Biomedical Sensor Properties of Flexible PolyVinyliDene Flouride

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ABSTRACT

The flexible piezoelectric material PVDF is discussed with respect to its properties for uses in biomedical engineering.

Categories and Subject Descriptors

B.3.m [**General Input/Output]**

General Terms

Theory

Keywords

Piezoelesticity, Sensors.

1. INTRODUCTION

The piezoelectric properties of the material PolyVinyliDene Flouride, PVDF, were first pointed out by Kawai [1] in 1969. Since then the material has been found useful in hundreds of applications [2, pp. 58-59] among which are 28 in the medical field, including assistive devices, such as switches, Braille readers, hearing aids, and speech intensification. The material can be purchased in single layers or bi-oriented double (bimorph) layers or in cable form. There are also various co-polymers with sometimes advantageous properties {such as D vs E hysteresis loops in P(VDF-TrFE) [3]). The main advantage of PVDF as a piezoelectric material is in its flexibility. For example it can be bent to conform to a surface, such as a finger, to allow biomedical stimulation or response.

2. METHODS

2.1 Piezoelasticity of PVDF

Normally PVDF comes in sheet form and when processed to be piezoelectric is stretched in the x direction and electrically polled in the z direction. The commercially available Z direction thickness, t, is usually one of three micron values, 28, 52 or 100 with silver ink metallization on the top and bottom surfaces [4], though variations exist [5].

PVDF satisfies the linearized equations of any piezoelectric material which are written in matrix form [6] as

$$S = s^T + d^T.E \qquad D = d^T + \varepsilon.E$$

(the superscript T is matrix transpose)

In these, as matrix equations, we use the standard tensor to vector renumbering

$T = [T_{11}\ T_{22}\ T_{33}\ T_{23}\ T_{13}\ T_{12}]^T$
$= [T_1\ T_2\ T_3\ T_4\ T_5\ T_6]^T$= stress vector (force/area in Newton/meter^2; 1 Newton = 0.2248 pounds)

$S = [S_{11}\ S_{22}\ S_{33}\ 2{*}S_{23}\ 2{*}S_{13}\ 2{*}S_{12}]^T = [S_1\ S_2\ S_3\ S_4\ S_5\ S_6]^T$ = strain vector (length of deformation; per unit length)

$E = [E_1\ E_2\ E_3\}^T$ = electric field vector (Volt/meter)

$D = [D_1\ D_2\ D_3]^T$ = electric displacement vector (Coulomb/meter^2)

$s = s^T$ = compliance constant matrix (Pascals=Pa=m^2/Newton)

d = strain constant matrix(Coulomb/Newton)

e = dielectric constant matrix: (Farads/meter)

Although there are four structural versions for piezoelectric PVDF the standard one is for the mm2 crystal structure for which the matrices take the following form with the constants found from various sources [2, p.3] – [8] (often with conflicting values) to be roughly.

$$s := 10^{-11} \cdot \begin{pmatrix} .42 & -.07 & -.08 & 0 & 0 & 0 \\ -.07 & 4.31 & -.76 & 0 & 0 & 0 \\ -.08 & -.76 & 9.55 & 0 & 0 & 0 \\ 0 & 0 & 0 & 46.45 & 0 & 0 \\ 0 & 0 & 0 & 0 & 22.75 & 0 \\ 0 & 0 & 0 & 0 & 0 & 15.56 \end{pmatrix}$$

$$d := 10^{-12} \begin{pmatrix} 0 & 0 & 0 & 0 & -30.7 & 0 \\ 0 & 0 & 0 & -4.28 & 0 & 0 \\ .25 & -4.05 & -33 & 0 & 0 & 0 \end{pmatrix}$$

$$\varepsilon := 10^{-10} \cdot \begin{pmatrix} 1.06 & 0 & 0 \\ 0 & 1.06 & 0 \\ 0 & 0 & 1.06 \end{pmatrix}$$

Of considerable interest are the coupling coefficients, especially the thickness, k_{31}, and the transverse, k_{33}, ones, given by

$$k_{31} = d_{31}/\sqrt{s_{11}\varepsilon_{33}} = 0.012 \qquad k_{33} = d_{33} / \sqrt{s_{33}\varepsilon_{33}} = -0.328$$

These allow determination of mechanical motion versus applied voltage. However, large stresses and strains are often used in which case a square-law behavior is found in s_{11} and d_{31} [8] as well as in temperature change, which have [9]

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$s_{11}=s_{11bias}+\alpha_{11}\Delta T+\beta_{11}\Delta T^2$ $d_{31}=d_{31bias}+\alpha_{31}\Delta T+\beta_{31}\Delta T^2$

where ΔT is the change in temperature (in degrees Kelvin) around the bias (=ambient). Numerically

$\alpha_{11}= 1.06\text{x}10^{-21}$, $\beta_{11}=1.059\text{x}10^{-25}$ $\alpha_{31}= 1.87\text{x}10^{-22}$, $\beta_{31}=7.25\text{x}10^{-27}$

PVDF also has a relatively strong temperature dependent dipole moment [9] which makes it pyroelectric with a pyroelectric voltage coefficient ρ_T=30 [2, p.35] allowing for relatively large voltage change with temperature. Thus, the change in voltage across a film of thickness, t, is given by

$\Delta V=\rho_T * t * \Delta T/\varepsilon$

where ε=dielectric constant = $106\text{x}10^{-12}$ C/Vm.

Some of the other constants of interest are the mass density ρ = 1.8 Kg/m^3, electrical and mechanical loss tangents of 1.8 (at 1KHz) and 5 %, ability to obtain sheets of large lengths, ℓ, (to over 200 meters [5,p.5]), tensile strength of over 60 MPa, and elongations at break of over 40%.

2.2 Equivalent Circuits

Based upon the linear piezoelectric equations, one can derive various equivalent circuits which are useful for computer aided designs. For example, if the material is excited/forced in the thickness mode and losses are not considered, following the techniques presented in the thesis of Mohammad [10, p. 52], a possible equivalent circuit is that shown in Fig. 2, where U_3 and F_3 are velocity and force in the Z direction. V and I are voltage and current across and through (silver ink) electrodes on the upper and lower (Z=t and 0) surfaces. Losses, which are generally small, can be included by resistors in series with the inductors. In meters the dimensions are ℓ = length in X direction, w = width in Y direction and t = thickness in Z direction. For Fig. 2 the turns ratio, n, characteristic velocity, ν, characteristic admittance, Yo, and capacitance, Co, are given by

$$n = \frac{w\ell}{t}\frac{d_{33}}{s_{33}} = \frac{w\ell}{t}(-0.36), \quad \nu = \frac{1}{\sqrt{\rho \cdot s_{33}}} = 7.24 \cdot 10^4,$$

$$Y_o = \frac{1}{w\ell}\sqrt{\frac{s_{33}}{\rho}} = \frac{1}{w\ell}7.284 \cdot 10^{-6},$$

$$Co = \frac{w\ell}{t}\varepsilon_{33}(1 - k_{33}^2) = \frac{w\ell}{t} \cdot 9.46 \cdot 10^{-11}$$

And

$$\begin{bmatrix} I_3 \\ U_3 \end{bmatrix} = \begin{bmatrix} sCo + n^2 y_a & -ny_a \\ -ny_a & y_a + y_b \end{bmatrix}\begin{bmatrix} V_3 \\ F_3 \end{bmatrix}$$

where (with s complex frequency)

$$y_a(s) = Y_o(\text{ctanh}(st/\nu) - \frac{1}{\sinh(st/\nu)})$$

$$y_b(s) = Y_o \text{ctanh}(st/\nu)$$

As an example, a sheet of PVDF of t=28microns, ℓ=0.1m, w=0.1m has Co=33.8nanoFarads and Yo=72.8milliMhos. If a force, F_3, is applied to this sheet open circuited, then a voltage $V_3=[ny_a/(sCo+n^2y_a)F_3$ will appear; for example a sharp compressive hit (negative F_3 approximating an impulse) of one Newton (about ¼ pound) gives a voltage that is the inverse Laplace transform of the transfer function (and approximating by the first terms in the hyperbolic's series)

$$\frac{-ny_a(s)}{sCo+n^2y_a(s)} \approx \frac{-nYo(t/2\nu)}{Co+n^2Yo(t/2\nu)}$$

which is a sharp pulse of 61.6 milliVolts plus many small exited resonances which are in the GHz region.

These results assume that the x and y velocities and forces are zero but nonzero ones can be incorporated by putting in parallel with the capacitor two other 2-ports, one for x and one for y forces and velocities, of similar form to those for the z components.

3. DISCUSSION

We have presented some of the characteristics of PVDF which make it very useful for biomedicine. Due to the piezoelectricity being formed by aligning molecules it can also be destroyed by excessive heat. Besides this, it may be subject to weakening due to a very large number of recycles.

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