APC International, Ltd.

Electronic Supplies for Piezomechanics:

An Introduction

Content **Page**

Introduction

1. Points of attention!

Piezo actuators are first candidates to drive motion systems, when at least one of the following features is required:

- Ultra-precise positioning
- High stiffness for high resonance frequencies
- High Forces
- Ultra-fast mechanical switching, shock generation
- Vibration control
- No energy consumption under static conditions

The performance of a piezo-actuating system depends not only on the actuator, but to the same extent on the power supply.
Any mismatch between the electronic supply, actuator and application reduces efficiency both technically and economically .

The important electrical parameters of interest are voltage range, current, power, noise, bandwidth, power efficiency (energy recuperation).

Check at least the following parameters carefully:

Voltage:	controls stroke and force generation
Currents:	define minimum rise/fall times, repetition frequencies
Electrical noise:	determines precision, accuracy

High power arrangements require well adapted actuator.

Hardware to prevent thermal and mechanical overloading and damaging.

Take care about the heat management and sufficient mechanical preloading of your piezoceramic structure.

Do not use piezo amplifiers with higher voltage ratings than defined for your actuator.
Accidental over-voltage will destroy your actuator immediately.

When you cannot find a solution matching your needs: Contact APC International.

2.1. Any piezo-electrical component is an electrical capacitor:

Two electrodes are covering the piezo-ceramic material (fig.1).

The PZT ceramic acts as the electro-active dielectric material of the capacitor structure with dielectric constants ε ranging within 2000 – 5000.

The large dielectric constant is a necessary precondition, that a high energy conversion density is exhibited by piezo-components under non-resonant driving conditions.

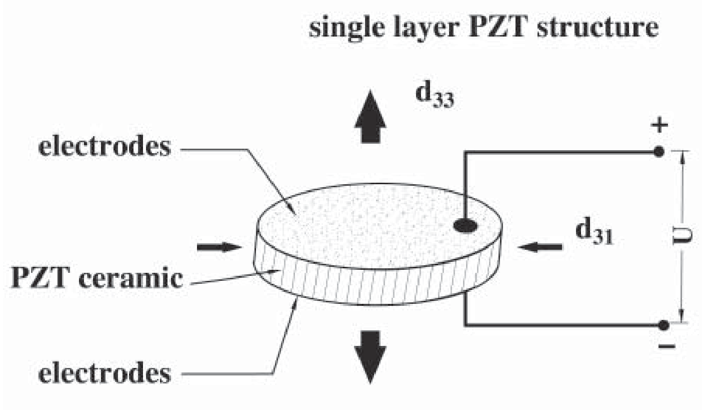


Fig.1 Schematic of a single layer piezoelectric element

The application of a voltage U to the capacitor structure creates an electrical field E according

$$E = U/d$$

This electrical field induces the piezo-mechanical reaction like strain and / or force.

Realistic actuator capacitances

The bandwidth-diagrams (power diagram) shown in the amplifiers' data sheet have been derived by using ideal capacitors .

The PZT actuator capacitances stated in the data-sheet show tolerances of approx. +/-15%
The values are so-called small signal/low fi eld values. Because PZT actuators are non-ideal capacitors the capacitance value depends further on the applied voltage, load conditions etc.

► For selecting a sufficiently powerful amplifier in order to get the desired response bandwidth, multiply the nominal capacitance values of an actuator at least by a factor of 1.5 for evaluating the current requirements (for room temperature operation).

At cryogenic temperatures, the capacitance values of piezo-components are strongly reduced by one order of magnitude!

Take further notice, that the data sheet values refer to the standard PZT material. Modifications towards special PZT compositions like HP and HS/HT will show altered values.

Control voltage and electrical fields:

Typically, the maximum stroke ratings of piezo actuator stacks are related to a driving field E of 2 kV typically: the thicker the PZT layers are within a stack structure, the higher is the necessary operating voltage to get full strain.

Low voltage multilayered co-fired stacks are using ceramic layer-thicknesses up to 100 µm and can be operated up to 200 V typically.

High voltage stacks use much thicker layers (typically 0.5 mm) and need therefore up to 1000 Volts driving voltage to get sufficiently high field strength.

2.2. Polarity of piezo devices

Piezo actuating devices are specified for uni-polar, semi-bipolar and bipolar operating ranges.
To make the optimum use of these driving strategies, a distinct understanding of the technical background of the polarity definition is necessary.

Generating piezo-electricity within PZT-ceramics:

Piezoelectricity of polycrystalline PZT ceramics is not an inherent effect like in single crystalline quartz.
Piezoelectricity is induced within polycrystalline PZT ceramics by an artificial poling process after the sintering of the ceramic.
This is achieved by applying a high electrical field E (order of magnitude:kV/mm) to the virgin piezo-electrical component.
This generates the so called polarization within the PZT-ceramics, represented as a vector P.
The polarization P is parallel to the generating electrical field E as shown in fig. 2 (A)
This polarization P is the reason for the piezoelectricity within PZT ceramics.

Notice:
PZT-ceramics can be de-poled under certain adverse conditions.
The magnitude of the original polarization is then reduced or diminishes and /or the direction of the polarization P is changed in an unwanted way.
The performance of your piezo-device will then be destroyed.

De-poling can happen, when a too high electrical field E (equivalent a too high voltage) is applied non-parallel to P (as shown below for the examples fig. 2 B,C,D)

De-poling can further be caused by too high temperature (see Curie-temperature Tc) too high pressure

When piezo-elements are operated within their specification ranges with regard to applied voltages, temperatures and loads, de-poling is avoided.

The following driving modes of piezo-actuators are characterized by the non-coincidence of E and P!:

B, anti-parallel operation of a single PZT layer
This occurs, when the driving voltage polarity and thereby the direction of the electrical field E is reversed compared to 1 a.
The motion characteristic is therefore reversed
d33: the layer thickness decreases with increasing voltage: a multilayer stack shrinks
d31: the diameter of the layer expands

Limitations:
A too high electrical counter-field E can de-pole the actuator structure.
It is necessary to stay within the specified voltage ranges
Pay attention to a superposition other de-poling effects like temperature, very high loads.
When using the anti-parallel operating mode (see chapter 3.3.)

Semi-bipolar operation or PZT-components is used to increase the total stroke / blocking force of ring- and stack- actuators and PZT-tubes.
Bipolar operation allows simple driving electronics to generate bidirectional vibrations.

Examples of semi-bipolar and symmetric bipolar operation are:
Ultrasonic devices
Scanner tubes
Stacks, rings

C, shear mode:
A shear mode PZT layer is based on an in plane polarization P.
Upon the application of an electrical field perpendicular to P, a shear motion of the layer occurs, characterized by the piezo-electric constant d15.
The application of a bi-polar voltage (e.g. by an amplifier SVR) a lateral shift in both directions is generated.

Limitations:
A too strong electrical field E can switch the poling vector P irreversibly out of plane parallel to the applied electrical field E. The shear mode is then irreversibly destroyed .
Keep the driving conditions well within the specifications to avoid de-poling!

D, bending mode:
Piezo-benders (bimorphs) are wide-spread piezo-components consisting of two or more laminated PZT layers. These layers are operated with different strain rates resulting in a bending motion of the structure. (similar to a thermobimetal)
(see catalogue "piezo-electric benders")
In the simplest case such a bimorph bender is activated by a bi-polar signal (e.g. by a bipolar SVR amplifier).
In this case one of the layers is then operated anti-parallel as shown in fig. 2(B).

Stay strictly within the driving specifications of the bimorph element to avoid de-poling in the bi-polar driving mode.

Notice:
Piezo-benders (bimorphs) can be operated without de-poling risk by using the electrical preload activation technique.
Example: BMT amplifier for low voltage benders BM (see catalogue "piezo-electrical bending elements").

2.4. Electrical Power and Currents

Piezo-actuators are electro-mechanical power converters.
The instantaneously applied power P(t) to charge the capacitor is

$$P(t) = U(t)\, I(t)$$

where U(t) and I(t)mean the actual voltage and current levels at a distinct moment during the charging/discharging process.
Current I(t) can be expressed as

$$I(t) = C\, dU(t)/dT$$

!
The most important consequence in practice is, that the current ratings of your power supply determine the minimum rise/fall times and repetition frequency of your piezo actuating system
!

The electrical balance can be expressed in more practical terms:

W is the electrical energy put into actuator's capacitance, when charged up to a voltage level U

$$W = \tfrac{1}{2} CU^2$$

When this charging process is done within a rise- time Δ t, the instantaneous charging power P_{in} is

$$P_{in} = W / \Delta t$$

The related charging current I is $I = C\, \Delta U/\Delta t$

A 1 µFarad capacitor will be charged within 1 msec up to 1000 Volts by a (constant) current of 1 Ampere
The related instantaneous power charging is 500 Watts.
Pulse operation as with the HVP-power switch can result in pulse currents of Hundreds of Amperes and peak-powers >> 100 kiloWatts

The repetitive charging of a capacitance with a frequency f requires an average charging power P_{av}

$$P_{av} = W \cdot f$$

The average charging current I_{av} is $I = C\, U\, f$.

Cycling a 1 µFarad capacitor with 100 Hz between 0 V and 1000 V requires an average charging current of 100 mAmperes.

The average charging power is 50 Watts.

Check amplifiers data sheet both for peak and average currents when selecting for rise-times and repetition frequencies.
Take into account realistic actuator capacitances: see chapter 2.1.!
A few percent of the average power consumption are dissipated into heat and cause self-heating!
(see next page)

3.1. Actuator's self heating

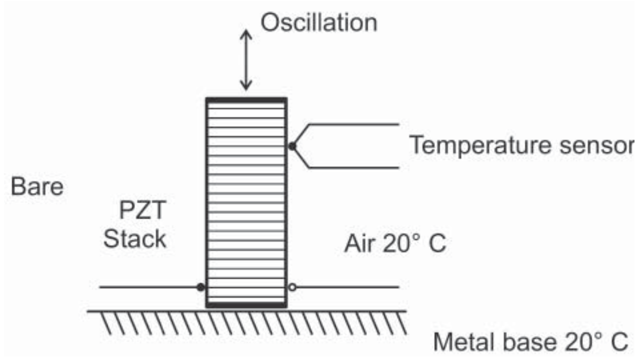
Self heating of an actuator is a consequence of the electro-mechanical power conversion by the piezoeffect. It must be taken into account mainly for operation of piezo-systems at room-temperature or elevated temperatures. At cryogenic temperatures, capacitances and loss factors of piezo-devices are strongly reduced and are of no concern in most cases.

Self heating of an actuator occurs under dynamic operating conditions only.
When an actuator's capacitance is permanently charged and discharged a small part of this power balance is converted into heat.

Under static conditions, a piezo actuator does not consume energy/power and therefore it does not show self-heating! When generated heat is not remove from the stack by heat management, stack's will reach rather high temperature levels over time.
The consequences of a strong increase of actuator's temperature are:
• variation of actuator's properties
• actuator damage due to over-temperature

Practical test for self-heating:

Fig. 3 shows schematically a bare actuator element, fi xed with one side to a metal base with temperature 20°C



Dynamic full stroke cycling in air (20°C) has been carried out at various frequencies.
No further heat management has been applied:
Heat removal occurs therefore only via the metal base and air convection.
Temperature has been measured at the moving top of the stack.
The following equilibrium conditions for various stacks have been found after cycling for 5 – 15 minutes between 0 V and U_{max}:

	Temperature at 100 Hz	Frequency for heat up to 80°C
OEM stack PSt 150/5x5/20	42°C	340 Hz
OEM stack PSt 150/10x10/20	60°C	160 Hz
OEM stack PSt-HD200/7x7/45	70°C	125 Hz
OEM stack PSt 150/7x7/40	62°C	155 Hz
Ring actuator HPSt 150/14-10/12	38°C	440 Hz
Ring actuator HPSt 150/20-15/12	39°C	430 Hz
Bare stack PSt 1000/25/60 HS/HT-material	115°C	65 Hz

The degree of self-heating (energy-dissipation) depends on:

A, physical dimensions and shape of the actuator (defines the cooling efficiency by the ratio: actuator surface / active PZT volume, ring-actuators show therefore the lowest heat up tendency.)

B, energy dissipation rate (determined mainly by the induced strain and type of PZT-material)

C, operating temperature
At cryogenic temperatures loss factor and capacity are extremely reduced.

Notice: Energy-dissipation and self-heating do not depend on the multilayer design (low voltage / high voltage)
The resulting stack temperature depends on the environmental temperature, the energy dissipation and the heat sinking conditions like mounting conditions (mechanical contact of end-faces, air circulation, heat management means).

3.2. Dynamic operation and heat management

The above mentioned experiment shows, that careful heat management for removing the heat from the ceramic stack is a must for long-term dynamic operation of a piezo-component at increased frequencies.
Ring actuators can be cooled by the inner and outer surfaces and show then the best heat management results.
An efficient heat management is a must for dynamic bipolar operation to prevent de-poling of the ceramics.

Ask for the "Thermostable" option for APC International actuators

Example:

Fig. 4 Actuators PSt-HD200/10/xx VS 15 thermostable with and without cooling airfins

A PSt-HD 200/10/45 VS15 actuator has been supplied with a heat-management configuration: "thermo-stable" option + air cooling fins + forced air cooling (see leaflet "PSt-HD200 low voltage actuators")

The actuator has been powered by a LE 200/500 amplifier (200 Vpp, 5 Amperes) for a 1.4 kHz / 200 V_{pp}, oscillation, resulting in a equilibrium temperature of 87 °C.
The standard stack without heat management can stand only 1/10 of this frequency limit for long-term operation.

3.3. Bipolar operation and temperature

The stability of the piezo-electrical effect within PZT-ceramics against electrical de-poling depends strongly on temperature.

To make use of the full advantage of the bipolar driving mode attention is to be paid to the temperature dependence of the de-poling / coercive fi eld $(-)E_{dep}$ (fi g.5).

$(-)E_{dep}$ defines the electrical counter-field, where the original polarization P diminishes and the piezocomponent looses its performance.

To avoid de-poling, stay away from the coercive fi eld limit and operate your piezo-devices within the safe area.

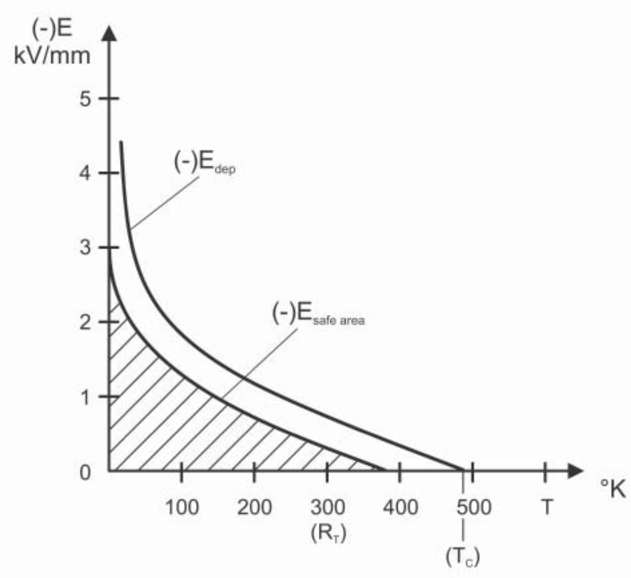


Fig. 5
Schematic of temperature dependence of the de-poling (= coercive) field strength $(-)E_{dep}$
Safe operation without the risk of de-poling a piezo structure by counter-fields below $(-)E_{safe\ area}$

The main aspects are:

A, at cryogenic temperatures all kinds of PZT-ceramic become extremely stable against electrical de-poling
B, at high temperatures (Curie-temperature), the poled PZT-ceramic de-poles thermally without any contribution by a de-poling field(-)E
Take notice, that the Curie-temperature depends strongly on type of PZT.
(in practice from 150 °C (soft ceramic) up to > 320°C (hard ceramic))

Consequences:

Operation at cryogenic temperatures

All kinds of PZT ceramics become very stable against de-poling and electrical break-down!
The response characteristic stroke/voltage becomes highly linear.

Much higher driving and counter-voltages can be applied compared to room temperature operation
This can be used for compensation for the reduction in piezoelectric strain efficiency of PZT-ceramics at low temperatures.

Example:

PSt 150 actuators can be operated with
+ / - 150V at 77°K
+ / - 300 V at 4°K.
Use APC International bipolar amplifiers!

Operation at room temperature

At room temperature the applicable counter-field depends on the type of PZT-material.

Hard PZT ceramics with high TC (e.g. the HS/HT ceramic) accept higher counter-fields than soft PZT ceramic with low TC.

As a general rule, PZT actuators can be operated with counter voltage at least up to 20% of the specified max. unipolar voltage rating.

E.g. a PSt 150 element can be operated with (-) 30 Volts. This gives an increase of stroke and force range of up to 30% (e.g. use SVR amplifiers for semi-bipolar operation).

Operation at temperatures >> room temperature

The above defined 20% rating for counter-voltages is applicable at temperatures of 50% of actuator's maximum operating temperature (°C).

For high temperature requirements use the PSt-HD200 low voltage actuators or high voltage elements based on the HS/HT-PZT-material (see brochure: "Piezomechanics: An introduction").

Temperature-critical applications must explicitly be tested for the acceptance of a bipolar driving scheme. When you are not sure whether a bipolar operation mode is applicable in your case (due to undefined high temperature and / or high load conditions)
=> use the unipolar mode.

Resonant versus non-resonant motion

Piezo actuators are mostly used for the non-resonant (broad band) generation of motion well below the fundamental resonance of the actuated system. Piezo-generated vibrations and oscillations can be varied then over a wide frequency range starting from DC.

Non-resonant motion of a PZT-actuator means a kind of forced motion, where actuator's stroke follows the electrical signal without phase delay.

In terms of mechanical oscillation energy "nonreso-nance" is characterized by the fact that no mechanical energy is stored within the actuator structure from cycle to cycle:
The whole mechanical energy content of the actuator is electromechanically converted by the piezo effect from cycle to cycle.

The resonance behavior of broadband actuators is characterized by a low quality factor Q (about 10). The above case differs completely from resonant single frequency action like ultrasonic devices:
Here the mechanical oscillation energy of the actuator content remains stored as mechanical vibration energy from cycle to cycle. A phase-delay of 90°exists between the exciting signal and the mechanical reaction of the system.

The electromechanical conversion of energy requires only a small fraction of the total stored energy content per cycle.

Large oscillation amplitudes are achieved by the resonant pileup of energy over a large number of cycles. Resonant devices are designed for large quality factors (Q >1000) and use therefore very hard PZTce-ramics. But this kind of ceramics shows usually low strain-efficiency in the non resonant case and therefore poor non-resonant actuator performance.

Because only a small amount of energy is electromechanically converted per cycle, the losses and self-heating under resonance are remarkably lower than for the forced non-resonant motion.

Non-resonant operating schemes

In the non-resonant case, the energy input per vibration cycle is related to the induced mechanical strain within the actuator.

High strain means, that an actuator is operated nearly over its complete voltage range,resulting in maximum stroke/strain/force generation of the actuator.

In practice high strain operation is only necessary, when the piezo actuator length must be kept as small as possible and shall produce an as large as possible stroke.

Reasons can be:

- space- limitations within the mechanical arrangement
- need for maximum stiffness
- need for a very high resonance frequency limit

High frequency generation with high strain results in:

- high power consumption
- maximum heat generation, focussed into a small actuator volume

Low strain means an activation with only a fraction of the maximum ratings of voltage / strain / stroke (e.g. 50% or less).

The "low strain" strategy uses a longer actuator of same cross section.
To get the same stroke as above it can be operated with a reduced voltage rating, e.g. a PSt 1000 of double length is operated then with max. 500 Volts only).

The energy consumption is then only 50% compared to case with the short PZT-element operated with 1000 Volts to get the same elongation:

$$W_{500\,V} = ½\,(2\,C_{1000\,V})\,(500\,V)^2 = 50\%\,W_{1000\,V} = 50\%\,(½\,C_{1000\,V}\,(1000\,V)^2)$$

The general advantages of the low strain technique are

- power requirement decreases linearly with the reduction of the strain.
  (here 50% of the above high strain case)
- reduced heat-generation by reduced power consumption.
  The generated heat is dissipated into a larger actuator volume and surface => actuator's temperature rise is equivalently smaller.

Conclusion:

For high dynamic operation the low strain strategy has remarkable advantages compared to the high strain operation mode with regard to power consumption and self-heating. High strain operation shall only be applied, when other side conditions do not allow the low strain mode.
The following examples show the advantage of the low

Selecting the right amplifier for high frequency/low strain excitation:

strain strategy for generating higher frequency levels. The main aspect is, that the used power supplies are adapted to the really needed reduced voltage level. This is the optimum power match for generating high frequencies.

Example:

A PSt 1000/10/40 VS 18 actuator shall vibrate with reduced strain to get 20 µm stroke p-p.
A 500 V_{p-p} signal to the actuator is obviously required.
Using a SVR1000 amplifier (output current approx. 8 mA) gives then a limiting frequency of about 60 Hz.
The SVR 500 amplifier with the same power rating (output current now approx. 15 mA) is able to generate a 120 Hz oscillation of same stroke.

The SVR500 shows therefore the better power match than the SVR1000 for this case due to the higher current rating.

Other examples for high frequency generation are following actuator/amplifier combinations:

Actuator / amplifier	stroke, µm max.	frequency, Hz
PSt 1000/10/15 VS18 / SVR150:	2.7	approx. 1.8 kHz
PSt 1000/10/15 VS18 / LE150/025:	2.7	approx. 7 kHz
HPSt 500/15-8/L=3 / LE 150/100EBW:	0.8	approx. 40 kHz
PSt 1000/35/40 VS 45 / LE200/500:	8	approx. 4 kHz

Voltage control strategies are currently mostly used to operate piezo-actuators

In open loop operation the consequences are the unwanted side-effects like nonlinearity, hysteresis and creep (fig. 6a).

Notice:

When piezo-ceramics is operated at cryogenic temperatures, the response stroke/voltage becomes highly linear (but the total stroke is strongly reduced).

Piezo-actuators behave like capacitors, when operated below the fundamental resonance (section 1.) Then the driving voltage U is equivalently the amount Q of electrical charge stored within the capacitance according to

$Q = U / C$

Now it is found that the open loop relation between stroke and charge Q shows an strongly improved linearity and reduced hysteresis by one order of magnitude! (fig. 6b)

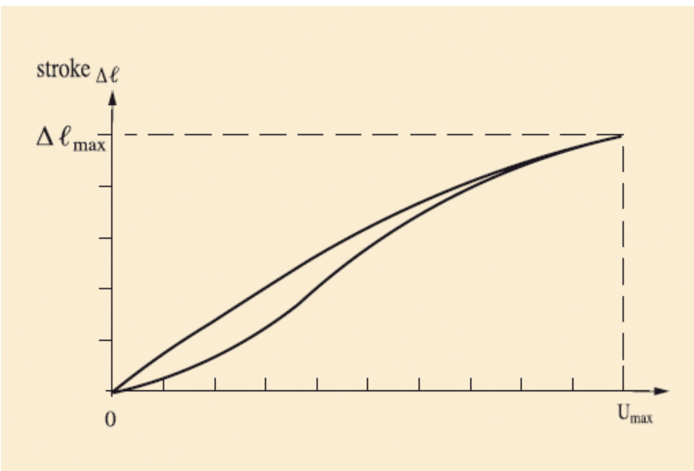


Fig 6a
Nonlinear piezo stroke response under voltage control

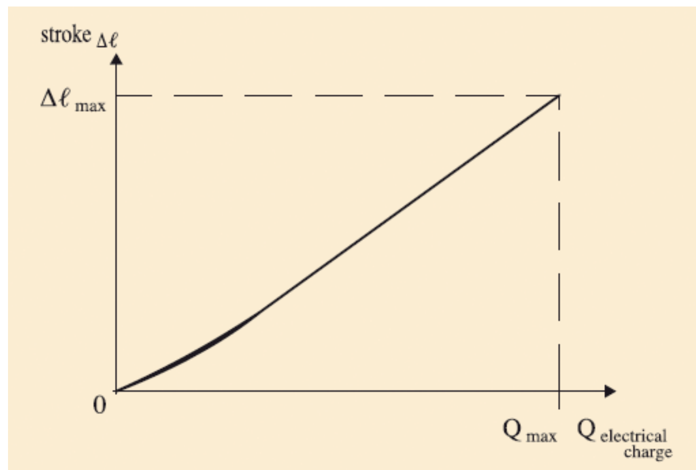


Fig. 6b
Linear stroke response of a piezo-stack under electrical charge control

Using the linear charge relation, the kinetic parameters are

Actuator position	~ electrical charge content Q of actuator
Change of position	~ variation of charge content (dQ)
Velocity	~ electrical current I = (dQ/dt)
Acceleration	~ $dI/dt = d^2Q/dt^2$

The electrical current I controls the parameter "velocity" of an actuator open loop with high linearity.

A sine-shaped current signal produces a harmonic oscillation nearly without any side-bands with regard to "position" and "velocity". "Position" and "velocity" delayed in phase by 90°.

In practice, current control has been established in highly dynamic vibration and motion control, where the control laws are dealing preferentially with the parameters "velocity" and "acceleration" and not with "position".

High precision positioning tasks will always require a kind of feedback control strategy, standard voltage amplifiers are well suited for this purpose.

6. Electrical contacting/wiring of piezo electric devices

PZT discs, stacks, rings, tubes

The indicated polarity of a piezo-device reflect the poling conditions of the PZTceramics in factory.
Applying a voltage according this polarity is in accordance with the unipolar operation of the piezo-device as described in section 2.3.

Bare ceramic piezo-components:
In most cases, the positive pole is marked.
Color code:
Red wires indicate the +/positive pole.

Piezo actuators with casing and coaxial wiring.

APC International standard is positive voltage on inner conductor.
The coaxial shield is then negative and used as ground for the actuator operation and casing.

On request actuators and amplifiers with negative polarity can be offered optionally.
For some of the LE amplifiers optionally a polarity selector is offered.

Bipolar piezo-components

Bi-polar piezo-devices can show a polarity-indicator too:
This allows to determine the direction of the induced piezo-motion in relation to the applied voltage. Inverting the wiring will invert the direction of motion relative to the driving signal.

Notice: Amplifier polarities.

Bipolar amplifiers or amplifiers with optional polarity setting
like the LE power versions can show colour coded output plugs
(banana plugs):

Red = hot line = high voltage output (independent of set polarity)
Black = ground in all cases

This is in accordance with the parallel coaxial outputs:
The center conductor bears high voltage,
the shielding is ground in any case.

General:

capacitor relation C = Q/U
charging/discharging current

$$I(t) = C\, dU/dt$$

Average current l, t repetition rate,
U_0 maximum voltage

$$I_a = U_0\, C/t$$

Sinuoidal excitation:

Unipolar signal

$$U(t) = U_0 /2\, (1-\cos 2\pi ft)$$

Current

$$I(t) = U_0\, C \pi f \sin (2 \pi ft)$$

U_0 = max. supply voltage, f = frequency,
C = actuators capacitance

Peak current

$$I_p = \pi\, U_{max}\, C f$$

Average current

$$I_a = U_{max}\, Cf$$

Peak current exceeds average current by factor ð .
Current booster needed for optimum power efficiency.

Symmetric triangular signal:

Peak current

$$I_p = U_{max}\, Cf$$

Average current

$$I_a = U_{max}\, Cf$$

No current booster necessary.

Pulse excitation:

Actual voltage $U_a(t)$ of actuator:

$$U_a(t) = U_0\, (1 - e^{-t/RC})$$

Charging current $I_c(t)$

$$I_c(t) = (U_0 - U_{a(t)})/R$$

R load resistor of pulse generator

Peak current at pulse onset:

$$Ic_{max} = U_0/R$$

Average current

$$I_a = U_0\, Cw$$

w repetition rate, U_o supply voltage

Power balance:

Energy content E of a charged capacitance

$$E = ½\, CU_0^2$$

Average power consumption PA during cycling with repetition rate w

$$P_A = ½\, CU_0^2\, w$$

Dissipated power (self heating problem)
During the charging/discharging cycles, the transferred power is partially dissipated into heat according

$$P_{dis} = \tan \delta\, CU_0^2\, w$$

tan δ dissipation factor 5 - 10% of total power with common PZT actuator ceramics.

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