Monolithic Multilayer Actuators

This brochure is a supplement to CeramTec’s “Piezoelectric Components” publication, where a number of terms and correlations used herein are described in detail. Abbreviations and symbols are explained in the glossary.

The function of monolithic multilayer actuators is based on the piezoelectric effect. A piezoceramic material expands in the direction of the electrical field when a voltage is applied to it. The required field strength to gain a deformation of 1.5 to 1.7 ‰ is approx. 2000 V/mm. The actuators described here are consisting of up to 500 layers of ceramic material only 0.1 mm thick, manufactured by using a specially developed stacking and sintering technology. Therefore, maximum displacement can be achieved by a voltage of only 200 V.

Handling and Assembly

In practical use, piezoelectric actuators exhibit a number of properties which distinguish them from other electronic components. These differences should be carefully taken into account.

For this reason, actuators require engineering support and meticulous attention throughout application, development, and implementation phases.

Labor safety

Electrically speaking, an actuator resembles a very powerful capacitor. Charged to 200 V, a large actuator with a capacitance of, say, 7 µF may be fatal if its terminals are inadvertently touched.

In working with actuators, it is necessary to provide terminals that are safe against accidental contact. Other safety precautions, such as the use of safety glasses are strongly recommended.

Piezoceramics

Monolithic multilayer actuators contain brittle piezoceramic materials. They should not be touched with metal tools, and must be protected against shock and impact loads. Particularly the end faces, which are ground to a high level of flatness, are highly susceptible to chipping and scratching.

Assembly

Actuators may generate forces of several kN and produce displacements in the µm range. The coupling of an actuator to the driven mechanical assembly therefore must be free of backlash.

Ideally, the actuator’s end face should be in direct contact with a ground metal surface. The contact pressure should be equal to at least one-half of the actuator’s blocking force FB.

If a ground metal surface is not available as a mating contact area, it is necessary to fill the resulting gap with an epoxy resin that cures to the hardnerness of glass. The necessary amount of mechanical pre-stressing should be duly taken into account in this context.

Active surfaces

When an actuator is in operation, a high field strengths of up to 2000 V/mm may be present on its surface.

Since the actuator is expected to elongate (i.e., expand longitudinally), its insulating coating is very thin. It is sufficient to prevent an electrical breakdown, however it does not protect against the high internal voltages involved or safeguard the actuator against mechanical damage.

Insulation

An actuator must be insulated from the housing in which it is mounted since only its end faces are insulated in an electrically reliable manner by ceramic layers measuring about 1 mm in thickness. We recommend that the actuator should be mounded with an air gap of approx. 1 mm in between actuator and housing.

The use of shrinkable tubing, adhesive tapes or sealing compounds for insulation purpose needs care in selecting the materials and extreme care for the mounting operations. Any contamination trapped beneath those materials is suspect to cause electrical breakdown sooner or later.

During assembly, care must be taken not to damage the actuator’s sides or edges (no metal tools, no mechanical contact with lateral surfaces). The actuator must not be contaminated with electrically conducting substances (e.g., lettering, finger prints, metal abrasion particles, flux, diesel, hydraulic fluid, etc.) We therefore recommend that all assembly operations should be performed with gloves and plastic tools.
Characteristics and control

Deformation characteristics
The fact that an actuator will expand in an electrical field is primarily due to the resulting rotation and alignment of domains (i.e., crystal areas of identical polarisation direction). This displacement of domains causes non-linearities and hysteresis effects.

- The operation of the actuator can be improved by mechanical pre-stressing with a near-constant force over the expansion stroke. Pre-stressing forces between 0.5 and 1.0 FB have been found to give ideal results.
- An actuator’s stroke can be accurately adjusted by using a strain gauge with a closed loop control, adjusting the operating voltage. The application of a negative electrical voltage of up to -50 V is possible and will increase the displacement of the actuator. However, this operating mode may be unsuitable for dynamic applications because polarisation processes in the actuator material will result in additional power losses through dissipation, heating up the actuator.

Capacitance
In terms of electrical properties, actuators resemble large capacitors. Their capacitance depends on the temperature and on the voltage applied. The low-signal capacitance we measured at 1 V and 100 Hz may double under real-life operating conditions (120 °C, 200 V). In pulse mode, charging currents of up to 50 A may be encountered. Electronic control circuitry must be designed to be able to handle these characteristics.

Force buildup
Actuators can produce very high forces (several kN) within a very short periods of time (a few μs). The associated acceleration rates can destroy the actuator. Thus, if an unrestrained charged actuator is short-circuited, it will contract faster than its inert mass is able to follow. The actuator will immediately disintegrate.

- A mechanical pre-stressing device must prevent the actuator from being loaded with tensile stress. Even in static applications, a pre-stressing force of approx. 0.5 FB is highly recommended to stabilise the mechanical assembly.
- Actuators must not operate faster than it is permitted by the resonance frequency of the actuator and the driven mechanical system. \( T_m \approx 1/v f \)
Shorter control pulses are possible but will require careful design of the control system, actuator, and driven mechanical assembly.

Power dissipation
Domain movements within the electrical field are associated with mechanical and electrical losses. Actuators will become hot in operation. The power dissipation rate may reach 80 % of the input power level.

- An actuator’s surface temperature must not exceed 120 °C. The dissipation of power can be reduced by:
  - using sinusoidal control signals wherever possible,
  - minimizing the input frequency and voltage.

In many cases active cooling cannot be avoided. Often it will be sufficient to circulate dry compressed air around the actuator.

Resonant mode
The power dissipation rate can be significantly reduced by operating the actuator in resonance with the driven mechanical assembly. In this case, a small control voltage will result in a high stroke amplitude.

Thus, if the configuration has a mechanical Q-factor of 10, which corresponds to that of a “normal” mechanical lever system, the rated actuator amplitude can be achieved with as little as 20 V. Power dissipation will remain low even at high frequencies (several kHz).

If mechanical power is drawn from the system, damping will occur. This results in a reduced oscillation amplitude and a shift in resonant frequency. Therefore the power output of such systems is limited. In many applications this operating mode is being used successfully.

Control and operation

Power dissipation
The displacement (s) of an actuator follows the received charge (Q) with good linearity. Therefore the flowing current (I = dQ/dt) is an equivalent to the velocity of the actuator endplates (v = dv/dt). The steepness (slew rate) of fluctuations in the current (dI/dt) are then an equivalent to the acceleration (a = dv/dt) of the actuator endplates. Voltage controlled switching amplifiers often destroy actuators by sending bursts of charge causing extremely high acceleration rates. We recommend the use of slew rate controlled amplifiers or at least a strictly limited output current.

Driving equipment
Applying a D.C. voltage to an actuator over extended periods of time will cause it to attract water molecules due to the strong electrical field. This moisture is capable of diffusing through polymer coatings. Once underneath the coating, it will increase the leakage current (after a few hours) and, ultimately, may cause the actuator to fail.

- Statically operated actuators must be encapsulated in metal or placed in a flow of dry air (< 10 % rH).
- The adsorption effect is reversible if the voltage has not been applied for too long (approx. 10 minutes at 200 V). Pulses loads are not critical for a piezoceramic actuator.
- Any condensation of moisture in the actuator’s operating environment must be avoided.
Control and operation

Test conditions
The product life of an actuator is highly dependent upon the individual application. Our endurance tests are performed under the following conditions:

- Pre-stress: 0.5 FB
- Control signal: 200 Vp-p, trapezoid, unipolar
- Rise time: 140 µs
- Holding time: 1 ms
- Fall time: 140 µs
- Frequency: 200 Hz
- Surface temp.: 120 °C

Under these conditions, the product life of an actuator exceeds 10⁹ cycles. Our longest running tests have reached over 6 x 10⁹ cycles, corresponding to a permanent operating time of approx. 2 years. This value exceeds the product life of most other electrical and mechanical components in the application environment.

Resonant mode
The product life of actuators operating in resonant mode will be enhanced. 10¹¹ cycles have been reached under the following conditions:

- Pre-stress: 0.5 FB
- Control signal: 40 Vp-p, sine-wave, unipolar
- Frequency: 14 kHz
- Surface temp.: 60 °C

D.C. operation
On D.C. excitation, actuators can reach a product life of 3000 hrs. at 200 V as long as the air humidity does not exceed 5% rH.

Fields of application
Piezoelectric actuators are used in a broad and diverse range of applications, usually to benefit from their high actuating speed and stiffness, high power density, and controllable deformation characteristics.

Precision mechanics
- Servo drives
- Stepper motors
- Positioning tables
- Chart recorder drives

Mechanical engineering
- Pneumatic and hydraulic valves
- Vibration damping
- Engraving heads for intaglio printing
- Proportioning valves

Optics
- CCD camera systems
- Optical waveguide splicers
- Microscope tables
- Precision adjustment mechanisms

Automotive
- Fuel injection valves
- Anti-lock brake valves
- Auxiliary drives
- Noise suppression systems

Aircraft
- Rotor blade control flaps
- Adaptive wing systems
- Vibration damping and noise suppression

Acoustics:
- Sound emitters
- Vibration generators
Capacitance and loss energy

Temperature characteristics

Energy balance (assuming f = F_B/2)

Actuator 7 x 7 x 40

Displacement, capacitance and loss energy versus temperature

Displacement versus charge

- \( W_{act} = \frac{1}{2} C U_B \)
- \( W_u = 0.14 \text{ J} \)
- \( W_{act} = (1 - \eta_u) \times W_u \)
- \( W_{act} = 0.077 \text{ J} \)
- \( W_{kin} = \frac{1}{2} c_3 \times (S_3/2)^2 \)
- \( W_{kin} = 0.033 \text{ J} \)
- \( W_{mech} = FB \times S_3/4 \)
- \( W_{mech} = 0.039 \text{ J} \)
- \( W_{therm} = W_{el} - W_{rev} - W_{mech} \)
- \( W_{therm} = 0.024 \text{ J} \)
- \( W_{mech} = F_B \times S_3/4 \)
- \( W_{mech} = 0.039 \text{ J} \)

Coupling coefficient: \( k^2 = \frac{W_{act} \times W_{mech}}{W_u} = 0.51; k = 0.71 \)
Power efficiency: \( \lambda = \frac{W_{mech}}{W_u} = 0.28 \)
Efficiency: \( \eta = \frac{W_{mech}}{W_u - W_{rev}} = 0.62 \)
Parameter conversion

The charts on the foregoing pages each apply to a specific component, but the parameter of interest can be easily converted for different component dimensions.

For a given voltage and mechanical strain, the following applies:

**Displacement:** depends solely on the active actuator length.

\[ L_{\text{active}} = L_{\text{total}} - L_{\text{passive}} \quad (L_{\text{passive}} = 2 \text{ mm in most cases}) \]

**Force:** depends solely on the actuator's active cross-sectional area.

\[ A_{\text{active}} = A_{\text{total}} - 0.6 \text{ mm x b} \]

**Capacitance:** depends on the active actuator volume.

\[ V_{\text{active}} = A_{\text{active}} \times L_{\text{active}} \]

Symbols and explanations

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<th>Symbol</th>
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<td>Nominal voltage</td>
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<tr>
<td>( S_3 )</td>
<td>Displacement</td>
<td>µm</td>
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<td>( F_V )</td>
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<td>( f_r )</td>
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<td>Mechan. energy</td>
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<td>( W_{\text{therm}} )</td>
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<td>( k )</td>
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<td>( \eta )</td>
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**UB** Nominal voltage V

This is the voltage to which all force and elongation data are related. In standard actuators, UB is 200 volts which is also the maximum operating voltage.

**\( S_3 \)** Displacement µm

Deformation of an actuator in the direction of the electric field (longitudinal axis L) at the nominal voltage.

**\( F_B \)** Blocking force N

Maximum actuator force achieved at the nominal voltage when the actuator is prevented from expanding. Since each setup has a finite inherent stiffness, FB is not directly measurable.

**\( F_V \)** Pre-stressing force N

Constant force protecting the actuator against tensile loads. The pre-stressing force is normally generated by means of a stiff spring.

**C** Capacitance F

Electrical low-signal capacitance (at 1 V measuring voltage). The large signal capacitance important for practical applications is about two times as high.

**\( f_r \)** Resonant frequency Hz

This is the serial resonant frequency of the actuator in its freely oscillating state. When the actuator is mounted in an application, the resulting resonance frequency \( f_r \) of the mechanical assembly will always be significantly lower.

**\( c_{33} \)** Stiffness N/m

Inherent rigidity of the actuator. In calculating actuator properties, the field strength dependence of \( c_{33} \) must be duly taken into account.

**\( W_{el} \)** Electrical energy J

Electrical energy absorbed by the actuator as it is charged. It can be calculated from the capacitance and ultimate charging voltage \((W_{el} = 1/2 C U_B^2)\).

**\( W_{el,\text{rev}} \)** Electrical energy J

Electrical energy supplied by the actuator during discharge.

**\( \eta_{el} \)** Electrical loss factor

Refers to the quotient of \( W_{el,\text{rev}} \) and \( W_{el} \).

**\( W_{\text{mech}} \)** Mechan. energy J

Mechanical energy delivered by the actuator. Wmech is a function of the mechanical actuator load. It reaches its maximum value if the force at the operating point is equal to one-half the blocking force \((W_{\text{mech}} = F_B s_3/4)\).

**\( W_{\text{mech},A} \)** Mechan. energy J

Mechanical energy stored by the actuator through its inherent rigidity. \( W_{\text{mech},A} \) cannot be converted into mechanical power \((W_{\text{mech},A} = c_{33}(s_3/2)^2)\).

**\( W_{\text{therm}} \)** Thermal energy J

Heat energy dissipated by the actuator \((W_{\text{therm}} = W_{el} - W_{el,\text{rev}} = W_{\text{mech}})\).

**k** Coupling coefficient

k² is the ratio between the total mechanical energy stored and the electrical energy absorbed \((k^2 = W_{\text{mech},A} + W_{\text{mech}}/W_{el})\).

**\( \lambda \)** Power efficiency

Ratio between the mechanical energy delivered and the electrical energy absorbed \((\lambda = W_{\text{mech}}/W_{el})\).

**\( \eta \)** Efficiency

Ratio between the mechanical energy delivered and the electrical energy consumed \((\eta = W_{\text{mech}}/W_{el} - W_{\text{mech}})\).