Piezo Film Sensors

Technical Manual

Internet Version

Part 6 of 18

Piezoelectric Basics

PIEZOELECTRIC BASICS

Mechanical to Electrical

Like water from a sponge, piezoelectric materials generate charge when squeezed. The amplitude and frequency of the signal is directly proportional to the mechanical deformation of the piezoelectric material. The resulting deformation causes a change in the surface charge density of the material so that a voltage appears between the electroded surfaces. When the force is reversed, the output voltage is of opposite polarity. A reciprocating force thus results in an alternating output voltage.

Piezo film, like all piezoelectric materials, is a dynamic material that develops an electrical charge proportional to a change in mechanical stress. Piezoelectric materials are not suitable static measurements (true dc) due to their internal resistance. The electrical charges developed by piezo film decay with a time constant that is determined by the dielectric constant and the internal resistance of the film, as well as the input impedance of the interface electronics to which the film is connected. Practically speaking, the lowest frequency measurable with piezo film is in the order of 0.001Hz. There are methods to achieve true dc response, but these require using the piezo film as both an actuator and sensor, monitoring change in the actuation resulting from the dc event.

The fundamental piezoelectric coefficients for charge or voltage predict, for small stress (or strain) levels, the charge density (charge per unit area) or voltage field (voltage per unit thickness) developed by the piezo polymer.

Charge Mode:

Under conditions approaching a short circuit, the generated charge density is given by:

$$D = Q/A = d_{3n}X_n \quad (n = 1, 2, \text{ or } 3)$$

The mechanical axis *(n)* of the applied stress (or strain), by convention, is:

1 = length (or stretch) direction
2 = width (or transverse) direction
3 = thickness direction

where

D = charge density developed
Q = charge developed
A = conductive electrode area
d_{3n} = appropriate piezoelectric coefficient for the axis of applied stress or strain
n = axis of applied stress or strain
X_n = stress applied in the relevant direction

It is important to note that the d_{3n} coefficient is commonly expressed in pico-Coulombs per Newton (pC/N), but the more correct form would be $(pC/m^2)/(N/m^2)$ since the areas (m^2) upon which the stresses or strains apply are very often different and cannot be "canceled".

Voltage Mode:

The open-circuit output voltage is given by:

$$V_o = g_{3n}X_n t \qquad (n = 1, 2, \text{ or } 3, \text{ as above})$$

where

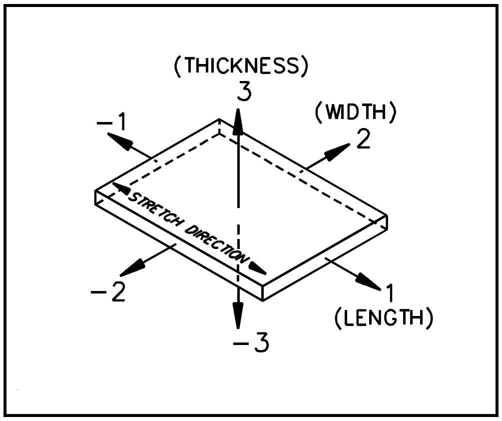
g = appropriate piezoelectric coefficient for the axis of applied stress or strain
X_n = applied stress in the relevant direction
t = the film thickness

Piezo Coefficients:

The most widely used piezo coefficients, d_{3n} and g_{3n}, charge and voltage respectively, possess two subscripts. The first refers to the electrical axis, while the second subscript refers to the mechanical axis. Because piezo film is thin, the electrodes are only applied to the top and bottom film surfaces. Accordingly, the electrical axis is always "3", as the charge or voltage is always transferred through the thickness (n = 3) of the film. The mechanical axis can be either 1, 2, or 3, since the stress can be applied to any of these axes, as shown in Figure 28.

Typically, piezo film is used in the mechanical 1 direction for low frequency sensing and actuation (< 100kHz) and in the mechanical 3 direction for high ultrasound sensing and actuation (> 100kHz).

Figure 28. Numerical classification of axes



Directionality:

Piezoelectric materials are anisotropic. This means that their electrical and mechanical responses differ depending upon the axis of applied electrical field or axis of mechanical stress or strain. Calculations involving piezo activity must account for this directionality.

EXAMPLE 1:

A 1.45 psi load (10,000 N/m^2) is applied to a piezo film switch of 2.54 cm length, 2.54 cm width and 110μm in film thickness. The switch element is rigidly backed, so the force acts to compress the film's thickness (therefore g_{33} mode). In this example the load acts on the length by width area of the piezo film. The open circuit voltage developed across the thickness of the piezo film is:

$$V_o = -g_{33} X t$$

$$g_{33} = -339 \times 10^{-3} \frac{V/m}{N/m^2}$$

where:

V/m is Volts out per meter of piezo film thickness

N/m^2 is stress applied to the relevant film area. The conversion from psi to N/m^2 is approximately 7,000.

$$V_o = -\left(-339 \times 10^{-3} \frac{V/m}{N/m^2} \right) (-10{,}000\, N/m^2)(110 \times 10^{-6} m)$$

$$V_o = -0.373 \text{volts}$$

EXAMPLE 2:

The same piezo film element as in EXAMPLE 1 is subjected to a force (10,000 N/m^2 x $0.0254m^2$ = 6.45 Newtons), but in this example, the film switch is configured as a membrane having a compliant backing. Now, the force acts on the thickness cross-sectional area (wt). The piezo film is being stretched by the load, so it is acting in the g_{31} mode.

$$V_o = -(3g_{31}\left(\frac{F}{wt}\right)(t) = -(g_{31})\left(\frac{F}{w}\right)$$

$$g_{31} = 216 \mathrm{x} 10^{-3}\frac{V/m}{N/m^2}$$

$$V_o = -\left(216 \mathrm{x} 10^{-3}\frac{V/m}{N/m^2}\right)\left(\frac{6.45\,N}{2.54 \mathrm{x} 10^{-2} m}\right)$$

$$V_o = -54.9\,\text{volts}$$

The sharp increase in output voltage results because the force is applied to the much smaller cross-sectional area of the film. The small area results in a correspondingly higher stress.

Dynamic Range

Piezo film has a vast dynamic range. The sensor has been used to detect the impact of high speed particles in space having a mass of 10^{-12} grams, and at the other extreme, measures shock waves at 300,000 atmospheres produced during weapons testing. A recent study was conducted to determine the maximum output energy of a 52µm thick film, having an area of 155.5 mm x 18.5 mm. The film was subjected to approximately 350 MPa (in the stretch or "n = 1" direction) without failure. The charge generated was found to be very linear, with the following measurements made at maximum applied stress:

Maximum Charge Observed: 20µC, giving 6.95 mC/m^2
Maximum Voltage Observed: 1600 V, giving 30.8 x 10^6 V/m
Maximum Energy Converted: 30.9 mJ, giving 207 kJ/m^3

Later experiments showed that about 10% of the above energy levels can be sustained for long periods of time without measurable damage to the piezo film element.

Electrical to Mechanical

When a voltage is applied to a sheet of piezo film, it causes the film to change dimensions due to the attraction or repulsion of internal dipoles to the applied field.. With one voltage polarity is applied, the piezo film becomes thinner, longer and wider. The opposite polarity causes the film to contract in length and width and become thicker. An ac voltage causes the film to "vibrate".

The amount of deformation is given by the piezoelectric "d_{3n}" constant:

for **length** change $\Delta l = l d_{31}\ V/t$

where

Δl = change in film length in meters
l = original film length in meters
d_{31} = piezoelectric coefficient for length ("n=1" direction) change in meters per volt
V = applied voltage across the thickness (t)

for **width** change $\Delta w = wd_{32}V/t$

where

d_{32} = piezoelectric coefficient for width ("n=2" direction) change

for **thickness** change $\Delta t = td_{33}V/t = d_{33}V$

where

d_{33} = piezoelectric coefficient for thickness ("n=3" direction) change

EXAMPLE 3:

A piezo film of 3 cm length (l), 2 cm width (w) and 9µm thickness (t) is subjected to an applied voltage of V=200 volts in the 3 (thickness) direction. The amount of strain S resulting from this electrical input is d times the applied field.

In the l direction:

$$S_1 = \frac{\Delta l}{l} = d_{31}(V/t) \quad \text{where } d_{31} = 23 \times 10^{-12}\,\frac{m/m}{V/m}$$

$$\Delta l = d_{31}(V/t)\,l = \left(23 \times 10^{-12}\,\frac{m/m}{V/m}\right)\frac{(200\,V)(3 \times 10^{-2}\,m)}{(9 \times 10^{-6}\,m)}$$

$$\Delta l = 1.53 \times 10^{-5}\,m \quad \text{or} \quad 15.3\ \mu m$$

In the t direction:

$$\Delta t = td_{31}(V/t)\,l = d_{33}V = \left(-33 \times 10^{-12}\,\frac{m/m}{V/m}\right)(200\,V) = 6.6 \times 10^{-9}\,m \ \text{ or } \ 66\text{Å}$$

Actuators

Generally, piezo film actuator designs depend on the application requirements such as operating speed, displacement, generated force, and available electrical power. Piezo film technology offers various design options to meet such application requirements. Those design options include:

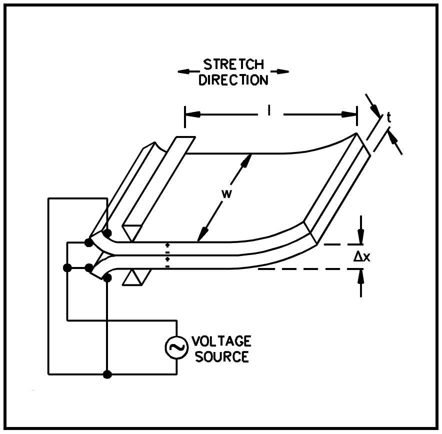
- Customized electrode patterns on one or both sides of the piezo film sheet.
- Multilaminate structures or bimorphs.
- Fold-over or scrolled multilayer structures.
- Extruded piezo tubes and piezo cables.
- Cast piezo polymer on various substrates
- Molded 3-D structures.

Each design option mentioned above has advantages and disadvantages. For example, scrolled multilayer actuators can generate a higher force but may sacrifice some displacement.

Bimorph

Like a bimetal strip, two sheets of piezo film of opposite polarities, adhered together form a bending element, or "bimorph" (Figure 29). An applied voltage causes one film to lengthen, while the other contracts, causing the unit to bend. An applied voltage of opposite polarity bends the bimorph in the opposite direction. The bimorph configuration converts small

Figure 29. Piezo film bimorph



length changes into sizable tip deflections, but producing low force. Thicker films and multilayers improve the force developed by the bimorph, but sacrifice displacement unless the unit can be operated at higher fields.

The amount of tip deflection and the force developed are given by:

$$\Delta x = 3/4 d_{31}(l^2/t^2)V \quad \text{meters}$$

and

$$F = 3/2 Ywd_{31}(t/l)V \quad \text{Newtons}$$

where

Δx = displacement at dc
F = generated force
d_{31} = piezoelectric coefficient in the "1" direction
l,t,w = length, thickness, and width of piezo film
V = applied voltage (Volts)
Y = Young's modulus of piezo film ($2x10^9 N/m^2$)

By applying an ac voltage, the bimorph can act as a fan, similar to an insect wing. Although the piezo film bimorph does exhibit a dc response, maximum tip deflections are obtained when the unit is operated at resonance, determined by the length and thickness of the bimorph beam.

EXAMPLE 4:

100 volts are applied across a 2 cm long cantilever bimorph comprised of two strips of 9μm PVDF. The resultant tip displacement Δx is:

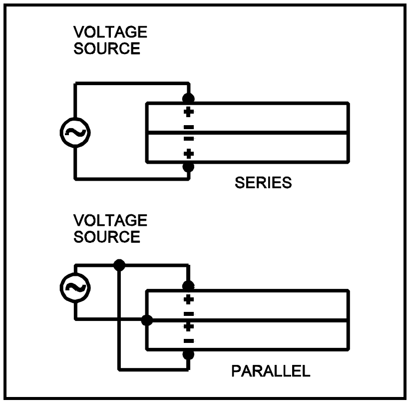
$$\Delta x = \frac{3/4 V d_{31} l^2}{t^2}$$

$$\Delta x = \frac{3/4(100V)\left(23 x 10^{-12} \frac{m/m}{V/m}\right)(2 x 10^{-2}\ m)^2}{(9 x 10^{-6}\ m)^2}$$

$$\Delta x = 8.52mm$$

As shown in the equations, more displacement can be obtained from a longer bimorph. Larger forces can be obtained from a wider bimorph. The ratio of displacement at a resonance frequency and dc is defined by Q which indicates a mechanical gain. A typical Q value for a piezo film bimorph is 20 to 25.

Figure 30. Lead attachment methods for a bimorph



For example, a 5 mm long 70µm thick bimorph with 120 volts dc creates a displacement of 57µm. With the same bimorph, however, displacement can be 1.4 mm at the resonant frequency of 580 Hz. For applications that require a higher force, such as cooling fans, multilayer construction can be considered. The resulting output force is proportionally increased by the number of layers.

In terms of electrical connections to the bimorph, there are two basic methods as shown in Figure 30 — parallel and series connections. In order to generate the same amount of displacement, the parallel connection requires a lower voltage than the series connection. Series connections, on the other hand, draw less current than parallel connections. For both parallel and series connections, the total electrical power to the actuator is identical. However, it is obvious that the lead attachment of the series connection is much simpler than that of the parallel connection for manufacturing purposes. Typical applications of the bimorph bender are cooling fans, toys, and decoratives.

Scrolled Actuator

The generated force and displacement of a scrolled piezoelectric cylinder in Figure 31 are expressed as follows:

$x = d_{31}El$ Meters

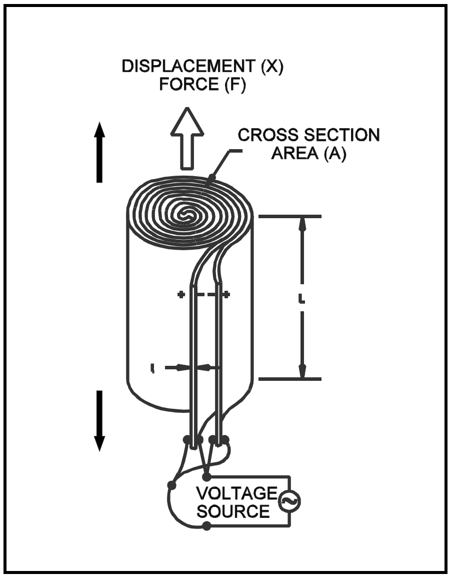
$E = V/t$ Volts/meters

$F = Yd_{31}EA$ Newtons

$f = (1/2\pi)\sqrt{YA/l(M_e + 0.405\,M_p)}$

where
- x = displacement at dc (meter)
- F = generated force (Newton)
- f = resonance frequency
- l,t = Length, thickness of piezo film (meters)
- M_e = externally loaded mass (kilograms)
- M_p = piezo actuator mass (kilograms)
- A = cross sectional area (m^2)
- Y = Young's modulus (N/m^2)
- E = electrical field (volt/meter)

Figure 31. Scrolled piezo film actuator



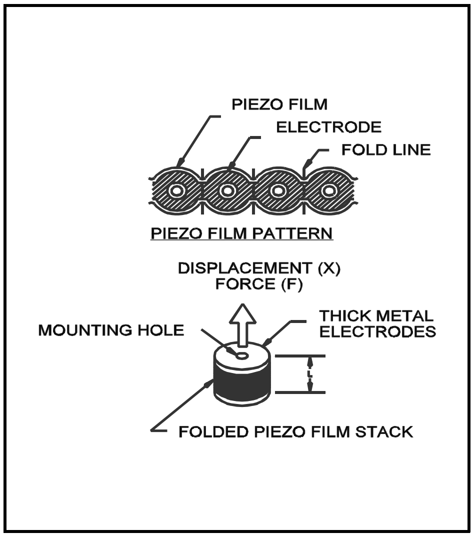
As shown in the equations, a scrolled actuator can generate more force and can respond with a higher resonant frequency by increasing the cross sectional area. A longer actuator generates more displacement but reduces the response speed. Note that the actuator output, with $M_e = 0$, will be maximized when the length *l* is adjusted to satisfy the resonant condition. As an example, the performance of a 12 mm diameter, 25 mm long scrolled actuator can be maximized at 32 kHz operation.

Folded Actuator

Another design option for a high speed, high force actuator is to fold over a long sheet of piezo film as shown in Figure 32. This design effectively creates a parallel wired stack of piezo film discs. The center hole is used to secure the actuator to a base. Design equations of the scrolled actuator also can be applied to this type of actuator. In the previous equations, d_{31} should be replaced with d_{33} ($-33\text{x}10^{-12}$ C/m^2) for a folded actuator. An example of specifications for the folded actuator is shown below:

Displacement: 1 μm/1 mm length
Generated force: 15 kg/10 mm dia.
Frequency: dc - 100 kHz
Drive voltage: 800 volts

Figure 32. Folded piezo film actuator



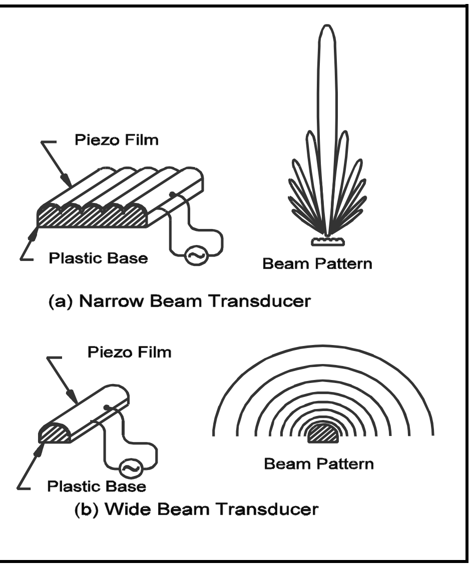
Compared to mechanical or piezo ceramic actuators, multilayer piezo film actuators have fewer ringing problems due to their lower Q. Applications of multilayer actuators are micropositioners for industrial equipment, acoustic wave generators and ink jet printers.

Ultrasonic Actuators

Ultrasonic actuators, as discussed in this section, exclude very high frequency (> 1 MHZ) transmitter applications. The use of piezo film in these very high frequency applications, like medical ultrasound imaging and nondestructive testing, use thickness mode operation, d_{33},.This section deals with low frequency ultrasound (20-100 kHz) where the piezo film can be used in the length change (d_{31}) mode.

The advantage of piezo film in low frequency ultrasound can be found from the flexibility of the material. Piezo film can be easily curved to make circular transducers as shown in Figure 33. The beam pattern is determined by the number of half circular elements and their diameter. The operating frequency is determined by the diameter of the half circular elements. Note that the difference between Figures 33(a) and 33(b) is their number of active elements and diameters. To widen the beam coverage, the number of active elements should be reduced. With a cylindrical transducer, a 360° beam pattern is obtained.

Figure 33. Piezo film ultrasound transducers



In ultrasound applications, a narrow beam with minimum side lobes is required for remote distance measurements. On the other hand, a wide beam, as wide as 180° or more, is required for applications like automobile rear bumper proximity sensing. Figure 33 shows design configurations for both narrow beam and wide beam ultrasound transducers.

The applications for piezo film in through-air ultrasonic actuators include distance ranging for vehicle backup safety, physical security systems, air flow velocity (doppler) sensors, and inter-object communications. Similar constructions can be produced for underwater or fluid sensing, including flow sensors, level sensors, and communications.