Introduction – Instruction for using

Piezo electrical actuators are new to the field of micro-positioning. They provide performance levels that cannot be achieved by conventional drive mechanisms.

However, the field of piezo electrics is complex and requires clarification.

These pages should give an introduction into the working principles and advantages of piezo electrical actuators. By using the index we hope you may be able to refer to the relevant information quickly and efficiently. The examples given should present a feeling of the performance of the actuators.

The parameters and dimensions used in measuring piezo electrical actuators are described on page 6.

Conversion tables for frequently used physical values such as temperature, pressure, angle … you will see at page 113.

Basic remark

For designing new products containing piezo elements it is helpful to know about the theory and principle relations between many parameters. However, the formulas given here can give only a rough estimation depending on many environmental conditions. Before starting with the theoretical aspects we give you some basic remarks – the results of working long years with piezo electrical elements.

Often you will find these remarks also at the end of each chapter in orange boxes.

Sealings

Epoxy versus ceramic sealing

It is a well known fact that the most critical parameter for piezo electrical elements is a high humidity in direct contact with the ceramic material. Most of our elements and stages are at least double sealed. A special epoxy sealing is followed by a special silicon rubber material for additional protection against humidity and electrical break through.

Important for the epoxy sealing is some elasticity which yields in an excellent sealing even if the piezo ceramic expands.

We do not recommend using hard sealing materials e.g. ceramic sealings. Since ceramic sealing is a hard material, it may have advantages for vacuum (low outgassing), but it may get cracks over the time if the piezo element expands. Please see also chapter 3.9. working under vacuum conditions. If you consider different sealing materials as offered from ***piezosystem jena***, please ask about long term tests over many years.

For best reliability we recommend using only piezo elements proven over many years in many applications such as those used by ***piezosystem jena***.

Our goal is to provide our customers with innovative but proven systems. Only when our customers are successful on the market over many years they will be satisfied with ***piezosystem jena***.

OEM applications

Chapter 11 will tell you basics about the reliability of piezo electrical elements.

Considering piezo elements for industrial applications, it is useful to work with a lower voltage than specified. Working with 100V instead of the maximum voltage extends lifetime and allows for more motion if needed in the future.

Atmosphere conditions working under normal conditions

Piezo elements from ***piezosystem jena*** are sealed against humidity and normal environmental conditions.

For higher humidity conditions we offer special sealings. If necessary, ***piezosystem jena*** can provide actuators hermetically sealed for work under extreme environmental conditions.

Vacuum operation

Piezo elements can work under different pressure conditions even at ultra high vacuum conditions. For minimum outgassing, piezo actuators for ultra-high vacuum are specially prepared using as little insulating materials as possible. For this reason, these high vacuum elements are not recommended for work under normal pressure conditions to avoid the risk of electric arcing. Also for safety reasons, piezo elements with vacuum option should not be used under normal conditions.

Pressure region 100–0.01hPa

Because of the low insulation of the environmental gas in this pressure region piezo elements prepared for vacuum conditions should not be used. Due to the small amount of insulation electric arcing may lead to damage to the actuator.

Before using piezo actuators in this pressure region, please ask our team for additional help.

Piezo electrical actuators

In the last few years, piezo electrical actuators have found a niche in the field of micro-positioning. The main advantages of these actuators are their high resolution (to sub-nanometers) and their high dynamics.

Other advantages of these actuators are the generation of large forces (up to 50 tons) and a large dynamic range of motion (up to mm range). Piezo electrical actuators can also operate in a vacuum, have no mechanical play and have no wear.

Piezo electrical elements are very efficient requiring low energy for work under quasi-static conditions as well as under high external loads.

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Piezo electrical elements from ***piezosystem jena*** are extremely well suited for applications in:

- optics, laser applications
- high resolution positioning such as active and adaptive optics, integrated optics, photonics
- communication techniques, fiber optics
- microbiology, gene technology
- machining, tool adjustment, valves, piezomotors.

The advantageous properties of piezo electrical actuators may only be utilized when they are operated under the correct conditions.
It is important to understand how the different properties are related to one another. An improvement in one property may be at the sacrifice of another, for example.

Example number 1
A piezo electrical actuator has to move a high external mass. In principle, it is not a problem to do this, but as the external mass increases, the resonant frequency will rapidly decrease.

Piezo electrical elements have a very high inner resistance, so no current is needed for static or quasi-static work. But by their na ture, piezo elements are capacitors. If they work dynamically, a high current is necessary for charging and discharging. So, often in a dynamical application, the maximum current of the power supply determines the shortest rise times of the actuators.

Our team from ***piezosystem jena*** is experienced in working with piezo elements and we can give advice in solving your positioning problems.
We can advise you of the parameters you should induce to reach an optimal result when working with piezo electrical elements.

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1 Piezo electrical effect – inverse piezo electrical effect

The result of external forces to a piezo electrical material is positive and negative electrical charges at the surface of the material. If electrodes are connected to opposite surfaces, the charges will generate a voltage U.

$$U = \frac{d \cdot F}{C} \qquad (1.1.)$$

d – piezo electrical module; parameter of the material (depending on the direction)
C – electrical capacitance

By generating forces F to the piezo electrical material, the volume (bulk) of the material will be approximately constant.

The Curie brothers first discovered piezo electricity in 1880. It was found by examination of the crystal TOURMALINE.

Modern applications of the piezo electrical effect can be found in sensors for force and acceleration, musical discs, microphones, and also in lighters.

An applied voltage to a piezo electrical material can cause a change of the dimensions of the material, thereby generating a motion. Lippmann predicted this inverse piezo electrical effect and the Curie brothers were the first to experimentally demonstrate it.

For actuators, the inverse piezo electrical effect was applied with the development of special ceramic materials.
Materials for piezo electrical actuators are PZT (lead-zirconium-titanate). For the electrostrictive effect the materials used are PMN (lead-magnesium-niobate).

When speaking about actuators, the phrase "piezo electrical effect" is often used – strictly speaking, it should be called "inverse piezo electrical effect".

2 Design of piezo actuators

2.1. Piezo stacks – stacked design

Piezo stacks consist of a large number of contacted ceramic discs. The electrodes are arranged on both sides of the ceramic discs and are connected in a parallel line as shown. Piezo stacks are also called actuators, piezo electrical actuators or piezo electrical translators.

The maximum motion caused by the inverse piezo electrical effect depends on the electrical field strength and saturation effects of the ceramic material. The breakdown voltage of the ceramic limits the maximum field strength. Normally, piezo stacks work with a maximum field strength of 2kV/mm. This strength can be reached with different voltage values if used with different thickness of the single ceramic plates.

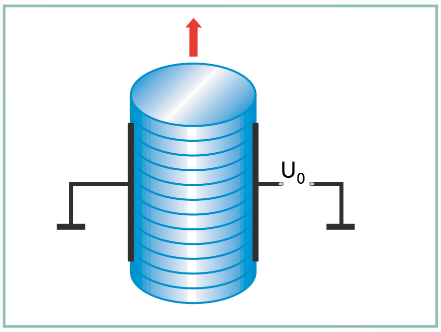

***Figure 2.1.1.** construction of a piezo stack*

Example number 2
An actuator consists of 20 ceramic plates. The thickness of one plate is 0.5mm. The total length of the actuator is 10mm. The actuator will reach a maximum expansion of approximately 10µm for a voltage of 1000V.
For plates with a smaller thickness the maximum voltage will be less. Modern multi-layer actuators consist of ceramic laminates with a thickness of typically 100µm.

Example number 3
A multi-layer actuator with a total length of 10mm consists of 100 disks with a thickness of 100µm. The stack will reach nearly the same expansion of 10µm with a voltage of 130V. However, it should be mentioned that the capacitance of this multi-layer actuator is much higher than the capacitance of high voltage devices. This can be important for dynamical applications (see also section 3.7: Capacitance, section 5: Dynamic properties and chapter 14: Electronics).

It is more complicated to produce multi-layer piezo electrical actuators. Because of the advantage of the lower voltage, some companies are developing so called monolithic actuators. This means, the green sheet ceramic will be laminated with the electrode material. In this way, the full actuator will be made as one system. So the actuator will have the equivalent parameters (for example a high stiffness) of a solid ceramic material. Such monolithic actuators are provided by ***piezosystem jena***.

Piezo stacks with and without mechanical pre-load
Because of their construction, the compressive strength of piezo stacks is more than one order of magnitude larger than its tensile strength. Mostly, the glue used to laminate or fix the actuators determines the tensile strength.
When actuators are used for dynamical applications, compressive and tensile forces occur simultaneously due to the acceleration of the ceramic material. To avoid damage to the actuators, the tensile strength can be raised by a mechanical pre-loading of the actuator. Another advantage of the pre-load is better stability of the actuators with a large ratio between the length and the diameter. Normally the mechanical pre-load will be chosen within 1/10 of the maximum possible loads. You can find more information in sections 4 and 5 of the piezoline.

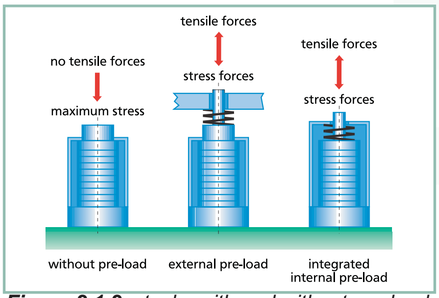

***Figure 2.1.2.** stacks with and without pre-load*

We recommend to use a pre-loaded actuator from ***piezosystem jena*** when:
- tensile forces can affect the actuator
- they are used in dynamical applications

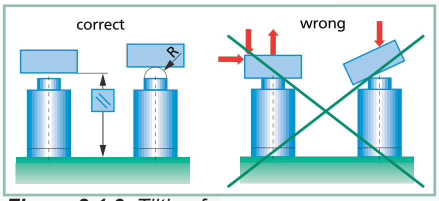

***Figure 2.1.3.** Tilting forces*

Actuators without pre-load should be mounted on the end faces. This can be done using adhesive or threads in the bottom of the housing. You should not apply shear, cross-bending or torsional forces to the actuator. Clamping around the circumference is not allowed. External forces on the top of the actuator should mainly be in the direction of expansion central to the end faces.

If you wish a detailed discussion, please contact our team or your local dealer!

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2.2. Tube design

For this actuator there is the used transversal piezo electrical effect. The tubes are made from a monolithic ceramic; they are metalized on the inner and outer surface. Normally, the inner surface is contacted to the positive voltage. If an electric field is applied to the tube actuator, a contraction in the direction of the cylinder's axis, as well as a contraction in the cylinder's diameter, results in a downward motion. If the outer electrodes are divided, the tube can work as a bimorph element. In this way, it is possible to reach a larger sideways motion. Piezo tubes are used for mirror mounts, inchworm motors, AFM (atomic force microscopes) and STM microscopy.

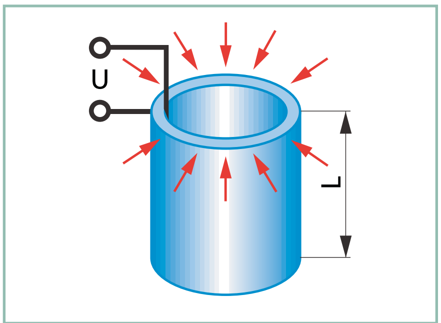

Figure 2.2.1. *piezotube*

Example number 4
Consider a tube actuator with a diameter of 10mm, a wall thickness of 1mm and a length of 20mm. The maximum operating voltage is 1000V. So, the applied field strength is 1kV/mm. The transversal piezo electrical effect shows a relative contraction of approximately 0.05%. For the length of 20mm, one will get an axial contraction of 10µm.
Simultaneously the circumference of 31.44mm will be shorter by 15µm. This is related to a radial contraction of 4.7µm.

2.3. Bimorph Elements

These elements are made from two thin piezo electrical ceramic plates mounted on both sides with a thin substrate. The principle is similar to thermo bimetal circuits.

Applying opposite field strength to the ceramic plates, one plate shows a contraction, the other will expand. The result is bending in the order of sub-mm up to several mm. Bimorph elements use the transversal piezo electrical effect (see also section 4), the working piezo electrical module is the d_{31} coefficient. Piezo electric bimorph elements have a resonant frequency of several 100Hz. Because they show a large drift (creep) while doing static work (because of shear stress in the layers) they are often used in dynamic applications. Because of their construction, they have a low stiffness and they cannot make a parallel motion (almost circular).
In the following figure, two kinds of piezo electrical bimorph elements are represented.

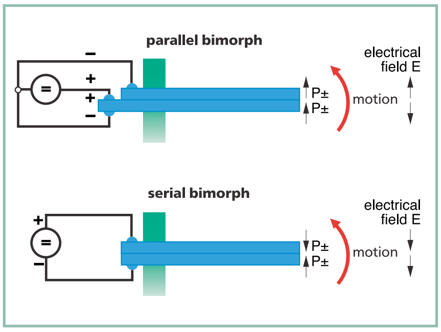

Figure 2.3.1. *serial and parallel bimorph*

Serial bimorph
Both piezo electrical plates are polarized in opposite directions. A voltage is applied to the electrodes on the ceramic plates on the outside. If a voltage is applied and the plate shows a contraction, the other will show an expansion.

Parallel bimorph
A metal plate middle electrode is between the two ceramic plates. The polarization of both ceramic plates is in the same direction. The bending of this bimorph will be reached by applying opposite voltages to the electrodes. Because of the metal plate in the middle, these bimorph elements have a higher stiffness.

2.4. Hybrid Design

For many applications it is necessary to have a motion on the order of 50µm–300µm (for example fiber coupling problems). To use stacked actuators for a motion of 300µm, one needs a translator with a length of 300mm, independent of whether you are using high or low voltage stacks. The high capacitance is another disadvantage of such large stacks. Because of the inhomogeneous expansions of the ceramic plates, the top plate of the stack will always show a slight tilting motion.

That's why bimorph elements are not suited for parallel motion or force generation.

piezosystem jena has developed a hybrid piezo electrical element for parallel motion with high accuracy. A lever design of the construction gives very compact dimensions. We have developed the hybrid elements for three dimensional motions. Since we use solid state hinges, mechanical play does not occur.

The working principal is shown in the figure below.

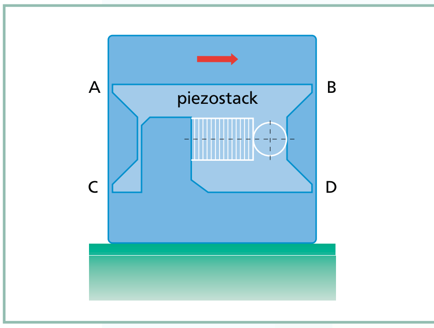

Figure 2.4.1. *Parallelogram design*

The flexmount points A,B,C and D are solid state hinges. ***piezosystem jena*** uses a monolithic design; the motion is achieved by bending these flexmounts.

Because of the rectangular design and the thread holes, it is very simple to combine these elements with normal mechanical stages.

The advantage is a much higher accuracy and an excellent resolution of the motion. Because most of these elements have an integrated pre-load, they are suited for dynamical motions (see also section 6: lever transmission!).

Please note the following advantages of piezo electrical driven stages:

When a piezo element is working, no manual forces are required to position the stage.
Using only mechanical positioning systems, the position cannot be held if the external forces are removed. These positioning problems (for example for fiber coupling) can be avoided by using piezoelectrical elements.

Example number 5
The piezo elements miniTRITOR 38 from ***piezosystem jena*** generates a rectangular motion of 38µm in x, y and z direction. Integrated solid state hinges

with parallelogram design provide parallel motion without any mechanical play. The dimensions are 19mm x 19mm x 16mm. Another element is the piezo element PX 400. This element gives a motion of 400µm; the dimensions are 52mm x 48mm x 20mm. This element is also suited for dynamical motion. For more details please see our data sheets and section 6 of this catalog.
For comparison, a piezo stack with 400µm motion would need at minimum a length of 400mm!

3. *Properties of piezo mechanical actuators*

3.1. Expansion

The relative expansion $S = \Delta l/L_0$ (without external forces) of a piezo element is proportional to the applied electrical field strength. Typical values of the ceramic materials are $S \approx 0.1–0.13\%$ (field strength E = 2kV/mm).

$$\frac{\Delta l}{L_0} = S = d_{ij} \cdot E \qquad (3.1.)$$

S – relative stretch (without dimension),
d_{ij} – piezo module, parameter of the material,
$E = U/d_s$ electrical field strength,
U – applied voltage.

The maximum expansion will raise with increasing voltage. The relation is not perfectly linear as predicted by equation (3.1.). The characteristic curve reflects the inherent hysteresis (see also section 3.2.). The maximum expansion that can be achieved by using normal stacks is up to 300µm. The length of such a stack will be 300mm!

Typical piezo stacks have motion of 20–100µm. For greater expansion, actuators with a lever transmission are superior.

It is possible to combine piezo electrical elements with mechanically or electromechanically driven systems. So, the motion will be several cm, although the motion will show mechanical play.

3.2. Hysteresis

Because of their ferroelectric nature, PZT ceramics show a typical hysteresis behavior. If voltage is applied in a positive direction and then in a negative direction (bipolar voltage), one can obtain the curve you see below. ***(Figure 3.2.1.)***
If the voltage is increased, the movement increases. The maximum motion (point A) will be limited by saturation and by the voltage stability (voltage break down) of the ceramic material. If the voltage is reversed, the piezo element shows a contraction. After removing the voltage, a permanent polarization will remain. Therefore the motion of the piezo element is not zero (point B). If a definite negative voltage is applied (so-called coercitive voltage; point C) the motion will be zero microns.

The piezo element will contract when the negative voltage is increased. At the same time the polarization of the dipole in the ceramic begins to change. At point D the polarization of most of the dipoles is changed, so that the element will expand again for increasing negative voltage up to point E. If the negative voltage is reversed, the piezo element will contract according to the behavior from point A to point B, so point B is again the point which refers to the remaining polarization. By further increasing the voltage (now positive) the element contracts (up to point F) with polarization changes. By further increasing the voltage, the element expands to point A.

The butterfly curve shows that by applying bipolar voltage it is not possible to accurately determine the position of the piezo element. For example, for the same voltage, the element can be in position G or in position F.

Thus, normally one works with unipolar voltage outside the region of saturation and breakdown and outside the region of polarization changes. So piezo elements show the well-known expansion characteristics. ***(Figure 3.2.2.)***
To get a larger motion, it is possible to work with a negative voltage in the order of up to 20V (for multi-layer elements). Therefore we drive our elements with voltages from -20V up to +130V.

Working in that range, you find the typical expansion curve of piezo elements. The typical width of the hysteresis is 10–15% of the commanded motion.

Working in a smaller voltage range, the hysteresis is also smaller. This is also shown in the figure 3.2.2.

Each piezo element provided by ***piezosystem jena*** comes with the measured curve of its hysteresis.

Hysteresis of closed loop systems
In closed loop systems the closed loop control electronics compares a given or wanted motion (e.g. through modulation input signal) with the actual position measured by the sensor system. Any deviation in both signals will be corrected. Thus closed loop systems do not show hysteresis within the accuracy of the closed loop system. For more details see chapter 8 and 9.

below: butterfly diagram of piezo ceramics

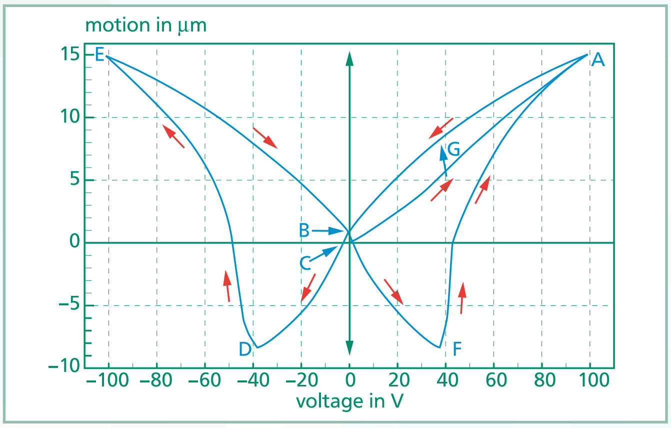

Figure 3.2.1. *Via the applied voltage, the motion of the element will follow the points ABCDEF.*

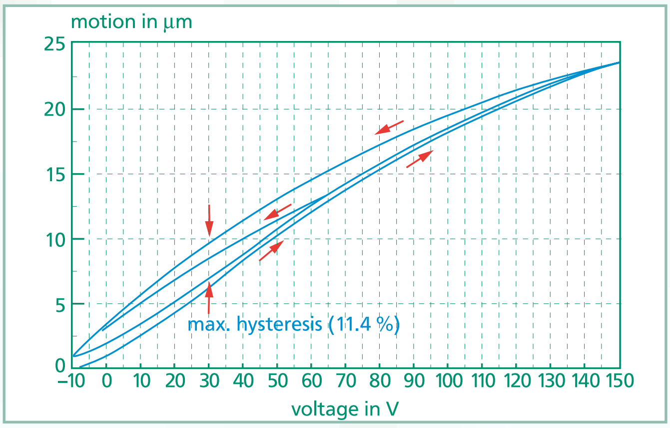

Figure 3.2.2. *Typical hysteresis curve of a multilayer piezostack*

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OEM elements for industrial applications

For piezo elements working under industrial conditions, we recommend working with voltages up to a maximum of 100V in order to achieve the best long term reliability. This is important, especially if the piezo element must work constantly with maximum expansion (under maximum voltage) over a long time period. Please see also chapter 11: reliability!

3.3. Resolution

Independent of the hysteresis, the piezo electrical effect as a solid state effect has a very high resolution. A piezo element PX 38 from ***piezosystem jena*** was examined in a special experiment and a motion of 1/100nm was detected.

Therefore the resolution is limited by the noise characteristic of the power supply. Our power supplies are optimized to solve this problem (please see also section 9.1. and 10.1.).

Example number 6

Our NV40/1CLE has a voltage noise of < 3mV at the output. Relative to 150V maximum voltage this is a value of $2 \cdot 10^{-5}$. Operating a piezo element with a maximum expansion of 20µm, the mechanical noise of this system will generate oscillations in the order of 0.04nm.

We have several different voltage amplifiers (power supplies). A compact 3 channel supply, or power supplies in 19 inch eurosystem.

3.4. Polarity

In general our piezo elements work with a positive polarity. A minimum reversal voltage on the order of 20% of the maximum voltage (for example –20V for 130V multi-layer elements) will increase the total expansion. A higher reversal voltage is not recommended because of depolarization effects. On request, it is possible to construct the elements with positive or negative polarity.

3.5. Stiffness

A piezoelectrical actuator can be described by a mechanical spring with constant stiffness c_T^E. The stiffness is an important parameter for characterization of the resonant frequency and generated forces.

$$c_T^E = \frac{A}{s_{33}^E \cdot L_0} \qquad (3.5.1.)$$

The stiffness is proportional to the cross section A of the actuator. The stiffness decreases with an increasing actuator length L_0. In reality the dependence is more complicated. The stiffness is also related to other parameters, e.g. how the electrodes are connected.

When the electrodes are not connected, there is no way for the energy to be dissipated; therefore in this case the stiffness has its largest value.

Stiffness

However, formula 3.5.1. does not describe the reality exactly enough. Depending on the kind of operation (static, dynamic operation) and the environment influence (load, electrical parameters of the electronic supply, small or large signal operation) the stiffness can vary up to a factor of 2 or more. Thus using formula 3.5.1. can give only a rough estimation of the expected properties of the piezo elements. Please consider, the electrical capacitance measured for piezo elements with small signals can increase up to 2 times when operated with large signals (under full motion).

Example number 7

An actuator with a cross section of 5 x 5 mm² and an active length of 9mm has a stiffness of c_{T1}^E = 120N/µm. With the same construction (cross section, mate-rial) but double the length (18mm), the stiffness will be a half stiffness (60N/µm). If an actuator with a cross section 4 times larger (for example 10mm x 10mm, length 18mm) is used, the stiffness will be 240N/µm.

3.6. Thermal Effects

Temperature variation is an important factor nithe accuracy of a micropositioning system. The thermal expansion coefficient of stainless steel for example, is about $12 \cdot 10^{-6}\,K^{-1}$. Imagine a cube of 10 · 10 · 10mm³. At temperature change of only 1K leads to an expansion of more than 0.1µm in each direction. With these relationships in mind, it is easy to understand that the calibration of piezo elements with integrated measurement systems depends on the temperature. If the operating temperature is different from the temperature during calibration, errors will occur.

When speaking about temperature coefficients of piezo elements, we must consider three effects:

a) The temperature behavior of the piezo ceramic material depends on the type of ceramic material. Piezo stacks operating with high voltages show a positive temperature coefficient on the order of $\alpha_{HV} \approx (7 - 10) \cdot 10^{-6}\,K^{-1}$.

Multi-layer stacks show a negative temperature coefficient of $\alpha_{NV} \approx -6 \cdot 10^{-6}\,K^{-1}$ in the range up to 120°C.

The thermal length variation of a whole short circuit actuator (e.g. series P, PA, PAHL) is the sum of the thermal expansions of the piezo ceramic and of the metal parts of the actuator.

$$\Delta l_{therm} = \left(L_{piezo} \cdot \alpha_{piezo} + L_{metal} \cdot \alpha_{metal}\right) \Delta T \qquad (3.6.1.)$$

Δl_{therm} = thermal expansion of the whole actuator
L_{piezo} = length of the piezo stack
L_{metal} = length of the metal housing
α_{piezo} = temperature coefficient of the piezo ceramic
α_{metal} = temperature coefficient of the metal housing
ΔT = temperature differential

Example number 8

If the temperature around a PA 16 actuator changes from 20°C to 30°C the length difference at a voltage of 150V (full stroke) is

$$\Delta l_{actuator} = \Delta l_{steel} + \Delta l_{stack} + \Delta l_{piezoeffect}$$

The length of the steel parts is 16mm:

$$\Delta l_{steel} = 16 \cdot 10^{-3}\,m \cdot \frac{12 \cdot 10^{-6}}{K} \cdot 10K = 1.92\mu m$$

The length of the piezo is 19mm:

$$\Delta l_{stack} = 19 \cdot 10^{-3}\,m \cdot \frac{-6 \cdot 10^{-6}}{K} \cdot 10K = -1.14\mu m$$

So the total difference is $\Delta l_{actuator} = 0.78\mu m$.

b) The piezo effect itself also depends on the temperature. In the range <260K, the effect decreases with falling temperature with a factor of approximately 0.4% per Kelvin

$$\alpha_{piezoeffect} = 4 \cdot 10^{-3} \cdot K^{-1}$$

In the region of liquid nitrogen (T_1; ca. 77 K), the expansion due to the piezo effect will be around 10–30% of the expansion at room temperature (T_0). Assuming the relation between the change of the piezo electrical expansion with temperature is linear, it can be expressed as:

$$\Delta l_{T_1} = \Delta l_{T_0}\left(1 - \alpha_{piezoeffect}\Delta T\right)$$

Δl_{T_1} = expansion at T_1
Δl_{T_0} = expansion at room temperature
$\Delta T = T_0 - T_1$
$\alpha_{piezoeffect}$ = temperature coefficient of the piezo effect

In the range of 260 K to 390 K the change of the piezo effect can be neglected.

Example number 9
To estimate what maximum stroke by a PX 100 at -195 °C (liquid nitrogen) can be expected, the temperature difference to -10 °C should be calculated. So it is ΔT= 185 K. The estimated stroke is around 25 µm.

*see **(Figure 3.6.1.)***

c) The ferroelectric hysteresis decreases with falling temperature. The hysteresis of piezo electric actuators is a result of the ferroelectric polarization (see also chapter 3.2.). At very low temperatures of four Kelvin for example, there are almost no changes of the electrical dipoles (domain switching) and so there is very little hysteresis. In the region of room temperature, the influence of temperature variations to the hysteresis can be neglected.
*see (**Figure 3.6.2.)***

But please take into account:
Although the piezo effect decreases with falling temperature, piezo electric actuators principally can work at very low temperatures – down to the temperature of liquid He (4 K).

If you want to work in a low temperature regime, please tell us about this fact, so we can prepare the actuator for this temperature region.

Stages
The temperature behavior for elements integrated into a lever design depends on both the temperature effect for the piezoelement and the behavior of the stage. It may differ from the behavior described above for the piezo element itself. Because of the different constructions used for different stages a general rule cannot be given.

Closed loop stages
Please take care to use closed loop stages at near the temperature at which they were calibrated. Only at the temperature of calibration, piezo elements show the best accuracy.

3.7. Capacitance

As mentioned a stack actuator consists of thin ceramic plates as dielectricum and electrodes. This is a system of parallel capacitors.

$$C = n \cdot \varepsilon_{33} \cdot \frac{A}{d_s} \qquad (3.7.1.)$$

n – number of ceramic plates, ϵ_{33} – dielectric constant, A – cross section of the actuator or the ceramic plates, d_s – thickness of a ceramic plate.

Example number 10
A multi-layer stack with an (active) length of 16mm, a cross section of 25mm² and a thickness of the ceramic plates of 110µm consists of approximately 144 plates. With a relative dielectricity of ϵ_r = 5400 one yields a capacitance of the actuator of approximately 1.6µF (see formula 3.7.1).

Capacitance of multi-layer actuators – capacitance of high voltage actuators

Let us consider the following comparison:

Example number 11
A multi-layer actuator (index 1; parameter see example number 10) should be replaced by a high voltage element with the same length (index 2). For simplicity, both stacks consist of the same material. Refer to formula 3.7.1. The thickness of the ceramic plates of the high voltage actuator is 5 times larger ($d_{s2} = 5 \cdot d_{s1}$) so the number of plates is 5 times lower ($n_2 = 1/5 \cdot n_1$).
Thus the capacitance of the high voltage actuator is much lower than the capacitance of the multi-layer actuator
$C_2 = C_1/25$.

The operating voltage for the same expansion is lower for multi-layer stacks. But the capacitance is increasing quadratically.

Please note
Because of the higher capacitance of low voltage multi-layer stacks, these actuators need much more current in dynamical applications. The current can be neglected for static and quasi-static motions.

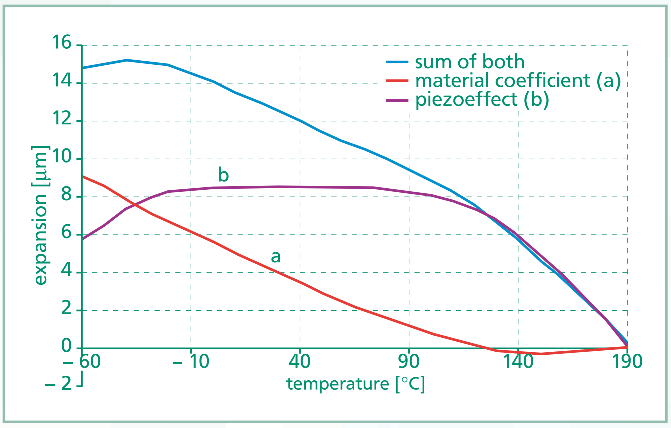


Figure 3.6.1. *Example of temperature dependence of multilayer ceramic L_{piezo}=18mm at room temperature.*

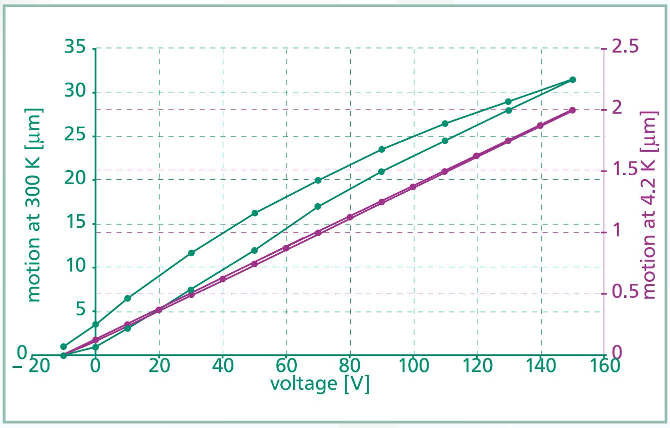


Figure 3.6.2. *Hysteresis curve of a PA 25 element at room temperature and at 4 K.*

piezoline

Please note
The piezo electrical properties of actuators are not constant as assumed in simple descriptions. Most of the parameters depend on the strength of the internal field. Most of the values given in the literature are for low electric fields. These values can differ for high electric fields. As an example, the capacitance for high voltage operation is nearly twice that given for low voltages.

3.8. Drift – creep (open loop systems)

Another characteristic of piezo electrical actuators is a short dimensional stabilization known as creep. A step change in the applied voltage will produce an initial motion followed by a smaller change in a much longer time scale as shown in the figure 3.8.1.
As one can see, the creep will be within 1% to 2%, in a decade of time. The creep depends on the expansion Δl, of the ceramic material (parameter of the material γ), on the external loads, and on time. The dependence of the creep can be shown also as a logarithmic dependence of time.

$$\Delta l(t) = \Delta l_{0.1}(1+\gamma \lg \frac{t}{0.1\,s}) \quad (3.8.1.)$$

$\Delta l_{0,1}$ - motion length after 0.1 s after ending of rise time of the voltage.

In this case we reach a value for $\gamma \approx 0.015$. The value of γ depends on the material, the construction and the environmental conditions (e.g. forces).

When the motion (voltage) is stopped, after a few seconds, the creep practically stops.

Repeatability for periodical signals
When working with periodic signals, the repeatability of a position will not be deteriorated with creep. Because of the strong time dependence of the motion, creep occurs in all oscillations in the same order.

In the figure 3.8.2. we have shown a periodic oscillation of a mirror mount PSH. The power supply is a normal power supply controlled by a function generator. The full tilting angle is approximately 380 arcseconds. In the picture there is a section of only 10 arcseconds (from 302“ up to 312“). It can be seen that the repeatability is better than 0.1“ which is better than 0.03%.

As a result of this experiment, we have reached a high repeatability within the system without a closed loop control. For such experiments the repeatability is only determined by the quality of the power supply.

3.9. Working under vacuum conditions

The piezo electrical effect, in general, works also under vacuum conditions. The only problem arises from the outgassing of the materials used.

For protection of both people and the piezo electrical actuators from electrical breakdown, the actuators are insulated using rubber materials. However, these materials exhibit some outgassing characteristics. That is why piezo electrical actuators for vacuum applications are produced from materials (for example, adhesives) with low outgassing characteristics. We do not use any rubber materials. Consequently the outgassing is extremely low.

We can offer most of our elements with vacuum options.

Please note
In the pressure region between 0.01 hPa, up to 100 hPa the gases used have a very low insulating behavior. If piezo elements with vacuum options (prepared with materials with very little outgassing) are used in this pressure region, the elements can be damaged because of electrical breakdown. Piezo electrical actuators prepared for vacuum applications should not be used in this pressure region. For safety reasons, piezo elements with vacuum options must not be used in environments where someone can touch the contacts.

Example number 12
The piezo electrical driven optical slit from ***piezosystem jena*** was especially prepared for vacuum applications. Up to a pressure of $5{\cdot}10^{-9}$ hPa, no influence of outgassing of the piezo element was detected. The piezo elements were not heated.

Heating, baking out of piezo elements
Piezo elements from ***piezosystem jena*** can be baked out up to 80°C (175°F) without problems. Elements with special preparation can be baked out up to 150°C (300°F).

3.10. Curie's Temperature

The ferroelectric nature, and so the piezo electrical properties, will be lost if the material will be heated over the Curie point, 150°C. So it is important to work below the Curie temperature T_c.

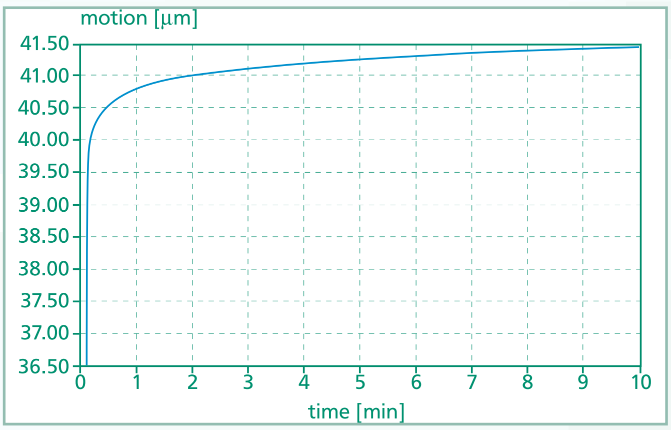


Figure 3.8.1. *creep PU 40*

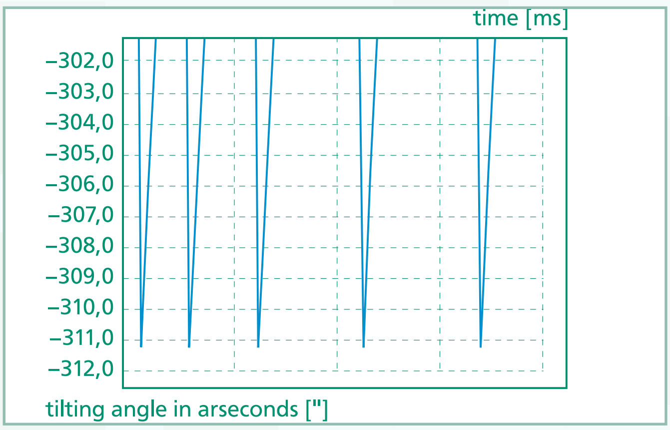


Figure 3.8.2. *repeatability of a position with periodic motion of a mirror mount*

piezosystem jena

The Curie temperature is dependent on the material. Normally, multi-layer actuators have a Curie temperature of 150°C. High voltage actuators have a Curie temperature up to 250°C.

In special cases it is possible to work with other ceramic materials with varied Curie temperatures.
If a piezo ceramic is heated (for example by dynamical motion) up to the Curie temperature, thermal depolarization will occur. If temperature parameters are not given we recommend working in temperatures up to $T_c/2$ (normally up to 80°C).

If materials become depolarized, the piezo effect is lost. However, the application of a high electrical field to the actuator can restore it. Thus, special piezo electrical materials can be annealed (baked out) in the vacuum chambers.

The heating of piezo actuators can be ignored when working under static and quasi-static conditions. It should be taken into account for dynamical applications (see section 5).

If there is a particular problem, please contact us for more information!

4. *Static behavior of piezo electrical actuators*

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

The motion is expressed by the equation:
longitudinal effect:

$$S_z = \frac{\Delta l_z}{l_z} = s^E_{33} \cdot T_z + d_{33} \cdot E \qquad (4.0.1.)$$

transversal effect:

$$S_{x,y} = \frac{\Delta l_{x,y}}{l_{x,y}} = s^E_{11} \cdot T_{x,y} + d_{31} \cdot E \qquad (4.0.2.)$$

S – strain, relative motion, T = F/A – mechanical tension pressure (e.g. caused by external forces), s_{ii} – coefficient of elasticity (reciprocal value of the young modulus), Δl_z – expansion of the actuator in z dimension, l_z – length of piezo electrical active part of the actuator, $E=U/d_s$ – electrical field strength, U – applied voltage

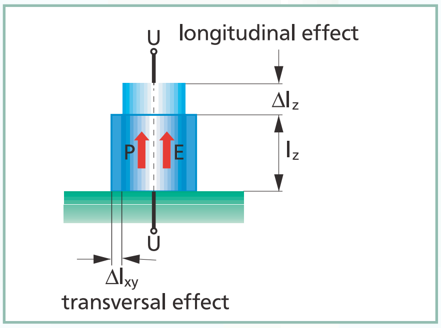


Figure 4.1. *stacked actuators with longitudinal expansion and transversal compression*

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

Typical coefficients are:

coefficient	dimension	PZT
d_{33}	(m/v)	$700 \,.\, 10^{-12}$
d_{31}	(m/v)	$-275 \,.\, 10^{-12}$
S^E_{33}	(m^2/v)	$20 \,.\, 10^{-12}$
S^E_{11}	(m^2/v)	$15 \,.\, 10^{-12}$
tanδ	–	3-5 %
k	–	0,65

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

For the sake of simplicity, if not otherwise mentioned, from now on we will refer to the longitudinal piezo electrical effect, however all relations can be written in the same manner for the transversal effect.

$$S = \frac{\Delta l_z}{l_z} = S^E_{33} \cdot T + d_{33} \cdot E = \frac{F}{c_T \cdot L_0} + d_{33} \cdot E \qquad (4.0.3.)$$

The first term of the equation (4.0.3) describes the mechanical quality of an actuator as a spring with a stiffness c_T. The second term describes the expansion in an electrical field E.

The static behavior can be stated using formula (4.0.3).

4.1. No voltage is applied to the actuator, E = 0

The actuator is short-circuited. Formula (4.0.3) becomes
$S = \Delta l/L_0 = s_{33} \cdot T$. The deformation of the actuator Δl is determined by the stiffness of the actuator c_T^E because of the action of an external load with the pressure T, so it becomes “shorter“.

$$\frac{\Delta l}{L_0} = \frac{F}{L_0 \cdot c^E_T} \cdots \text{or} \cdots \Delta l = \frac{F}{c^E_T} \qquad (4.1.1.)$$

L_0 - length of the actuator.

The stiffness c_T^E of an actuator can be calculated by taking into account the stiffness of the ceramic plates. This approximation assumes that the adhesive between plates is infinitely thin.

Monolithical multi-layer actuators perform well in this respect, giving stiffness on the order of 85%–90% of the stiffness of the pure ceramic material. Especially for high voltage actuators, the stiffness of the metallic electrodes and the adhesive have a large influence on the stiffness of the stack.

Example number 13
On a stack with a stiffness of a given c_T^E operates at an external force of F = 70N, using formula (4.1.1) it is easy to calculate the compression of a stack of 1µm.

4.2. No external forces, F = 0

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

$$\Delta l_0 = \frac{F}{c_T} + d_{33} \cdot E \cdot L_0 = (F = 0) = L_0 \cdot E \cdot d_{33} \qquad (4.2.1.)$$

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

Example number 14
Let us consider a multi-layer stack with the following parameters:

Piezoelectrical constant
$d_{33} = 635 \cdot 10^{-12}$ m/V
Active length
$L_0 = 16$mm

piezoline

The thickness of a single plate is 100µm. The operating voltage is 150V (–20…+130V). The field strength is E = 1.5kV/mm.

The expansion will be Δl_0 = 15µm without external forces (see formula 4.2.1.).

4.3. Constant external loads, F = constant

Operating with constant force F or weight, the actuators will be compressed (see ***Figure 4.3.1.***).

$$\Delta l_n = \frac{F}{c_T} = \frac{m \cdot g}{c_T} \qquad (4.3.1.)$$

However, the expansion Δl_0 due to the applied voltage will be the same as when an external force is not applied (see formula 4.2.1.).

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

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

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

Standard actuators from ***piezosystem jena*** with a cross section of 5 x 5mm² show depolarization effects for external loads > 1kN. Please see the given parameters in our data sheets!

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

4.4. Changing external loads and forces, F = f (Δl)

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

$$\Delta l = E \cdot d_{33} \cdot L_0 - \frac{c_F}{c_T} \cdot \Delta l \qquad (4.4.1.)$$

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

$$\Delta l = \Delta l_0 \cdot \frac{c_T}{c_T + c_F} \qquad (4.4.2.)$$

A part of the motion will be needed to compensate the external forces, therefore the final motion becomes smaller (see also ***Figure 4.4.1.***).

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

Example number 15
The actuator PA 16/12 has a stiffness of c_T = 65N/µm. The motion Δl_0 without external forces is 16µm. This actuator is assembled in a housing with a pre-load stiffness c_F = 1/10 c_T.
In comparison with formula (4.4.2.) the motion will decrease to 14.5µm. If the stiffness of the pre-load is increased to 70% of the stiffness of the actuator c_F = 0.7 c_T = 46N/µm, the motion will reach only Δl = 9.4µm.

Using equation (4.4.2.) we can calculate the effective forces, which can be reached with an actuator operating against an external spring.

$$F_{eff} = c_T \cdot \Delta l_0 \cdot \left(1 - \frac{c_T}{c_T + c_F}\right) = c_T(\Delta l_0 - \Delta l) \qquad (4.4.3.)$$

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

Example number 16
Again, we will use the actuator PA 16/12. For motion without external load Δl_0, the stiffness is c_T = 65N/µm. This actuator is working against a spring with a stiffness c_F = 64N/µm. In this assembly the actuator will reach an effective force of 516N. When it operates with an external spring with a stiffness of 500N/µm, it will reach an effective forces of F = 920N.

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

Integrated pre-loads of piezo electrical actuators are external forces. The value of the integrated pre-load often reaches 1/10 of the maximum possible load of the actuator. That is why the shorter expansion of pre-loaded actuators is very low.
But pre-loaded actuators can work under tensile forces. They are well suited for dynamical applications.

4.5. Blocking forces, Δl = 0

The actuator is located between two walls (with an infinitively large stiffness). So it cannot expand (see formula 4.2.1.):

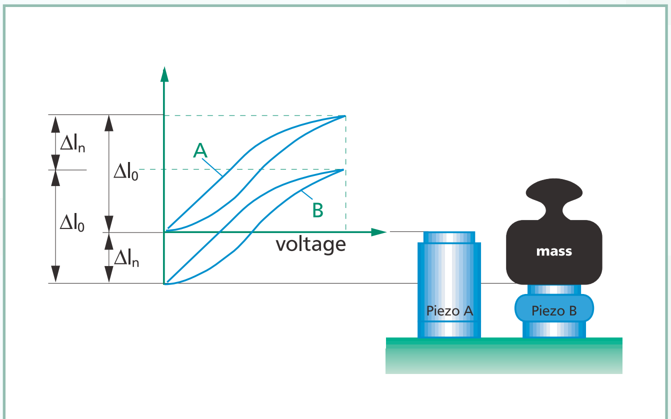


Figure 4.3.1. *motion under external constant force*

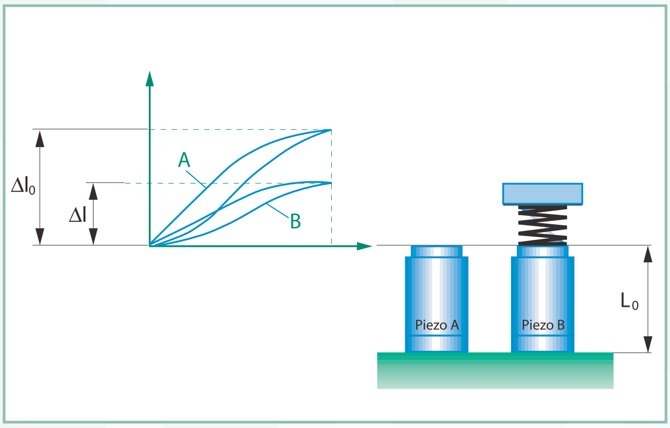


Figure 4.4.1. *motion dependence of external spring forces*

$$0 = -\frac{F}{c_T} + d_{33} \cdot E \cdot L_0 \qquad (4.5.1.)$$

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

$$F_{max} = C_T \cdot \Delta l_0 \qquad (4.5.2.)$$

This force is called blocking force of an actuator.

Operating against external spring forces, actuators show the following behavior of the generated forces in dependence on the expansion. This stress diagram is valid for typical actuators used by ***piezosystem jena***. (see ***Figure 4.5.1.***)

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

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

Example number 17

An actuator of the type PA 16/12 ope r ates to an ex ternal spring, with out loads the ac tuator reaches a motion of 16µm. A generated force of 320N is demanded. What motion can be reached under such condi tions?

Answers

Look at the diagram, the vertical line beginning at the point of 320N crosses over to the actuator´s PA 16/12 curve. The horizontal line, beginning at this point of the cross over will end in the value of the possible motion, approximately 11µm. The same result can be calculated using (4.4.3.).

For the real expansion Δl under external spring forces we yield from (4.4.3.) Δl = $\Delta l_0 - F_{eff} / c_T$. The stiffness of the actu - ator is c_T = 85N/µm. The result will also be Δl = 11µm.

Please note:

In practice an infinitely stiff wall or clamping to the actuator cannot be realised. For this reason an actuator will not reach its maximum theoretical force in reality. Please note also that if the actuator should generate its blocking forces it will not show any motion!

4.6. Push and Pull forces

Piezo ceramic stacks can withstand high pressure push forces (push forces are opposite the direction of motion). However due to their construction as a multilayer element they can withstand only low pull forces (tensile forces in the direction of motion). Piezo stages consist of a combination of a multilayer piezo ceramic stacks, working within a special construction for the magnification of motion. This construction can include different kinds of preloading mechanisms allowing for higher pull and push forces to the piezo stages.

Push and pull forces specified in this catalog indicate maximum forces to be applied to the piezo stages, or piezo actuators without mechanically damaging the elements.

If the applied forces are higher than the specified values the elements can be damaged and might not work properly.

Please note:

Push and pull forces can change the offset of the motion as well as the total motion range. This change can vary with the type of load (static load, or operation opposite a spring type force). Please see also chapter 4.3; 4.4; 4.5 and chapter 6 of the piezoline. Specifically dynamic operation (acceleration, change of the speed) generates dynamic forces to the piezo element! Please be sure they do not exceed specified push or pull forces.

If the application requires higher forces than those specified, please contact our engineers. Depending on the stage it might be possible to modify the element for higher forces.

Closed loop systems

As mentioned above, external forces, such as different environmental conditions can change the offset, and the motion of a piezo element. These forces can effect the specifications and thus the calibration can be changed. If a closed loop system is to be operated under different conditions, than those of which it is calibrated for, please contact our engineers. Please see also chapter Calibration and Special Calibration.

5. Dynamic properties

5.1. Resonant frequency

Piezoactuators are oscillating mechanical systems, characterized by the resonant frequency f_{res}. The resonant frequency is determined by the stiffness and the mass distribution (effective moved mass) within the actuator. Actuators from ***piezosystem jena*** reach resonant frequencies of up to 50kHz.

$$f^0_{res} = \frac{1}{2\pi}\sqrt{\frac{c_T}{m_{eff}}} \qquad (5.1.1.)$$

An additional mass M loaded to the actuator decreases the resonant frequency of this system.

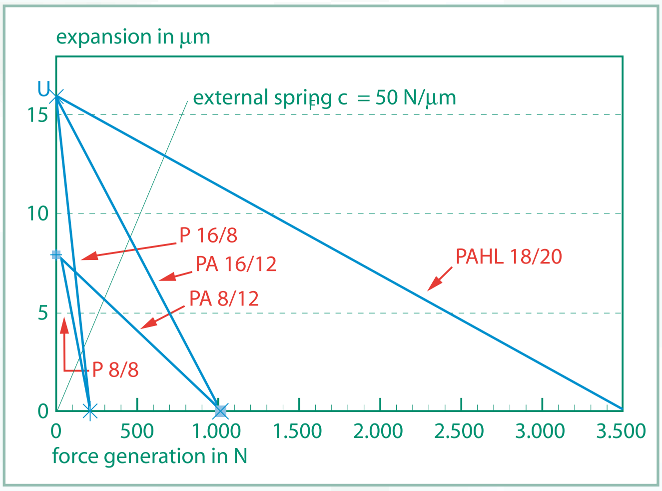


Figure 4.5.1. *stress strain diagram of piezoelectrical actuators*

piezoline

$$f^1_{res} = \frac{1}{2\pi}\sqrt{\frac{c_T}{m_{eff} + M}} = f^0_{res} \cdot \sqrt{\frac{m_{eff}}{m_{eff} + M}} \qquad (5.1.2.)$$

That is why the resonant frequency of a complete system can deviate considerably from the resonant frequency of the single actuator. This is an important fact for example when using the mirror for fast tilting. Actuators using a lever transmission for larger motions, get resonant frequencies typically within the range of 300Hz up to 1.5kHz.

In our data sheets for some elements not only the resonant frequency is given, but also the effective mass. Knowing the effective mass it is possible to estimate the resonant frequency with an additional mass (using formula 5.1.2.).

You will find more information about the simulation of dynamic properties in chapter 7.

Please note!
Because of the complexity of this field, such calculations give only approximate values. These values should be experimentally verified by tests.

Example number 18
The resonant frequency of the actuator PA 25/12 is f^0_{res} = 12kHz. The effective mass can be estimated by m_{eff} = 10g. This actuator has to tilt a mirror with a mass M = 150g. Because of this mass, the resonant frequency changes to f^1_{res} = 3kHz.
Moving with the resonant frequency, the amplitude of the actuator is much higher as in the non-resonant case. Actuators with a lever transmission show super-elevations up to 30 times and higher in comparison to the non-resonant case.
When working with frequencies near the resonant frequency, one needs a much lower voltage for the same result. But please be careful! This advantage can damage your actuator if the motion exceeds the motion for maximum voltage in the non-resonant case!

We strongly recommend
Actuators should be used with frequencies of approximately 80% of the resonant frequency. Please consider also the heating of piezo electrical elements while in dynamic motion.

Do not hesitate to contact us for solving your special problem!

5.2. Rise time

Because of their high resonant frequency, piezo actuators are well suited for fast motions. Applications have been in valve technology and for fast shutters. The shortest rise time t_{min} which an actuator needs for expansion, is determined by its resonant frequency.

$$t_{min} \approx \frac{1}{3 \cdot f_{res}} \qquad (5.2.1.)$$

When an actuator is given a short electrical pulse, the actuator expands within its rise time t_{min}. Simultaneously, the actuator's resonant frequency will be excited. So it begins to oscillate with a damped oscillation relative to its position. A shorter electrical pulse can result in a higher super-elevation but not in shorter rise times!

The figure 5.2.1. shows a typical answer to a short electrical excitation of a piezo actuator PAHL 40/20 from ***piezosystem jena***. Although the excitation pulse has a duration of approximately 8µs the rise time of the actuator is only 20µs. This value agrees with the resonant frequency of 16 kHz.

5.3 Dynamic forces

While working in the dynamical regime, compressive stress and tensile forces act on piezo electrical actuators. The compressive strength of piezo actuators is very high, but they are very sensitive to tensile strength. But both forces F_{dyn} occur in the same order while moving dynamically (formula given for sinusoidal oscillation).

$$F_{dyn} = \pm 4\Pi^2 \cdot m_{eff} \cdot \frac{\Delta l_0}{2} f^2 \qquad (5.3.1.)$$

$\Delta l/2$ – magnitude of the oscillation (Δl full motion of the actuator).

A large acceleration operates on the ceramic and electrode material.

$$\alpha = \frac{\Delta l_0}{2} \cdot (2\pi f)^2 \cdot \sin\varphi \qquad (5.3.2.)$$

ϕ – angle of the phases of the oscillation.

Example number 19
An actuator with a motion of 20µm and an operating frequency of 10kHz has an acceleration of 39500m/s². This value exceeds the acceleration of the earth by 4000 times.

Please consider dynamical forces while in dynamical motion.
They also appear without external loads!

That is why it is necessary to use pre-loaded actuators for dynamic applications. PA or PAHL signify pre-loaded actuators from ***piezosystem jena***.

Actuators without pre-load can only be used for small motions in special cases!

Please note
When working under dynamical conditions, the current, which will be needed for the motion, can reach large and critical values. For calculation of the required current, see also section 10, especially section 10.2. and 10.3.

6. Actuators with lever transmission system

Most of our elements work with an integrated lever transmission (see figure 2.4.1., page 93). This construction has some advantages:

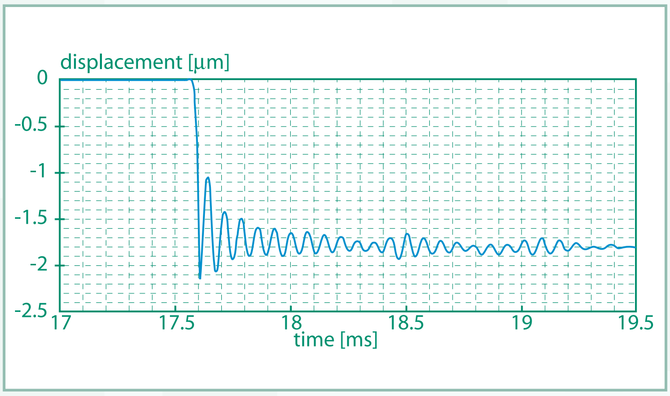


Figure 5.2.1. *answer of a piezo element series PAHL to an excitation voltage step of 20V*

piezosystem jena

- The motion can be much higher than the motion of the stack type actuator.
- Because of using a parallelogram design, the parallelism of the motion is much better than the parallelism of the motion of a simple stack.
- Because of solid state hinges, mechanical play does not occur. The fineness of the motion will be similar to that of actuators without lever transmission.
- Solid state hinges work without wear for a long time.
- Because of the lever transmission the capacitance of the whole system is much lower than the capacitance of an equivalent stack (with the same motion). This can be advantageous for dynamic applications because of the lower electrical current requirements (see also section 10.2. Current).

As an approximation, piezo actuators with an integrated lever transmission can be seen as an actuator with a new stiffness and a new resonant frequency. In our data sheets these values are given for our elements.

Piezo electrical actuators with lever transmission have the electrical capacitance of a stack and they have a high inner resistance.

The essential changes to “normal” stack type actuators are:

The motion will be transmitted by the transmission factor TF:

$$\Delta l_2 = TF \cdot \Delta l_1 \tag{6.1.}$$

The stiffness decreases quadratically with the transmission factor:

$$c_{ges} = c_F + \frac{c_T}{(TF)^2} \tag{6.2.}$$

c_T – stiffness to the stack, c_F – stiffness of the lever transmission construction.

Because of the lower stiffness the superelevation will be higher (up to 100 times and more in relation to the motion in the non-resonant frequency range).

The resonant frequency decreases linearly with the transmission factor TF.

$$f_{res}^2 = \frac{1}{TF} \cdot f_{res}^1 \tag{6.3.}$$

While the resonant frequency of a one-sided fixed piezoelectrical stack reaches frequency values up to 50kHz, the resonant frequency of systems with integrated lever transmission will reach values of 30Hz up to 1.5kHz.

If the chosen experimental equipment is unfavorable, additional subordinate (cross) resonant frequencies may occur. The values of these frequencies can only be lower than the actuator´s main resonant frequency.

The blocking force (see also section 4.5.) decreases linearly with the transmission factor.

$$F_{max_2} = \frac{1}{TF} \cdot F_{max_1} \tag{6.4.}$$

Cross motion

Because of the principle of a lever transmission with parallelogram design, the motion in one direction is followed by a small motion in the other rectangular direction. Though the motion follows a parabolic curve, the end faces will make a parallel motion. As mentioned, the parallelism due to the lever transmission system is better than the parallel motion of the stack itself.

The order of this cross motion is approximately 0.2% but depends on the specific construction parameters.

For example, a TRITOR element with 40µm motion in the x direction will make a simultaneous motion of about 50nm in the y direction. For most applications this will not disturb the positioning precision. But in other cases it should be taken into account.

Because of the relation of 500:1 between the aspired motion and the cross motion, it is easy to understand that this parabola can also be described by a straight line. Hence, cross motion can be minimized by optimizing the straightness of the piezo element.

This was done for the piezo element PU 100. By alignment the cross motion was minimized to less than 15nm. (see ***Figure 6.2.***)

New design without cross motion

Caused by the mechanical construction NanoSX actuators do not show any cross motion.

7. *Simulation of dynamic properties*

7.1. Transformation of electrical and mechanical properties

The piezo electrical effect describes the electromechanical coupling behavior of ferroelectrical materials. A theoretical model of electromechanical transducers is given with an electromechanical network. This network consists of electrical and mechanical components, which are connected via a specific four-pole circuit with the coupling factor y.

Using this model makes it possible to simulate the dynamic behavior of piezo electric actuators.

The equivalent electrical circuit of piezo electrical actuators can be determined with the help of an electrical impedance analyzer. With the equivalent electrical circuit, it is possible to simulate the dynamic behavior of the corresponding actuator system. The electrical model can be implemented in stan-

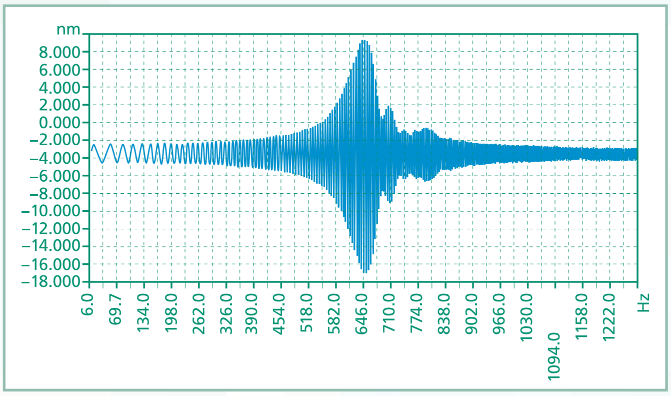


Figure 6.1. *resonant frequency of piezo element with lever transmission series PU 100*

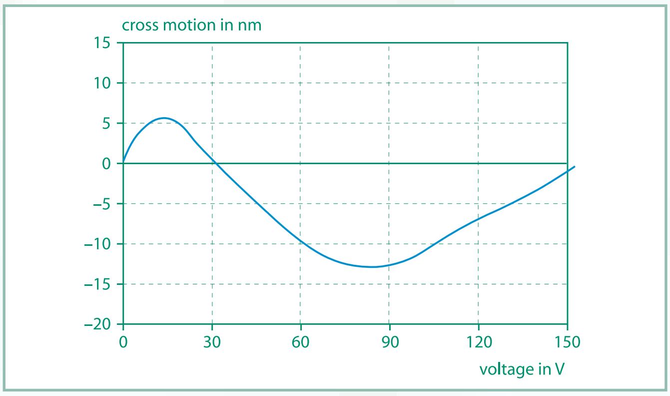


Figure 6.2. *optimization of the cross motion of a piezo element PU 100*

dard simulation programs and, thus, whole systems, including the power supply and a closed loop control circuit, can be simulated.

In the case of piezo electrical transducers, the components of the theoretical networks are: the electrical free capacitance C_b, the mechnical elements compliance n (mechanical stiffness n^{-1}), effective mass m and the intrinsic mechanical losses h. Due to the reciprocal network characteristic with the coupling factor y, the following relation can be given:

Electric	**Mechanic**
Voltage u	force F · y
Current i	velocity v · y^{-1}
Inductivity L	mass m · y^2
Capacitance C	compliance n·y^{-2}
Resistance R	intrinsic losses h^{-1} · y^2
Parallel circuit	serial connection
Serial connection	parallel circuit

A transformation of the mechanical components to the electrical side of the four-pole network leads to the model of the equivalent electrical circuit of piezo electrical actuators. *(see **Figure 7.1.1.)***

with:
$$C_n = y^{-2}\cdot n$$
$$L_m = y^2\cdot m$$
$$R = y^2\cdot h^{-1}$$

The representative electrical circuit gives a linear approximation of the electromechanical system. The characteristic equation of this network is similar to the characteristic equation of a simple spring–mass-oscillator. If a force F is applied to a mechanical spring with the stiffness n^{-1}, the displacement x is given with $x=F_k\cdot n$. With the given coupling relation, the equivalent equation for the electrical network is

$$x = \frac{u_{cn}}{y}\cdot y^2\cdot C_n = y\cdot u_{cn}\cdot C_n \qquad (7.1.)$$

The voltage u_{cn} is given with

$$\frac{u_{cn}}{u} = \frac{1}{(s+b)^2 + a^2} \quad \text{with} \quad a = \sqrt{\frac{1}{C_n\cdot L_m} - b^2};$$
$$b = \frac{R}{2\cdot L_m} \quad \text{and} \quad s = j\cdot 2\cdot\pi\cdot f \qquad (7.2.)$$

Therefore the characteristic equation for the mechanical displacement of piezo electrical transducers can be determined from the equivalent electrical circuit:

$$x = \frac{y\cdot u\cdot C_n}{(s+b)^2 + a^2} \quad \text{with} \quad a = \sqrt{\frac{1}{C_n\cdot L_m} - b^2};$$
$$b = \frac{R}{2\cdot L_m} \quad \text{and} \quad s = j\cdot 2\cdot\pi\cdot f \qquad (7.3.)$$

The resonant frequency is given by:

$$f_{res} = \frac{1}{2\cdot\pi}\cdot\sqrt{\frac{1}{L_m\cdot C_n}} \qquad (7.4.)$$

As mentioned before, the model of the equivalent electrical circuit corresponds to a linear approxiamation of the real coupling behavior of electromechanical transducers. This model includes neither the piezo electrical hysteresis nor the creep and saturation of polarisation. Further restrictions of this model are given with the special characteristic of the piezo electrical material parameters. All specific material properties (e.g. compliance, capacitance, piezo electric coefficient) are dependent on the applied electrical field. This dependence is not to be considered by the linear model.

Example number 20

We tried to find a simulation model for our actuator PU 90.

This model should be able to calculate the dynamic behavior of this element with different additional masses.

An additional mass leads to higher inductivity L_m in the model:

$$L_m = y^2\cdot(m_{eff} + m_{add}).$$

m_{eff} is the effective moved mass of the actuator system without an additional load and m_{add} is the additional mass. To calculate L_m for any loads, it is necessary to find the values for y and m_{eff}. This can be done with two measurements on an electrical impedance analyzer (with different loads). We made four measurements to reach a higher reliability in our model.

From these measurements, we obtained the following values for the model of the actuator system PU 90:

m_{eff} = 89.8 g; y = 2.12 m/As;
R = 38.92 Ω; C_n=171 nF; C_b=1.56 µF

With this model we calculated the resonant frequency with respect to an additional load and we simulated the response of this actuator to a voltage step.We proved our model with some additional measurements which were done with the aid of an interferometer displacement sensor. The results are given in the diagrams. ***(Figure 7.1.2./3./4.)***

Simulation models of several of ***piezosystem jena***'s actuator systems were made. With these models it is possible to determine significant mechanical parameters for the dynamic use of piezo electrical actuators. In this way, custom-designed actuator systems can be realized much easier and more efficiently.

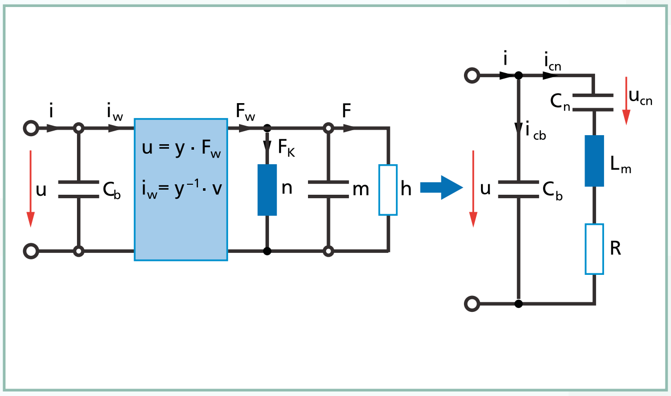


***Figure 7.1.1.** Mechanical scheme and equivalent electrical network of piezo electrical transducers*

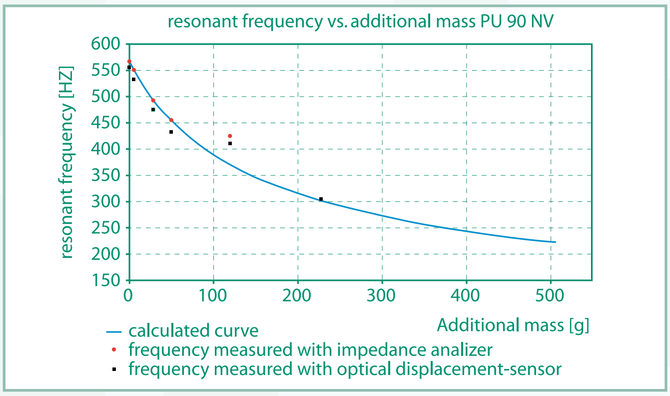


***Figure 7.1.2.** Calculated resonant frequency of the actuator PU 90 with respect to an additional load.*

7.2. FEM optimization

A lot of applications require special mechanical properties to be considered from the beginning of the development. Additional loads to be moved dynamically require a complex optimization process of the stage. Using only formula 3.5.1. or 6.2. does not allow one to develop optimized stages. The full construction should be designed using FEM calculations. With our extensive experience in FEM calculations we can optimize more accurate parameters as stiffness, minimum tilting properties and others.

The following 2 pictures show how to optimize a stage for minimum cross motion. Cross motion occurs if one axis is moved (here the y-axis) but the other axis still shows a small motion. This cross motion is a result of a non-optimized construction, material imperfections and other factors.

In figure 7.2.1. the stress inside a stage is shown while the stage moves in y axis. Tensile forces in x-axis occur leading to a tilt of 67µrad (calculated by FEM analysis) because of the above-mentioned imperfections.

In figure 7.2.2. the holes for mounting the stage are replaced; optimized for a minimum x tilt. The result is a tilt of 6,6µrad, which is 10 times smaller than the non-optimized stage in figure 7.2.1.

piezosystem jena uses its extensive experience in FEM calculations to develop special products optimized for the very special needs of your particular application.

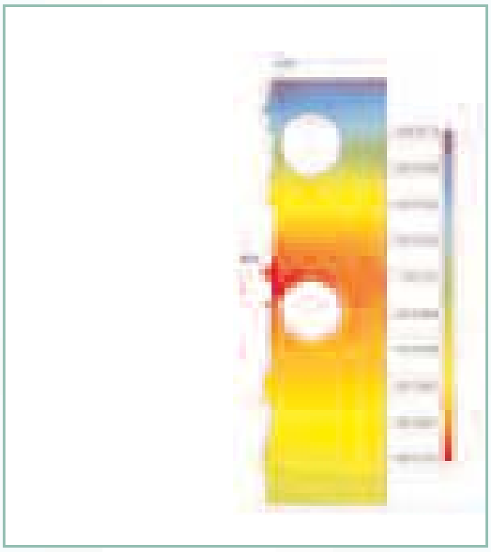


Figure 7.2.1. *non-optimized stage*

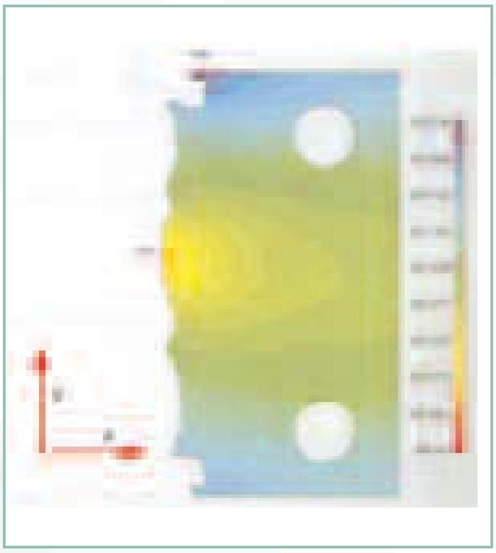


Figure 7.2.2. *optimized stage*

8. *Position control – closed loop systems*

Because of the nearly unlimited resolution of the motion, piezo electrical actuators are excellently suited for high precision positioning in the µm range to the nm range.

However, because of the hysteresis the relation between the applied voltage and the actuator's motion is not unique.

There are some applications in practice where the high resolution of the motion is necessary, but the absolute positioning accuracy is not. The classic example is the problem of fiber positioning. The light of one fiber has to be coupled most efficiently into a second fiber, the knowledge of the absolute position of the fiber is not important.

Another example:
If it is possible to return after each positioning event (transaction) to the 0 voltage position, the hysteresis does not affect the event (see also chapter 3.8.).

Of course some applications demand a high positioning repeatability. This can be reached by combining piezo electrical actuators with a measurement system. Because of their high dynamics, piezo electrical actuators are well suited for a closed loop system with a measurement system.

piezosystem jena uses different measurement systems. With strain gages it is possible to reach a position accuracy of 0.1–0.2%. Better results can be reached with special inductive and capacitive sensors.

You have to be careful working with a measurement system! Each measurement system always measures the motion at the place were the measurement system is located.
Variations between the measurement system and the point which should positioned (such as temperature effects), cannot be detected by the system.

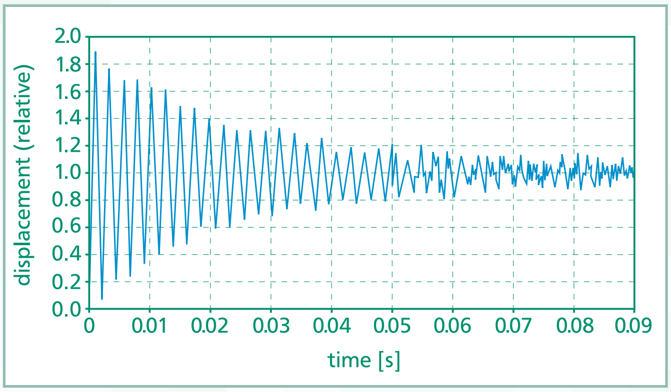


Figure 7.1.3. *PU 90 with additional load 51g, measured response to a voltage step*

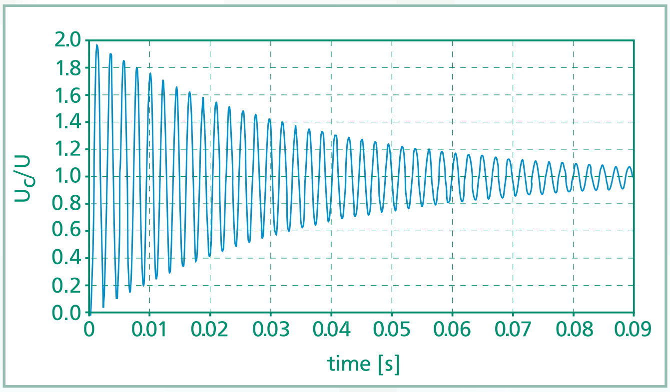


Figure 7.1.4. *PU 90 with additionl load of 51g, simulated response to a voltage step.*

piezoline

piezosystem jena has developed piezo elements with a measurement system and we have also developed complete electronic controllers with integrated closed loop control. The closed loop is controlled by a PI or PID regulation circuit; the actual position measured is shown on the display.
*(see **Figure 8.1.**)*

Please note:
Often it is not possible to widen a piezo electrical element with a measurement system. Therefore it is important to investigate carefully if an integrated measurement system is really needed. Of course such a system with sensors is more complicated and more expensive than a piezo electrical system without measurement system.

If a measurement system is used in a closed loop system, the full range of the motion will be smaller by about 10–20% to preserve the dynamic of the closed loop regulation.

9. Characterization of measurement systems

Introduction

The influence of the ferroelectrical hysteresis and the effect of the time dependent creep limit the best mechanical parameters of piezo electrical actuators. In a large number of applications these effects do not play an important role. For other applications it is advantageous to implement a closed loop system. In a closed loop system the motion of the actuator will be measured and any unwanted changes from the given position will be corrected by the closed loop electronics.

piezosystem jena uses different types of measurement sensors:

- strain gage measurement systems and
- capacitive sensors.

Strain gages are very compact. They can be integrated in nearly all piezo electrical translation stages from ***piezosystem jena***.

Capacitive sensors should be used for systems needing the highest accuracy and/or dynamics. In some cases it is necessary to measure the displacement somewhere outside of the actuator. To provide the best performance for special requirements it is necessary to know the fundamental properties of the different sensor systems. In all cases it must be taken into account that, for µm and sub-µm accuracy, the full system has to be optimized (actuator, sensor, electronics, environmental conditions, etc.).

9.1. Resolution

The piezo electrical effect is a real solid state effect. In theory there is no limitation to the resolution; an infinitely small change in the electrical field gives rise to an infinitely small mechanical displacement. The real world offers some limits in resolution, which are caused by electrical, mechanical, acoustic and thermal noise.

mechanically:
The mechanical resolution is determined by the design of the drive. Piezo actuators from ***piezosystem jena*** are made with flexure hinges. Due to this construction principle no mechanical play arises, whereby the mechanical resolution is unlimited.

electrically:
During operation the resolution indicates how much the piezo actuator moves if no motion is indicated i.e. the output voltage of the amplifier is to remain constant. This resolution is determined by the noise of the output voltage. Here only the frequency range of the output voltage is taken into consideration, which the actuator is able to follow.
Usual piezo actuators with lever transmission of ***piezosystem jena*** have a resonant frequency between 200Hz and 750Hz, so the output voltage is measured only up to this frequency. Frequencies above this range can not be converted into a motion by an actuator. A voltage noise of 0.3mV means that the piezo actuator has a resolution of 0.2nm, related to a total travel of e.g. 100µm @ 150V (total voltage range: -20 …+130V).

$$\text{resolution} = \frac{(\text{total stroke} \cdot \text{voltage noise})}{\text{voltage range}}$$

For the resolution in the closed loop mode the noise of the measuring system must be additionally considered. Therefore the noise of the output voltage in the closed loop mode is measured.
This value depends on the used actuator, the measuring system, the adjusted control parameters and the amplifier. The commutation of the resolution is made according to the formula indicated above.
The data for non-linearity related to the position, repeatability and lower and upper voltage limit are provided on the calibration report sent with the system.

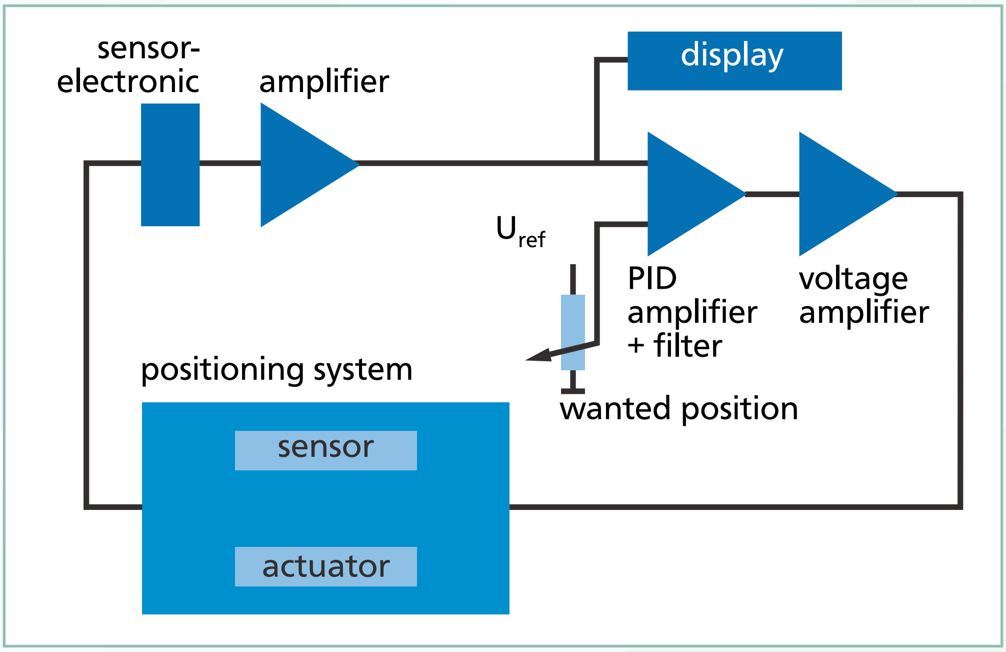


Figure 8.1. *principle of the closed loop control*

To measure the resolution of a closed loop system we used a PX 100 with capacitive sensor and a power supply NV 40/3 CLE.
The investigations were done considering best environmental conditions as mentioned above.
The element was driven with a square function of approximately 40mV amplitude.

In figure 9.1.1. and 9.1.2. we show the sensor voltage and the measurement signal of the laser beam interferometer.
The measurements were done for two different filter frequencies of the sensor electronics -10Hz and 1KHz.

You can see that the sensor signal with the 10Hz filter seems to be even better than the interferometer signal.
The reason is that higher frequencies do not pass the 10Hz filter of the electronics and thus they are not measured. The sensor seems to be less noisy which can result in a higher accuracy of the full system.

Please note
The highest positioning resolution requires very stable measurement conditions. The best measurement conditions are:

- a well-grounded environment
- an area far from electromagnetic fields (use shielded cables)
- vibrationally isolated conditions (an actively damped table is recommended)
- stable temperature conditions

Otherwise the environmental conditions will determine the resolution of the experiment.

9.2. Linearity

In the ideal case, the relation between the input signal (signal defining the position of an actuator) and the output signal (realized motion) should be linear.
When speaking about systems with integrated sensors, the linearity of the sensor (plus sensor electronics) is an important quality parameter.

Absolute position calculated from sensitivity
The linearity describes the approximation of the relation between indicated and true position.
With the measured voltage (MON) the reached position is to be calculated on the basis of the formula below.

The current values for the following calculations are taken from the calibration protocol (e.g. see page 108).

$$\text{reached position} = \frac{\text{measured voltage - minimum voltage}}{\text{sensitivity}} \qquad (9.2.1.)$$

Example number 21
minimum voltage = - 0.007V*
total stoke = 400µm*
sensitivity = 0.0248V/µm*

measured voltage = 3.864V

$$\text{reached position} = \frac{\text{measured voltage - minimum voltage}}{\text{sensitivity}}$$

$$\text{reached position} = \frac{(3.864 + 0.007)\mu m}{0.0248}$$

$$= 156.088\mu m$$

* values are given in the calibration protocol

Absolute position calculated from sensitivity with consideration of the non-linearity
As already mentioned, the monitor output voltage gives the best values for the current position of the system.
Taking into account the measured non-linearity of the positioning system (see calibration curve) the absolute position calculated from the sensitivity should be corrected by the non-linearity.

The deviation of the true actuator position from this linear relation is the non-linearity. This is described by a polynomial function of higher order. In order to calculate the true actuator position on the basis of the measured voltage, the non-linearity must be taken into account.

$$\text{reached position} = \frac{\text{measured voltage - minimum voltage}}{\text{sensitivity}} + \text{total stroke} \cdot \text{nonlinearity}_{@position}/100 \qquad (9.2.2.)$$

Example number 22
minimum voltage = - 0.007V*
total stroke = 400µm*
sensitivity = 0.0248V/µm*
non-linearity$_{@157\mu m}$ = 0.037%

measured voltage = 3.864V

$$\text{reached position} = \frac{\text{measured voltage - minimum voltage}}{\text{sensitivity}} + \text{total stroke} \cdot \text{nonlinearity}_{@position}/100$$

$$= 156.088\mu m + 148nm$$

$$= 156.236\mu m$$

* values are given in the measurement report

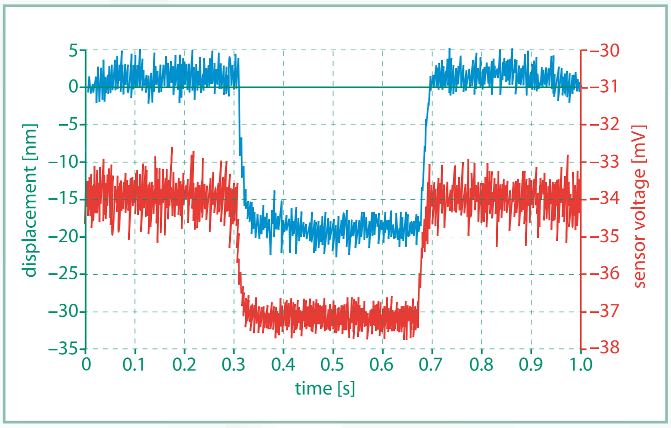


Figure 9.1.1. *voltage signal from the capacitive sensor (red line) in comparison with the interferometer signal (blue line). The filter frequency of the sensor was set to 1kHz.*

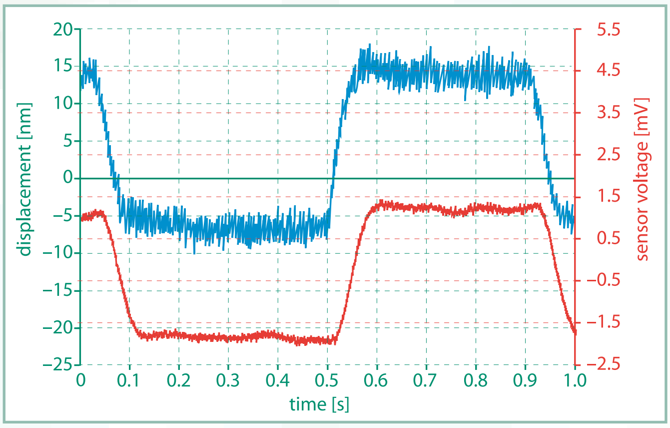


Figure 9.1.2. *voltage signal from the capacitive sensor (red line) in comparison with the interferometer signal (blue line). The filter frequency of the sensor was set to 10Hz.*

piezoline

Taking into account the non-linearity of 148nm at the position of the system of 156µm (MON = 3.864V) had to be corrected to 156.236µm. We determine the linearity of a sensor system in the following way: We operate the piezo actuator with a sinus wave over the full range of motion. The motion of the system will be measured by the inte - grated sensor and by the laser beam interferometer.

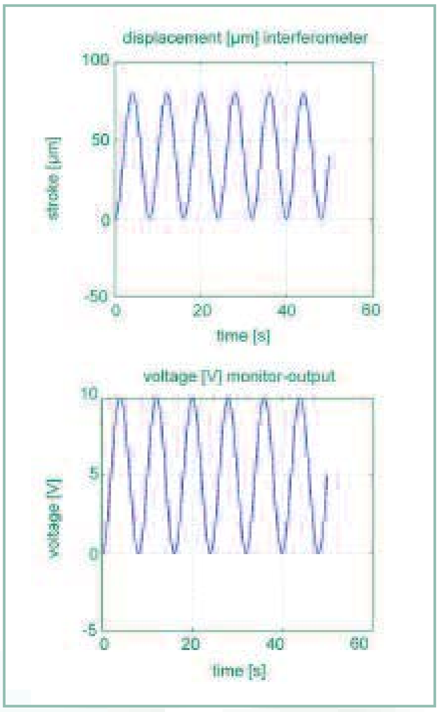


Figure 9.2.1. *sensor output signal and signal from laser beam interferometer*

Figure 9.2.2. shows the linearity of a PX 100 system with a strain gage measurement system.

9.3. Repetition accuracy (repeatability) ISO 5725

The repetition accuracy designates the error which arises if the same position from the same direction is approached again and again. In order to achieve a certain position repeatedly the same modulation voltage must be applied. The difference between modulation voltage and monitor voltage is regulated to zero by the electronic controller. The deviation of the different reached positions is indicated by repeatability. In the provided calibration protocol the maximum value of this error is indicated.

Note
The exact position of piezo elements cannot be accurately represented by an amplifier display due to its resolution. For highly exact positioning requirements it is recommended to supervise the position over the monitor voltage. For this an appropriate digital voltmeter is necessary.

9.4. Dynamic properties of a closed loop system

As stated, all single parts of a closed loop system influence the dynamic properties. This includes the properties of the actuator, of the sensor and the electronic system.

Please note
When speaking about the properties of the actuator, it means the actuator as integrated into the real experiment. Additional masses or any forces from outside can influence the dynamic properties dramatically. Since we do not know how an individual might make use of our actuators, we did not load additional masses onto the actuators in our experiments. You will find further details about dynamical properties in chapter 5.

The closed loop electronics, utilizing control algorithms (P, PI, PID etc.) also affect the dynamic behavior. Each control system has to be calibrated with the special actuator. Do not change any modules or actuators of a closed loop control system!

Do not hesitate to ask us if you have any questions!

For a correct analysis of the dynamical properties, the damping curve and the phase shift over the frequency variation has to be measured. The dynamic function for operating the element should be investigated with respect to the containing frequency.
The driving frequency must be smaller than the maximum frequency of the full system. To ensure this, any curve differing from a sine wave form should be analyzed so as not to exceed the containing frequencies. Therefore, a Fourier transform must be made.

Of course this is not very practical.

An approximation in control theory says that the maximum system frequency of a feedback controlled system should be ten times less than the lowest characteristic frequency of the open loop system.
To give a simple impression of what we achieve in closed loop, we did some pure tests with the elements PX 100 with strain gage sensor. The element was driven with a rectangular function of 10Hz with an ampli-

piezosystemjena

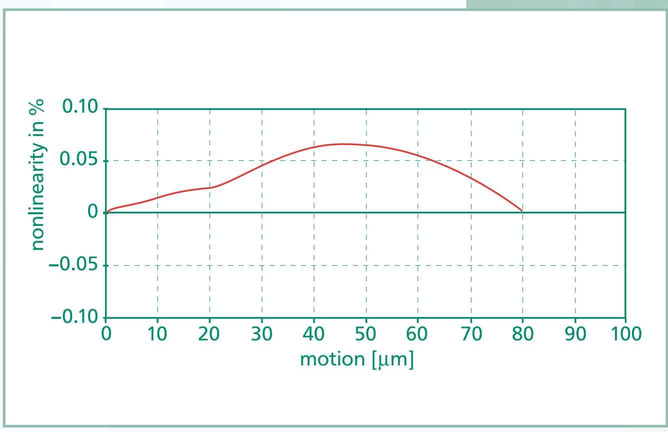


Figure 9.2.2. *linearity of a PX 100 with strain gage (SG)*

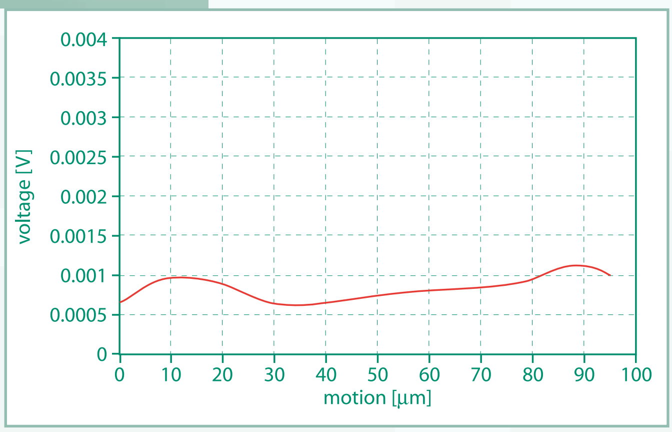


Figure 9.3.1. *typ. repeatability for a PX 100 with capacitive measurement system*

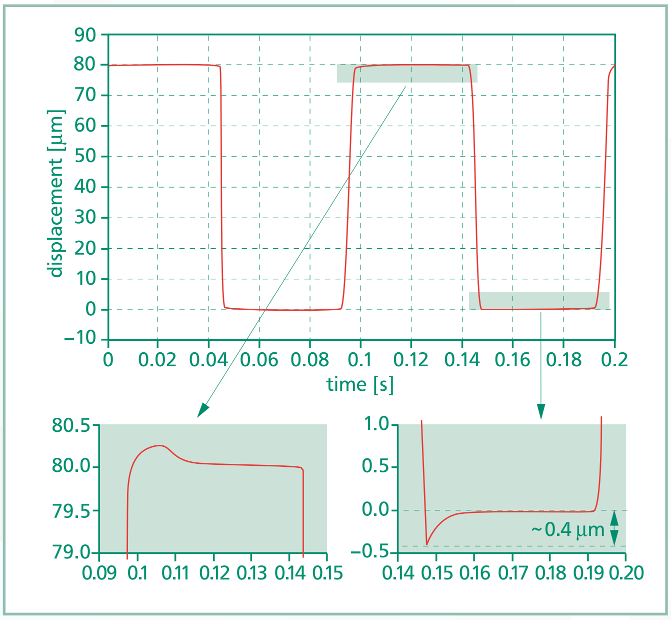
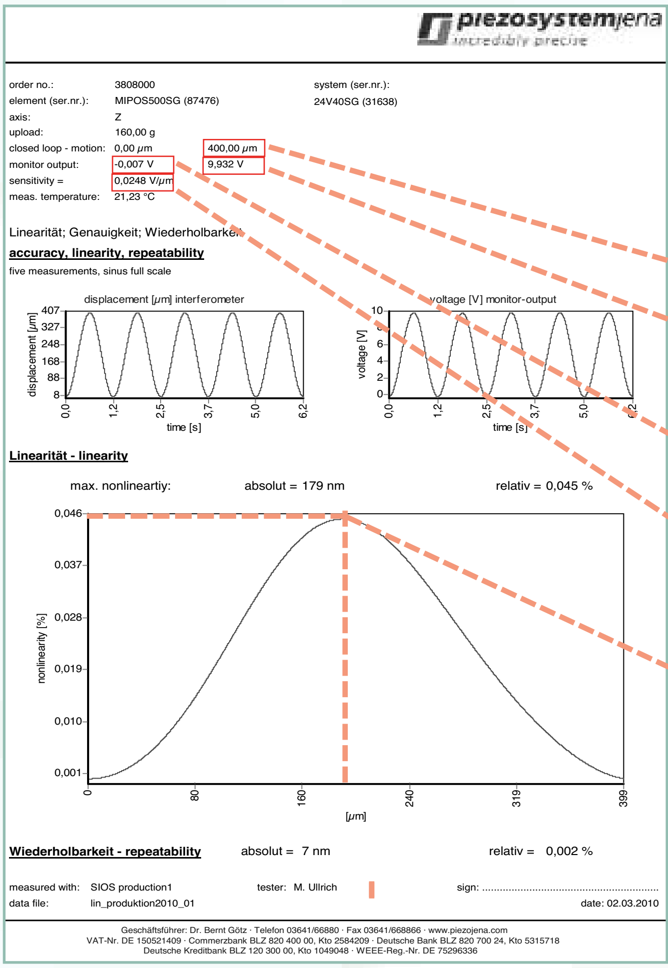


Figure 9.4.1. response time of a closed loop system PX100 with a strain gage measurement system

tude of approximately 50% of the full motion. We determined the time in which the system reached an accuracy of 99% and 99,9% of the final position *(see **Figure 9.4.1.**)*.

	dynamic work in closed loop	dynamic work in open loop
ENV 40 module	not recommended	not recommended
ENV 300 module	within the bandwidth of the system	within the bandwidth of the system
ENV 800 module	within the bandwidth of the system	within the bandwidth of the system


piezosystemjena
incredibly precise

order no.: 3808000
element (ser.nr.): MIPOS500SG (87476)
axis: Z
upload: 160,00 g
closed loop - motion: 0,00 µm 400,00 µm
monitor output: -0,007 V 9,932 V
sensitivity = 0,0248 V/µm
meas. temperature: 21,23 °C
system (ser.nr.): 24V40SG (31638)

Linearität; Genauigkeit; Wiederholbarkeit
accuracy, linearity, repeatability
five measurements, sinus full scale

Linearität - linearity

max. nonlineartiy: absolut = 179 nm relativ = 0,045 %

Wiederholbarkeit - repeatability absolut = 7 nm relativ = 0,002 %

measured with: SIOS production1 tester: M. Ullrich sign: ....
data file: lin_produktion2010_01 date: 02.03.2010

Geschäftsführer: Dr. Bernt Götz · Telefon 03641/66880 · Fax 03641/668866 · www.piezojena.com
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Deutsche Kreditbank BLZ 120 300 00, Kto 1049048 · WEEE-Reg.-Nr. DE 75296336

9.5. Calibration protocol for closed loop system

Each closed loop system to be delivered to our customers is calibrated to reach the optimum values in linearity and repeatability.
These data are shown in calibration protocol coming with the system.

meaning of parameters

a) Total range of motion

b) Maximum corresponding voltage (voltage at the monitor output, system switched into closed loop operation)

c) Minimum voltage (closed loop) at monitor output

d) Sensitivity (range of voltage related to the full range of motion)
(see also formula 9.2.1)

e) nonlinearity@200µm = 0.0447% = 179nm

How to calculate the nonlinearity in nm from the data of the calibration protocol: (see 2nd term of formula 9.2.2)

$$\text{nonlinearity} = \frac{\text{max. motion} \cdot \text{nonlinearity}_{@200\,\mu m}\,(\%)}{100}$$

$$\text{nonlinearity} = \frac{400\mu m \cdot 0.0447(\%)}{100}$$

nonlinearity = 179 nm

10. *Electronics supplied for piezoactuators*

10.1. Noise

In chapter 3.3. we mentioned that the sensitivity of piezo electrical actuators is only limited by the voltage noise of the power supply. If a power supply has a noise given by ΔU, the mechanical motion ΔX, determined by this noise will be:

$$\Delta x = \Delta l \cdot \frac{\Delta U}{U} = \left[\begin{matrix} \Delta l = L_0 \\ U = U_0 \end{matrix}\right] = L_0 \frac{\Delta U}{U_0} \qquad (10.1.1.)$$

Where U is the current voltage to the piezo-element, Δl is the expansion for the voltage U.

Power supplies from ***piezosystem jena*** are developed and optimized especially for piezo electrical actuators. So they have excellent noise characteristics, which allows positioning in the nm range.
(see ***Figure 10.1.1.***)

Example Number 23
The power supply NV 40/3 CLE is suited for 3 channels (e.g. a TRITOR element for 3D positioning). This device has a voltage noise of < 0.3mV. For a maximum output voltage of 150V this is a dynamic range of < $2 \cdot 10^{-6}$. For a piezo element with a motion of 50µm we yield a mechanical noise of 0.1nm.

10.2. Current

For dynamical motions all power supplies from ***piezosystem jena*** have a modulation input for each channel. So it is possible to generate oscillations given by a function generator via the modulation input. The electrical properties of piezo electrical actuators are such that they act as capacitors with a high inner resistance of typically $10^{10}\Omega$.

electrical capacitance of:
high voltage actuators: 60nF
multi-layer low voltage actuators: 1800nF

For static and quasi-static applications the current needed does not play any role. Because of their high resistance piezo electrical actuators practically do not need current to hold a position. They can also hold a position after separation from the power supply (please consider the safety instructions!). For dynamical applications we should consider the problem of charge and discharge the large capacitances C. The maximum current i_{max} that would be needed for the actuator is:

$$i_{max} = C \cdot \frac{dU}{dt} \qquad (10.2.1.)$$

dU/dt – rise time of the voltage.

The amount of the current needed can be very high for dynamical operations, so the rise time of the voltage and so on of the motion is often determined by the maximum current of the power supply.

For a dynamical operation with a sinusoidal function, the maximum current i_{max} is determined by:

$$i_{max} = \pi \cdot f \cdot C \cdot U_{pp} \qquad (10.2.2.)$$

i_{max} – peak current required for sinusoidal operation (in A)
U_{pp} – peak-peak drive voltage (in V)
f – frequency (in Hz)
C – capacitance of the actuator (in F)

The average current for this operation is

$$i_{av} = \frac{i_{max}}{\pi} \qquad (10.2.3.)$$

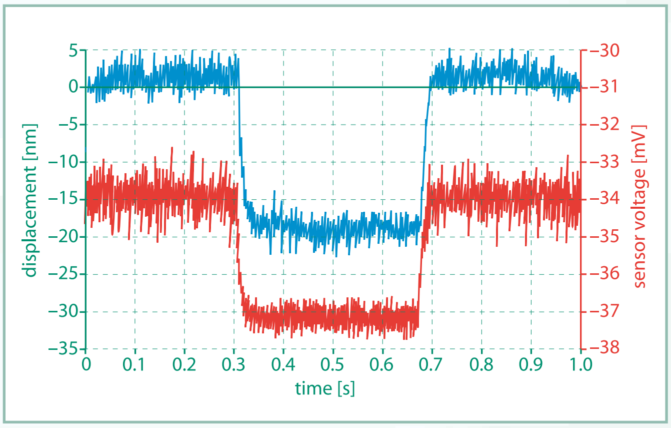

Figure 10.1.1. Noise of the power supply NV 40/3 CLE

10.3. Electrical power

Because of the high current which is needed for dynamical applications, the necessary electrical power is high as well. The power P_{max} for sinusoidal oscillation (with frequency f) of a piezo element with capacitance C will be:

$$s = j \cdot 2 \cdot \pi \cdot f \qquad (10.3.1.)$$

P_{max} – peak power (in W)
U_{pp} – peak-peak drive voltage (in V)
U_{max} – maximum output voltage of the amplifier (in V)
f – operating frequency (in Hz)

The average current for this operation is

$$P_{av} = \frac{P_{max}}{\pi} \qquad (10.3.2.)$$

Example Number 24
The piezo element PAHL 18/20 is suited for high loads and it has a capacitance of 7µF (for small field strength). This value can rise up to 14µF for large operating electrical fields. For an oscillation of 1kHz an actuator with 7µF capacitance requires a current of 3.3A. For a capacitance of 14µF one needs a current of nearly 7A. The output power will also increase 2 times and it will reach 1000W. For such electrical power, heating of the actuator should be considered (see also section 10.6. power loss).

10.4. Switched regime – oscillations with rectangular form

Due to their properties piezo elements can work in a switching regime (e.g. for valve applications). For the voltage supply we use an electronic switch. If a short pulse is given to an actuator, the output voltage (also the voltage at the actuator) U(t) will rise depending on the time t, the capacitance of the actuator C and the inner resistance of the power supply R_i.

$$U_A(t) = U_0\left(1 - e^{-\frac{t}{R_i \cdot C}}\right) \qquad (10.4.1.)$$

U_0 – maximum output voltage of the supply.

If the inner resistance of the power supply R_i is small enough, the output voltage increases very quickly. This can be realized faster than

the minimum rise time of the actuator, which is determined by the resonant frequency (see also section 5.1.). That's why the actuator is not able to expand faster. In such case the actuator will expand corresponding to the given electrical charges and so the expansion will reach an intermediate state smaller than the maximum output voltage U_0 of the power supply.
In this way it is possible to generate a continu ing signal form with an electrical switch by a series of charging and discharging pulses.

10.5. Coupling factor

The mechanical energy W_{mech} stored in the piezoelectrical material is created as a consequence of applied electrical energy. The electromechanical coupling factor k_{33} describes the efficiency of the conversion of the electrical energy W_{electr} into stored mechanical energy W_{mech}.

$$k_{33}^2 = \frac{d_{33}^2}{\varepsilon_{ee}^T \cdot S_{33}^E} = \frac{W_{mech}}{W_{ges}} \qquad (10.5.1.)$$

It can also be seen that the coupling factor depends on the direction and the parameters of the material. The formula is given here for the longitudinal effect.

The above mentioned formula is valid only for static and quasi-static conditions. Power losses (e.g. by warming) are not included. The electrical power, which is not converted into mechanical energy (as expressed by the coupling factor), is given in form of electrical charges. These charges are returned to the power supply while unloading the actuator's capacitance.

For piezoelectrical materials, the coupling factor k_{33} reaches values up to $k_{33} = 0.68$.

10.6. Power losses – dissipation factor

In the static regime the actuator stores energy $W = \frac{1}{2} \cdot C \cdot U^2$. While unloading the piezo elements most of the electrical energy returns to the power supply. Only a small part will be converted into heating the actuator. These dissipation losses are expressed by the dissipation factor, the tangent of the loss angle δ.

$$P = P_{OUT} \cdot \tan\partial \sim f \cdot C \cdot U^2 \cdot \tan\partial \qquad (10.6.1.)$$

Example Number 25
Let us consider the data given in example 24 (section 10.3). For the modulation of the piezo element PAHL 18/20, an electrical power of approximately 1000W is necessary. The dissipated energy will be in the order of 50W, concentrated to a volume of 2ccm. After a short time, the actuator will be heated into in the region of the Curie temperature and the piezo element will stop work ing. In such cases effective cooling will be necessary!

Power optimization
In some cases the choice of power supplies and piezo elements can be optimized for minimum power requirements. It might be better to use a longer stack with a lower operating voltage.

11. Lifetime – reliability

When speaking about lifetime of piezoelements 3 factors must be considered:

1. working under static conditions
2. working under dynamic conditions
3. lifetime of stages with solid state hinges

11.1. Working under static conditions

The determined effect limiting the lifetime of piezoelectric actuators is the ion migration of the electrodes due to the applied electrical field and the environment conditions (humidity and temperature). The best conditions for long lifetime are dry environment conditions and operating voltages as low as possible.

The most important method used to increase the lifetime of piezo electric actuators is to seal the ceramic against humidity. This can be done with an appropriate coating or a sealed housing. Especially if the application requires a long period of permanently applied DC voltage, a sealed housing is strongly recommended.

A calculation of the lifetime of piezo electric actuators can be given with respect to measurement tests that were conducted under the most hostile conditions. These investigations were done with common multilayer stack-type actuators in a totally sealed housing.
With respect to the given measurement conditions, some acceleration factors are used to calculate the lifetime under more realistic conditions. An estimation for the reliability of piezo electric actuators can be given with the following equation:

$$MTTF_E = MTTF_M \cdot A_V \cdot A_H \cdot A_T$$

– (MTTF = mean lifetime)

with:

$MTTF_E$ – estimated mean lifetime value

$MTTF_M$ = 500 h – reference value at maximum voltage (150V) at temperature of 40°C (104°F) and a relative humidity of 90%

$A_V = \left(\frac{150}{V_r}\right)^{3.2}$ – acceleration coefficient due to voltage V_r (DC)

$A_H = \left(\frac{90}{H_r}\right)^{4.9}$ – acceleration coefficient due to humidity coefficient Hr

$A_T = \left(\frac{3}{2}\right)^{\frac{40-T_r}{10}}$ – acceleration coefficient due to temperature T_r

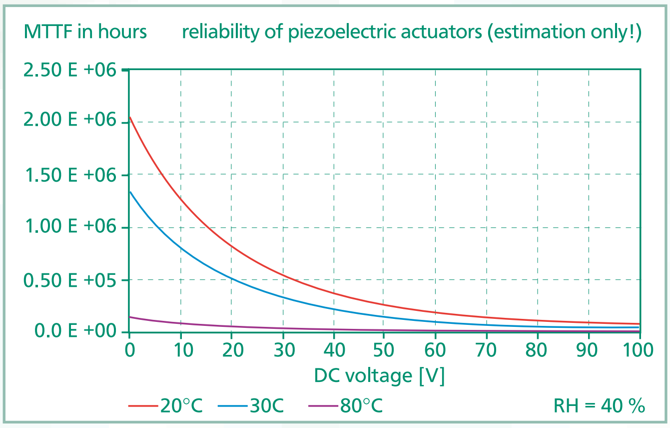

***Figure 11.1.1.** reliability of piezo electric actuators*

piezoline

Please note:
The calculations do not include some conditions, which may occur in practice (pressure conditions, quality of the sealing, handling and operating conditions). That's why the real lifetime of the actuator may differ from the calculated value.
The reliability of multilayer actuators can be very high, several tens of years. But the piezo elements have to be handled carefully and kept away from humid environmental conditions. Most of the piezo elements from ***piezosystem jena*** are sealed to reach a high reliability!

11.2. Working under dynamic conditions

As mentioned in 11.1. working under static conditions electric break can occur because of the migration of the electrode material into the ceramic layers. The reason may be high humidity and a constant electric field under high voltage. Working dynamically the reliability is much higher. A changing electric field converts the direction of the electrodes, migration is much less than under static conditions. There is no formula describing reliability under dynamic conditions because of the large number of technical parameters.
Piezo elements of ***piezosystem jena*** have been used for over 18 years in many different applications in research and development as well as in many industrial applications. Year by year we deliver many thousands of actuators to many customers. Proper handling during the construction of piezo electrical stages and working together with our customers ensures a long term reliability of our products without any significant failure rates.

11.3. Lifetime of stages with solid state hinges

Piezoelements consisting of a piezo stack integrated into a metal stage with solid state hinges are stable over a long period of time, if designed properly. The solid state hinges result in a lever transmission of the motion of the stack, which is amplified several times. If care is taken that the bending always keeps in its elastic range, a long lifetime exceeding billions of (10^9) of cycles can be guaranteed.
Because of our many years of experience, we know how to develop stages with a long and reliable lifetime. When operating piezo elements avoid excitation in the range of the resonant frequency of the stage. When this resonant frequency is excited, ringing and overshooting can lead to oscillations much higher than the resonant frequency, finally leading to a break of the solid state hinges.

Most failures of piezo elements occur because of improper mechanical handling and use of the elements. For proper handling and use please see also chapter 2.

12. *Piezo electrical, electrostrictive and magnetostrictive actuators*

When using a solid state effect for generating a motion, piezo electrical actuators are the most commonly used actuators. But a motion can also be generated by using other effects such as the electrostriction and magnetostriction.

We will give you an overview about these other principles.

Overview

	piezo electrical effect	electrostrictive effect	magnetostrictive effect
material	PZT	PMN	Terfenol
Curie temperature	150–350˚C	10˚C	ca. 380˚C
phase of material	ferroelectrical	paraelectrical	ferromagnetical
prepolarisation	synthetic by electric field	remanent	synthetic by electric field
dependence of expansion	S~E	$S \sim E^2$	$S \sim H^2$
hysteresis	10–15 %	2–3 % * (ΔT very small)	1–3%
electrical equivalence	capacitance	capacitance (5 x higher)	inductivity
electr. control	voltage	voltage	current
coupling factor	up to 0.65	up to 0.65	up to 0.75
tanδ	0.05	<0.05	–
temperature range	up to 70% T_C	ΔT~30K	up to 70% T_C
temperature dependence of the effect	small	large	small

*only in a very small temperature range

Electrostriction
The electrostriction effect basically exists parallel to the piezo electrical effect.
The electrostrictive effect can be used above the Curie temperature. So electrostrictive materials are made from ceramics with a low Curie temperature. Electrostrictive actuators are also built as stack type actuators. The expansion of electrostrictive materials is nearly the same as for piezo electrical materials.
In a small temperature regime of a few degrees electrostrictive materials show a small hysteresis (2–3%). But outside of this temperature range the hysteresis is larger than the hysteresis of piezo electrical materials. So electrostrictive materials can be used only in a small temperature region (ΔT ~ 10K). That is why these actuators do not find such a wide range of applications like piezo electrical actuators.

Magnetostriction
A ferromagnetic material shows expansion under an applied external magnetic field. This effect is called the magnetostrictive effect and can be used for the construction of actuators. The material used is Terfenol.

Compared with the piezo electrical and electrostrictive effect magnetostrictive actuators show similar properties. Magnetostrictive actuators have a higher Curie temperature and there is the possibility of thermal separation of the cooling system and the magnetostrictive material.

13. Guidelines for using piezo electrical actuators

Piezo ceramics are relatively brittle materials. This should be noted when handling piezo electrical actuators. All piezo elements (also elements with pre-load) are sensitive to shock forces.

Piezo elements without pre-load (e.g. series P, elements with lever transmission) should not be used under tensile forces (see also drawing in section 2).

Applications in which tensile forces or shear forces occur should be realized by pre-loaded elements. On request we can optimize the integrated or external pre-loads for special applications.

During dynamical uses can occur internal tensile forces due to the acceleration of the ceramic element itself (see also section 5 dynamic properties).

Pre-loaded piezo elements have a top plate with threads. Please note the depth of the treads. Do not apply large forces for fixing screws at the piezo elements!

Actuators are capacitive loads. Do not discharge actuators by short circuiting the leads. Ensure dielectric strength of your power supplies, wiring and connectors to prevent accidental arcing.

Abrupt discharging may cause damage to the stacks.

Piezo electrical actuators such as stacks or various piezo elements with lever transmission work as capacitors. These elements are able to store electrical energy over a long time and the stored energy may be dangerous.

Connect and disconnect the elements only when the power supply is switched off. Because of the piezo electrical and pyroelectrical effects piezo actuators can generate electric charges if there are changes in the external mechanical loads or the temperature of the actuator.

Before you begin to work with any piezo electrical actuating system note:

Switch off the power supply and discharge the actuator properly by setting the supplies to zero. If the actuator is disconnected, use a resistor for discharging the actuator. Do not switch on the power supply when the actuators are disconnected. Be sure that the electrical contact of the operator to the output connectors of the power supply is not possible when the supply is switched on!

Power supplies for piezo elements are developed especially for these elements. Do not use these supplies for other applications.

Disclaimer

piezosystem jena cannot be held responsible and shall incur no liability for errors in this catalog.

used units and dimensions

a	acceleration [m/s²]
A	cross section of a stack or a single piezoceramic plate [mm²]
C	capacitance of the actuator [F]
c_F	stiffness, constant of an external spring (for example: preload) [N/µm]
$c_T=c_T^E$	stiffness of the actuator, translator (for E = constant) [N/µm]
$d = d_{ij}$	piezoelectric strain coefficient (tensor form); depending on the material and the direction [m/V = C/N]
d_{33}	piezoelectric strain coefficient for the longitudinal effect (typ. 300 – 500 . 10^{-12} C/N)
d_s	thickness of a single ceramic plate [mm]
E=U/L0	external electric field strength [V/m]
F_{eff}	effective force, which can generated by an actuator for a given voltage [N]
F_{max}	blocking force of the actuator, maximum force which can be generated by the actuator at maximum operating voltage (if the actuator is mounted in a position where it can´t expand itself) [N]
F	force [N]
f	frequency [Hz]
f_{res}	resonant frequency [Hz]
i_{max}	maximum output current of the amplifier that is necessary for loading the actuators capacitance [A]
k	electromechanical coupling factor [without dimension]
L_0	length of the actuator (in a good approximation this length can be taken also for the length, which is piezoelectrically active $L_0 \approx l_z$ [mm])
l_z	length of the piezoelectrically active part of the actuator [mm]
Δl_z	expansion of the actuator in z-direction [µm]
$\Delta l_{x,y}$	expansion in x or y direction [µm]
Δl_0	expansion of an actuator without any external loads of forces [µm]
Δl	expansion in general (also under external loads) [µm]
m_{eff}	effective mass (mass that will be moved), for an actuator that is clamped at one side, as a good approximation can be taken: $m_{eff} \approx m/2$ [g]
M	additional mass loaded to an actuator [g]
n	number of piezoelectrical plates of an actuator [without dimension]
P	electrical power [W]
P_{out}	electrical power which is needed by the actuator [W]
R_i	inner resistance of the power supply; amplifier [Ω]
S	relative strain [without dimension]
s_{ii}	elasticity or compliance tensor (reciprocal value of the “Young modul”) [m²/N]
S_{33}	elasticity for the longitudinal effect [m²/N]
T_C	Curie temperature [C]
T=F/A	mechanical stress (e.g. because of an external force) [N/m²]
t	time [s]
U_0	maximum operating voltage [V]
U	actual voltage at the actuator [V]
$U_A(t)$	voltage at the actuator in dependence of the time [V]
TF	factor of a lever transmission [without dimension]
α	linear thermal coefficient of expansion [1/K]
$\tan\partial$	tangent of the loss angle; ∂-loss angle [without dimension]
ϕ	phase angle of an oscillation [without dimension]
ϵT_{33}	absolut dielectricity constant (typ. $\epsilon T_{33} \approx 5400$; $\epsilon_0 = 8{,}85 \times 10^{-12}$ F / N)