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Adaptive control of stiffness by electroactive polyurethane

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ABSTRACT

For applications concerning vehicle suspension or the membranes of acoustic loud speakers, a conventional stiffness control method is both useful and desired. However, without total replacement of the material itself or its structure, modification of the stiffness is not an easy matter. Besides, the technology of electro active polymers (EAPs) is a fast-moving topic. The high electro-induced strain level of these materials is an attractive advantage compared to many other mechanical/electrical converging sensor/actuator materials such as piezo devices. This paper presents an easy and innovative method to control the stiffness of EAPs. First, a polyurethane (PU) sample was pre-stretched in the 1-direction, and clamped at both ends. Then, an electrical field was induced in the 3-direction. The positive elongation in the 1-direction created a force opposite to that of the pre-stretching since the specimen was clamped. From the equation of force valence, a simple stiffness equation was obtained with the ratio between the pre-stretching force and the force created by the electrical stimuli. Concerning the electrical saturation in the EAP material, the variation in stiffness could be expressed by the equation of electrical field. With a simple experimental viewing, more than 30% of stiffness variation could be obtained with a moderate electrical induction, <32 V/μm.

1. Introduction

Ranging from vehicle suspensions to membranes for acoustic speakers, the application fields of EAPs are vast if the stiffness of the material can be easily modified. In general, there are only two ways to alter the stiffness; a total change of the material or of its structure. The stiffness of a vehicle tire can be changed by a surface treatment with an adhesive spray. This exists commercially and it is called stiffness control entrainment. It is an easy and reasonable method compared to a case where the entire material has to be replaced. The reverse change is, however, not considered.

As the result of research on adaptive stiffness control, there exists a method that fixes the limitation of deformation of a spring [1]. If a spring is covered by ER fluid, a magnetic induction is enough to limit its maximum deformation, and thereby is stiffness. This is a quite conventional adaptive control method. Its use is, however, limited since the structure must be totally covered with the fluid. Moreover, applying the technique to another type of structure is difficult. Based on these points, the adaptive stiffness is an interesting open issue.

Electroactive polymers (EAPs) have attracted much attention during the last decades as electric/mechanical conversion sensor and actuator materials. Not only is the fabrication easy and cheap, giving several variations of materials, but also a specific advantage lies in their high electrostrictive strain level. Polyurethane (PU), one of the dielectric elastomers, generates more than 30% of strain under a moderate electrical field < 20 V/μm, and carbon black (CB)/PU composite films can create more than 50% under the same electrical condition, <20 V/μm, according to a study carried out in our laboratory [2,3].

This paper proposes an innovative method to adaptively control material stiffness using EAPs. It demonstrates that it is possible to change the stiffness of a pre-stretched PU film by simple electrical stimuli. The stiffness of a wide surface area of the material can be modified. The electrical induction was limited to a low level so that a wearable device can be targeted later on. After the model, an experimental procedure with a small dimension specimen is presented.

2. Theory

2.1. Change of stiffness by induced electrical field after pre-stretching

When a PU thin film is stretched in the 1-direction, the corresponding stress creates an elongation that can be written as $\tau_{mech.} = cS$. Here, c and S are the mechanical factors corresponding to the elastic compliance and the strain in the 1-direction,

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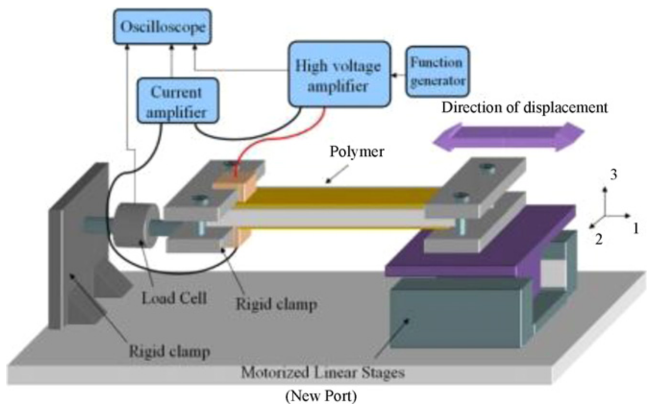

Fig. 1. Experimental setup.

respectively. When the electrical field is induced in the 3-direction of the film, there occurs an elongation in the 1-direction since the electrostrictive coefficient of PU is negative. Under natural conditions, without clamping, these two elongations have the same direction.

Now, we consider a model for a fixed condition. A PU thin film, clamped at both ends, is stretched in the 1-direction, after which an electrical field is induced in the 3-direction using the specific experimental setup system shown in Fig. 1. After the fixation with the pre-strain S_0, no elongation could occur, and the electrical induction thus led to another stress in the 1-direction according to $\tau_{ele.} = \alpha P^2$. Here, α and P are electrical factors, i.e., the electrical coefficient and the polarization created by electrical induction, respectively. Both α and P^2 are positive values.

If there is no clamping, the total stress τ_t in 1-direction under mechanical and electrical stimuli can be expressed from the well known electrostrictive constitutive equations as follows:

$$\tau_t = \tau_{mech.} + \tau_{ele.} = cS_0 + \alpha P^2 \tag{1}$$

Here, the polymer ends are fixed before the electrical induction. The mechanical stress and the stress caused by electrics have the opposite direction, and thus create the total stress according to

$$\tau_t = cS_0 - \alpha P^2 \tag{2}$$

Multiplying this equation by the surface A, the equation of the force F is obtained with the stiffness $K = cA/L$ as

$$F_t = \frac{cA \cdot u_0}{L - \alpha AP^2} = Ku_0 - \alpha AP^2 \tag{3}$$

Here L is the length of the specimen and u_0 is the initial deformation by the pre-strain, $u_0 = S_0 L$.

Besides, the electrical induced stress can be also written as $\tau_{ele.} = c' S_{ele}$. The elastic compliance is no longer the constant coefficient c but the variable coefficient c' because the strain, S_{ele}, is fixed at the pre-strain, $S_{ele} = S_0$, under the variable stress caused by electrical induction τ_{ele}. The second term of Eq. (3) thus becomes

$$\alpha AP^2 = Ac' S_{ele} = K' u_{ele} \tag{4}$$

To clearly differentiate it from the stiffness of the specimen without the electrical induction, $K = F/u_0$, the varied stiffness was expressed as K' here. It depends purely on the electrical induction, so that $K' = f(E)$.

With this variable stiffness, the total force in Eq. (3) is rewritten as

$$F_t = Ku_0 - K' u_{ele} \tag{5}$$

Since the experimental condition involved two fixed ends, $u_0 = u_{ele}$. This gives

$$F_t = u_0(K - K') \tag{6}$$

Now we have clearly and simply obtained the varied total stiffness under the electrical induction after pre-stretching

$$K_t = K - K' \tag{7}$$

A comparison of stiffness with and without the electrical induction can be simply made by comparing the total force and the pre-strain force, F_m, as follows.

$$\frac{K_t}{K} = \frac{F_t/u_0}{F_m/u_0} = \frac{F_t}{F_m} \tag{8}$$

2.2. Saturating polarization

The relation between the polarization and the induced electrical field is linear when the induced electrical field E is small. In this case, $P = \varepsilon E$, is supposed to be nonlinear when E is increased in the polymeric material, as shown in Fig. 2(a) [4,5].

This nonlinearity appears also in the $S(E)$ relation. For some time, we have considered the strain saturation of a polymeric material to be caused by the electrical saturation. However, numerous approaches might be used to express such saturation. Among them, we propose an equation that takes into account the polarization saturation [4]:

$$P = \varepsilon E_{sat} \tan h\left(\frac{E}{E_{sat}}\right) \tag{9}$$

where ε and E_{sat} correspond to the relative permittivity and the coefficient related to the electrical field, respectively. From our recent work, we know that $E_{sat} = 1.53 E_{con}$, where E_{con} is the electrical field value and where $d^2S/dE^2 = 0$ [4].

The strain created by electrical stimuli is thus,

$$S_{ele} = QP^2 = Q \times \left(\varepsilon E_{sat} \tan h\left(\frac{E}{E_{sat}}\right)\right)^2 \tag{10}$$

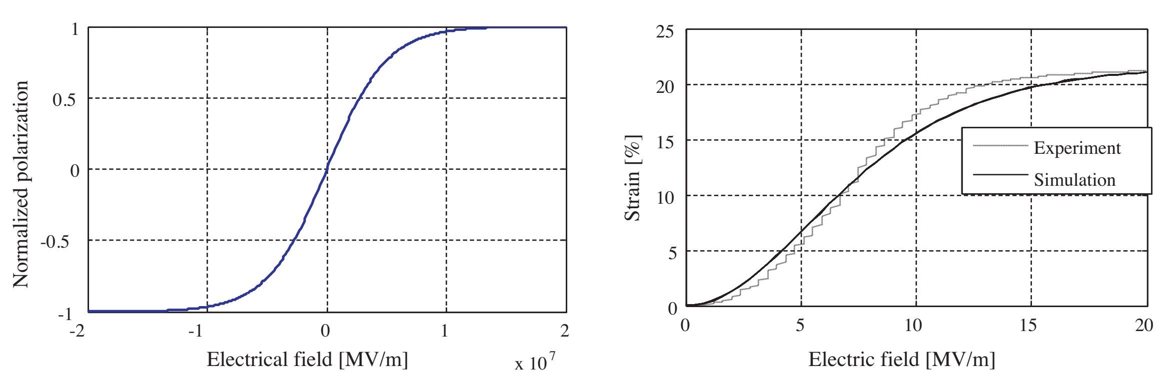

Fig. 2. (a) Saturating polarization and (b) saturating strain in the polymeric material. Experimental data and simulation for (b).