PYROELECTRIC AND THERMAL STRAIN EFFECTS OF PIEZOELECTRIC (PVDF AND PZT) DEVICES

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Piezoelectric devices respond to temperature variations in a changing temperature environment. The temperature-induced voltage generation of piezoelectric sensors can be further divided into two major components: the pyroelectric effect and the thermal strain effect. In this study, these two temperature-induced components of distributed piezoelectric polyvinylidene fluoride (PVDF) and lead-zirconate-titanate (PZT) sensors are compared using a new 3-D thin piezothermoelastic solid finite element. A piezoelectric laminated square plate is used in a case study. Analyses suggest that the pyroelectric effect of PVDF sensors is much more prominent than the thermal strain effect. However, the PZT sensors exhibit the opposite phenomena. Distributed control of the plate with a temperature-induced deflection is also demonstrated.

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1. INTRODUCTION

Active ‘intelligent’ structure systems with integrated self-sensing, diagnosis, and control capabilities are crucial to the development of next generation high-performance systems [1, 2]. Among all popular active materials (e.g. piezoelectrics, electrostrictive materials, shape memory alloys, electromagnetoelastic materials, electrorheological materials, etc.) available today, piezoelectrics can be used for both sensors (the direct piezoelectric effect) and actuators (the converse piezoelectric effect) [3]. Accordingly, piezoelectric materials are widely used as sensors and actuators in recent years. Electromechanics and control effectiveness of piezoelectric sensors and actuators are extensively studied. However, temperature effects to distributed piezoelectric sensors and actuators and their sensing and control effectiveness are not well understood.

Mindlin [4] studied electromechanical couplings of linear piezothermoelastic mediums. Nowacki [5] examined the solution uniqueness of piezothermoelastic differential equations. Nowacki [6] investigated the temperature influence of elastic-dielectric mediums and proposed a reciprocity theorem. Tzou and Howard [7] proposed a piezothermoelastic shell vibration theory, and derived thermoelectromechanical equations and boundary conditions. Applications of the theory to distributed sensing and control were also discussed. Tzou and Ye [8] studied the piezothermoelectricity of distributed sensors and evaluated control effectiveness of a piezoelectric laminated system with dynamic and thermal excitations. In this study, piezothermoelastic effects of distributed piezoelectric polyvinylidene fluoride (PVDF) and piezoceramic lead-zirconate-titanate (PZT) sensors
are investigated. Pyroelectric and thermal strain effects of the piezoelectric transducers subjected to temperature excitations are studied. A new three-dimensional (3-D) thin hexahedron piezothermoelastic solid finite element with three internal degrees of freedom (dof) is formulated using a variational formulation. A system equation for the piezoelectric continuum exposed to combined elastic, electric, and thermal fields is formulated. Distributed sensing equations are derived; pyroelectric and thermal strain effects of the piezoelectric transducers of a laminated plate are investigated. Voltage profiles and deflection control of the plate are evaluated.

2. FINITE ELEMENT FORMULATION

In a conventional configuration of piezoelectric laminated structure, the piezoelectric sensor/actuator layers are usually much thinner than that of the laminated host structure. Accordingly, it is very inefficient if the whole laminated structure is modeled by isoparametric finite elements. In addition, if the thickness to width ratio is too small, conventional isoparametric finite elements can introduce ill-conditioned results due to excessive shear stresses in the thickness direction. In this section, mathematical derivatives of a thin piezothermoelastic eight-mode solid element are outlined. Piezothermoelastic characteristics of piezoelectric sensor layers are studied.

2.1. PIEZOTHERMOELASTIC CONSTITUTIVE RELATIONS

It is assumed that the piezoelectric continuum is exposed to three fields: a displacement field, an electric field, and a temperature (thermal) field. The constitutive relations can be represented by three equations: (1) a Duhamel–Neumann equation \( T_0 \), (2) an electric displacement equation \( D_0 \), and (3) an entropy equation \( \delta \) \([4, 8]\).

\[
T_0 = e_{33}^{\text{el}}(S_{33} - S_{33}^0) - e_{33}^{\text{me}}E_3 - \lambda_0^3 \theta, \tag{1}
\]

\[
D_0 = e_{33}^{\text{el}}(S_{33} - S_{33}^0) + \varepsilon_{33}^0 E_3 + p_0^3 \theta, \tag{2}
\]

\[
\delta = \lambda_0^3 (S_{33} - S_{33}^0) + p_0^3 E_3 + \chi \theta, \tag{3}
\]

where \( e_{33}^{\text{el}} \) are the elastic moduli; \( S_{33} \) are the strains; \( S_{33}^0 \) are the initial strains; \( e_{33}^{\text{me}} \) are the piezoelectric coefficients; \( E_3 \) are the electric fields; \( \lambda_0^3 \) are the temperature stress coefficients; \( \theta \) is the temperature; \( \varepsilon_{33}^0 \) are the dielectric constants or permittivities; \( p_0^3 \) are the pyroelectric constants; and \( \chi \) is a material constant \((\chi = \rho c \phi \theta_b^{-1})\) where \( c \) is the specific heat at constant volume and \( \rho \) is the mass density. Note that \( \theta \) can be regarded as the temperature rise from the stress-free reference temperature \( \theta_b \). In addition, the superscripts \( E, \theta \) and \( S \) denote the coefficients defined at a constant electric field, temperature and strain, respectively. The strain \( S_0 \) and electric field equation \( E \) are respectively defined by the gradient of displacement \( u \) and electric potential \( \phi \), i.e. \( S_0 = \frac{1}{2}(u_{\nu} + u_\nu) \) and \( E = -\phi \). 

2.2. 3-D PIEZOTHERMOELASTIC FINITE ELEMENT

As discussed previously, the thickness of the piezoelectric sensor/actuator layers is usually small compared with its width and length in piezoelectric laminated structures. Accordingly, a non-conforming (thin) hexahedron piezoelectric finite element is developed to deal with this problem \([9, 10]\). A 3-D piezothermoelastic thin hexahedron solid finite element is formulated in this section. Three additional internal nodes for an interpolation
function of field variables are defined, and these additional dof can be condensed by
Guyan's reduction scheme [9–11]. Shape functions, nodal variables, element energy
functionals are defined first, followed by the piezothermoelastic system equations and
distributed sensing/controls. Note that a matrix notation is adopted in the finite element
formulation.

Assuming the shape functions, one can define all field variables in matrix notations as:

\[
\{\mathbf{u}\} = [\mathbf{N}_u]\{\mathbf{U}\}, \quad \phi = [\mathbf{N}_\phi]\{\mathbf{\phi}\}, \quad \theta = [\mathbf{N}_\theta]\{\mathbf{\Theta}\}, \quad (4a, b, c)
\]

\[
\{\mathbf{S}\} = [\mathbf{B}_s]\{\mathbf{U}\}, \quad \{\mathbf{E}\} = -[\mathbf{B}_e]\{\mathbf{\phi}\}, \quad \{\mathbf{g}\} = -[\mathbf{B}_g]\{\mathbf{\Theta}\}, \quad (5a, b, c)
\]

where \(\{\mathbf{u}\}, \{\mathbf{S}\}, \{\mathbf{E}\}, \{\mathbf{g}\}\) denote the displacement, strain, electric field, and temperature
gradient vectors; \([\mathbf{N}_u]\), \([\mathbf{N}_\phi]\), and \([\mathbf{N}_\theta]\) are the shape function matrices for the nodal
displacement vector \(\{\mathbf{U}\}\), nodal potential vector \(\{\mathbf{\phi}\}\), and nodal temperature vector \(\{\mathbf{\Theta}\}\),
respectively; \([\mathbf{B}_s]\) = \([\mathbf{L}_u]\)[\(\mathbf{N}_u\)], \([\mathbf{B}_e]\) = \([\mathbf{L}_\phi]\)[\(\mathbf{N}_\phi\)], and \([\mathbf{B}_g]\) = \([\mathbf{L}_\theta]\)[\(\mathbf{N}_\theta\)]; and \([\mathbf{L}]\) is a differential
operator:

\[
[\mathbf{L}_u] = \begin{bmatrix}
\frac{\partial}{\partial x} & 0 & 0 \\
0 & \frac{\partial}{\partial y} & 0 \\
0 & 0 & \frac{\partial}{\partial z}
\end{bmatrix}, \quad (6a)
\]

\[
[\mathbf{L}_\phi] = [\mathbf{L}_u] \cdot [\begin{bmatrix}
\frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z}
\end{bmatrix}]'. \quad (6b)
\]

Nodal variables and shape function matrices of an eight-node thin piezothermoelastic
solid element are defined as follows:

\[
\{\mathbf{U}_i\} = \sum_{i=1}^8 [\mathbf{\tilde{u}}_i, \tilde{v}_i, \tilde{w}_i]', \quad (7a)
\]

\[
\{\mathbf{\Phi}_i\} = \sum_{i=1}^8 [\mathbf{\tilde{\phi}}_i], \quad \{\mathbf{\Theta}_i\} = \sum_{i=1}^8 [\mathbf{\tilde{\theta}}_i], \quad (7b, c)
\]

\[
[\mathbf{N}_u] = \sum_{i=1}^8 \begin{bmatrix} N_i & 0 & 0 \\
0 & N_i & 0 \\
0 & 0 & N_i \end{bmatrix}, \quad (8a)
\]

\[
[\mathbf{N}_\phi] = \sum_{i=1}^8 [\mathbf{N}_u], \quad [\mathbf{N}_\theta] = \sum_{i=1}^8 [\mathbf{N}_u], \quad (8b, c)
\]

Note that the subscript \(i\) denotes the nodal variables, and \([\cdots]\) denotes a row vector.
Recall that the strains \(\mathbf{S}\) are defined by the first derivative of displacement vector
\(\{\mathbf{U}\}\) using a differential operator matrix \([\mathbf{L}_u]\). The electric field vector \(\{\mathbf{E}\}\) is defined
by the electric potential $\phi$ using a gradient operator $\nabla$, i.e. \( \{ E \} = -\nabla \phi \), where $\nabla = \{ \partial / \partial x, \partial / \partial y, \partial / \partial z \}$.

\[ [B_x] = \sum_{i=1}^{s} \begin{bmatrix} \partial N_i/\partial x & 0 & 0 \\ 0 & \partial N_i/\partial y & 0 \\ 0 & 0 & \partial N_i/\partial z \end{bmatrix}, \quad \text{(9a)} \]

\[ [B_y] = \sum_{i=1}^{s} \begin{bmatrix} \partial N_i/\partial y \\ \partial N_i/\partial x \\ \partial N_i/\partial z \end{bmatrix}, \quad \text{(9b)} \]

\[ [B_z] = \sum_{i=1}^{s} \begin{bmatrix} \partial N_i/\partial z \\ \partial N_i/\partial x \\ \partial N_i/\partial y \end{bmatrix}, \quad \text{(9c)} \]

2.4. INTERNAL DEGREES OF FREEDOM

Conventional isoparametric solid elements have significant deficiencies in ‘thin’ structural applications. If the element thickness is thin compared with the element span, an excessive shear strain energy is stored in the thickness direction. Accordingly, the stiffness coefficients in the thickness direction become much higher than those in the planar directions. This leads to poor estimations and inaccurate results [12]. An important technique for improving the behavior of isoparametric elements is to introduce internal dof.

The original piezoelectric hexahedron solid element was an eight-node hexahedron solid element [9]. The added three internal nodal dof are numbered from 9 to 11. By adding these internal dof to the dependent variables, one can derive the displacement \( \{ u \} \) vector as:

\[ \{ u \} = [N,][U,] + [\tilde{N},][\tilde{u},], \quad \text{(10)} \]

where \([N,]\) is the displacement shape function matrix for nodal displacements \( \{ U, \} \), and \([\tilde{N},]\) is the extra mode shape function matrix for the added internal dof \( \{ \tilde{u}, \} \). \([N,]\) and \( \{ \tilde{u}, \} \) are represented as:

\[ [N,] = \sum_{i=1}^{n} \begin{bmatrix} N_i & 0 & 0 \\ 0 & N_i & 0 \\ 0 & 0 & N_i \end{bmatrix}, \quad \text{(11a)} \]

\[ \{ \tilde{u}, \} = \sum_{i=9}^{11} [\tilde{u}, \tilde{v}, \tilde{w},]. \quad \text{(11b)} \]

Note that the internal dof \( \{ \tilde{u}, \} \) are not physical displacements, but they can be regarded as generalised co-ordinates, or as ‘displacements’ relative to the nodal displacements. These ‘displacements’ vanish at all element edges, so that these dof are internal and have no physical effect on inter-element compatibility. The strain-displacement equation can be written as:

\[ \{ S \} = [B,][U,] + [\tilde{M},][\tilde{u},], \quad \text{(12a)} \]
where

\[
\begin{bmatrix}
\partial N_i/\partial x & 0 & 0 \\
0 & \partial N_i/\partial y & 0 \\
0 & 0 & \partial N_i/\partial z \\
\partial N_i/\partial z & 0 & \partial N_i/\partial x
\end{bmatrix}
\]

These internal dofs are directly condensed on the element level once its element matrices are developed [3].

2.5. SYSTEM EQUATION

Considering a global functional is a summation of all element functionals, i.e. \( \mathcal{F}_u = \sum \mathcal{F}_{u_e} \), \( \mathcal{F}_\phi = \sum \mathcal{F}_{\phi_e} \), and \( \mathcal{F}_\theta = \sum \mathcal{F}_{\theta_e} \), one can write the element energy functionals \( \mathcal{F} \) in a matrix representation:

\[
\mathcal{F}_{u_e} = \frac{1}{2} \{ U \}' [K_{uu}]{\{U\}} + \{ U \}' [K_{u\phi}]{\{ \phi \}} + \{ U \}' [M_{uu}]{\{ \dot{U} \}}
\]

\[
+ \{ U \}' [C_{uw}]{\{ \dot{U} \}} - \{ U \}' [K_{uw}]{\{ \Theta \}} - \{ U \}' [F_{ue}].
\]

(13)

\[
\mathcal{F}_{\phi_e} = \frac{1}{2} \{ \phi \}' [K_{\phi\phi}]{\{ \phi \}} - \{ \phi \}' [K_{\phi\theta}]{\{ \Phi \}} - \{ \phi \}' [K_{\phi\omega}]{\{ \omega \}} + \{ \phi \}' [F_{\phi_e}].
\]

(14)

\[
\mathcal{F}_{\theta_e} = \frac{1}{2} \{ \theta \}' [K_{\theta\theta}]{\{ \Theta \}} + \theta_0 \{ \theta \}' [K_{\theta\omega}]{\{ \dot{U} \}} - \theta_0 \{ \theta \}' [K_{\theta\omega}]{\{ \dot{\phi} \}} + \{ \Theta \}' [H_{\omega\omega}]{\{ \dot{\Theta} \}} - \{ \Theta \}' [F_{\theta_e}].
\]

(15)

where \([M_{uu}]\) and \([H_{\omega\omega}]\) are the mass matrices; \([C_{uw}]\) is the damping matrix; \([K_{uu}]\) (where \(x \) and \( y \) are \( u, \phi, \theta \)) are the stiffness matrices defined for the displacement, electric, and temperature fields; \([F_{ue}]\) is the external mechanical excitation; \([F_{\phi_e}]\) is the electric excitation which is the control voltage determined by control algorithms in active vibration control applications; and \([F_{\theta_e}]\) is the heat excitation. The superscript \( t \) denotes the matrix/vector transpose. Taking variations of \( \mathcal{F}_{u_e}, \mathcal{F}_{\phi_e}, \mathcal{F}_{\theta_e} \) with respect to the independent variables \( \{ U \}, \{ \phi \}, \{ \theta \} \), one can derive three nodal governing equations of the piezoelectroplastic element. Assembling all the element matrices, one can derive the global system equation as (in a matrix form):

\[
\begin{bmatrix}
M_{uu} & 0 & 0 \\
0 & C_{uu} & 0 \\
0 & 0 & C_{\theta\theta}
\end{bmatrix}
\begin{bmatrix}
\dot{U} \\
\dot{\phi} \\
\dot{\Theta}
\end{bmatrix}
+ \begin{bmatrix}
0 & 0 & 0 \\
0 & K_{\phi\phi} & -K_{\phi\omega} \\
-\theta_0 K_{\theta\phi} & H_{\omega\omega} & 0
\end{bmatrix}
\begin{bmatrix}
U \\
\phi \\
\theta
\end{bmatrix}
= \begin{bmatrix}
F_{ue} \\
F_{\phi_e} \\
F_{\theta_e}
\end{bmatrix}.
\]

(16)

This equation shows the couplings of electric, displacement, and temperature fields. In high frequency oscillations, the dynamic couplings of heat transfer with the structural deflection and electric field are small. Thus, one can neglect the coupling terms \( \theta_0 [K_{\theta\phi}]{\{ \dot{U} \}} \) and \( -\theta_0 [K_{\theta\phi}]{\{ \dot{\phi} \}} \) in static or (most) vibration sensing and control applications. The electric excitation can be used as control inputs. Note that the damping can be actively enhanced in a velocity feedback. Detailed piezoelectroplasticity and control of continua are discussed next.
3. PIEZOTHERMOELASTICITY AND CONTROL

As discussed previously, in static and high frequency oscillations, the dynamic (rate) couplings can be neglected, and a decoupled quasi-static formulation can be derived. Consequently, the solution procedures can be divided into (1) calculating the temperature field and (2) analysing the piezothermoelasticity and control of the piezoelectric continua or laminates [8]. In practice, it is not necessary to calculate all three variables simultaneously. Temperature field can be calculated based on a given thermal excitation

\[ [H_{\omega t}][\dot{\Theta}] + [K_{\omega t}][\Theta] = \{F_t\}. \]

(17)

Besides, the displacement and electric potential equations can be decoupled using Guyan's reduction scheme [9, 10]. The condensed system equation becomes

\[ [M_{\omega t}][\ddot{U}] + [C_{\omega t}][\dot{U}] + [K^*][U] = \{F_s\} + [K_{\omega t}][K_{\omega t}^{-1}][F_c] \]

\[ + ([K_{\omega t}] - [K_{\omega t}][K_{\omega t}^{-1}][K_{\omega t}] - [\Theta]). \]

(18)

where \([K^*] = [K_{\omega t}] + [K_{\omega t}][K_{\omega t}^{-1}][K_{\omega t}]\) and \((\cdot)^{-1}\) denotes the matrix inverse. If the electric potential distribution is of interest at one time instant, the electric potential \(\{\phi\}\) can be calculated by

\[ \{\phi\} = [K_{\omega t}]^{-1}([K_{\omega t}][U] + [K_{\omega t}][\Theta] - \{F_e\}). \]

(19)

Note that both the displacement and the electric potential distribution are functions of mechanical, temperature, and electric excitations. In sensing applications, the electric excitation \(\{F_e\}\) is usually set zero in the potential equation \(\{\phi\}\), i.e.

\[ \{\phi\} = [K_{\omega t}]^{-1}([K_{\omega t}][U] + [K_{\omega t}][\Theta]). \]

(20)

As a common practice, the sensor signal is amplified and fed back into the distributed actuator to generate control forces opposing the motion of the continuum [3, 9, 10]. Based on the temperature field and piezothermoelastic effects of distributed sensor/actuator, feedback control of piezoelectric structures can be calculated.

4. CASE STUDY

Piezothermoelastic effects (pyroelectric effect and thermal strain effect) of distributed piezoelectric sensors made of polyvinylidene fluoride (PVDF) and lead zircono titanate (PZT) are respectively studied and compared. Two dimensional voltage profiles induced by the temperature effects are evaluated. Note that a finite separation of surface electrodes is required to warrant this spatially distributed characteristics. A square plexiglas plate \((40 \times 40 \times 1.6 \text{ cm})\) laminated with distributed piezoelectric layers on the top and bottom surfaces is studied, Fig. 1. The piezoelectric layers are distributed on the top and bottom plate surfaces and each of them is divided into four equally segmented elements \((16.47 \text{ cm} \times 16.47 \text{ cm} \times 40 \mu\text{m})\) each, and the plate is simply supported on four edges. These segmented elements are electrically isolated, and are separated by an element length. In later studies, two kinds of piezoelectric materials: (1) polymeric PVDF and (2) piezoceramic PZT are studied; their material properties are summarised in Appendix A. Piezothermoelastic behavior of these two kind distributed sensors are studied, and their respective pyroelectric and thermal strain effects are evaluated.
4.1. FINITE ELEMENT MODELING

The simply supported plate is divided into $17 \times 17$ mesh, and each piezoelectric patch is divided into $7 \times 7$ mesh. Accordingly, there are 289 elements for the plexiglas plate and 392 elements for all eight piezoelectric patches. There are 3924 dof (i.e. 3412 displacement dof and 512 electric dof). However, only 324 master dof are used in the time-domain integration when the reduction procedures are applied. It is assumed that a temperature of $5{}^\circ\text{C}$ difference is imposed on the piezoelectric laminated plate and the top is $5{}^\circ\text{C}$ hotter than the bottom. Piezothermoelasticity and control of the plate are studied. It was observed that the temperature-induced voltage generation can be divided into two effects: the pyroelectric effect and the thermal strain effect [8]. These two distinct effects of PVDF and PZT distributed sensors are specifically investigated and compared.

Figure 2. Pyroelectric effect of PVDF sensors.
4.2. PIEZOTHERMOELASTICITY OF PVDF SENSORS

Piezothermoelasticity of PVDF sensors are studied in this section. Figure 2 shows the voltage generated by the pyroelectric effect and Fig. 3 shows the voltage by the thermal strain effect in a segmented PVDF sensor (second piece). It is observed that the pyroelectric effect is much more prominent than the thermal strain effect in PVDF sensors.

4.3. PIEZOTHERMOELASTICITY OF PZT SENSORS

In this case, the polymeric PVDF sensor layers are replaced by the piezoceramic PZT sensor layers, and their respective pyroelectric and thermal strain effects are studied. Figure 4 shows the voltage generation due to the pyroelectric effect and Fig. 5 shows the voltage due to the thermal strain effect. Note that the thermal strain effect is more important than the pyroelectric effect in PZT sensor layers.

4.4. THERMAL DEFLECTION AND CONTROL

In this case, a temperature difference of 5°C is imposed on the plate. (The top surface is 5°C hotter than the bottom surface.) Due to the temperature-induced thermal gradient, the plate center is deflected upward, i.e. a ‘convex’ like deformation appears. Figure 6 shows the deformed plate. Next, this thermal-induced deflection is to be controlled by using PVDF and PZT actuators, respectively.
Figure 7 shows the PVDF controlled plate. The control voltage is set at 1800 V which is applied to those distributed actuators on both top and bottom surfaces. Note that the deflection is only controlled by \( \approx 10\% \). Figure 8 shows the PZT controlled response when 108 V is applied to the distributed PZT actuator layers. Note that the thermal deflection is almost totally controlled. Further study finds that the plate is totally controlled at 111 V. Apparently, PZT actuators are much more powerful than the PVDF actuators, as predicted. This example gives a quantitative comparison of these two distributed actuators.

5. DISCUSSION AND CONCLUSIONS

Distributed piezoelectric layers are widely used as distributed sensors and actuators in active structural systems recently. This paper investigates the temperature effect these piezoelectric sensors and actuators using the finite element technique. Especially, the temperature-related pyroelectric effect and thermal strain effect in distributed piezoelectric layers were studied. Sensing the actuation effectivenesses of distributed polymeric PVDF and piezoceramic PZT devices were quantitatively compared.

Finite element formulations were presented first and applications to distributed sensing and control were introduced next. A simply supported piezoelectric laminated plate was used in a case study. Analyses suggest that the temperature can introduce voltages (piezothermal effect) via two effects: (1) the pyroelectric effect and (2) the
thermal strain effect. The pyroelectric effect is a direct temperature effect. The thermal strain effect is an indirect (secondary) temperature effect, because the voltage generation is caused by the thermally induced strain which is introduced by the temperature variation. It was observed that the pyroelectric effect is significant in PVDF layers and insignificant in PZT layers. However, the thermal strain effect is insignificant in PVDF layers and significant in PZT layers, based on the material properties used in this study. (Note that PVDF layers are used in thermal imaging devices and systems because of their significant pyroelectric effect.) It is also quantitatively proved that the PZT actuators are much more effective than the PVDF actuators in deflection controls. However, it should be pointed out that the commonly available polymeric piezoelectric PVDF (e.g. Kynar or Solef) has a breakdown voltage around 30 V/μm which reflects a maximum voltage of 1200 V for 40 μm PVDF. Besides, a typical PZT (e.g. G-1195) ceramic has a polarization field of $2.4 \times 10^6$ V/m and the maximum coercive field is $1.2 \times 10^6$ V/m. The maximum voltage allowed for the 40 μm G-1195 PZT is only 48 V. Apparently, the applied control voltages in the control simulations exceeded the present material limitations which deserve further advancement to warrant more practical applications.

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REFERENCES

### Table A1

**Material properties of plexiglas, PVDF and PZT piezoceramic**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Plexiglas</th>
<th>PVDF</th>
<th>PZT</th>
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<td>Young's modulus (GPa), $Y$</td>
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<td>Density (kg/m$^3$), $\rho$</td>
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<td>$1.80 \times 10^3$</td>
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<td>Thermal conductivity (W/m$^2$K), $K$</td>
<td>0.035</td>
<td>0.19</td>
<td>0.17</td>
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<tr>
<td>Thermal expansion (C$^\circ$/C), $\alpha$</td>
<td>$6.0 \times 10^{-5}$</td>
<td>$1.25 \times 10^{-4}$</td>
<td>$1.2 \times 10^{-5}$</td>
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<tr>
<td>Piezo strain constant (m/V $\times 10^{-19}$), $d_{ii}$</td>
<td>0.10</td>
<td>1.79</td>
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<td>Electricity permittivity (F/m $\times 10^{-10}$), $\epsilon_{ii}$</td>
<td>$5.79 \times 10^{-3}$</td>
<td>1.65</td>
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<tr>
<td>Pyroelectric constant (C/m$^2$K), $P_{ii}$</td>
<td>$0.25 \times 10^{-4}$</td>
<td>$0.25 \times 10^{-4}$</td>
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<tr>
<td>Temperature range (°C)</td>
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<td>Max operating voltage (V/µm)</td>
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<td>Breakdown voltage (V/µm)</td>
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