Piezo Theory: Chapter 1 - Physics & Design

Piezoelectric effect – inverse piezoelectric effect

The result of external forces to a piezoelectric 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.

$$U = \frac{d \cdot F}{C}$$

Figure 1.1

d - piezoelectric module; parameter of the material (depending on the direction)

C - electrical capacitance

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

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

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

An applied voltage to a piezoelectric material can cause a change of the dimensions of the material, thereby generating a motion. Lippmann predicted this inverse piezoelectric effect and the Curie brothers were the first to experimentally demonstrate it. The first applications were in ultrasonic systems for underwater test and also underwater communications.

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

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

Design of piezoactuators

Piezostacks 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 in figure 1.2. Piezostacks are also called actuators, piezoelectric actuators or piezoelectric translators.

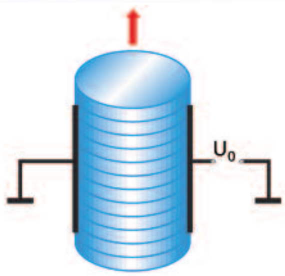

Figure 1.2 Construction of a piezostack

The maximum motion caused by the inverse piezoelectric 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 2 kV/mm. This strength can be reached with different voltage values if used with different thickness of the single ceramic plates.

Example 1

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 (high voltage actuator).

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 and works at voltages typically 130V high.

Example 2

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 10 µm 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.

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It is more complicated to produce multi-layer piezoelectric actuators. Because of the advantage of using 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 Newport Corporation.

Piezostacks 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 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.

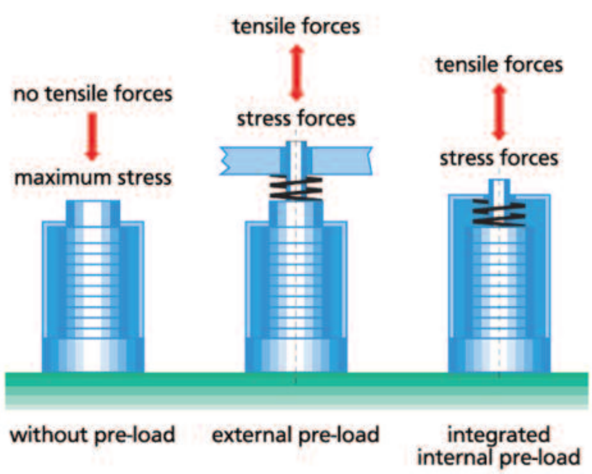

Figure 1.3 Piezos with and without preload

We recommend using a pre-loaded actuator from Newport Corporation when:

- tensile forces can affect the actuator
- they are used in dynamical applications
- shear forces (shear strain) affect the actuator (external forces perpendicular to the direction of motion)

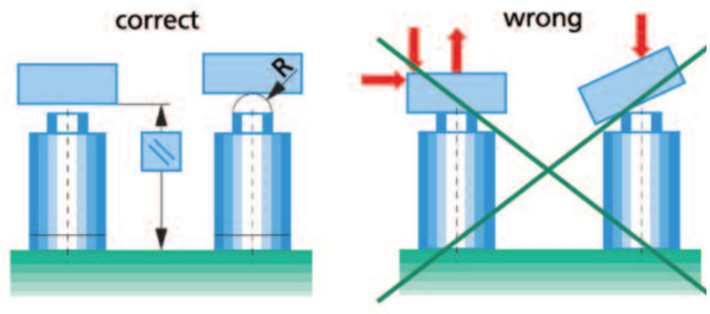

Figure 1.4 Tilting forces

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.

Properties of piezo mechanical actuators

Expansion

The relative expansion S =△l/L0 (without external forces) of a piezoelement is proportional to the applied electrical field strength. Typical values of the ceramic materials are S△0.1 - 0.13% (field strength E = 2kV/mm).

$$\frac{\Delta l}{L_0} = S = d \cdot E$$

Figure 1.5

S - relative stretch (without dimension)

d = dij - piezo module, parameter of the material

E = U/ds electrical field strength

U - applied voltage

ds - thickness of a single disk.

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The maximum expansion will raise with increasing voltage. The relation is not perfectly linear as predicted by equation (1.5). The characteristic curve reflects the inherent hysteresis (see also section 1.6). 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 piezostacks have motion of 20 - 100µm. For greater expansion, actuators with a lever transmission are superior.

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

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 following curve.

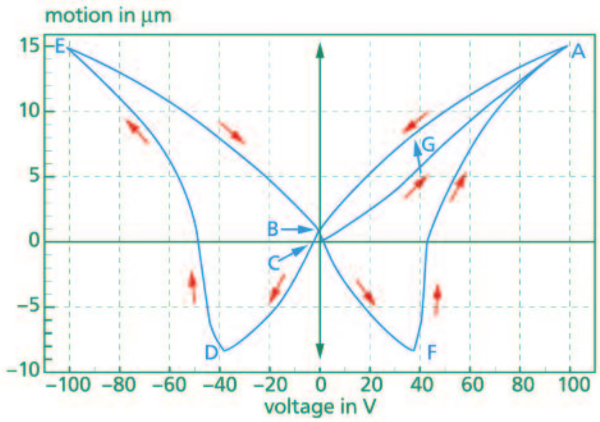

Figure 1.6 Via the applied voltage, the motion of the element will follow the points ABCDEF.

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 piezoelement shows a contraction. After removing the voltage, a permanent polarization will remain. Therefore the motion of the piezoelement 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 piezoelement 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 piezoelement 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 piezoelement. 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 piezoelements show the well-known expansion characteristics.

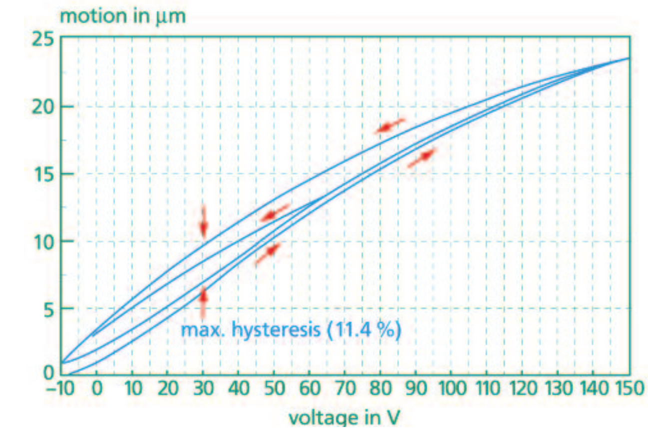

Figure 1.7 Typical hysteresis curve of a multilayer piezostack

To get a larger motion, it is possible to work with a negative voltage in the order of 10V 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 piezoelements. The typical width of the hysteresis is 10 - 15% of the commanded motion.

Working in a small voltage range, the hysteresis is also smaller. This is also shown in the figure 1.7 above.

Each piezoelement provided by Newport Corporation comes with the measured curve of its hysteresis.

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Hysteresis 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. OEM elements for industrial applications for piezoelements 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 piezoelement must work constantly with maximum expansion (under maximum voltage) over a long time period.

Resolution

Independent of the hysteresis, the piezoelectric effect as a solid state effect has a very high resolution. A piezoelement NPX200 from Newport Corporation was tested in an interferometer and a motion of 0.4nm was detected.

Therefore, the resolution is limited by the noise characteristic of the power supply. Our power supplies are optimized to solve this problem.

Example 3

Our plug in PC card has a voltage noise of ? 3mV at the output. Relative to 150V maximum voltage this is a value of 2 · 10-5. Operating a piezoelement with a maximum expansion of 20µm, the mechanical noise of this system will generate oscillations in the order of 0.4mm.

You are invited to speak with our team about various power supplies for their specification.

We have several different voltage amplifiers (power supplies). A compact 3 channel supply, or power supplies in 19 inch eurosystem. A very interesting supply is our plug in PC card, which controls up to 3 different piezoelements directly from the PC.

Stiffness

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

$$c_T^E = \frac{A}{s_{33}^E \cdot L_0}$$

Figure 1.8

The stiffness is proportional to the cross section A of the actuator. The stiffness decreases with an increasing actuator length L0. 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 1.8 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 1.8 can give only a rough estimation of the expected properties of the piezoelements.

Please consider, the electrical capacitance measured for piezoelements with small signals can increase up to 2 times when operated with large signals (under full motion).

Example 4

An actuator with a cross section of 5 x $5mm^2$ and an active length of 9 mm has a stiffness of $cT1^E$ = 120N/µm. With the same construction (cross section, material) but double the length (18mm), the stiffness will be a half stiffness (60 N/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.

Thermal Effects

Temperature variation is an important factor in the accuracy of a micropositioning system. The thermal expansion coefficient of stainless steel for example, is approximately $12 \cdot 10^{-6}\ K^{-1}$. Imagine a cube of $10x10x10mm^3$ - 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 piezoelements with integrated measurement systems depends on the temperature. If the operating temperature is different from the temperature during calibration, errors will occur.

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When speaking about temperature coefficients of piezoelements, 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 $?_{HV}$ (7 - 10)·10^{-6} K^{-1}.

Multi-layer stacks show a negative temperature coefficient of $?_{NV}$? -6·10^{-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.

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

Figure 1.9

Δltherm = thermal expansion of the whole actuator

Lpiezo = length of the piezo stack

Lmetal = length of the metal housing

αpiezo = temperature coefficient of the piezo ceramic

αmetal = temperature coefficient of the metal housing

ΔT = temperature differential

Example 5

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

$$\Delta l_{Aktor} = \Delta l_{Stahl} + \Delta l_{stack} + \Delta l_{Piezoeffekt}$$

Figure 1.10

The length of the steel parts is 16 mm:

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

Figure 1.11

The length of the steel parts is 19 mm:

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

Figure 1.12

So the total difference is $\Delta l_{actuator}$=0.78µm

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

$$\left(\alpha_{piezoeffect} = 4 \cdot 10^{-3} \cdot K^{-1}\right)$$

Figure 1.13

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

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

Figure 1.14

Δl_{T1}= expansion at T1

Δl_{T0} = expansion at room temperature

$\Delta T = T_0 - T_1$

αpiezoeffect= temperature coefficient of the piezo effect

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

Example 6

To estimate what maximum stroke by a NPX200 at -195°C (liquid nitrogen) can be expected, the temperature difference to -10°C should be calculated. So it is ΔT=185K. The estimated stroke is around 25µm.

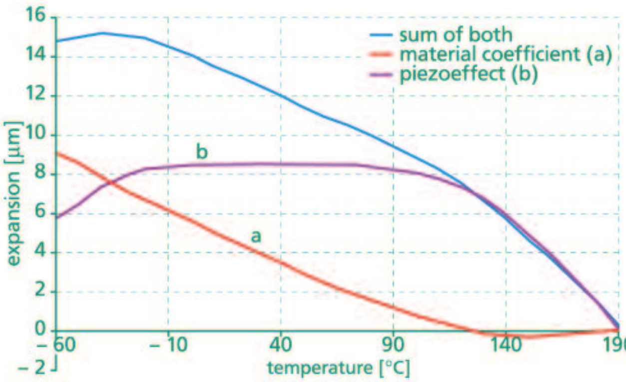

Figure 1.15 Example of temperature dependence of multilayer ceramic L_{piezo}=18mm at room temperature.

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c) The ferroelectric hysteresis decreases with falling temperature. The hysteresis of piezoelectric actuators is a result of the ferroelectric polarization. For example, at very low temperatures of four Kelvin 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.

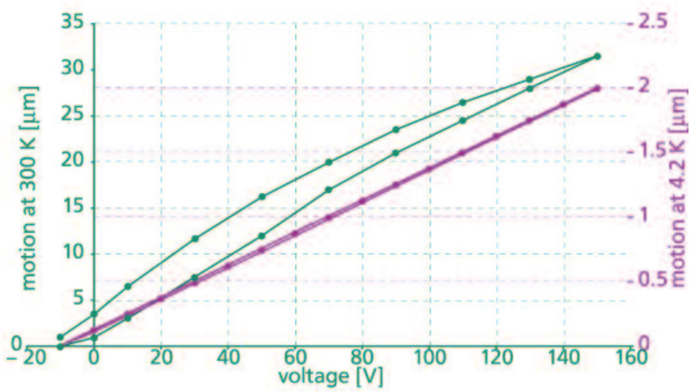

Figure 1.16 Hysteresis curve of a NPA 25 element at room temperature and at 4K.

But please take into account:

Although the piezo effect decreases with falling temperature, piezoelectric actuators principally can work at very low temperatures - down to the temperature of liquid He (4K).

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 piezoelement 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, piezoelements show the best accuracy.

Capacitance

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

$$C = n \cdot \varepsilon_{33} \cdot \frac{A}{d_s}$$

Figure 1.17

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 7

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 1.17).

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

Let us consider the following comparison:

Example 8

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 1.17. 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.

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Please note:

The piezoelectric 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.

Drift - creep (open loop systems)

Another characteristic of piezoelectric 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 1.18.

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.

$$\Delta l(t) = \Delta l_{0.1}\left(1 + \gamma \cdot \lg\frac{t}{0.1s}\right)$$

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

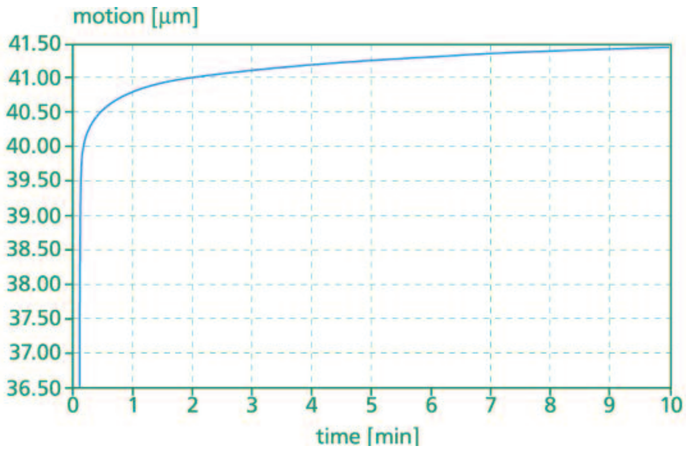

Figure 1.18 Creep of a PU 40

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 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.

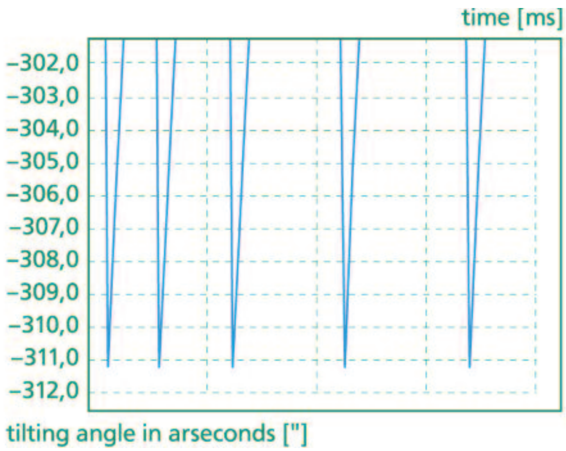

Figure 1.19 Repeatability of a position with periodic motion of a mirror mount

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