Piezoelectric materials are active materials whose properties can be actively tuned and controlled via electromechanical, magnetic, electrical, temperature, and high-energy light means. Furthermore, synergistically integrating smart materials, structures, sensors, actuators, control electronics, and artificial intelligence yields an active or adaptive (lifelike) structronic (structure + electronic) system with inherent self-sensing, diagnosis, and control capabilities. These new smart structures and structronic systems could revolutionize many engineering systems.

Piezoelectric material is one kind of smart material and piezoelectricity is an electromechanical phenomenon coupling the elastic field and the electric field (Figure 1). (Note that piezo means press in Greek.) Ever since the discovery of piezoelectric behavior by the Curie brothers (Jacques and Pierre) in 1880, this coupled electromechanical characteristic has brought a new dimension in transducer (sensor and actuator) applications. In general, a piezoelectric material responds to mechanical force/pressure and generates an electric charge/voltage, which is called the direct piezoelectric effect. Conversely, an electric charge/field applied to the material induces mechanical stresses or strains, and this is called the converse piezoelectric effect. The direct effect is usually the basis in sensor and measurement applications; the converse effect is for precision actuation and manipulation in control applications.

Piezoelectric materials have been applied to engineering applications since 1917. Recent research activities involving smart materials, smart (intelligent) structures, structronic systems, precision mechatronic systems, and microelectromechanical systems (MEMS) further renew a widespread interest in traditional piezoelectric materials and continua, elastic/piezoelectric composites, and thin-layer piezoelectric devices due to their high potentials in many advanced static and dynamic applications, e.g., aerospace/aircraft structures, robot manipulators, vibration/noise control and isolation, high-precision devices, microsensors/actuators, thin-film devices, MEMS, and microdisplacement actuation and control. This article provides an overview of the historic background, material varieties, fundamental piezoelectric theories, sensor and actuator applications, piezoelectric continua, outlook, and prospects. See also Sensors and actuators for distributed sensing and control applications.

Figure 1 Piezoelectric effect.
Piezoelectric Materials

Many natural and synthetic materials exhibit piezoelectric behavior; Table 1 summarizes popular natural and synthetic piezoelectric materials. Certain materials naturally exhibit piezoelectric behavior; however, other, especially synthetic, materials require an artificial poling process. The poling process involves applying a high electric field at an elevated temperature. The field aligns the molecular dipoles in the material and the dipoles are fixed into the aligned orientation when the material cools down while the strong field is still maintained. The poled piezoelectric material becomes anisotropic and it deforms when subject to an electric field and polarizes when subject to mechanical stress, although the original raw material was nonpiezoelectric and isotropic.

In general, synthetic materials can be fabricated into arbitrary shapes and geometries, while natural crystals usually remain in their natural formations and appearances. Accordingly, synthetic piezoelectric ceramics (e.g., lead zirconate titanate and lead lanthanum zirconate titanate) and polymers (e.g., polyvinylidene fluoride) are widely used in many sensor and actuator applications. Note that for low electric fields (<0.1 MV m\(^{-1}\) approximately), the linear proportionality between the strain and electric field is valid. However, for higher ac fields (>0.6 MV m\(^{-1}\) approximately), significant electromechanical hysteresis can occur as the response domain grows, which can cause servo-displacement control problems in precision piezoelectric actuator devices. These materials still have certain limitations, such as being fairly weak mechanically, and nonreproducible effects (e.g., hysteresis on the order of 10% or greater). While the range of piezoelectric applications is well documented, there are other desired applications that these materials cannot achieve effectively due to their properties, such as hysteresis, and low stroke. New high-authority materials, e.g., single crystal piezoelectric materials, are continuously being composed and evaluated. Fundamental piezoelectricity theory is presented next, followed by practical applications. Other advanced topics on piezoelectric continua are presented subsequently.

Linear Piezoelectricity

Linear piezoelectric theory indicates the coupling between the electric field (static coupling) and the mechanical (dynamic coupling) field (Figure 1), which is a first-order effect implying that an induced strain is proportional to the electric field and the direction of the displacement is dependent on the sign of the electric field. In this section, the linear piezoelectric theory is reviewed, and the relations among various elastic and electric constants are defined. Note that the pyroelectric effect – the temperature effect – will be discussed in a later section.

The linear piezoelectricity theory is based on a quasistatic assumption in which the electric field is balanced with the elastic field so that these two fields can be decoupled at a given time instant. The direct and converse piezoelectric effects are written as:

\[
D = eS + \varepsilon E \quad [1]
\]

\[
T = \varepsilon \varepsilon^T S - e^T E \quad [2]
\]

where \(D\) is the electric displacement vector\(^1\); \(T\) is the stress tensor (second-order); \(S\) is the strain tensor (second-order); \(E\) is the electric field vector; \(e\) is a tensor of piezoelectric stress coefficients (third-order); \(\varepsilon\) is the transposed tensor of \(\varepsilon\); \(\varepsilon^T\) is the dielectric tensor (second-order) evaluated at constant strain; and \(\varepsilon^T\) is the elasticity tensor (fourth-order) evaluated at constant electric field. If the piezoelectric tensor \(e\) is set to zero, eqns [1] and [2] become the conventional dielectric and Hooke’s equations. Note that the stress \(T\) and strain \(S\) are represented in column vectors:

\[
T = \begin{bmatrix} T_1 & T_2 & T_3 & T_4 & T_5 & T_6 \end{bmatrix}^T \quad [3]
\]

\[
S = \begin{bmatrix} S_1 & S_2 & S_3 & S_4 & S_5 & S_6 \end{bmatrix}^T \quad [4]
\]

\(^1\) IEEE piezoelectricity notation.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>List of common piezoelectric materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural crystals</td>
<td>Quartz, Rochelle salt, ammonium phosphate</td>
</tr>
<tr>
<td>Liquid crystals</td>
<td>Glass rubber, paraffin</td>
</tr>
<tr>
<td>Noncrystalline materials</td>
<td>Bone, wood</td>
</tr>
<tr>
<td>Textures</td>
<td>Piezoceramics</td>
</tr>
<tr>
<td>Synthetic piezoelectric materials</td>
<td>Lead zirconate titanate (PZT), barium titanate, lead niobate, lead lanthanum zirconate titanate (PLZT)</td>
</tr>
<tr>
<td></td>
<td>Crystals</td>
</tr>
<tr>
<td></td>
<td>Ammonium dihydrogen phosphate, lithium sulfate</td>
</tr>
<tr>
<td></td>
<td>Piezoelectric polymer</td>
</tr>
<tr>
<td></td>
<td>Polyvinylidene fluoride (PVDF or PVF2)</td>
</tr>
</tbody>
</table>
where the superscript $t$ denotes the vector or matrix transpose. Subscripts 1–3 denote the normal components and 4–6 denote the shear components. The electric field $E$ and the electric displacement (flux density) $D$ are also written in column vectors:

$$E = [E_1 E_2 E_3]^t$$

$$D = [D_1 D_2 D_3]^t$$

### Four Sets of Fundamental Equations

There are a number of ways to write the elastic, piezoelectric, and dielectric governing equations in which (1) stress and electric field, (2) strain and electric displacement, (3) strain and electric field are respectively used as dependent and/or independent variables. Table 2 summarizes the four sets of representations, including the equations defined above.

$s^0$ is the compliance matrix defined at constant dielectric displacement (note $s = c^{-1}$); $d$ is the piezoelectric strain constant matrix; $g$ matrix relates the open-circuit voltage at a given stress; $e$ is the piezoelectric stress constant matrix; $b$ matrix relates the open-circuit voltage at a given strain; $\beta^t$ is a free dielectric impermeability matrix evaluated at constant stress and $\beta^t$ can be obtained from the inverse of the dielectric matrix $\varepsilon$. The superscript $T$ (inside the matrix) denotes the properties measured at constant stress $T$. (Recall that $^t$ denotes a vector or matrix transpose and $^{-1}$ denotes the matrix inverse.). Table 3 shows that the four piezoelectric coefficient matrices $d$, $e$, $g$, and $b$ are all related. Note that an adiabatic condition ensures that no heat is added or removed from a given space or volume. The elastic constants are defined at the adiabatic conditions. The piezoelectric and dielectric constants of a piezoelectric material are defined at isothermal and adiabatic conditions. The piezoelectric material is assumed to be nonpyroelectric in this case. Again, the superscripts $T$, $S$, $E$, and $D$ denote the matrix/tensor defined at constant stress, strain, electric field, and dielectric displacement, respectively.

### Piezothermoelasticity

Certain piezoelectric materials are also temperature-sensitive, i.e., an electric charge or voltage is generated when exposed to temperature variations. This effect is called the pyroelectric effect. (Note that pyro originally means fire in Greek.) When temperature influences the piezoelectricity, the fundamental piezoelectric equations need to expand to include the temperature components, e.g., pyroelectricity and thermal elasticity. Thus, the fundamental piezoelectric equations become the piezothermoelasticity equations:

$$T = cS - eE - \lambda \theta$$

$$D = eS + cE + p\theta$$

$$\Theta = \lambda S + p'E + \alpha_s \theta$$

where $\lambda$ is the thermal stress constant vector; $\theta$ is the temperature; $p$ is the pyroelectric constant; $\Theta$ is the thermal entropy; $\alpha_s$ is a material constant ($\alpha_s = p_c \theta$ where $p$ is the material density and $c_v$ is the specific heat at constant volume).

### Engineering Applications

The discovery of piezoelectricity took place in 1880; however, it wasn’t until 1917 that Langvin invented the first engineering application—the depth-sounding device designed with Rochelle salt. Over the years, sophisticated piezoelectric theories have been proposed and refined; new piezoelectric materials have been discovered or synthesized; and novel piezoelectric devices have been continuously invented and applied to a variety of engineering systems. Table 4 summarizes a number of typical sensor and actuator applications. As discussed previously, sensor application is based on the direct piezoelectric effect; actuator application is based on the converse piezoelectric effect. A number of sample application areas are also summarized in Table 5. Note that these areas

### Table 2 Four sets of piezoelectric equations

<table>
<thead>
<tr>
<th>No.</th>
<th>Elastic relationship</th>
<th>Electric relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$T = c^0S - b^0D$</td>
<td>$E = -hS + b^0D$</td>
</tr>
<tr>
<td>2</td>
<td>$T = c^0S - d^0E$</td>
<td>$D = eS + c^0E$</td>
</tr>
<tr>
<td>3</td>
<td>$S = s^0T + g^0D$</td>
<td>$E = -g^0T + b^0D$</td>
</tr>
<tr>
<td>4</td>
<td>$S = s^0T + d^0E$</td>
<td>$D = cT + b^0E$</td>
</tr>
</tbody>
</table>

### Table 3 Relations among elastic, piezoelectric, and dielectric constants

<table>
<thead>
<tr>
<th>No.</th>
<th>Elastic</th>
<th>Piezoelectric</th>
<th>Dielectric</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$s^0$</td>
<td>$g = \beta^t d$</td>
<td>$\beta^t = d^0$</td>
</tr>
<tr>
<td>2</td>
<td>$s^0$</td>
<td>$e = d\varepsilon^t$</td>
<td>$\varepsilon^t = e^t - \eta^t$</td>
</tr>
<tr>
<td>3</td>
<td>$s^0$</td>
<td>$h = \beta^t e$</td>
<td>$\beta^t = h^t - \eta^t$</td>
</tr>
<tr>
<td>4</td>
<td>$s^0$</td>
<td>$h = g^0D$</td>
<td>$\beta^t = D^t - \eta^t$</td>
</tr>
</tbody>
</table>
are artificially categorized and lots of them are actually interrelated and somehow overlapped. In many cases, both sensor and actuator functions are often incorporated in these application areas. Advanced topics on (linear and nonlinear) piezoelectric shell continua and their derivatives are discussed next. For distributed sensing and vibration control of elastic continua (e.g., shells, plates, etc.) using distributed thin piezoelectric sensor/actuator layers, see Sensors and actuators.

Piezoelectric Continua and Advanced Theories

The Curie brothers initiated the studies of piezoelectric continua in 1880. Advances have continuously been made over the years (e.g., Mason, Cady, Mindlin, Tiersten, Sessler, Dömkeci, Tzou, and Rogacheva). Although studies of piezoelectric shells of specific shapes have advanced in the last few decades, most of them have primarily been concerned with wave propagation (i.e., in-plane motions), electromechanics, and vibrations of specific geometries with finite and infinite dimensions, such as thin rods, plates, rings, disks, and circular cylindrical shells. Later, more advanced geometries (such as spherical shells, shells of revolution, hollow ceramic cylinders, radially polarized composite piezoceramic cylinders, piezoelectric solid cylinder guided by a thin film, and wave propagations in a piezoelectric solid cylinder of arbitrary cross-sections) were investigated. Recent development of smart structures and structronic systems reveals the need to derive a more generic linear and nonlinear piezoelectric continuum theory applicable to distributed sensors and actuators in control of elastic continua and distributed parameter systems. Accordingly, piezoelectric theories based on a generic double-curvature deep shell with triclinic or hexagonal crystal structures have been investigated. Figure 2 illustrates a generic piezoelectric double-curvature deep shell defined in a triorthogonal coordinate system, in which $x_1$ and $x_2$ define the neutral surface and $x_3$ defines the normal direction; $R_1$ and $R_2$ are the radii of curvature of the $x_1$ and $x_2$ axes, respectively. Theories related to the generic shell can be, in general, applied to a number of common configurations and geometries.

Generic theories on piezoelectric shells of arbitrary shape are of importance in many applications. Theories derived based on the generic shell continuum can easily be simplified and applied to other common geometries (e.g., shells of revolution, spherical shells, conical shells, cylinders, cylindrical shells, plates, arches, rings, and beams) using four geometric parameters: two radii of curvatures ($R_1$ and $R_2$) and two Lamé parameters ($A_1$ and $A_2$). (See Sensors and actuators for detailed simplification procedures.)

Advanced (linear and nonlinear) theories of generic (triclinic and hexagonal) piezoelectric (thin, thick,
and composite) (deep or shallow) shells have recently been proposed. System equations coupling electric, elastic, and temperature fields are derived using the energy-based Hamilton’s principle. Generic equations of mechanical motion and mechanical boundary conditions, as well as a charge equation of electrostatics and electric boundary conditions are formulated. Temperature effects to these piezoelectric shell continua are also discussed and their effects on system characteristics and sensing/control effectiveness are evaluated. These concepts are briefly outlined next.

Thermoelectromechanical system equations of a nonlinear piezothermoelastic shell continuum, i.e., the von Karman-type geometric nonlinearity, are also presented to illustrate multifield coupling (Figure 2).

**Thermoelectromechanical Coupling of Nonlinear Piezoelectric Shell Continuum**

Hamilton’s principle is used in deriving the shell thermoelectromechanical equations and boundary conditions of the piezothermoelastic shell continuum. Hamilton’s principle assumes that the energy variations over an arbitrary time period are zero. Considering all energies associated with a piezothermoelastic shell continuum subjected to mechanical, temperature, and electric inputs, one can write Hamilton’s equation:

\[
\delta \int_{\Gamma} \left\{ \left( \int_{V} \left( \frac{1}{2} \rho \dot{u} \dot{u} + H(S, E, \Theta) + \Theta \Theta \right) dV - \int_{V} \dot{V} \right) - \int_{S} (\epsilon, \dot{U}_{j} - Q_{j} \phi) dS \right\} dt = 0
\]

where \( \rho \) is the mass density; \( H \) is the electric enthalpy; \( \epsilon \) is the surface traction in the \( \alpha \) direction; \( Q_{j} \) is the surface electric charge; \( \phi \) is the electrical potential; \( V \) and \( S \) are the volume and surface of the piezothermoelastic shell continuum, respectively; and \( U_{j} \) and \( \dot{U}_{j} \) are the displacement and velocity vectors. It is assumed that only the transverse electric field \( E_{3} \) is considered in the analysis and a linear variation of the displacement field in the shell, i.e., \( U_{j} = u_{j} + \beta \). Substituting all energy expressions into Hamilton’s equation and imposing the thin-shell assumptions, one can derive the nonlinear piezothermoelastic shell equations and boundary conditions of the continuum.

\[
- \frac{\partial (N_{12} A_{2})}{\partial x_{1}} + N_{22} \frac{\partial A_{2}}{\partial x_{1}} - \frac{\partial (N_{12} A_{2})}{\partial x_{1}} - N_{12} \frac{\partial A_{1}}{\partial x_{2}} - \frac{1}{R_{1}} \left[ \frac{\partial (M_{11} A_{2})}{\partial x_{1}} - M_{22} \frac{\partial A_{2}}{\partial x_{1}} + \frac{\partial (M_{12} A_{1})}{\partial x_{2}} \right] + M_{12} \frac{\partial A_{1}}{\partial x_{2}} + A_{1} A_{2} \rho \dot{u}_{1} = A_{1} A_{2} F_{1}
\]

\[
- \frac{\partial (N_{22} A_{1})}{\partial x_{2}} + N_{11} \frac{\partial A_{1}}{\partial x_{2}} - \frac{\partial (N_{12} A_{2})}{\partial x_{2}} - N_{22} \frac{\partial A_{2}}{\partial x_{1}} - \frac{1}{R_{2}} \left[ \frac{\partial (M_{22} A_{1})}{\partial x_{2}} - M_{11} \frac{\partial A_{1}}{\partial x_{1}} + \frac{\partial (M_{12} A_{2})}{\partial x_{1}} \right] + M_{21} \frac{\partial A_{2}}{\partial x_{1}} + A_{1} A_{2} \rho \dot{u}_{2} = A_{1} A_{2} F_{2}
\]

\[
- \frac{\partial}{\partial x_{1}} \left[ \frac{1}{A_{1}} \left( \frac{\partial (M_{11} A_{2})}{\partial x_{1}} - M_{22} \frac{\partial A_{2}}{\partial x_{1}} + \frac{\partial (M_{12} A_{1})}{\partial x_{2}} + M_{11} \frac{\partial A_{1}}{\partial x_{1}} + \frac{\partial (M_{12} A_{2})}{\partial x_{1}} + M_{21} \frac{\partial A_{2}}{\partial x_{1}} \right) + A_{1} A_{2} \left( \frac{N_{11}}{R_{1}} + \frac{N_{22}}{R_{2}} \right) \right] + A_{1} A_{2} \rho \dot{u}_{3} = A_{1} A_{2} F_{3}
\]

where \( u_{j} \) is the displacement in the \( x_{j} \) direction; \( \rho \) is the mass density; \( F_{j} \) is the external input; \( A_{1} \) and \( A_{2} \)
are the Lamé parameters, and \( R_1 \) and \( R_2 \) are the radii of curvature. Note that all terms inside the braces are contributed by the nonlinear effects, showing that the nonlinear influence on the transverse equation \( w_3 \) is significant. Also, the thermoelectromechanical equations are similar to standard shell equations. However, the force and moment expressions defined by mechanical, thermal, and electric effects are much more complicated than the conventional elastic expressions. Membrane force resultants \( N_\theta \) and bending moments \( M_\theta \) can be derived based on the induced strains (i.e., membrane strains \( \varepsilon^m_\theta \) and bending strains \( k_\theta \)).

\[
\begin{bmatrix}
N_{11} \\
N_{12} \\
N_{12} \\
M_{11} \\
M_{12} \\
M_{12}
\end{bmatrix} =
\begin{bmatrix}
A_{11} & A_{12} & A_{16} & 0 & 0 & 0 \\
A_{12} & A_{22} & A_{26} & 0 & 0 & 0 \\
A_{16} & A_{26} & A_{66} & 0 & 0 & 0 \\
0 & 0 & 0 & D_{11} & D_{12} & D_{16} \\
0 & 0 & 0 & D_{12} & D_{22} & D_{26} \\
0 & 0 & 0 & D_{16} & D_{26} & D_{66} \\
\end{bmatrix}
\begin{bmatrix}
\varepsilon^m_\theta \\
\varepsilon^m_\theta \\
\varepsilon^m_\theta \\
k_\theta \\
k_\theta \\
k_\theta
\end{bmatrix}
\]

It is observed that there are three components, mechanical, electric, and temperature, in the force/moment expressions. Superscripts \( \varepsilon \) and \( \theta \) respectively denote the electric and temperature components; \( N^\varepsilon \) and \( N^\theta \) are the electric- and temperature-induced forces; and \( M^\varepsilon \) and \( M^\theta \) are the electric- and temperature-induced moments, respectively. In actuator applications, these electric forces and moments are used to control the static and dynamic characteristics of shells. \( A_{ui} \) and \( D_{ui} \) are the extensional and bending stiffness constants. (Note that all zeros in the force matrix are replaced by the coupling constants \( B_\theta \) in a piezoelectric composites laminated sheet. The membrane strains and bending strains are coupled by the coupling stiffness coefficients \( B_\theta \) in the elastic force/moment resultants.) Substituting the expressions of \( N_{11}, N_{12}, N_{12}, M_{11}, M_{12}, M_{12} \) into the shell equations leads to the thermoelectromechanical shell equations defined in the neutral surface displacements \( u_1, u_2, \) and \( u_3 \). The transverse shear deformation and rotary inertia effects are not considered. The electric terms, forces, and moments, can also be used in controlling the mechanical- and/or temperature-induced excitations.

Based on Hamilton’s equation, one can also derive all admissible mechanical and electric boundary conditions. Admissible mechanical boundary conditions on the boundary surfaces defined by a distance \( z_2 \) and \( z_1 \) are respectively summarized in Table 6 and Table 7. The superscript * denotes the boundary forces, moments, displacements, and slopes. Usually, only either the force/moment boundary conditions or the displacement/slope boundary conditions are selected for a given physical boundary condition. In addition, additional transverse shear force terms \( Q_{13} \) are nonlinear components induced by large deformations. These force terms do not appear in the linear case. The shear stress resultants are defined as:

\[
V_{12} = N_{12} + \left( \frac{M_{12}}{R_1} \right) \\
V_{21} = N_{21} + \left( \frac{M_{21}}{R_1} \right) \\
V_{13} = Q_{13} + \frac{\partial}{\partial z_2} \left( \frac{M_{12}}{A_2} \right)
\]

<table>
<thead>
<tr>
<th>Force/moment</th>
<th>Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ( N_{11} = N_{11} )</td>
<td>( u_1 = u_1 )</td>
</tr>
<tr>
<td>2 ( M_{11} = M_{11} )</td>
<td>( \beta_1 = \beta_1 )</td>
</tr>
<tr>
<td>3 ( N_{12} + \frac{M_{12}}{R_1} = V_{12} )</td>
<td>( u_2 = u_2 )</td>
</tr>
<tr>
<td>4 ( Q_{13} + \frac{\partial}{\partial z_2} \left( \frac{M_{12}}{A_2} \right) )</td>
<td>( u_3 = u_3 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Force/moment</th>
<th>Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ( N_{22} = N_{22} )</td>
<td>( u_2 = u_2 )</td>
</tr>
<tr>
<td>2 ( M_{22} = M_{22} )</td>
<td>( \beta_2 = \beta_2 )</td>
</tr>
<tr>
<td>3 ( N_{21} + \frac{M_{21}}{R_1} = V_{21} )</td>
<td>( u_1 = u_1 )</td>
</tr>
<tr>
<td>4 ( Q_{23} + \frac{\partial}{\partial z_1} \left( \frac{M_{21}}{A_1} \right) )</td>
<td>( u_3 = u_3 )</td>
</tr>
</tbody>
</table>
where $V_{13}$ and $V_{23}$ are the Kirchhoff effective shear stress resultants of the first kind; $V_{12}$ and $V_{21}$ are the Kirchhoff effective shear stress resultants of the second kind. Note that all elastic-, electric-, and thermal-related terms are included in the force and moment expressions. These electric terms can be used, in conjunction with control algorithms, as control forces/moments countering mechanical- and temperature-induced vibrations in distributed structural control of shells. The nonlinear piezothermoelastic shell equations can be further simplified based on (1) linear approximation, (2) material simplification, and (3) geometry simplifications.

In order to assist design and application of piezoelectric devices in industry, new finite element formulations (thick and thin solid elements, shell/plate elements, and composite elements) and computer codes have been developed in recent years. Accordingly, thermo electromechanics, vibration behavior, sensing, and control encompassing all possible directions (e.g., three translational and two rotary coordinates) of the generic piezoelectric shell continuum (and its derived geometries) and applications to smart structures and strucronic systems are further explored and evaluated. Furthermore, distributed sensor and actuator can be surface- or thickness-shaped using the modal strain functions. In this case, the shaped sensor or actuator is only sensitive to the designated natural mode (i.e., the orthogonal modal sensor or actuator) and it is insensitive to other natural modes, based on the modal orthogonality of natural modes. (See Sensors and actuators for details on distributed sensor and actuator applications and their related theories.)

**Summary**

Piezoelectricity is one of the most important electromechanical coupling phenomena successfully applied to engineering applications today. Practical applications range from micro- (e.g., MEMS and microsensors and actuators) to macrosystems (e.g., smart structures and strucronic systems, aerospace structures, satellite systems, and gossamer systems) and many other applications in between (e.g., force/pressure sensors, precision actuators, robotics and mechatronic systems, and vibration/noise isolation and control). However, the performance of today's piezoelectric devices is still limited to material properties and deficiencies, e.g., nonlinearity, hysteresis effects, limited strain rates, breakdown voltages, and temperature instabilité, etc. These material properties need to be further improved in order to enhance future sensor/actuator performance and efficiency.

On the other hand, piezoelectricity typically represents the coupling of electric and elastic (mechanical) fields (Figure 1). Beyond the typical two-field coupling, there is a three-field coupling (temperature-electric-mechanical) and a four-field coupling (light-temperature-electric-mechanical; Figure 3). As the coupling complicates, the complexity of research issues increases, too. Although piezoelectricity has been around since 1880, there are still plenty of research issues that need to be addressed. Furthermore, novel applications and devices need to be continuously explored and utilized. (Note that other popular smart materials, e.g., electrostrictive materials, magnetostrictive materials, shape memory alloys, electro- and magnetorheological materials are introduced in separate articles.)

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1, A_2$</td>
<td>Lamé parameters</td>
</tr>
<tr>
<td>$c_v$</td>
<td>specific heat at constant volume</td>
</tr>
<tr>
<td>$D$</td>
<td>electric displacement vector</td>
</tr>
<tr>
<td>$E$</td>
<td>electric field vector</td>
</tr>
<tr>
<td>$P$</td>
<td>pyroelectric constant</td>
</tr>
<tr>
<td>$R_1, R_2$</td>
<td>radii of curvature</td>
</tr>
<tr>
<td>$S$</td>
<td>strain tensor</td>
</tr>
<tr>
<td>$T$</td>
<td>stress tensor</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>thermal stress constant vector</td>
</tr>
<tr>
<td>$\theta$</td>
<td>temperature</td>
</tr>
<tr>
<td>$\phi$</td>
<td>electrical potential</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>thermal entropy</td>
</tr>
</tbody>
</table>

See also: Electrorheological and magnetorheological fluids; Electrostrictive materials; Magnetostrictive materials; Sensors and actuators; Shape memory alloys.

**Further Reading**


Dökmeci MC (1983) Dynamic applications of piezoelectric...
Figure 3 Four-field light-piezoelectric-thermoelastic effect.
