followed by the algorithm for the shape control of the advanced actuator and it's validation through two illustrative shape control problems. Conclusions are drawn at the end of the paper.

2. Concept and philosophy

An active piezoelectric–ferroelectric layer in a stack actuator is shown in Fig. 1. Stack actuators are comprised of hundreds of active layers separated by surface electrodes. In order to generate a displacement, all layers are operated under the same voltage with the displacement output equals to the contribution of one layer multiplied by the number of layers. Fig. 2 shows the behavior of the active piezoceramic layer (PLZT) who's mechanical and electrical properties are summarized in Table 1 under compressive stress of 16 MPa and a biased potential difference of −50 to 675 V. The response is calculated using the model outlined in [3]. (Note that PLZT is selected here for demonstration only. Other ferroelectrics may also apply). Point 1 on the curve (Fig. 2) corresponds to the depoled domain state where the combination of the electrical and mechanical (compressive) loads encourages switching towards the plane perpendicular to the x_3 axis. Under these conditions, the net polarization and the piezoelectric tensor vanish, small changes in the applied potential difference do not yield a change of the displacement, and the slope of the displacement–voltage curve near Point 1 tends to zero. Point 2 in Fig. 2 corresponds to the fully polarized domain state where the spontaneous polarization of the domains is aligned as closely as the lattice directions allow to the direction of polarization along x_3 axis. At this state, the application of electrical field in the x_3 direction cannot trigger further switching. Thus, it is a "stable" electrical load that yields a "stable" elongation due to the linear piezoelectric response. This is demonstrated by the straight line between Point 2 and Point 3 in Fig. 2.

Points 1 and 2 are both observed under zero electrical field. However, they correspond to different levels of strain. Thus, moving from one point to another yields a significant jump in the displacement at the end of the layer. The concept developed here takes advantage of the large displacement range between these two domain states (i.e. between Point 1 and Point 2 or even between Point 1 and Point 3) to significantly extend the travel range. To achieve this, the active layer has to undergo *domain switching*, which is a highly nonlinear, hard to predict, and hard to control process. This aspect makes the usage and control of the nonlinear range a challenging task. To face this challenge, the active layer is operated here in two domain states

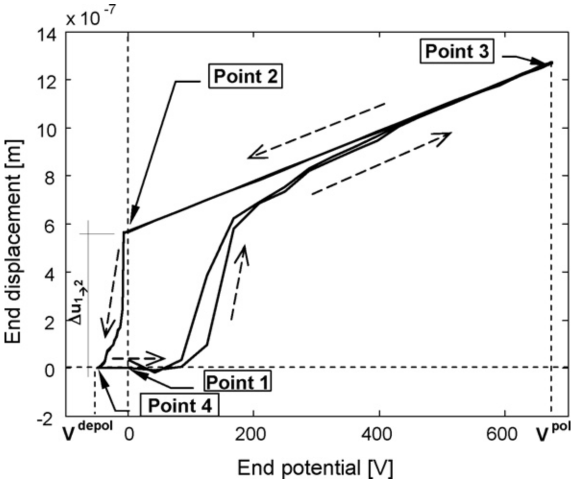

Fig. 2. Displacement vs. voltage response of the active layer under a compressive stress of 16 (MPa); Point 1: depoled domain state with zero voltage; Point 2: fully polarized domain state with zero voltage; Point 3: response to polarization voltage of 675 V; Point 4: response to depolarization voltage of −50 V.