Power Generation Using Piezo Film

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This note outlines the principles of electrical signal, energy, and power generation using piezoelectric PVDF film. Practical issues and assumptions will be highlighted, with a view to forming reasonable volumetric estimates for the available energy and/or power.

Topics discussed:

(1) Piezoelectric basics

(2) Stretch mode versus compression mode

(3) Limits of elongation

(4) Static and dynamic capacitance effects

(5) Energy basics

(6) Volumetric energy limit

(7) Power basics

(8) Volumetric power limit

(9) Energy conversion issues

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(1) Piezoelectric basics

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.

The fundamental piezoelectric coefficients for charge or voltage predict, for small stress (or strain) values, the charge density (charge per unit area) or voltage field (voltage per unit thickness) developed by the piezo polymer. At low stress levels, the charge and voltage outputs are linked simply by the capacitance of the film element, by the relationship $Q = C.V$.

Charge Mode:

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

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

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

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

and so the total charge collected is given by

$$Q = d_{3n}X_nA$$

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Note that the above relationship assumes that the total electrical surface area is exposed to the stress X_n. This need not always be the case, and if not, the active area must be treated as if initially isolated, then connected to the remaining film which acts simply as a capacitive load. The generated charge from the stressed area must be shared over the entire electrical surface area. In the same manner, it is also important to note that the d_{3n} coefficient is commonly expressed in units of picocoulombs per newton (pC/N where 1 pC = 10^{-12} C), but the more appropriate form would be (pC/m^2)/(N/m^2) since the area upon which the stresses or strains apply may be different from the electrical surface area, and therefore cannot always be "cancelled".

From the above equation, we can see that the charge available from a piezo film element increases linearly with the area of the film, as long as the entire area is uniformly stressed at a constant level. An example of a situation where the stress might not be uniform would be a film element bonded to a cantilever beam. The greatest stress occurs near the clamping point, and is near zero at the free end. If a small sensor was initially bonded to the beam in the vicinity of the clamp, then later doubling the length of the sensor would not double the available charge, as the average stress over the surface are of the film would be reduced. But if the small sensor was replaced with a sensor of same length but twice as wide, the charge output should then be doubled.

Voltage Mode:

Under conditions approaching an open circuit, the output voltage is given by:

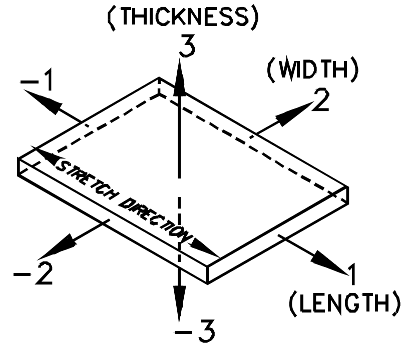
$$V = g_{3n}X_nt \qquad (n = 1, 2, \text{ or } 3, \text{ as above})$$

where

g_{3n} = appropriate piezoelectric coefficient for the axis of applied stress or strain
X_n = applied stress in the relevant direction
t = the film thickness

From this equation, we can see that the voltage response of a piezo film element is directly proportional to the thickness of the film (as long as the stress applied to the film remains independent upon thickness). An example of a situation where the stress would not be independent is if a mass were simply suspended from a film hung vertically. In this case, the force applied by the mass remains constant, and increasing the film thickness decreases the stress applied to the cross-section.

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 at right.

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).

(2) Stretch mode versus compression mode

If we have a limited, fixed value of force available, it can usually generate much greater stress if applied in the mechanical "1" direction (that is, along the stretch direction of the film) than if it is applied in the thickness direction. The reason is purely geometrical – because the film is very thin, the cross-sectional area of any practical film element tends to be very much smaller than its surface area. An obvious exception would be a very tiny active area formed on a relatively thick film. But consider as an example the MEAS part DT4-028K (p/n 1-1002149-0). The PVDF element is 22 mm wide, 171 mm long, and 28 μm thick. The electrical area is defined by the overlapping electrode area of 19 x 156 mm. If we were to clamp one end of the film and suspend a 1 kg mass from the other end, the stress would be borne by the mechanical cross-sectional area – in this case, an area of 616×10^{-9} m^2. The 1 kg mass exerts a force of approximately 9.81 N due to gravity, which results in a stress of 15.9×10^6 N/m^2 (or 15.9 MPa).

Although we cannot measure a true steady response from any piezo element (due to charge leakage either through the film itself, or into the connected electrical circuit), we could expect to measure the "step" signal as the load was applied, and perhaps for a few seconds afterwards, if we use a measuring circuit with a long electrical time constant.

In voltage mode, we would expect to see (using g_{31} value as quoted in the MEAS Technical Manual):

$$V = g_{31}X_1t = 0.216 \times (15.9 \times 10^6) \times (28 \times 10^{-6}) = 96.3 \text{ V}$$

or in charge mode:

$$Q = d_{31}X_1A = (23 \times 10^{-12}) \times (15.9 \times 10^6) \times (2.96 \times 10^{-3}) = 1.08 \times 10^{-6} \text{ C } (1.08\ \mu\text{C})$$

Now, if we apply the same 1 kg mass or 9.81 N force over, say, the active electrode area in a way that compresses the film in the thickness direction, we should use piezo coefficients that apply to the case where the film is clamped by the applied force. In this case, the second subscript of the piezo coefficient is designated "t". These values are not quoted in the Technical Manual, but are approximately g_t = -0.207 (V/m)/(N/m^2) and d_t = -22 (pC/m^2)/(N/m^2). The stress in this case is given by the force of 9.81 N applied over the area of 2.96×10^{-3} m^2, giving a value of around 3310 N/m^2 (or 3.3 kPa). The resulting outputs would be:

In voltage mode,

$$V = g_tX_tt = -0.207 \times 3310 \times (28 \times 10^{-6}) = -19.2 \text{ mV}$$

or in charge mode:

$$Q = d_t X_t A = (-22 \times 10^{-12}) \times 3310 \times (2.96 \times 10^{-3}) = 216 \times 10^{-12}\ \mathrm{C}\ (216\ \mathrm{pC})$$

The difference in output from applying the same force in tension, compared with compression, is here a factor of more than 5000:1. The equivalent factor for other cases will vary according to the geometry of film element used, and the way the force is applied, but this result is really quite typical. The practical effect of this large ratio is to make almost every piezo film sensor application to be dominated by the stretch-direction mode, or in simpler terms:

IF IT CAN STRETCH AT ALL, THEN IT WILL, AND YOU WILL SEE ONLY STRETCH!

Numerous tests and experiments using apparently rigid substrates have reinforced this belief. If a large piezo film sensor is bonded flat onto a thick block of metal of similar size to the sensor using double-coated pressure-sensitive adhesive tape, and then impacted in the vertical axis by a dropping ball or hammer, it will still demonstrate higher sensitivity at the edges than near the center. It is virtually impossible to obtain sufficiently rigid boundary conditions to obtain a response which approximates "pure thickness mode".

(3) Limits of elongation

Now that we have determined that most applications where mechanical force is to be converted into electrical energy will be dominated by the "d_{31}" or stretch mode, it is logical to consider next what the limit of mechanical stress or strain might be. At the very extreme, we know that the tensile strength at break (in the machine or stretch direction) lies somewhere in the range of 160 to 330 MPa. At breakpoint, the elongation of the film may reach >25%. Obviously, for practical and reliable operation of a generator device, we must operate well below the point where we expect failure to occur. But just as a datum, if we use the lower cited value of 160 MPa, what would this produce from a DT4-028K sensor as described in the examples in (2) above?

In voltage mode, we would expect to see

$$V = g_{31} X_1 t = 0.216 \times (160 \times 10^{6}) \times (28 \times 10^{-6}) = 967\ \mathrm{V}$$

or in charge mode:

$$Q = d_{31} X_1 A = (23 \times 10^{-12}) \times (160 \times 10^{6}) \times (2.96 \times 10^{-3}) = 109 \times 10^{-6}\ \mathrm{C}\ (109\ \mu\mathrm{C})$$

Thus, at very most, we would perhaps see 34-35 V per µm of thickness, when PVDF is taken close to its mechanical limit. In reality, the figure may well be lower, as will be described in the following section. The available charge is only limited by the area of film that can be deployed (whether as a single piece, or connected in multiple panels or laminated in multiple layers).

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The elongation (strain, S) which occurs in the film is related to the applied stress (X) through the Young's modulus of elasticity (Y):

$$Y = X/S = \text{approx } 3 \times 10^9 \text{ N/m}^2 \text{ (3 GPa)}$$

Therefore at the conservative break limit of around 160 MPa, the theoretical resulting strain would be:

$$S = X/Y = 0.053 \text{ or } 5.3\%$$

This can only be an approximation, since the behaviour of the film at or near the break point is difficult to predict, and may vary according to the rate of application of force, ambient temperature, and other factors. There is also inherent variability in the value of Y, to the extent that the value quoted in MEAS Technical Manual is 2-4 GPa.

To allow for a reasonable safety margin, we may decide to aim for about one-tenth of the above values – that is, to allow perhaps 0.5% elongation, or a maximum tensile stress of 16 MPa. Coincidentally, this corresponds to the case where a 1 kg mass is suspended from a DT4-028K element, as discussed in section (2) above.

A one-shot "disposable" device, or a device where excitation was allowed only for short periods with long rest time between excitations, might reasonably be allowed to operate at a higher fraction of the limiting stress.

(4) Static and dynamic capacitance effects

An informal study[1] has found that the capacitance of a piezo film element is influenced by the tensile stress applied, in three ways: first, a rapid step-change in capacitance, then (if the stress is maintained at a constant level) a steadily-increasing further "growth" in capacitance, persisting as long as stress is applied. Finally, an irreversible change was found to occur after high stress was applied for period of hours and then removed.

The initial "step change" was found to proportional to the square of the applied stress, and the further increase was then quadratic against the log of elapsed time with force applied.

Looking only at the step change, it was found that a stress of 10 MPa within the cross-section of a film element caused a reversible change of around 1% in capacitance, with less than 2% change at stress up to 17 MPa. At this level of stress, the irreversible change (after constant load is removed after period of hours) was below 0.04%. Thus the decision to set a nominal limit of 16 MPa in section (3) for continuously-operating devices seems reasonable.

An irreversible change in capacitance of 1% was reached at around 38-39 MPa. This stress level would create a dynamic reversible change of around 6 to 7%.

[1] "Effect of tensile stress on the capacitance of PVDF film", R H Brown, 12 Aug 2002

But the extrapolation of this data suggests a doubling in capacitance for 180 MPa and potentially a three-fold increase by 250 MPa. Under these conditions, the observed open-circuit voltage would greatly deviate from the expected linear law, and this suggests that a maximum value of around 1200 V will be observed from 52 µm PVDF under extreme tensile stress. Experiments performed by the author appear to confirm that open-circuit voltages in excess of about 1200 V cannot be obtained from 52 µm film, even for estimated stress levels in excess of 300 MPa.

Thus the "dynamic capacitance" effect plays a significant role at very high stress levels, but has much less effect at low stress. The rate of charge generation does not appear to be affected, so in applications where charge is collected almost independently from the open-circuit voltage (such as when a film element is coupled via a diode bridge directly to a large storage capacitor), the dynamic capacitance effect need not be considered.

(5) Energy basics

Let us return to the example of a DT4-028K element undergoing application of a tensile load of 1 kgf or 9.81 N. If we assume that the film is initially uncharged, it was shown in section (2) that the open-circuit output voltage would increase to 96.3 V. We also know from section (4) that the capacitance of the element will change by less than 2% under this stress, so we can neglect this for a first-pass energy estimate. The capacitance of this element under zero stress can be measured or calculated, and is approximately 11 nF.

The change in electrical energy is given by

$$W = \tfrac{1}{2}CV^2 = 0.5 \times 11 \times 10^{-9} \times (96.3)^2 = 51.0\ \mu J$$

Now, if this electrical energy is removed from the film (by discharging it into an external circuit), the voltage will return to zero. But the stress is still applied, and if it is later removed, the film will develop a voltage of the same magnitude but of opposite polarity (i.e. -96.3 V) across its electrodes. Because the voltage term is squared, the sign is immaterial, so exactly the same energy is made available again (i.e. 51.0 µJ).

So the total electrical energy available from the application and removal of the 1 kg mass is 102 µJ. This value is not directly influenced by the shape of the force/time curve – if the load had been applied in a half-sine shape with 9.81 N at peak value, the same electrical energy would be available at peak stress, and if removed, would be come available again when the stress returned to zero.

In other words, we can generally assume that the electrical energy available from a unipolar force input signal is actually $W = CV^2$, with the "one-half" term removed, and where V represents the peak value of the open-circuit voltage.

What would happen if we applied the same force to two such strips connected mechanically and electrically in parallel (for example, if they were bonded one on top of the other, with positive faces inwards and in electrical contact)? The stress in the cross-section of the double-thickness strip would be halved, so the voltage output would also be halved. The V^2 term falls to a quarter of its original value, but the capacitance is doubled, bringing the final result to one-half of the original single-strip energy.

If we connect the elements electrically in series, we have two strips each at V/2 giving V as the end-to-end value, and therefore we come back to the original V^2 level but with half the capacitance, and so again one-half of the original energy level.

Let's now connect the strips mechanically in series but electrically in parallel. In this case, the stress is the same as for the single strip, the capacitance is doubled, and so the final energy is also doubled.

If we keep this mechanical arrangement but connect the film elements electrically in series, the capacitance will fall by a factor of two. In this case, the end-to-end voltage will be doubled, bringing about a 4-fold increase in the V^2 term, and the final result will also be double the energy of the original single strip experiment.

Therefore adding more film need not increase the energy available – the film must be configured in a way the "makes the most" of the available mechanical input. In this case, the force was kept constant. Different findings would arise if the stress were kept constant instead. But in any case, doubling the volume of PVDF material used can at best double the available electrical energy. In other words, the available electrical energy is linearly proportional to the volume of film under stress.

(6) Volumetric energy limit

Before going on to consider any practical issues surrounding the actual harvesting or conversion of the available "potential" electrical energy, let's take a look at the volumetric result (energy per unit volume) corresponding to the above calculations.

The total energy of 102 µJ was made available by an "active volume" (i.e. the electrode surface area, times the film thickness) of $(2.96 \times 10^{-3}) \times (28 \times 10^{-6}) = 82.9 \times 10^{-9}$ m^3. This calculates out as an energy density of 1.23 kJ/m^3 (or 1.23 mJ/cm^3)

Just as a reference point, we can estimate the energy input into the system from calculation of the change in length of the strip. We saw in (3) that the strain (S) was 0.053, and therefore the absolute change in length of the film is given by $\Delta L = SL = 0.0053 \times 156 \times 10^{-3} = 827 \times 10^{-6}$ m (or 0.83 mm). The change in potential energy of the mass of 1 kg as it changes in height by this amount is given by

$$\Delta W = mg\Delta h = 1 \times 9.81 \times 827 \times 10^{-6} = 8.11 \text{ mJ}$$

Because we took into account both the application of this load, and then its removal, we should take two such transitions, or 16.22 mJ, as the effective mechanical input. Using this value, we can see that the theoretical conversion efficiency (mechanical to electrical) is just 0.63% for stress at this level.

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Let us now consider the energy at the limiting stress case. If we take the lower limit of the tensile stress at break (160 MPa) and assume that instead of the theoretical 967 V open-circuit, we have instead around 500 V but from a capacitance that has doubled to 22 nF due to the dynamic capacitance effect, then the full excursion (to peak, then back to zero) of the force signal will generate

$$W = CV^2 = 22 \times 10^{-9} \times (500)^2 = 5.5 \text{ mJ}$$

giving a volumetric energy density of 66 kJ/m^3 (or 66 mJ/cm^3). In the absence of the dynamic capacitance effect, we would have seen a value of 124 kJ/m^3. In fact, real-life one-shot experiments (taking a similar PVDF element close to mechanical destruction) have generated up to 200 kJ/ m^3.

So we see a relatively high ratio between the open-circuit energy available from a possible one-shot event, and a level that is conservatively rated for long-term, continuous or repetitive use. For any specific example of a continuously-operating generator, the survival limit should be carefully explored (under worst-case extremes of environmental conditions). Even a small increase in peak applied stress could cause significant increase in the available energy, due to the V^2 term.

Again, just for reference, let's consider the mechanical input that might create the above result. The 10X increase in stress would come from a 10X increase in mass applied, so 10 kgf. The strain would be also be 10X at 0.053 and the elongation 8.3 mm, giving a 100X change in PE of the mass of 811 mJ. The mechano-electrical conversion efficiency has increased slightly, but only to 0.68%. In the absence of the dynamic capacitance effect, the efficiency at this critical stress level would have been about 1.28 %.

(7) Power basics

Taking the full force excursion and both "halves" of the electrical result as outlined above, we have around 100 μJ from a single event that is not specifically time-dependent. The event may be repeated many times per second, with the only real risk being fatigue, wear, or potentially self-heating due to the mechanical loss factor. Let's assume that the full load-unload cycle may be repeated ten times per second. This gives 1 mJ/s, or 1 mW, theoretically available from the DT4-028K element.

(8) Volumetric power limit

Relating the above assumption into a volumetric figure, we obtain 1 mW from the active volume of 82.9×10^{-9} m^3. This calculates out as a power density of 12 kW/m^3, or 12 mW/cm^3.

(9) Energy conversion issues

In the above discussions, it has been assumed that an open-circuit voltage V appearing across the plates of a capacitor (the film element) with capacitance C can supply at that instant an energy given by $W = ½CV^2$. At the same time, the charge held within the capacitor is given by $Q = CV$. Let's consider what happens if the charge is fed over a diode bridge onto a large storage capacitor – say 100 µF – at the instant of peak stress (and therefore peak energy). We know the open-circuit voltage is high (96.3 V), and we will assume for this discussion "ideal" diodes, where the energy loss caused by their finite forward voltage drop and their power dissipation when conducting can all be ignored. The bridge will conduct, and the storage capacitor is effectively connected directly across the piezo film element. In this case, the stored charge (1.08 µC) will be shared across the parallel combination, but since the storage capacitor is so much larger than the source, we can ignore the source and calculate the final voltage as $V = Q/C = 10.8$ mV. The equivalent energy level is still given by $½CV^2$ but with new values of C and V, giving a final result of 5.8 nJ. When the load is removed, we'll see a further charge pulse, bringing the voltage across the storage capacitor of 20.8 mV, so the stored energy increases to 21.6 nJ. This is a factor of some 4700 times less than the open-circuit case.

Clearly, transferring charge directly from a high potential to a low potential has incurred significant energy loss. One traditional means of energy conversion from a high impedance source to a low impedance load is the step-down transformer. In the case above, however, the values of inductance that would be required make the principle unworkable. For example, if we wish to achieve a voltage step-down ratio of 100:1 using the 11 nF source capacitance (i.e. the DT4-028K element) with a 100 µF storage capacitor and expect an effective frequency (or repetition rate) of 10 Hz, then the primary inductance must be on the order of 2000 H and the secondary around 2 H. Such values would require a transformer of great physical size (practical PCB-mounting inductors normally having values in the mH or µH range). The direct use of a transformer to step down the voltage from a piezo film element is therefore ruled out for virtually all practical applications. A notable exception was an electronic detonator application, where a relatively low-power but explosive mechanical event was used to stretch a DT4-052K element close to destruction, giving a very fast risetime. The single energy pulse from the film was successfully transformed down from very high voltage (> 1 kV) to around 25 V into 22 µF using a specially designed air-cored transformer, with good conversion efficiency.

Note that, if a large storage capacitor is already partly charged, then the effective electrical efficiency improves significantly. If we take the example above, with 100 µF load, and assume that it is initially at 3 V (for example), then our two charging pulses of 1.08 µC each will result in a final voltage of 3.0216 V, representing an increase in stored energy of 6.5 µJ. This is still low compared with the open-circuit case where around 100 µJ is available, but considerably better than the 21.6 nJ step observed when the storage capacitor is initially at 0 V.

Some interesting conversion schemes based upon switching DC-DC converters have been proposed (see, for example, Schenck, N. S., "A Demonstration of Useful Electric Energy Generation from Piezoceramics in a Shoe", M.I.T. May 1999). Ultimately each application places different specific requirements on energy levels, transfer, and conversion, so there is perhaps no single generic solution. Exploration in this area continues.

Piezo film clearly offers interesting possibilities in the field of power harvesting and energy generation. It is lightweight, flexible, compliant, and may be formed into an almost unlimited choice of shape and size. The base polymer is formed in continuous rolls, around 45 cm wide, and is usually sheeted to receive screen-printed conductive ink electrodes. Geometries from a few square mm to thousands of sq cm are easy to print. Laminated structures can combine many thin piezo film layers in parallel to offer relatively high charge generation density. Because the modulus of the material is low, it is possible to construct devices with low frequency yet also relatively low quality factor, so that energy may be harnessed over a range of frequencies with a single resonant device. A prototype multi-layer mass-loaded cantilever structure has demonstrated 0.75 μC/g sensitivity at 12 Hz resonance, with an overall film geometry of 25 x 13 x 0.8 mm.

Our application engineers are available to discuss specific needs or design concepts for OEM solutions.

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