Piezo-Mechanics: An Introduction

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1. Generation of motion by piezo-electrical devices

1.1. Piezomechanical effects

Piezo-actuators like stacks, benders, tubes, rings make use of the deformation of electro-active PZT-ceramics (PZT: lead (Pb) zirconia (Zr) Titanate (Ti)), when they are exposed to electrical fields. This deformation can be used to produce motions and / or forces.
The above effect is the complementary effect to piezoelectricity, where electrical charges are produced upon application of mechanical stress to the ceramics. As an analogy the term "piezo-mechanics" was introduced in the early 80's of the past century to describe the conversion of electricity into a mechanical reaction by a piezo-material.

For piezo-mechanical conversion in the simplest case a single PZT layer is used.
Such a PZT monolayer structure as shown in fig.1a acting as a capacitive element defined by 2 thin conductive electrode coatings enclosing the piezo-ceramic as dielectric.

When this "piezo-capacitor" is charged by applying a voltage, the deformation is created.

➜PZT actuators are "moving capacitors"

Thickness mode (d33 effect)

Piezo stack actuators and stacked piezo rings make use of the increase of the ceramic thickness in direction of the applied electrical field (d33 effect). Stacking of several layers towards a multilayer structure increases equivalently the total stroke. In practice, axial strain rates up to 2‰ of stack's length can be achieved under certain conditions.

Planar mode (d31 effect)

Similar to normal elastic deformation of a solid state body, the thickness expansion (d33) of a PZT layer is accompanied by an in-plane shrinking (fig.1a). This is called the d31 effect, being complementary in motion and showing roughly half linear strain compared to the d33 effect.

The d31 effect is mainly used for bending structures (uni/mono-morphs, bimorphs ect. and piezo-ceramic tubes).

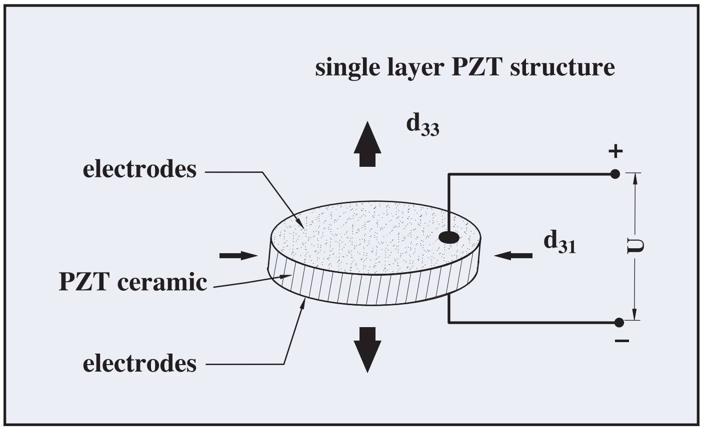


Fig. 1a: Schematic of a piezoelectric single layer element

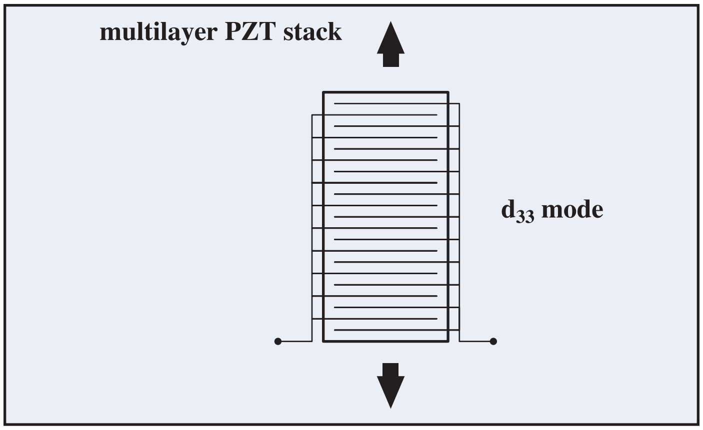


Fig. 1b: Schematic of an axially acting multilayer piezo-stack

1.2. Actuator design: Piezostacks and stacked piezo ring actuators

Piezo-actuators were used preferentially in the past for quasistatic precision positioning tasks, but find now increasing interest in completely new fields of application like dynamically actuated mechanics (e.g. valves, fuel injection devices) or adaptive smart structures (shape tuning, vibration generation and cancellation, mode tuning).
It is self-evident, that this extreme broad variety of application characteristics cannot be covered by one general purpose type actuator.

The main parameters to adapt a piezo actuator to a distinct application are:
A. selection of proper PZT material defining achievable strain, stroke, energy balance, temperature range etc.
B. preparation of a highly reliable and efficient stack structure e.g. shock and vibration resistant electroding
C. sealing for corrosion resistance
D. packaging of the ceramic stack e.g. under rules of preloading and heatmanagement for dynamic applications
E. special actuator system design e.g. antagonistic systems with a 2-element push-pull arrangement
F. performance and reliability of actuator systems depend further on the electrical driving characteristics (see chapter 7): like voltage / charge / currentcontrol operating strategies and unipolar / semibipolar / bipolar operation

Currently, the following basic stack designs are used

Bare stacks

The mounting and motion transfer is always done via the endfaces.
Never hold a bare stack by sideway clamping.
The designation in data sheet is PSt **A / B / C** with
A. max. driving voltage in forward polarity
B. diameter of the ceramic
C. nominal max. unipolar stroke

Ring stacks (stacks with center hole) fig. 2

The need for ring structures is twofold:
A. when an accessible system's axis is needed for transmissive optical setups or the feedthrough of mechanical parts is required
B. to increase bending stiffness by diameter enlargment of the stack without the need of increase of the operated ceramic volume (e.g. for longstroke elements) Ring actuators provide further the utmost cooling performance due to potential access of the inner and outer surface by cooling media.

The designation of ring actuators is as above with HPSt A/B1-B2/C, where B1 and B2 are the outer and inner diameter of the ceramic stack

Cased stacks with internal preload mechanism (fig. 3)

The incorporation of piezo stacks into a metal casing generally improve reliability and stability against mechanical impact and deteriorating environmental influences. The implementation of a preload mechanism compensates for tensile stress, where the ceramic is extremely vulnerable to (details see section 3.4.).
A stainless steel casing is indicated by the addendum VS in the order code.

A PSt 1000/10/80 VS 18 actuator is a high voltage actuator for 80 µm stroke, contained in a preloaded stainless steel casing with 18 mm diameter.

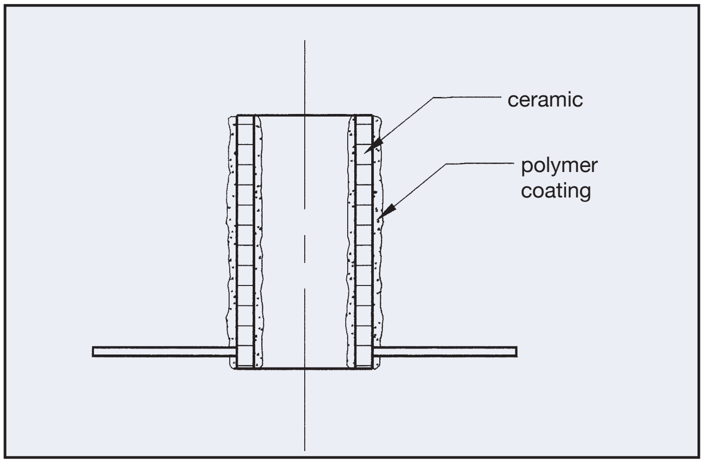


Fig. 2: Schematic of a stacked ring actuator

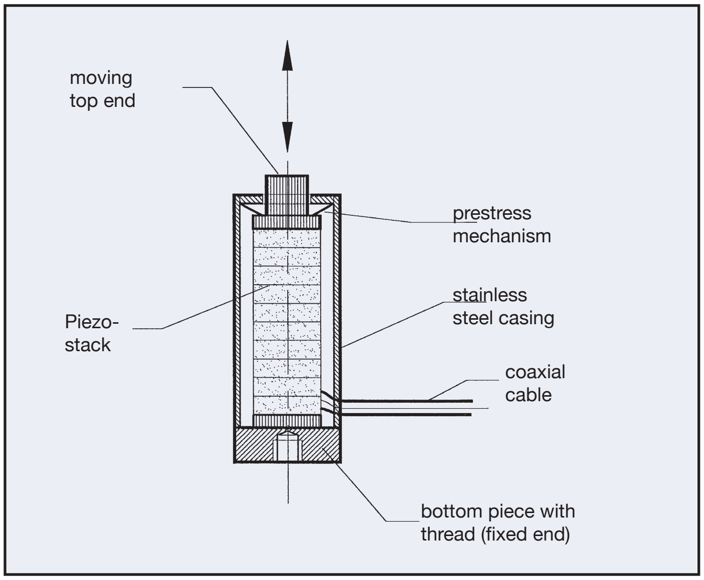


Fig. 3: Schematic of an actuator with prestress

1.3. Actuator characterization by stroke and force

Like any other “electrical motor”, a piezo actuator converts electrical energy into motion and/or force what is coupled to an external mechanism. This can be in the simplest case a component, what shall be shifted from one position to another one. More complex applications are dynamic applications like valve control or the setup of adaptive/smart structures where piezo-mechanical elements are incorporated.
In all these cases the interaction between the actuator and the driven mechanism must be analyzed. This mechanical interaction is ruled by the stiffnesses (= inverse compliances = spring constants) of the two system parts: “actuator” and “actuated mechanics” (see Section 3.6.).

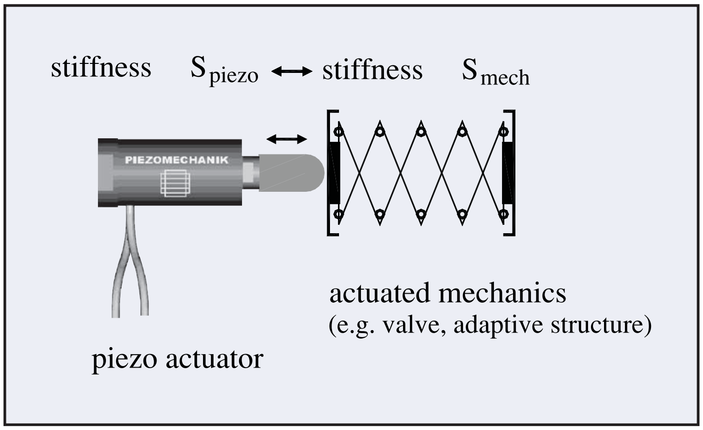


Fig. 4: Schematic of a piezo actuated system: A piezo actuator interacts with a coupled mechanism, where the piezomechanical performance is defined by the two interacting stiffnesses Spiezo and Smech.

To characterize the actuator performance two basic experiments are carried out to determine actuator’s stroke and actuator’s force generation as functions of.

1.3.1. Voltage – stroke characteristic

Condition:
The coupled mechanics show stiffness $S_{mech} = 0$
For $S_{mech} = 0$ a piezo stack shows maximum stroke
No force variation is generated (constant preload)

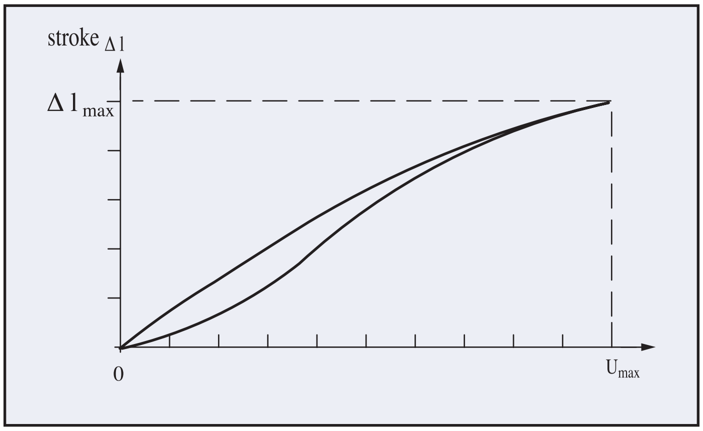


Fig. 5:
Schematic voltage/stroke diagram of a stack actuator

1.3.2. Voltage – blocking force characteristic

Condition:
$S_{mech} = \infty$, actuator cannot expand
For $S_{mech} = \infty$, the piezo stack generates maximum change of force: the blocking force.
No stroke is generated

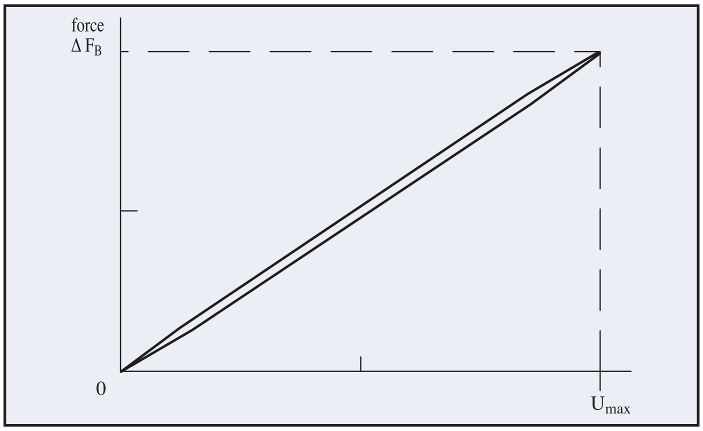


Fig. 6:
Schematic voltage/blocking force diagram for a piezostack. The force response shows remarkably lower hysteresis than the stroke diagram (depends on preload conditions).

1.3.3. Intermediate states (0 < Smech < ∞)

In practice piezo actuators interact mostly with mechanical systems showing an intermediate stiffness value between 0 and ∞.
Then the piezoactuator distributes its "activity" partially into generation of stroke and partially into generation of force, where "partially" depends on the quantitative reltion of actuator's and mechanic's stiffnesses.

The achievable force-stroke relations in a real system can be derived in the following way:

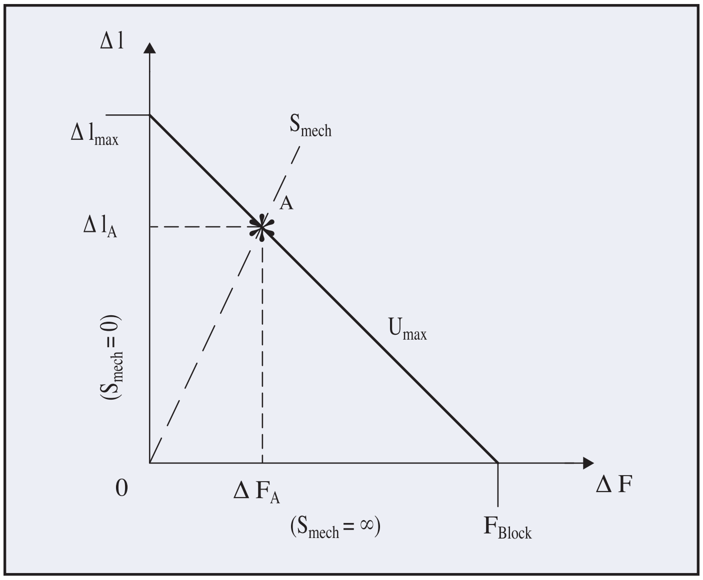


Fig. 7: Shows a diagram spanned by piezo actuator's max. stroke versus blocking force

Make the following two steps:
– draw a line from piezo actuators max. stroke Δl_{max} to max. blocking force F_B (______) (at same volt ages)
– draw a line from origin with a slope according the stiffness S_{mech} of the coupled mechanics:
N/µm (_ _ _ _)

These two lines intersect at point A.

The coordinates of A: (Δl_A, ΔF_A) show the achievable stroke and force at maximum excitation voltage of the actuator.

Notice:
This schematic represents a linearised actuator's response. It does not take into account stroke enhancement effects as described in section 3.4. C. Especially the high power material HP (section 2.2.2.) shows improved performance.

For $S_{mech} = S_{piezo}$ the achievable displacement is 50% of the maximum displacement l_{max} and the achievable force variation is 50% of the blocking force F_B.

Under this condition the mechanical energy transfer efficiency E from the actuator into the mechanical system is maximized (matching point).

1.4. Energy/Power balance

Piezo actuators are "motors" converting electrical energy P into a piezomechanical response.
The (non resonant) electrical energy content P of an electrically charged piezostack is

P = 1/2 CU2 C = actuator's capacitance
U = applied voltage

The piezomechanical response are
Stroke: Δl
Force generation: ΔF
Mechanical energy $E = \Delta l \times \Delta F$

1.4.1. (Nano)Positioning philosophy:

Here the user of an actuator is mainly interested in the displacement/stroke Δl of the actuator and (maybe) the ultrafine positioning capability down to the subnanometer range. A variation of force or generation of mechanical energy during piezo actuator's action is not a priority. In terms of energy efficiency, piezoactuators are then not well matched for most positioning applications, because only a small part of actuator's energy content is needed to be transferred to the coupled mechanics.
Optimizing piezo actuators for dynamic positioning purposes means that the electrical energy input shall be as low as possible to get a certain displacement. Or with other words, actuator's capacitance (in relation to the driving voltage) shall be as low as possible to minimize the electrical current/power requirements for a distinct dynamic response (e.g. for oscillating arrangements):

➜A PZT material with low dielectric constant ε together with a high piezoelectric constant d33 is required.

For dynamic positioning purposes APC International provides excellently adapted PZT materials like the standard ceramic and the HS/HT ceramic, showing high strain together with low dielectric constant.
Low ε materials have other interesting properties too: high operating temperatures and high stability against depoling. So energy aspects are not the only one criterion for selecting this type of PZT ceramic.

Notice:
Low dielectric ultrasound PZT materials show rather small strain rates under non resonant conditions and are not optimized for actuation.

Examples for positioning strategy
The "mother of piezo actuation" were optics, where actuators are used frequently to shift a distinct optomechanical component with ultrahigh accuracy to get an optimum adjust e.g. of a laser resonator.
Optomechanical components like stages or mirror mounts are usually systems using soft reset springs and show therefore low stiffnesses.
Adjusting of optomechanics by piezo actuators does not require a production of high mechanical energies or forces.
An example for high dynamic positioning is fast valve control, where the actuator is shifting a mechanical part like a small ball or a needle to open or to close the valve.

1.4.2. Power optimisation

"Positioning" according 1.4.1. ruled piezo actuation now for nearly 30 years, but new applications are emerging, where a piezo actuator must be adapted to other strategies: In these cases a piezoactuator shall provide high displacements together with high force generation to achieve high mechanical energy transfer.
Examples are adaptronic/smart structures of high stiffness, which shall be highly deformed by integrated actuators. This is a requirement to ensure large mechanical energy transfer.
Examples e.g. adaptive frame structures of machines, car bodies, wings of air planes for active vibration excitation and cancellation or shape optimization.

➜ High mechanical energy shall be transferred into a mechanical structure.
➜To provide this large mechanical energy output, an increased electrical energy input is required via a reasonable large electrical capacitance of the actuator to get a high mechanical energy density within the ceramics.
➜A PZT material is requested showing an elevated dielectric constant ε combined with a very high strain and force generation rate.
Notice: Large ε materials are widely offered, but often do not show the wanted large piezomechanical response.

➜APC International is offering the high power PZT material HP, which shows the highest mechanical energy density available for PZT ceramics. The energy density is roughly double that of standard materials (like PZT 5A) or the HS/HT material. To get the same power out from "positioning actuators", the actuator volume must be simply doubled with consequences for weight, space and price compared to the energy optimized HP material.

With a HP based actuator PSt 1000/25/100 mechanical pulse powers of more than 100 kWatts have been generated.

2. Piezoelectric and electrostrictive ceramics

PZT ceramics will be the heart of solid state actuation for the near and mid future.
New electroactive materials like highest strain/single crystalline formulations cannot compete for technical and cost reasons for broad applications at the moment.
APC International provides a set of piezoelectric PZT ceramic materials for stack manufacturing, which covers a very wide range of applications.
This is true both for co-fired low voltage as well as discretely stacked high voltage materials.
The standard program has been defined by compromising technical performance and pricing.
Nevertheless, special materials are available on request.

2.1. Low voltage actuators (cofired monolithic stacks)

Operating voltage range: (–)30 V thru (+)150 V
Operating temperature: –50 °C thru +100 °C
Axial coefficient of thermal expansion (CTE): approx. –3 ppm/°C
Vacuum compatible
Low voltage actuators for cryogenic applications on request.
Low voltage actuators based on HP, HS/HT materials on request (see below)
Low voltage actuators for other voltage ranges (e.g. 200 V) on request

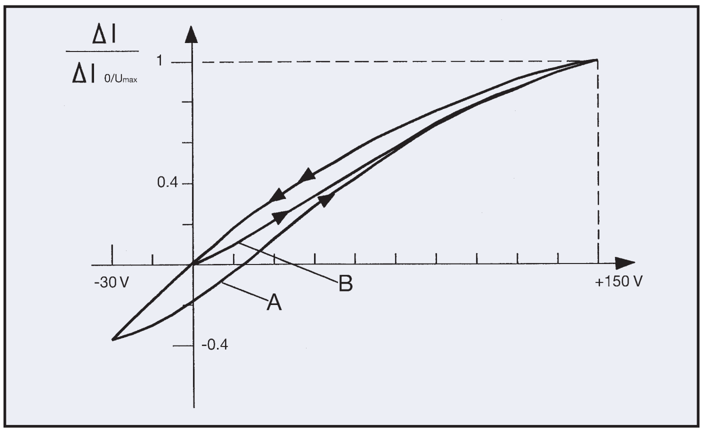


Fig. 8:
Normalized stroke/voltage diagram of low voltage stacks (relative stroke 1 for voltage step 0 V/U_{max})
A. For bipolar operation in the range (–)0.2 U_{max} thru (+)U_{max}
B. For unipolar operation in the range 0 V thru (+)U_{max}

2.2. High voltage actuators

2.2.1 Standard PZT

Operating voltage range: (–)100 V thru (+)1500 V for PSt 1500 … stacks
(–)200 V thru (+)1000 V for PSt 1000 … stacks
Operating temperature: –60 °C thru +120 °C
Axial coefficient of thermal expansion (CTE): approx. +1 ppm/°C
Vacuum compatible
Actuators for cryogenic (–273 °C) applications on request (e.g. tuning of superconducting accelerator resonators)

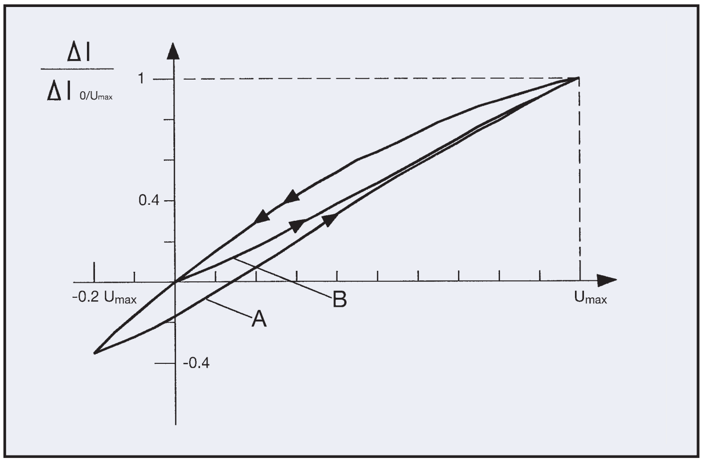


Fig. 9:
Normalized stroke/voltage diagram of standard high voltage stacks PSt 500 and PSt 1000
A. For bipolar operation in the range (–)0.2 U_{max} thru (+)U_{max}
B. For unipolar operation in the range 0 V thru (+)U_{max}

2.2.2 High power PZT HP

High Power HP PZT material is the choice, where high mechanical power generation is required. Stroke and force generation under high load are remarkably larger than for the standard or HS/HT material. The energy output is roughly doubled.
The HP material is used for adaptronic applications, where the mechanical energy transfer to a coupled system shall be maximized.
The electrical capacitance is higher by about 80% compared to the standard configuration.

Operating voltage range: (–)100 V thru (+)1500 V for PSt 1500 … stacks
(–)200 V thru (+)1000 V for PSt 1000 … stacks
Operating temperature: –60 °C thru +120 °C
Axial coefficient of thermal expansion (CTE): approx. +1 ppm/°C
Vacuum compatible

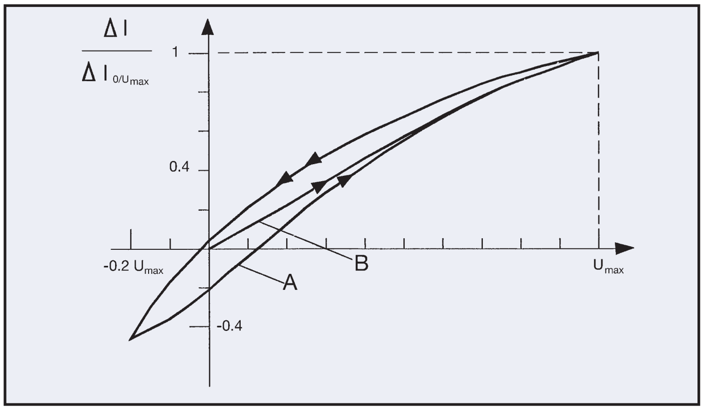


Fig. 10:
Normalized stroke/force diagram for HP modified high voltage actuators. Relative stroke = 1 at U_{max}
A. For bipolar operation in the range
(–)0.2 U_{max} thru (+)U_{max}
B. For unipolar operation in the range 0 V thru (+)U_{max}

2.2.3. High temperature/high stability PZT: HS/HT

The main feature of the HS/HT material is the stability of strain and force characteristics under varying temperatures or load forces.
Electrical capacitance and achievable strain exceed slightly standard PZT

Operating voltage range: (–)100 V thru (+)1500 V for PSt 1500 … stacks
(–)200 V thru (+)1000 V for PSt 1000 … stacks
Operating temperature: –60 °C thru +120 °C
Axial coefficient of thermal expansion (CTE): approx. +1 ppm/°C
Vacuum compatible

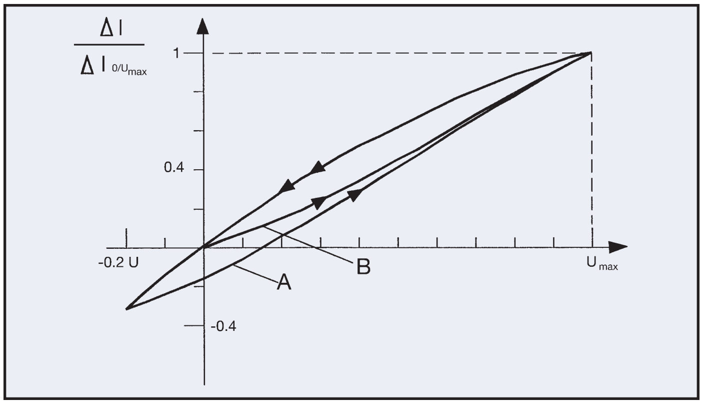


Fig. 11:
Normalized stroke/force diagram for HS modified high voltage actuators. Relative stroke = 1 at U_{max}
A. For bipolar operation in the range
(–)0.2 U_{max} thru (+)U_{max}
B. For unipolar operation in the range 0 V thru (+)U_{max}

Options:

Actuators for cryogenic (–273 °C) applications on request (e.g. tuning of superconducting accelerator resonators)
High temperature application (up to 200 °C on request)

HS/HT material is used for high frequency/high speed actuation like
high dynamic valve controls shaker applications scanning

2.3. Electrostrictive PMN ceramics

This material is used preferentially for static positioning applications.
On one side it outperforms PZT stacks by a strongly reduced hysteresis (approx. 2%) and absence of creep.

But unfortunately these features are true only in a very narrow temperature range of approx. +/–5 °C around room temperature. Further the electrical capacitance of electrostrictors is remarkably higher than for comparable PZT elements.
Electrostrictive devices are restricted mainly to laboratory use for certain adjustment tasks. High dynamic operation leads to self-warming and then the systems drifts away from the optimum temperature range.
Electrostrictive devices show no defined poling direction, any voltage polarity can be applied resulting in a positive stroke with increase of voltage. Therefore no stroke enhancement by semibipolar operation is achieved.
Electrostrictive actuators are available as low voltage and high voltage stack elements.

Operating temperature: +20 °C thru +35 °C

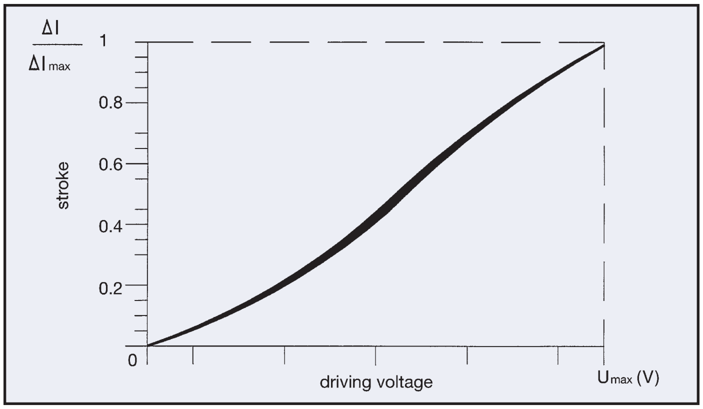


Fig.12a: Normalized stroke/voltage characteristic for electrostrictive actuators, unipolar operation only.

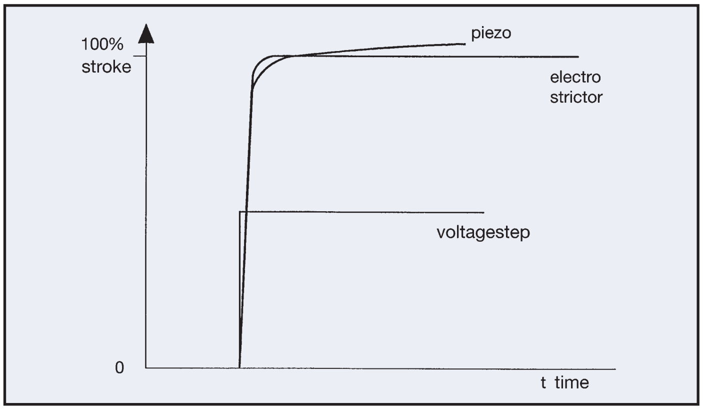


Fig.12 b: Creep of piezoactuators versus electrostrictors. Creep in PZT is noticed only for a few seconds after application of a voltage step and then declines. It varies in the percent range of the initial achieved stroke.

3. Comments on datasheet

The problem in comparing data of actuators from different suppliers is, that specifications and data on piezo stacks are often defined in different ways.
Therefore it is necessary to understand to some extent the background of the specified parameters to ensure a reasonable decision for and proper use of a certain piezo-element.

Especially for highly sophisticated applications, a profound consulting is recommended to check for all relevant aspects when designing a piezo active arrangement.
Contact APC International, when you make first steps towards piezo actuation.

3.1. Voltage polarity

Piezostacks can be operated by unipolar or semi-bipolar voltage signals.
When special PZT-material is used even a symmetrical bipolar operation is possible (see APC International catalog: "Long life bipolar stacks").
In case of unipolar or semibipolar driving mode, attention must be paid for correct voltage polarity, when connecting a piezostack to a power supply. Otherwise, the PZT actuator can be deteriorated in its action by depoling, when the maximum voltage is applied.
A simple check for correct polarity is, when a harmless low voltage signal is applied and the stack actuator expands with increase of voltage.

Bipolar actuators are insensitive to polarity reversal by definition, but the mechanical response inverts e.g. the stacks shrinks upon application of a counterpolar voltage.
APC International actuators with casing and power supplies are manufactured for positive polarity with reference to ground.
Bare piezostacks wired by two pigtails are manufactured potential free, so any power supply polarity can be used when connected correctly to the piezostack.

3.2. Stroke and positioning

Any PZT material can be operated to some extent with a countervoltage opposing the burned-in polarity. Compared to unipolar activation, the semibipolar mode results in wider total voltage swing with the expected consequences: increase of stroke, blocking force and energy density.
A 20% countervoltage (of the specified maximum forward voltage) is applicable to any material. The yield in stroke (and blocking force) can be up to 30% then compared to the unipolar situation.The energy content can be enhanced up to 50% and more. Hard PZT materials like PZT ceramic HS/HT can withstand still higher electrical counterfields than the above defined 20%.

The data sheet show two values for the maximum stroke. These are related to semibipolar operation (higher value equiv. larger voltage swing) and conventional unipolar operation (lower value) e.g. the PSt 150/7/40 VS 12 element is specified with 55 µm/40 µm stroke meaning: 40 µm stroke for unipolar 0 V/+150 V activation and 55 µm for the semibipolar –30 V/+150 V swing.

A piezostack's maximum stroke is proportional to stack's length. Strain rates of approx. 1– 2‰ are usually achieved.
The data sheet show nominal values for "no load" condition at room temperature.

The achievable real stroke depends on the mounting conditions like preload and stiffness of attached mechanics (see sections 1.3.3.).

One of the most important features of piezoactuators is the ultrafine positioning capability down to the subnanometer range (provided the electronic supply shows a sufficiently high quality with respect to noise and signal resolution).
Please take notice, that piezo-elements show an infinitely large relative positioning sensitivity: This means that an infinitely small voltage variation leads to an infinitely small mechanical shift. Unfortunately the step width for a distinct macroscopic voltage variation is not calibrated as characterized by the hysteresis in the voltage stroke/diagrams.
To do absolute positioning a position measuring systems must be introduced to detect the mechanical shift and to match the voltage signal for setting to the desired position.
An introduction to the philosophy of feedback controlled positioning is shown in APC International catalog "PosiCon feed back control electronics".

Notice: The stroke characteristic becomes more linear and non-hysteretic when stroke is set into relation to the electrical charge content of the piezo actuator instead voltage (see chapter 7).

3.3. Electrical capacitances

Piezo-stacks are a kind of multilayer capacitors. So the electrical capacitance is the result of the structure (number, thickness and cross section of the layers) and the used PZT material (dielectric constant ε) on the other side.
The large difference in capacitance values of low voltage versus high voltage stacks (of same size) are mainly due to the structural difference in thickness and number of layers. It is self-evident, that both types produce the same piezo-mechanical performance in all aspects, when the same material and the same driving electrical field is used.

The electrical capacitances stated in the data sheet are usually measured as so-called "small signal" values, where a small voltage signal in the Volt range excites the capacitance dynamically and the induced current is measured. For "normal" capacitors, the derived "capacitance" is valid for larger voltages too, because capacitance does not vary with voltage.
With "piezo capacitors" this situation changes towards the more complex situation, that capacitance of an actuator varies to some extent with voltage, temperature, load. Therefore the stated capacitances are only a rough number. Capacitance data are needed to value the electrical currents or powers to get a distinct dynamic reaction. Please take therefore into account at least a factor 1.5, when checking for a proper power supply.
Notice: approx. 5% of the power consumption of the "piezo capacitor" is dissipated into heat.

3.4. Prestress/Preload

In a lot of applications of piezo-stacks a socalled prestress or preload is applied:
This means the application of constant force e.g. by a kind of spring mechanism, compressing the stack. In a lot of piezo actuated systems, the whole mechanical system is preloaded against the actuator, so that any backlash by alternating load force directions is avoided.

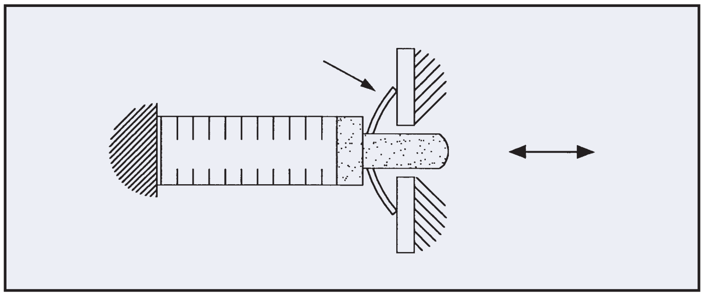


Fig.13: Schematic of a preloaded stack

The reasons for preloading are twofold:
A. Symmetrical push/pull performance:
Pure PZT ceramics can only produce high pushing forces, but cannot withstand larger tensile forces. To get more symmetrical push-pull-performance of an actuator a kind of resetting force must be introduced into the system: the simplest arrangement is a passive preload by a kind of spring mechanism.

B. Improved dynamics
"Dynamics" means "acceleration forces". It is selfevident from basic physics, that dynamic contraction result in a tensile loading: so compensation for this tensile force is needed by a sufficient high preload. Then the actuator can be operated in a highly dynamic way (high frequency oscillations, pulsed operation. Without prestress, the actuator will fail.

Notice: Very high accelerations during actuator switcing (risetimes far below 100 μseconds) by improper power supplies may create higher internal oscillating modes. Even very high preload maybe insufficient to prevent ceramic damage.
Co-fired stacks are more sensitive to this effect than discretely stacked high voltage elements.
These problems can be overcome by proper electronic supplies using pulse current shaping
(see chapter 7).

C. Improvement of piezo-mechanical performance Certain piezo-ceramics show strain enhancement, when a high load pressure is present.

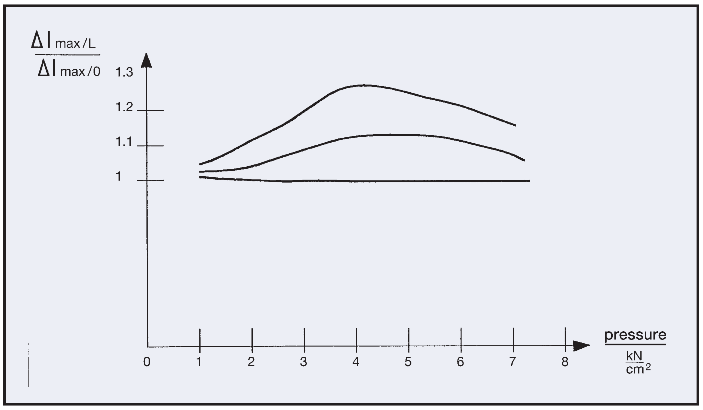


Fig.14: Strain enhancement upon prestress for different PZT materials.
The high power HP materials shows the strongest reaction, whereas the stabilized material HS/HT is insensitive to preload. The standard material is an intermediate formulation.

The very high power capability of HP ceramics is related to this enhancement effect.

Preload design criteria
An optimum preload design fulfills two basic requirements:

• The preload mechanism shall provide high forces together with an as low as possible stiffness. Only then the preload force does not vary with piezo actuator's motion and maximum stroke is achieved.

• The force level of the prestress must be high enough to reset the moved masses attached to the actuator sufficiently fast according the mass acceleration law

preload force $F = m \cdot \Delta l/t2$

m: attached mass
Δl: actuator's stroke
t: minimum reset time defined by desired operation frequency

Preload forces up to 50% of actuator's maximum load capability are applied sometimes to get symmetrical push/pull performance.
In a lot of applications the complete actuated mechanics is preloaded against the actuator avoiding push-pull (oscillation of force direction) with risk of backlash.

Active resetting:
The above mentioned preloading is a kind of passive technique using e.g. reset springs.

An alternative are antagonistic systems, where two piezo actuators are facing each other and shifting an in-between mounted component. The actuators operate with complementary push-pull motions.
The advantage is, that the actuators must not act against a permanent counterforce and no resonances emerge from reset springs. On the other side, larger capacitances must be handled. The simplest antagonistic arrangement is using bipolar stack actuators with opposing polarity setting. So the system can be operated with one driving signal for both actuators.

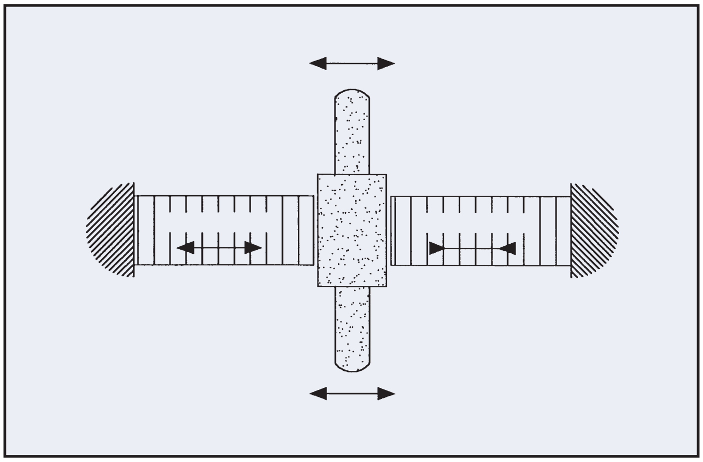


Fig. 15: Schematic of a bipolar antagonistic actuator system for active resetting.

3.5. Max. compressive load

The max. load or max. compressive force capability is not a hard limit for the maximum applicable force, where a damage must be immediately expected, when slightly exceeded.
As shown in fig.14, the achievable maximum strain can depend on the applied compressive force.

The maximum applicable load is defined as the force level, where the actuator shows a reduction in performance
lower than the zero load performance.
Notice: The reduction in performance is reversible.
A mechanical damage of the ceramic structure occurs under remarkably higher loads.

Attention must be paid to actuators with a critical length/diameter ratio because of the increasing risk of buckling (Typically factor of 15–20). High bending stability by large diameter designs can also be achieved by using ring actuators instead of bulky stacks. The advantages are equivalently lower electrical capacitances.

3.6. Stiffnesses

Like any other solid state body, a piezo actuator shows a distinct elasticity.
This elasticity is described by Hooke's law, where a deformation Δl is related to the applied ΔF force by

$$\Delta F = S\ \Delta l$$

defining thereby the
spring constant = stiffness S = inverse compliance

In contrast to "normal" passive materials the unique feature of piezo-ceramic is to show a variable stiffness, depending on the electrical driving scheme as it is shown by following simple experiments:
A compressive force ΔF shall be applied to the piezo stack and the resulting compression Δl of stack's length is measured.
Following situations can now be distinguished:

a) the actuator leads are short circuited or connected to a voltage amplifier with constant output voltage setting,

b) the actuator leads are open,

c) the actuator is connected to a position feedback control unit.

In a) a distinct actuator stiffness Svolt = const.= ΔF/Δl is derived.

In b) roughly the double stiffness compared to a, is observed (depends on type of PZT material and to some extent on manufacturing technique of the stack)

In c) a nearly infinitely high stiffness is seen, no compression occurs (within the feedback control range).

The data sheet show the actuator stiffness for voltage control.

The reason for the difference in a) and b) is easily understood: The application of a compressive force to PZT leads to the generation of electrical charge via the normal piezoelectric effect.

In case a): short circuiting the leads (or holding the voltage level constant via a voltage amplifier) the generated electrical charges can flow and equilibrate.

In case b): the generated charges cannot flow due to open leads and a voltage is generated creating a stabilizing electrical field acting against the mechanical compression => higher stiffness than a)

The case c) leads self-evidently to virtual infinitely high stiffness, because the feedback makes any compressive deflection to zero.

These basic phenomena find their equivalents in different types of electrical supplies for driving a piezo actuator:
a) corresponds to open loop voltage control
b) corresponds to open loop charge (or current) control
c) is realized by closed loop position control.

Voltage control fits excellent to the needs of low dynamic precision positioning, where no high requirements for dynamic stiffnesses are given. This was the situation for the past decades.
Motion control by open loop charge or current control of piezo actuators leads to remarkably higher stiffnesses than the open loop voltage control. Currently applications are becoming more and more important, where high dynamic stiffnesses are requested to modulate high stiffness structures (see chapter 7).

3.7. Blocking force

The maximum blocking force shown in the data sheet is defined for maximum semi bipolar voltage swing. Details for blocking forces see section 1.3.2.

3.8. Resonances

As any other solid state body, a piezostack shows resonant modes. In the data sheet the axial resonances for a one side fix oscillation of the stack are shown.
Usually piezostacks are operated broadband non resonantly well below stack's resonance frequency.
When the piezo actuator is attached to a mechanical system, the resonance of the total system will be lower for several reasons:

A. Due to the mass m of the attached mechanics, which results in a new actuator resonance frequency according the spring/mass system's law (where the stack acts as the "spring")

$$f_{res} = {}^{1}/_{2}\pi \sqrt{(S/m)}$$

B. The resonant modes of the attached mechanics (e.g. optomechanical components like translation stages have resonances in the 100 Hz region).

Mechanical resonances of a piezo-actuated system can be easily detected by using the piezo-stack as vibration sensor. When the piezo-actuator is connected to an oscilloscope, the ringing signal can be monitored, when the mechanics is excited by a short knock.

3.9. Thermal properties

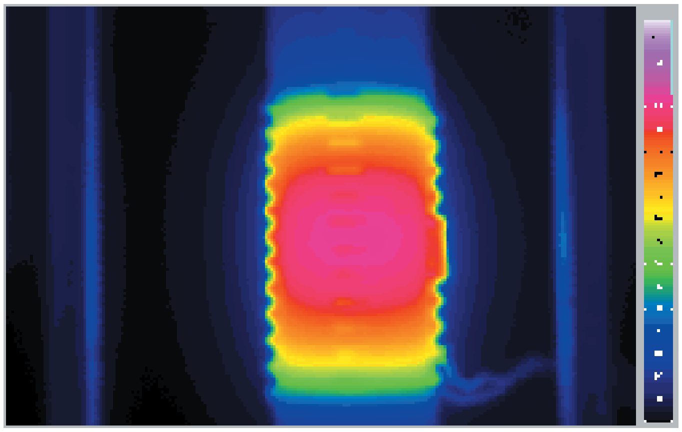
The stability of piezoactuators at high temperatures is not only determined by the properties of the piezoceramic, but also by the used accessory materials such as insulating coatings, electroding, adhesives etc...
The Curie temperature of the ceramic is in most cases not the limiting factor. An important aspect for industrial application is, that actuators shall not only withstand wide temperature variations, but also shall show only small changes in their properties. Here the material composition HS is unrivaled (see chapter 3.2.). The use of actuators under cryogenic conditions is a standard application.

Selfheating
Piezoactuators show self-heating proportional to the reactive power balance during dynamic operation, increasing therefore with actuation frequency and amplitude. The tendency to dramatic self-heating is further enhanced by the poor internal heat management for standard mounted actuators with the sole mechanical contacts of the ceramic stacks via the endfaces.

Heat-sinking by this arrangement is very poor due to the low thermal conductivity of PZT ceramic and the poor heat transfer for cased actuators with an airgap between ceramic stack and casing.

The consequences are severe frequency limitations for the operation of piezoactuators to avoid overheating. Normal low voltage actuators with mid sized diameters tend to overheat for frequencies in the range of about 200 Hertz/full stroke operation.

To make use of the full dynamic potential of piezoactuators with high frequency/amplitude rates in long-term operation, a consequent heat management is necessary to remove heat efficiently from the piezostack.
The solution is the unique ThermoStable configuration provided to APC International actuators (option 3.9.).



Thermal expansion
Low voltage actuators show a thermal axial expansion coefficient of –3 ppm/°K (measured for short circuited actuator).
Discretely stacked high voltage actuators show higher values due to the ceramic/metal/adhesive compound structure of about +1 ppm/°K. High voltage actuators from other sources sometimes show very high thermal expansion due to oversized adhesive layers.
For actuators with casing the mechanical endpieces contribute to the total thermal expansion. This effect can be minimized by the use of INVAR alloy.

Low temperature properties:
The piezomechanical and electrical properties of PZT ceramic depend on temperature. When piezoactuators are cooled down to 77 °K (LN2) or even lower towards the 4°Kelvin region, any PZT ceramic behaves like a piezoelectrically very hard piezo material featuring
- strong reduction of electrical capacitance
- reduction of loss factor / reduced hysteresis
- reduced piezoelongation factor d33
- strong increase of the coercive field strength

The last point means, that at low temperatures a piezostack becomes extremely stable against electrical depoling and other destabilizing effects.
So a much wider voltage swing (bipolar operation) compared to room temperature is possible now.
Thereby, the loss in stroke for low temperature can be partially compensated for.

In the following the main properties of the standard soft PZT PSt 150 actuators are compared for roomtemperature and cryogenic temperatures.

Standard PSt 150	capacitance	stroke for 0V/ (+)150V	max. operating voltage range
roomtemp.	100%	100%	(–) 30V / (+) 150V
77 °K	15%	20%	(–) 150V / (+) 150V
4 °K	5%	6%	(–) 300V / (+) 300V

Other PZT materials show qualitatively the same trend. For hard and semi hard PZT materials the loss in stroke during cool down is not dramatic as for soft PZT materials as used with the standard PSt 150 stacks.

Fig. 16: IRthermography of a piezostack PSt 1000/16/40 conventionally mounted via the endfaces in thermal Equilibrium for 1000 V/150 Hertz excitation.
The hotspotting in the stack's center with about 100°C is evident as well as the temperature gradient towards the cool endpieces (approx.30°C).

3.10. Lifetime, reliability

Lifetime and reliability of actuator stacks do not only depend on inherent features like material, electroding, coating etc., but depends strongly on the quality of mechanical and electrical coupling. These points are defined by the system design provided by the user.

To characterize the most important aspects for reliability and lifetime, two extreme driving conditions shall be discussed.

A. High dynamic cycling
An example is the mechanical switching of piezo-stacks with risetimes of 50 to100 μsec over the full stroke. This is e.g. true for the newest generation of Dieselfuel injectors.
Lifetime and reliability are defined as achievable cycle numbers. Up to 1010cycles are achievable at the current state of the art.
This is due to the fact, that life time limitation comes from the high acceleration forces and mechanical stress created inside the stack components like the ceramic body and its surface electrodes. Cracking can lead to insulation break down or to rupturing the electrodes, when improperly designed. Ceramic cracking can be compensated for by rather high pre-load forces (up to 50% of the max. force load) and well matched driving electronics.
Discretely stacked high voltage elements are a kind of composite structure and show better reliabilities than monolithic cofired low voltage elements under pulsed operation.
Especially APC International high voltage actuators with their unique electrode design are highly resistant to stress induced failures and electrode rupturing.
High power electronics for actuator switching shall provide the necessary slew rate in charging current to get the necessary actuator acceleration. But a superimposed current jitter shall be strictly avoided, because it creates high mechanical stress by exciting higher mechanical oscillation modes. These cannot be compensated for sufficiently by external preload. The consequences are stress induced failures of the stack arrangement. Usually electrical pulse generators for actuator switching provide a kind charge or current control instead voltage control to improve current's quality (see chapter 7.).

B. Static operation
On the first glance, the application of a constant or nearly constant voltage signal seems to be uncritical. But experience shows, that under certain circumstances standard actuators are subject to a kind of electro-corrosion in on stack's surface, leading to a long-term degradation and final short-circuiting of the stack. This effect is accelerated by high environmental humidity, temperature and elevated voltage ratings.

Counter measures are improved surface coating techniques up to the use of ceramic surface blocking layers (ask APC International for "Buried electrode"-design).

Further long-term stability can be improved by proper design and electrical driving techniques.

A. Use longer stacks to reduce the necessary driving voltage level to get a distinct elongation.
B. No "stand by" mode. Switch of actuators, when not in use.
C. Make use of the semibipolar driving mode (see section 3.2.) to avoid high peak voltages.
D. Do not touch bare stacks with fingers nor bring them into direct contact with water and electrolytes.
E Use 100% isopropanol for cleaning.

4.1. Cryogenic operation

Low voltage and high voltage actuators can be modified for operation under cryogenic conditions even below LiquidHelium temperatures.

4.2. UHV compatibility

APC International standard actuators can be operated under high vacuum conditions without restriction. For use in ultra high vacuum (UHV) actuators can be adapted by the use of accessory materials with very low out-gassing rates. UHV modified actuators are bakeable to some extent.

4.3. Position detection

Most of APC International actuators can be provided with strain gauges in full and half Wheatstone bridge configuration for position detection. Together with the PosiCon-feedback control the actuators can be used for linearizing the expansion characteristic of the actuators, and for absolute positioning tasks. Actuator's hysteresis and creep are eliminated. External influences on the actuator system are compensated for as long as these are changing the strain state of the piezoactuator.

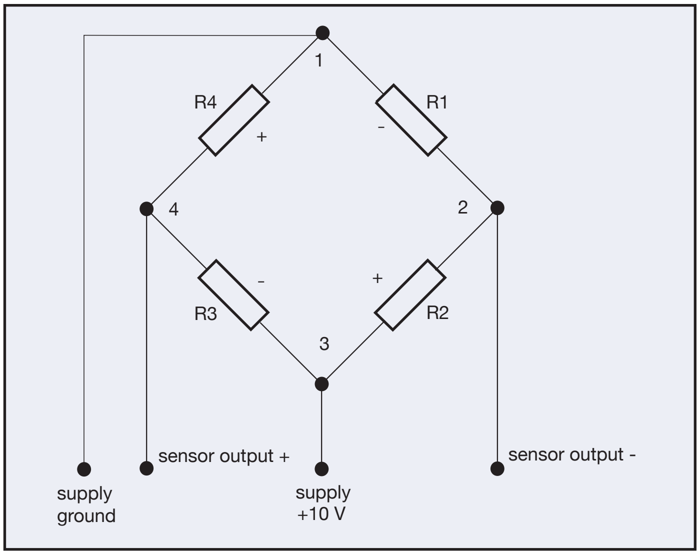


Fig. 17: Schematic of a Wheatstone bridge configuration of strain gauges for position detection

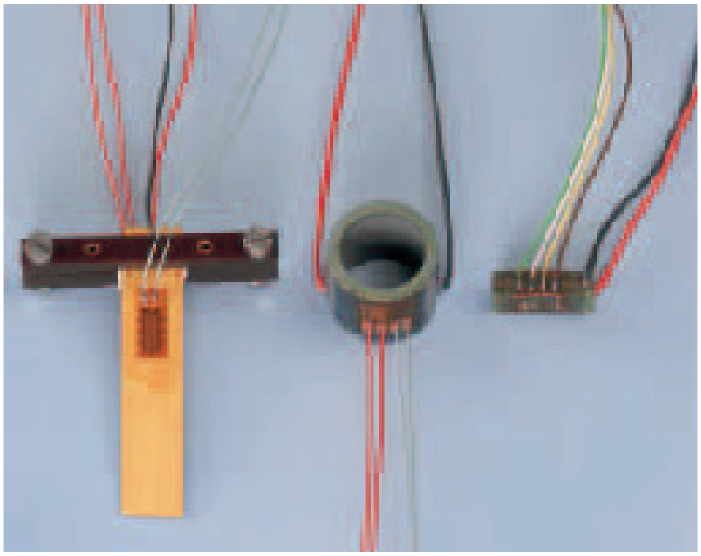


Fig. 18: Variety of piezoactuating components with surface mounted strain gauges

4.4. Internal force detection

Especially under dynamic load operation of actuators, the actual force balance can be of interest.
An elegant arrangement for force detection within an actuator can be obtained using the operating dualism of piezo ceramics: it can be also used for force detection too. In practice a small fraction of the ceramic stack is electrically separated from the actuating part. The small actuator section is separately contacted for charge or voltage detection purposes, thereby delivering information about force variations within the stack.

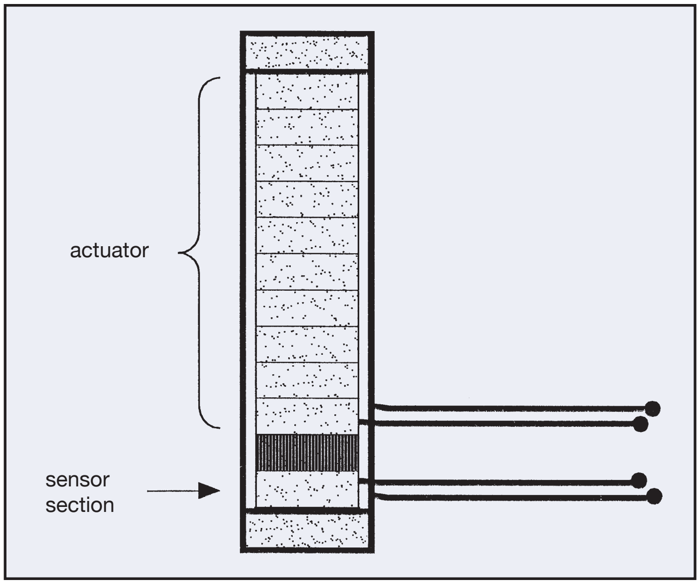


Fig.19: Schematic of an integrated actuator-force sensor configuration

4.5. Internal heat management, option "ThermoStable"

As shown in chapter 3.9. an efficient heat management within actuators is a prerequisit to achieve very high power levels in the dynamic operation of piezo actuators. This is provided by APC International "ThermoStable" modification of piezoactuators. The main aspect is the efficient transfer of heat from the ceramic stack's surface to the metal casing, from which the heat can be removed by conventional means. There- by any hotspotting within the ceramic stack is prevented, and no damages due to overheating occur even for very high power levels.
Measurements show only a minimum temperature difference of about 10 °C from ceramic to casing.

The immediate consequences are:

a. The thermal state of the actuator can be measured simply via the casing temperature, no internal temperature measurements are necessary.
b. No cooling media or liquids circulating within the actuator casing are necessary. Bulky arrangements are avoided.

When the "ThermoStable" modification is combined with a copper casing, a rather efficient heat sinking via the bottom piece to the supporting mechanics is achieved. The dimensions of this version are compatible to the standard dimensions of the actuators. Existing arrangement can simply be upgraded with respect to power applications. Alternative designs use air cooling fins to the casing for forced air cooling etc.

Example
An actuator PSt 1000/25/80 VS 35 (nominal capacity: approx. 2 µF) with standard ceramics was setup in "ThermoStable" casing with air cooling fins together with forced air cooling (see fig.20):

• The operation with a switching amplifier RCV 1000/7 (1000 V/7 A) leads to a casing temperature of only 95°C for dynamic cycling with 80 µm/1000 V and 900Hz

• The arrangement is well below any critical temperature limit (about 140 °C at casing).

• Additional means for heat extraction from the stack arrangement within the casing can be provided, so that a multikiloHertz/full stroke operation is possible.

The ThermoStable application is recommended for all actuator systems, where high power LE or RCV amplifiers or equivalent power sources are used.

Fig. 20: Different configurations for the heat management of actuators using the "ThermoStable" technique. Left side: actuator with copper casing for heat sinking. Right side: actuator casing with air cooling fins for forced air cooling.

4.6. Corrosion resistance

Piezoactuators are sometimes used in mechanical arrangements for handling chemical agents such as liquid fuels in piezo operated injection valves. Actuators sometimes come into direct contact with these liquids, which can cause actuator failure due to the degradation of common surface insulation layers on the ceramic used by other suppliers.
APC International stacks are rather insensitive to such influences due to proper surface modification as shown in section 3.10. reliability.
APC International offers additional modifications of the actuator stacks to improve the stability of the stacks against the attack of organic liquids or agents.

4.7. Special casings

APC International offers the modification of the casing's parts using special metals such as INVAR, aluminium, titanium etc. instead of the standard stainless steel.

4.8. Custom designed actuators

On request APC International is able to apply a wide range of modifications to actuators to optimize them for special applications such as watertight configurations, rugged versions for space applications, shaker setups for material testing etc.

Fig. 21: Large cross section custom designed actuator for active vibration cancellation, 56 mm diameter for very high loads of 100 kNewtons

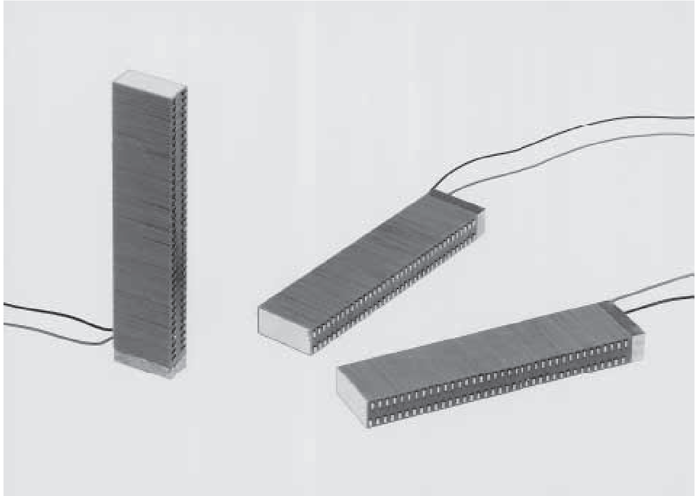


Fig. 22: Actuator stacks with rectangular cross section

5. Comparison of low voltage and high voltage actuators

5.1. Materials, dimensions

Low voltage, co-fired stacks:
The PZT material situation is no longer a concern for use in low voltage systems as it was in the past. In principle any PZT material can be used for thin-layered co-fired systems.
Low voltage and high voltage elements show the same piezo-mechanical performance, when comparable PZT material and driving fields are used.
Low voltage actuators are mostly used as small and medium sized elements with cross sections typically up to 10 x 10 mm. Larger cross sections lead to a dramatic increase of costs. Low voltage actuators become cheap in large quantities.
APC International standard low voltage actuator range is aiming for an as broad as possible compromise in performance and pricing. When you do not find a proper configuration: contact APC International for special solutions.

When selecting piezo-actuators, please keep in mind the availability of driving electronics. Bulky, big volume low voltage actuator require equivalently huge electrical currents in dynamic action compared to the high voltage equivalent.

Discretely stacked high voltage elements

Manufacturing of actuator prototypes of non-standard size and performance is much easier for high voltage elements than with low voltage elements. All kinds of PZT materials can easily be implemented.
High voltage elements can be set up as big volume stacks for heavy load /large force/large stroke/high power applications.

5.2. Electrical properties

The layer structure of a piezo stack and the used PZT material determine the electrical capacitance.
Low voltage elements use a larger number of thinner active layers compared to high voltage elements to get the same active stack's length. This results in an equivalently higher electrical capacitance, but the required charging power to drive a stack is the same in both cases:
When two actuators of same size, shape, and material are built up as one 200 V element and one 1000 V element, the capacitance of the low voltage stack is larger by a factor of 25.
When a driving current e.g. of 1 A is needed to get a distinctresponse from the 1000 V actuator, an equivalent 200 V actuator will need 5 Amperes. The power = U · I is the same for both cases.
The important point in practice is, that any lowering of the max. driving voltage is accompanied by an equivalent increase in the current levels to get a distinct dynamic response.
Big volume actuators in switching application may require currents up to Hundreds of Amperes, when designed as low voltage elements.

5.3. Temperature ranges

Low voltage elements are available as special designed elements for temperatures up to approx.160 °C–180 °C. With high voltage elements, limiting temperatures of 220 °C have been achieved.

Cryogenic applications are feasible both for low and high voltage types.

5.4. Vacuum compatibility

The operation both of high voltage and low voltage actuators is possible without problems in normal vacuum. Modifications towards UHV compatibility are offered.
The only problematic gas pressure range is rough vacuum in the Torr range, where glow discharge can be ignited by the applied electrical fields.
Low voltage elements can be operated here over the full voltage range, whereas to high voltage elements only a reduced voltage rating can be applied.

To handle the self-heating problem of actuators operated dynamically in vacuum, attention must be paid to a proper heat management via heatsinking.

5.5. Noble gas atmosphere

Care must be taken, when stack actuators are operated in a gas atmosphere containing He or Ar. Discharge processes can be ignited, leading to an insulation breakdown of the system. When this is accompanied by large power or current, local damages of the ceramic or insulation can take place irreversibly.
Therefore, actuators can be operated only with a reduced voltage.

5.6. Reliability

In practice high quality actuators both in low voltage or high voltage configuration are the result of a sequence of carefully carried out manufacturing steps, not only including the ceramic structure, but also the peripheral electroding, sealing etc.
Therefore no general statement can be given for reliability and lifetime. These aspects must be evaluated individually for each manufacturer.

One example is the electroding ofAPC International high voltage stack actuators.
Most manufacturers prepair the side electrodes of a stack as rather rigid solder bars. This works fine in static applications. But under dynamic operation, the alternating acceleration forces lead to fatigue and cracking of the side electrodes, what desactivates the stack partially or completely.

To avoid mechanical stress and fatigue in the side electrode configuration by rapid piezo action introduced in the 1970ies the electrode wrapping technology as shown in fig. 23 – fig. 26.
The result are stacks withstanding high frequency cycling within the Kilohertz/full stroke range or repetitive pulsed operation with mechanical powers of about 100 kilowatts over approx. 50 µsec.

For high dynamic applications, (e.g. like for Diesel fuel injection) monolithic co-fired stacks require obviously much more care about the mechanical design and preloading than discretely stacked high voltage elements, which are less sensitive due to their compound structure.

Example: surface supply electroding for high voltage stacks
Comparison of APC International stressfree feed through contacting with standard solder strip design.

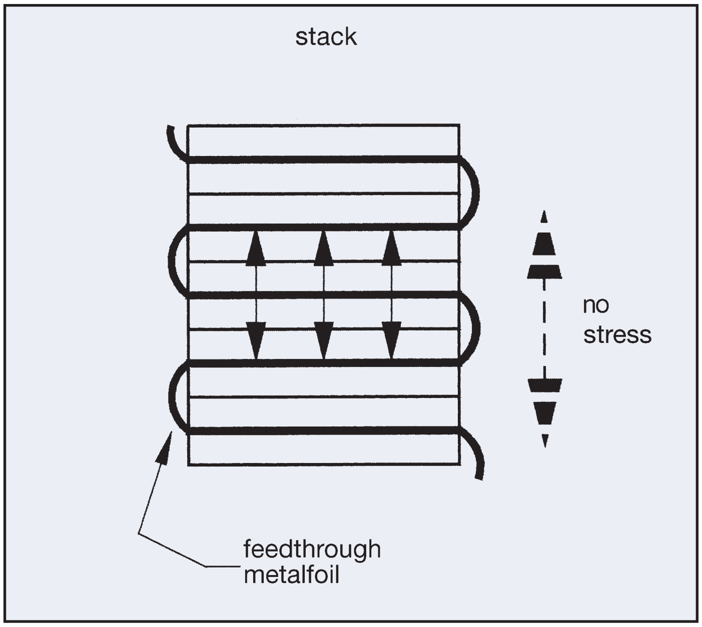


Fig. 23

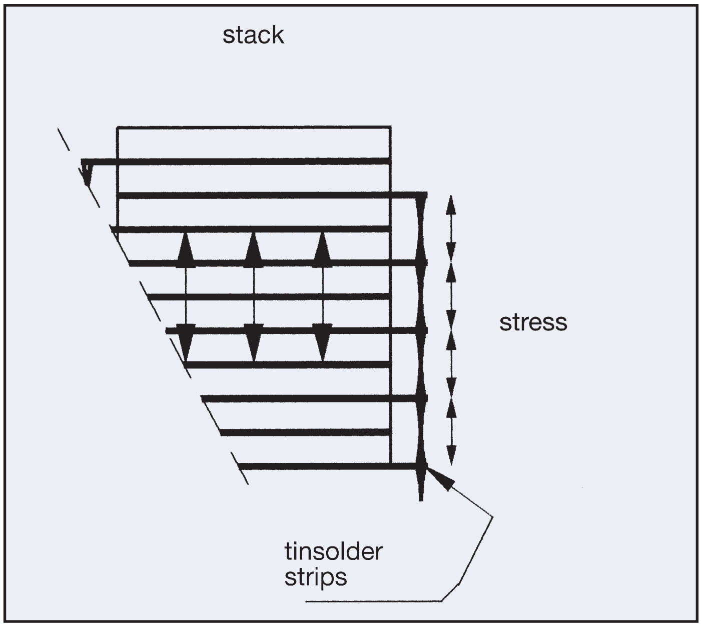


Fig. 25

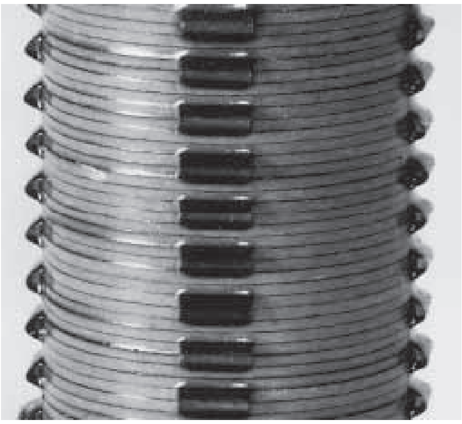


Fig. 24

Fig. 26

A. APC International actuator contact design with
feedthrough metalfoil showing low mass
and high flexibility to ensure stress free cycling
of electrode section
Advantage:
no material fatigue
very high reliability
for high dynamic cycling

B. Standard actuator design
with massive tinsolder strips for
side contact of stack

Risk of material fatigue during dynamic cycling
due to high inertial mass and rigidness of the
contact strip

6. Mounting procedures

Bare stacks

Mounting or adaption of piezo-stacks to mechanical systems is done using only the endfaces. The attached mechanics can be preloaded against the stack by using some kind of spring or flexmount. For glueing any kind of adhesive showing rather thin and rigid connections such as epoxies, cyano acrylates etc. can be used. Temperature curing is possible within the specified temperature range of the actuators.
Forces must only be applied in axial direction, especially for high stack length/diameter ratio.
Tensile forces must not exceed a few percent of the specified maximum compressive load.
For smaller cross sections, tensile forces should principally be avoided. Potential tensile forces are best compensated by a mechanical prestress mechanism. Shear and bending forces are again only applicable in the percent range of the stated maximum load force and are best avoided for small cross section stacks.
When actuators have piezoceramic endfaces, high forces must be introduced homogeneously distributed across the actuator's cross section, to avoid high local pressure. When high local pressure is applied, protect piezo ceramic endfaces by reinforcing them by a steel or corundum plate (see options).
Generally all influences which can potentially damage the surface coating of actuator's circumference must be avoided. Mechanical clamping at stack's circumference is not allowed.

Actuators with casing

Actuators with casing (esp. preloaded ones) are much more robust against mechanical impacts and environmental influences than bare stacks. But the best performance is again achieved when forces are applied axially to the stack. Tensile forces are applicable up to the internal prestress rate. Overstress by static tensile forces is principally avoided by the internal design, because the moving top then separates simply from the stack. Shear or bending forces are partially compensated by the mechanics of the casing, but the actuators performance can be reduced (indicated by reduced stroke or nonsteady motion). After eliminating this mismatch, the actuators will work again properly.

Ring actuators

In principle the same considerations for ring actuators (bare or with casing) as for stacks are valid. The only additional requirement is, to prevent any mechanical damage or attack of unwanted substances to the coated inner side of the ring. This is important for both bare rings and actuators with casing.

Tilting

Piezostack- and ringactuators are widely used in coherent optics for positioning purposes with subwavelength accuracy e.g. in interferometers, tunable etalons, resonantors. Most of these applications imply a pure translational motion. Users may assume, that piezoactuators do not show tilting of the endfaces during expansion but this is not necessarely true. Residual tilting of actuators can be caused by some inhomogenities in piezoefficiency of the ceramic or by other internal stress (e.g. from temperature variations). Stress can be further implied by external procedures e.g. by gluing mirrors to the endfaces or horizontal mounting of mass loaded actuators. It is up to the user of stacks to verify what tilt is acceptable and how his system behaves.

Following general qualitative rules can be given:

- Tilt increases with applied stroke in most cases
- Tilt is reduced for increasing actuator diameters, so small sized elements are rather critical
- Preloading improves stability against tilting
- Totally tilt-free arrangements for long strokes require some external guiding mechanism, so the piezo acts only as a pusher and parallelism is achieved by mechanical guiding.

Typical tilt rates for preloaded ring actuators HPSt…/15-8/...VS22 are in the range of 2–3 µrad/µm stroke.

7.1. Piezo-mechanics and electrical charge

According the simple capacitance equation

$$Q = U \cdot C$$

the voltage U emerging at capacitor's contacts is equivalent the stored electrical charge Q. For a normal capacitor the capacitance C is a constant.
The same consideration can be applied to a piezo actuator, what is mainly an electrical capacitor. The very important point is, that capacitance C is not longer constant, but varies to some extent with the driving conditions like voltage, load, temperature etc.

Nevertheless, the important advantage of the charge related description is, that the kinetic parameters "speed" and "acceleration" can be easily derived from the charge content Q of the actuator stack.

Actuator position	**~ electrical charge content Q**
Change of position	**~ dQ: change of electrical charge**
Speed v	**~ dQ/dt = current I**
Acceleration b	**~ $d2Q/dt^2$= dI/dT = current variation/current slew rate**

Controlling piezo actuators open loop via electrical charge and current show

- **linearization of motion**
- **increase of actuator stiffness**
- **increasing actuator's reliability under very high dynamic operating conditions**

7.2. Linearization of piezo motion

It is well-known since decades, that the charge/strain relation of PZT actuators become nearly linear and non-hysteretic (about 1%).

The diagrams 27 compare the stroke response for voltage and for charge control of a standard PZT stack when cycled with 20 Hz alternatively.
The linearization of piezo's action upon charge control is immediately seen. Hysteresis is reduced by more than one order of magnitude.

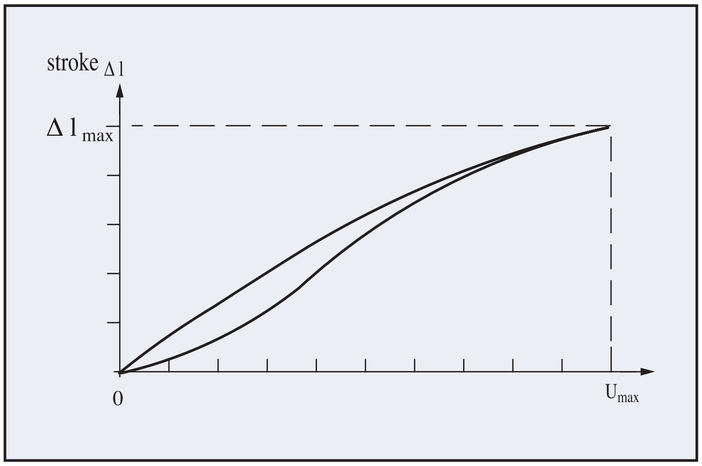


Fig 27a:
Voltage/stroke relation

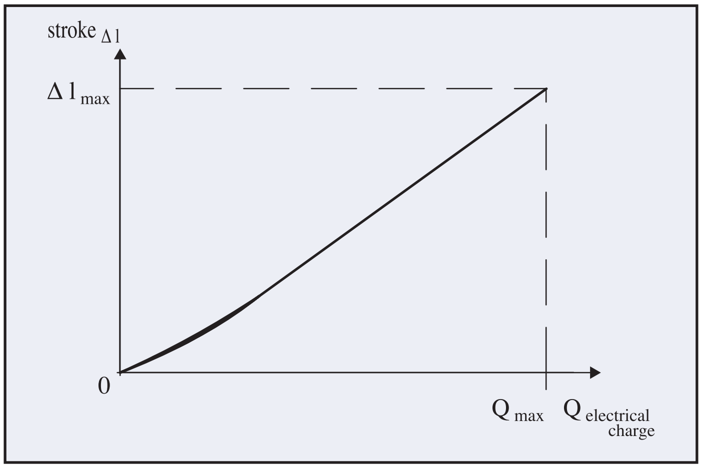


Fig. 27b:
Charge/stroke relation

Another "voltage" effect is **creep:**

A piezo actuator shows a small positive drift in expansion for a distinct time, when a voltage step is applied (see chapter 2.3. electrostrictive devices/fig. 12b).
This is a "ferroelectric" effect, where the polarization state of the ceramic alters as long as an electrical charge can flow (delivered by the voltage supply).
Creep can be immediately stopped, when the charge content of an actuator is kept constant.

This can easily be shown by a simple experiment:

A certain constant voltage is applied to a piezo actuator and the stroke is monitored.
Creep stops immediately, when the actuator is disconnected from the voltage supply (constant charge content).
(A very small negative drift in this case is caused by the self discharge of the actuator. The time constant of this self discharge is usually in the range of hours or days).

Consequences of linearization for practice: Pure mode excitation

Currently, the main advantage of linearization via the charge philosophy is the pure mode excitation in dynamic applications:

A sinusoidal electrical current will be converted into a monochrome sinusoidal oscillation without sidebands as it is the case for voltage controlled stroke with its nonlinearities and hysteresis.

Schematic of mechanical frequency spectra of a piezo actuator upon application of a single frequency

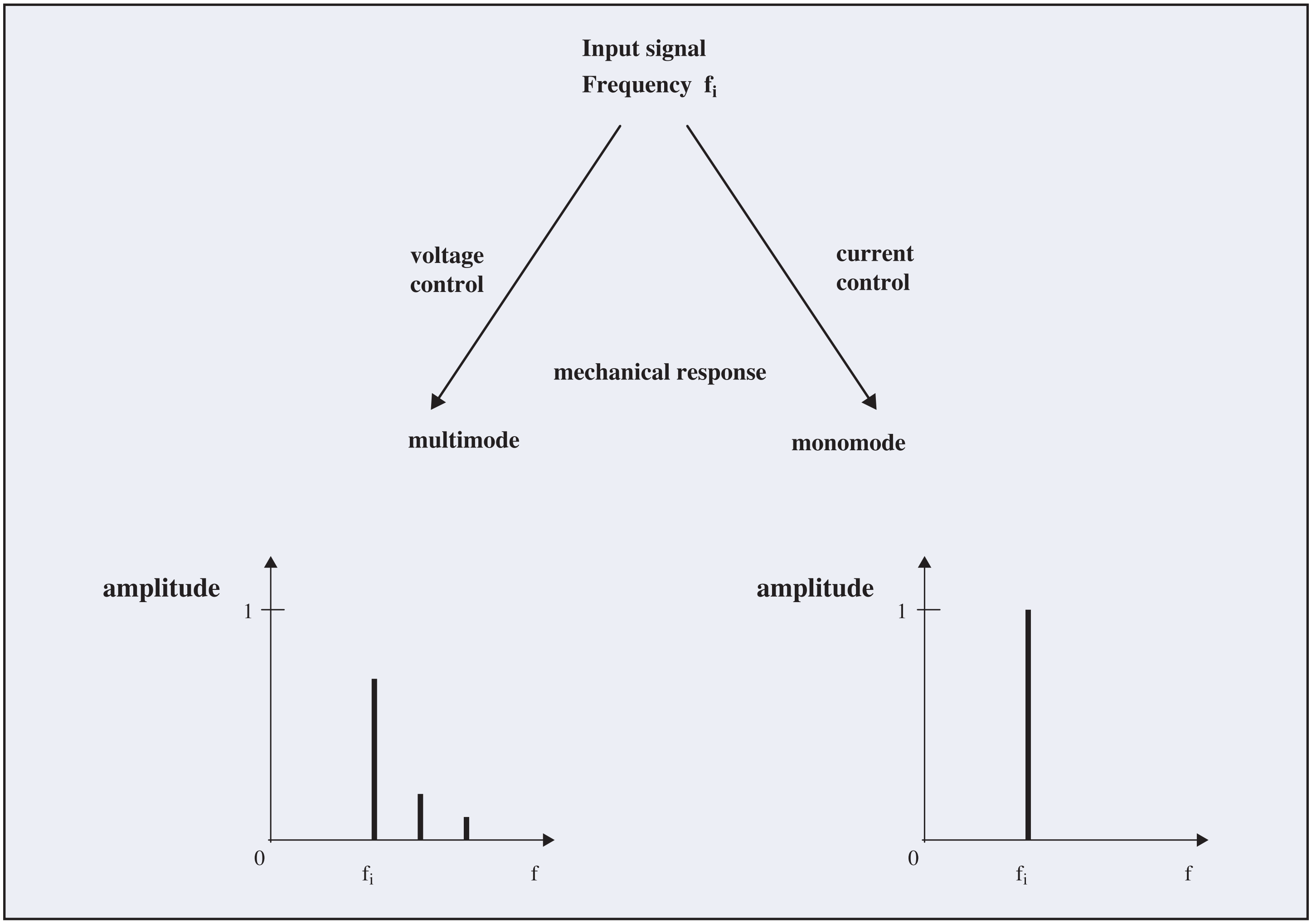


Fig. 28b:
Current signal

Fig. 28a:
Voltage signal

Notice:
Current controls "speed".
In case of harmonic excitation, there is a 90° phase shift to the variation of the position.

Precision positioning:

On the first glance, charge control seems to be "the trick" for simple open loop position control. But similar to the situation with electrostrictive elements, the "precision" of charge controlled positioning is only in the 1% range. Usually piezo actuators are used for much better resolution (10–4 to 10–6 or even higher): this can again be done only via a kind closed loop position feedback control. Therefore in most cases, closed loop piezo positioning via voltage control is acceptable. Advantages of charge or current control within feedback loops can be expected in lowering the response time for high speed positioning tasks.

7.3. Enhancement of stiffness by charge/current control

As shown in section 3.6. “Stiffnesses” (= inverse compliances), the effective stiffness of a piezo actuator depends again on its charge balance. Voltage control is not able to withstand the piezoelectric “generator effect” when the force load onto the actuator is externally varied: the generated electrical charges are equilibrated via the “voltage amplifier” to keep the voltage constant and this results in lower stiffness.
Charge control via a “current amplifier” withstands this “generator effect” under varying load because any unwanted flow of charges is blocked (by compensating the piezo generator effect by increasing correspondingly the output voltage of the amplifier):
The stiffness of a charge controlled system is remarkably higher than for voltage control.

In practice, the “charge philosophy” is used to realize high dynamic stiffnesses e.g. in adaptronic systems (e.g. vibration generation/cancellation) via current amplifiers.

7.4. Reliability

The actuator acceleration is related to the current slew rate dI/dt (see section 7.1.).

For high dynamic = high current applications, a current jitter superimposed to the regular signal introduces unwanted highest acceleration noise to the moving actuator. This can generate higher axial resonance modes within the stack actuator length, which cannot be completely be compensated for by high external preload. The consequence is a desintegration of the ceramic structure and failure of the actuator due to locally excited tensile stress within the stack.
So the charging current profile must be optimized on one hand to get the wanted high acceleration, but must be kept smooth to avoid unnecessary higher current variation.

Discretely stacked high voltage actuators are more stable against current jitter than monolithic cofired elements.

7.5. Electronic supplies for piezo action

Basics:
Any type of amplifier used for piezo control must provide voltage and current to transfer energy into a piezo actuated system.

Voltage amplifiers:
The input signal is magnified by the amplifier into a proportional output voltage signal.

Notice:
The voltage applied to a piezo actuator determines actuator’s position!

The variation of the induced current depends on the capacitance of the actuator, the slew rate and the regulation strategy of the amplifier.

When selecting a voltage amplifier following points are important:

a) proper voltage range, not exceeding the actuator voltage limits
b) sufficient high current to get sufficient large bandwidth
c) sufficient voltage stability and low noise to ensure a distinct position stability.

Voltage amplifiers were mostly used for piezo actuation in the past.

Current amplifiers:
Current amplifiers convert an input signal into a proportional jitterfree current output.

Notice:
Current amplifiers control actuator’s “speed v”. Position is varied with a distinct delay or phase shift.
In case of a harmonic oscillation, position varies with a 90°phase shift in relation to the signal input to the amplifier.

The variation of the induced output voltage depends on the load, frequency and the regulation strategy. Usually the amplifiers operate around a stable center voltage equivalently a distinct midposition of the piezo actuator.

Current amplifiers make sense for dynamic piezo applications as described in sections 7.1.–7.4. Therefore, current amplifiers control current above a distinct threshold frequency (approx. 5–10 Hz).

When selecting a current amplifier following points are important

a) sufficient high current to get sufficient large frequency bandwidth

b) proper voltage range, not exceeding the actuator voltage limits
A wider voltage range will definitely destroy the actuator, because the voltage variation is not externally controllable, but is a consequence from the current regulation.

U-I-Hybrid amplifiers

To get a widest application spectrum it is reasonable to combine a voltage amplifier stage and a current amplifier stage into one so-called "U-I-hybrid amplifier".

With the voltage amplifier stage, the position of a piezo actuator can be controlled in a static or low frequency mode. For dynamic motion above a distinct frequency threshold, the current amplifier stage is used to provide all the advantages of current control.
E.g. by this strategy an harmonic sine oscillation can be generated around a voltage defined center position.

Charge amplifiers

The charge content Q of a piezo actuator is related to its position (similar to voltage U, but with much better linearity and no hysteresis).
Charge control of piezo actuators is used mainly for very high dynamic applications in a kind of current control for a well-defined short pulse time transferring so a distinct charge quantity to the piezo. Such a mode is used for fast proportional Diesel-Fuel injection to provide low stress activation of a piezostack by the current mode and to reach a well defined final position.

APC International amplifier philosophy

APC International is offering a wide range of voltage and current controlling amplifiers as well as hybrid systems to get the best match for your application.

For low power/high precision positioning, the SVR amplifiers are ongoingly the best choice. Voltage amplifiers control primarely actuator's position, whereas current amplifiers control primarely actuator's speed.

For higher power application envolving LE amplifiers, voltage-, current- and hybrid-amplifiers configurations for low voltage and high voltage actuators are offered on request.

Please notice, that for current amplifiers, piezo actuators with casing must be modified.
Please contact APC International in any case about the used actuators, when you want to apply current or charge control.
Discuss with us in detail your needs in actuator application to ensure the best-matched system.

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