Piezo Theory: Chapter 2 - Static Properties

Static behavior of piezoelectric actuators

To generate an expansion in a piezoelectric actuator, the ceramic material must be pre-polarized. The majority of the dipoles must be oriented in one direction. If an electrical field is now applied in the direction of the dipoles, (here the z direction) the actuator will show an expansion in the direction of the field (longitudinal effect) and will show a contraction perpendicular to the field (transversal effect).

The motion is expressed by the equation:

longitudinal effect:

$$S_z = \frac{\Delta l_z}{l_z} = s_{33}^E \cdot T_z + d_{33} \cdot E$$

Figure 2.0

transversal effect:

$$S_{x,y} = \frac{\Delta l_{x,y}}{l_{x,y}} = s_{11}^E \cdot T_{x,y} + d_{31} \cdot E$$

Figure 2.1

S	strain, relative motion
T = F/A	mechanical tension pressure
s_{ij}	coefficient of elasticity
Δl_z	expansion of the actuator in z dimension
l_z	length of piezoelectric active part of the actuator
c_F	stiffness constant of the external spring for pre-load
c_T	stiffness of the actuator

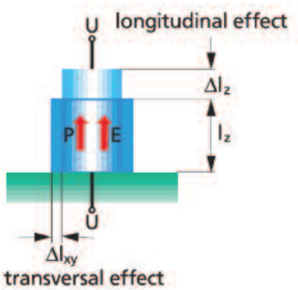

Figure 2.2 Stacked actuators with longitudinal expansion and transversal compression

Piezoceramics are pre-polarized ferroelectric materials; their parameters are anisotropic and depend on the direction. The first subscript in the d_{ij} constant indicates the direction of the applied electric field and the second is the direction of the induced strain.

Typical coefficients are:

Size	Unit	PZT
d_{33}	m/v	700×10^{-12}
d_{31}	m/v	-275×10^{-12}
s^E_{33}	m^2/N	20×10^{-12}
s^E_{11}	m^2/N	15×10^{-12}
tan 8	-	3 - 5%
k	-	0,65

The negative sign represents the contraction perpendicular to the field. Typically, high voltage actuators are made from "hard" PZT ceramics and multi-layer low voltage actuators are made from "soft" PZT ceramics.

For the sake of simplicity, if not otherwise mentioned, we will refer to the longitudinal piezoelectric effect. However all relations can be written in the same manner for the transversal effect.

$$S = \frac{\Delta l_z}{l_z} = S_{33}^E \cdot T + d_{33} \cdot E = \frac{F}{c_T \cdot L_0} + d_{33} \cdot E$$

Figure 2.3

The first term of the equation (2.3) describes the mechanical quality of an actuator as a spring with a stiffness cT. The second term describes the expansion in an electrical field E.

The static behavior can be stated using formula (2.3).

No voltage is applied to the actuator, E = 0

The actuator is short-circuited. Formula (2.3) becomes $S = \Delta l/L_0 = s_{33} \cdot T$. The deformation of the actuator Δl is determined by the stiffness of the actuator c_T^E because of the action of an external load with the pressure T, so it becomes "shorter".

$$\frac{\Delta l}{L_0} = \frac{F}{L_0 \cdot c_T^E} \cdots \text{or} \cdots \Delta l = \frac{F}{c_T^E}$$

Figure 2.4

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The stiffness c_T^E of an actuator can be calculated by taking into account the stiffness of the ceramic plates. This approximation assumes that the adhesive between plates is infinitely thin. Monolithical multi-layer actuators perform well in this respect, giving stiffness on the order of 85% - 90% of the stiffness of the pure ceramic material. Especially for high voltage actuators, the stiffness of the metallic electrodes and the adhesive have a large influence on the stiffness of the stack.

Example 9

On a stack with a stiffness of a given c_TE operates at an external force of F = 70N, using formula (2.5) it is easy to calculate the compression of a stack of 1µm.

No external forces, F = 0

The motion of a stack without any pre-load and without external forces can be expressed by:

$$\Delta l_0 = \frac{F}{c_T} + d_{33} \cdot E \cdot L_0 = (F = 0) = L_0 \cdot E \cdot d_{33}$$

Figure 2.5

The maximum expansion depends on the length of the stack, on the stack, on the ceramic material and on the applied field strength.

Example 10

Let us consider a multi-layer stack with the following parameters:

Piezoelectric constant $d_{33} = 635 \cdot 10^{-12}$ m/V

Active length L_0 = 16mm

The thickness of a single plate is 100µm. The operating voltage is 150V. The field strength is E = 1.5kV/mm.

The expansion will be Δl_0 = 15µm without external forces (see formula 2.6).

Constant external loads, F = constant

Operating with constant force F or weight, the actuators will be compressed (see Figure 2.6).

$$\Delta l_n = \frac{F}{c_T} = \frac{m \cdot g}{c_T}$$

Figure 2.6

However, the expansion l_0 due to the applied voltage will be the same as when an external force is not applied (see formula 2.5).

In cases where excessively high external forces are applied, depolarization may occur if there is no applied electrical field. This effect depends on the type of ceramic materials used.

This polarization may be reversed if an electrical field is applied.

However, the depolarization can be irreversible if the external forces have exceeded the threshold limit for that material. Damage to the internal ceramic plates may also occur. Therefore it is important to respect the given data for the relevant materials.

Standard actuators from *Newport Corporation* with a cross section of 5 x 5mm² show depolarization effects for external loads > 1kN.

Please see the given parameters in our data sheets.

If your problem needs additional clarification, do not hesitate to contact our team from *Newport Corporation.*

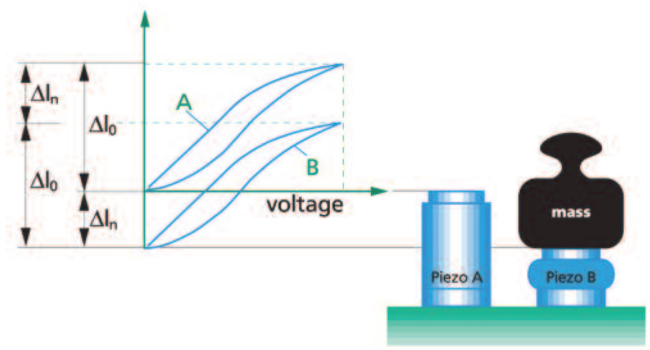

Figure 2.7 Motion under external constant force

Changing external loads and forces, F = f (ΔI)

As an example of changing external forces, consider attaching an external spring. Because of the spring's nature, the forces F, operating to the actuator, increase with the increasing displacement. If the external forces can be expressed as F = -cF·ΔL (cF stiffness of the spring) we get the following expansion of the actuator:

$$\Delta l = E \cdot d_{33} \cdot L_0 - \frac{c_F}{c_T} \cdot \Delta l$$

Figure 2.8

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e.g. the motion given in relation to the motion without external forces:

$$\Delta l = \Delta l_0 \cdot \frac{c_T}{c_T + c_F}$$

Figure 2.9

A part of the motion will be needed to compensate the external forces, therefore the final motion becomes smaller (see also figure 2.9).

If the stiffness of the actuator and the stiffness of the external spring are equal, the actuator will reach only half of its normal motion.

Example 11

The actuator NPA25 from Newport Corporation has a stiffness of c_T = 40N/µm. The motion l0 without external forces is 16 µm. This actuator is assembled in a housing with a pre-load stiffness c_F = 1/10cT. In comparison with formula (2.10) the motion will decrease to 16.4µm. If the stiffness of the pre-load is increased to 70% of the stiffness of the actuator c_F = 0.7 c_T = 46N/µm, the motion will reach only Δl = 9.4µm.

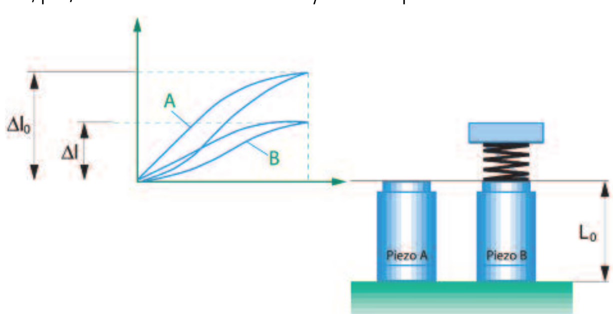

Figure 2.10 Motion dependence of external spring forces

Using equation (2.10) we can calculate the effective forces, which can be reached with an actuator operating against an external spring.

$$F_{eff} = c_T \cdot \Delta l_0 \cdot \left(1 - \frac{c_T}{c_T + c_F}\right) = c_T(\Delta l_0 - \Delta l)$$

Figure 2.11

Δl_0 - motion without external loads (µm), Δl - motion under external loads (µm).

Example 12

Again, we will use the actuator NPA25. For motion without external load l_0, the stiffness is c_T = 40N/µm. This actuator is working against a spring with a stiffness c_F = 64N/µm. In this assembly the actuator will reach an effective force of 431N. When it operates with an external spring with a stiffness of 500N/µm, it will reach an effective forces of F = 920N.

An external variable force operating with an actuator will decrease the full motion.

Integrated pre-loads of piezoelectric actuators are external forces. The value of the integrated pre-load often reaches 1/10 of the maximum possible load of the actuator. That is why the shorter expansion of pre-loaded actuators is very low.

But pre-loaded actuators can work under tensile forces. They are well suited for dynamical applications.

Blocking forces, Delta l = 0

The actuator is located between two walls (with an infinitively large stiffness). So it cannot expand (see formula from Figure 2.5):

$$0 = -\frac{F}{c_T} + d_{33} \cdot E \cdot L_0$$

Figure 2.12

In such a situation the actuator can generate the highest forces F_{max}.

$$F_{max} = C_T \cdot \Delta l_0$$

Figure 2.13

This force is called blocking force of an actuator.

Operating against external spring forces, actuators show the following behavior of the generated forces in dependence on the expansion. This stress diagram is valid for typical actuators used by *Newport Corporation*.

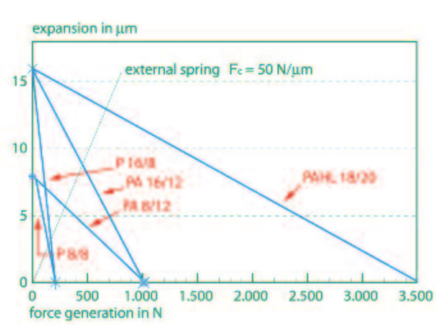

Figure 2.14 Stress strain diagram of piezoelectric actuators

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The cross over with the x-axis indicates the blocking force. The cross over with the y-axis shows maximum expansion without external forces. Also shown is the curve of an external spring. The cross over of this spring load line with the curve of the actuator gives the actual parameters, which can be reached with this actuator operating against a defined spring.

An actuator can generate the maximum mechanical energy if it is operating to an external spring with a stiffness of half the actuator stiffness ($c_F = ½ \cdot c_T$). In this case the actuator reaches only 67% of its normal (without external forces) expansion.

Example 13

An actuator of the type NPA25 operates to an external spring, without loads the actuator reaches a motion of 16µm. A generated force of 320N is demanded. What motion can be reached under such conditions?

Answers:

Look at the diagram, the vertical line beginning at the point of 320N crosses over to the actuator's NPA25 curve. The horizontal line, beginning at this point of the cross over will end in the value of the possible motion, approximately 11µm. The same result can be calculated using (2.11). For the real expansion l under external spring forces we yield from (2.11) $\Delta l = \Delta l_0 - F_{eff} / c_T$. The stiffness of the actuator is c_T = 85N/µm. The result will also Δl = 11µm.

Please note:

In practice, an infinitely stiff wall or clamping to the actuator cannot be realized. For this reason an actuator will not reach its maximum theoretical force in reality. Additionally, if the actuator should generate its blocking forces it will not show any motion.