ELECTROACTIVE POLYMER COMPOSITES - MECHANICAL RESPONSE, STABILITY, WAVE PROPAGATION AND BAND-GAPS

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Summary Electroactive polymers (EAP) are capable of large deformations in response to electric stimulus. A sketch of a planar actuator is shown in Fig. 1. The top and bottom faces of the soft dielectric are covered with compliant electrodes inducing an electric field through the material. The resulting Maxwell stress leads to the deformation of the material. The variety of possible applications of these "artificial muscles" motivated an intensive search for appropriate polymers. In particular, the concept of enhancing the responsiveness of EAPs by means of using heterogeneous materials is investigated.

INTRODUCTION

Theoretical background

The deformation of the material is characterized by the deformation gradient $F_{ij} = \partial x_i/\partial X_j$, where x_i and X_j are the position vectors of a material point in the deformed and reference states, respectively. The electric field at a point is $E_i = -\partial\phi/\partial x_i$, where ϕ is the electric potential. In incompressible and isotropic neo-Hookean dielectrics the electric displacement and the total stress tensor are

$$D_i = \epsilon_0 \epsilon E_i \quad \text{and} \quad \sigma_{ij} = \mu F_{ik} F_{jk} + \epsilon_0 \epsilon E_i E_j - p\delta_{ij}, \tag{1}$$

where ϵ_0 is the vacuum permeability, ϵ is the dielectric constant, μ is the shear modulus, p is the pressure, and δ_{ij} is the Kronecker delta [1]. In the expression for the stress the first term is the mechanical stress and the electrostatic "Maxwell stress" tensor is the second term. Assuming a quasistatic deformation, no magnetic fields and no body forces, the governing equations are

$$\frac{\partial D_i}{\partial x_i} = 0 \quad \text{and} \quad \frac{\partial \sigma_{ij}}{\partial x_j} = 0. \tag{2}$$

In the absence of free charges at the interfaces the electric field continuity conditions are $\llbracket E_i \rrbracket \hat{m}_i = 0$ and $\llbracket D_i \rrbracket \hat{n}_i = 0$, where $\llbracket \bullet \rrbracket \equiv (\bullet)^+ - (\bullet)^-$ is the jump across the interface and $\hat{n}_i$ and $\hat{m}_i$ are the unit vectors normal and tangent to the interface, respectively. The corresponding mechanical continuity conditions are $\llbracket F_{ij} \rrbracket \hat{m}_j = 0$ and $\llbracket \sigma_{ij} \rrbracket \hat{n}_j = 0$.

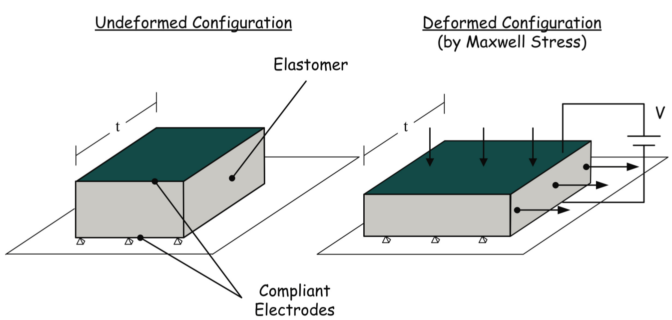

Figure 1. A sketch of a planar EAP actuator.

ENHANCEMENT OF THE ELECTROMECHANICAL COUPLING

In the limit of small strains it can be shown that a set of equations which is similar to the one presented in Eqs. (1) and (2) holds for the corresponding homogenized fields [2]. However, in this case the coupling term that corresponds to the "Maxwell stress" depends on the microstructure of the composite. Accordingly, with an appropriate optimization of the microstructure the coupling can be enhanced. A representative microstructure is shown in Fig. 2a, and corresponding actuation strains as determined both analytically and by a finite element simulation are shown in Fig. 2b. The theoretical optimal curve is depicted by the black curve and the blue cuve corresponds to the microstructure shown in Fig. 2b. The behavior of a representative homogeneous EAP is depicted by the green curve. Clearly, the usage of a heterogeneous EAP can intensify the response of the material by more than an order of magnitude [3].

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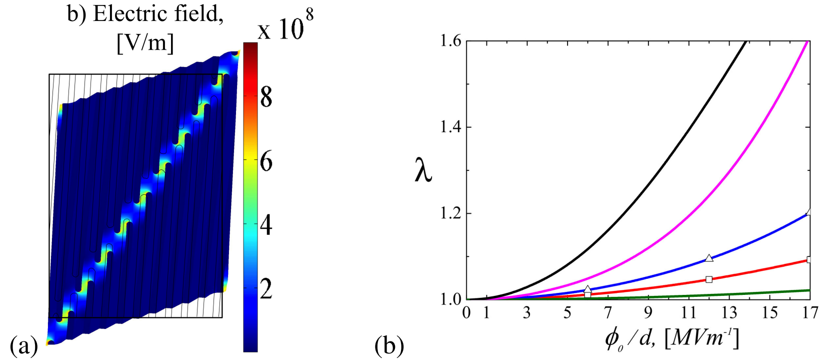

Figure 2. (a) The deformed state of the periodic actuator and (b) the resulting actuation stretch as a function of the electrostatic field.

INSTABILITIES

Instabilities in EAPs are identified by superimposing incremental deformations and increments in the electric field on top of a stable state. This phenomena can be used in "snap-through" actuators to further increase the mechanical response of the material to the electrostatic excitation. Lower levels of the critical fields that result in instabilities can be achieved in heterogeneous EAPs. In Fig. 3a the enlargement of the unstable domain of a laminated material subjected to different levels of electrostatic field is shown as a function of the phases volume fraction [4]. We observe that with an appropriate choice of the volume fraction the unstable domain can be controlled.

WAVE PROPAGATION

We investigate the propagation of waves in heterogeneous EAPs. This is accomplished by superimposing small-amplitude oscillating waves on a static deformed state of the solid. In heterogenous materials ranges of frequencies at which the waves cannot propagate can be identified. In heterogeneous EAPs these band-gaps, that can be used for vibration isolation, can be controlled by the electrostatic field. In Fig. 3b the blue regions correspond to these band-gaps in a laminated material made out of two commercially available phases. It can be seen how the ranges of forbidden frequencies can be shifted toward lower frequencies by increasing the intensity of the applied electric field [5].

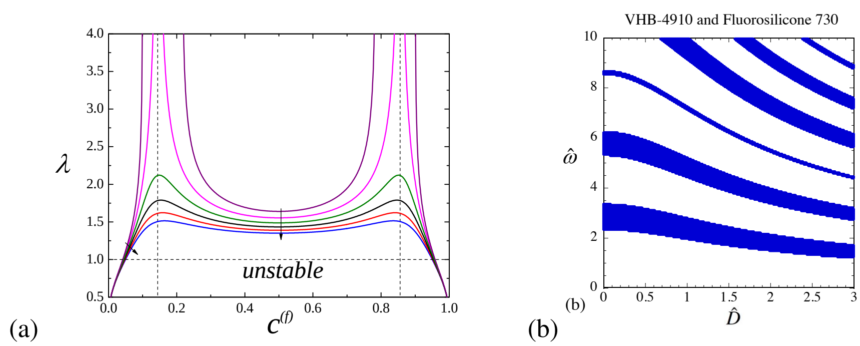

Figure 3. (a) Stable and unstable domains of layered EAP at different levels of electrostatic excitations and (b) band-gaps in a layered VHB-4910/Fluorosilicone 730.

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