A Primer in Piezo Actuation Technology

Welcome to the *Piezotechnics Handbook*, authored by Dr. Peter Jänker, Managing Director of Piezotechnics Dr. Jänker GmbH.

As an independent specialist in piezoelectric technology, our company is committed to innovation, precision, and reliability in the field of piezoelectric actuators and systems. Our mission is to provide customers with high-quality piezoelectric actuators and accessories — along with expert advice and dedicated support throughout the development of cutting-edge applications.

We look forward to supporting your projects with technical insight and customized solutions.

The 14th of May, 2025.

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Contents

Introduction

This manual provides newcomer a comprehensive introduction into piezo actuation technology. The customer will be able to perform a first analysis of his actuation tasks, the design of actuation system and the select right actuators and proper electronics.

The idea of piezo actuators is as simple as it is effective: an electric voltage controls a compact block of active piezoelectric material. It changes its length directly with the applied voltage and can run at very high power setting movements of loads.

Highlights of Piezo Actuation

Piezo actuation is a solid-state technology, which enables unique high technology solutions. The concept of piezo actuation is simple and elementary: A monolithic block of piezo material generates electrically controlled displacement. Due to unique characteristics piezo actuators extend the capabilities of established actuator principles with regards to important aspects:

- High force density, force up to 400 N per cm^2.
- High forces up to tons load capability.
- Displacement of stack actuators are up to 400 um and several mm for stacks with amplification gear or bender type actuators.
- Fast response: up to several ten kHz, tens of microseconds rise time and ultra high acceleration up to 100.000 $^{m}/_{s^2}$ are possible.
- High stiffness. Piezo is the only structural actuator.
- Solid-state – no friction, no lag and no wear.
- High stroke resolution. The travel is controllable up to the sub nm range.
- Retain position with very low power consumption.
- Unique form factor, scalable size down to mm dimensions.
- Piezo does not generate magnetic fields and does not interact with them.
- Conform with vacuum and cryogenic environment.
- Low drive voltage (150 V).
- Simple mechanical interfaces.
- High cycle number. Up to 10^{10} life.

Monolithic stack actuators are operated at moderate voltage levels of maximum 150 V, which is by factors lower than traditionally stacked actuators.

Multi-functional devices with performances concerning actuation, sensing capabilities for structural properties (strain, stress) and acceleration.

Applications

Piezo actuation has excellent and unique characteristics that allow unusual solutions. Piezo spurred innovation in a broad range of industries in the last decade. It made its way into valuable applications. Piezo are used for scientific instrumental techniques with atomic resolution. It is also in everyday uses such as ignitors lighters. The applications span is from piezoelectric controlled fuel injectors in automobile engines, vibration and noise reduction systems in helicopters to highly precise positioning equipment. Generally, the applications can be classified in four fields:

- Actuation,
- Voltage transformation,
- Energy harvesting,
- Sensing

Actuation

In the domain of **actuation** piezo cover a broad range of application:

Fast and precise positioning, production machinery, linear and rotary motors (replacement of high precision linear or rotary stepper motor), pumps, pneumatic and hydraulic valves, fuel injectors, dispenser, vibration source, structural actuation and form control, noise and vibration damping, optical and laser applications such as laser mirror alignment, scanning, materials and components testing, precise positioning devices in scientific instruments such as atomic force microscope, shaker, sound and dynamic force generation. For mass-market applications loudspeakers, inkjet printers are well known. Piezo effect Electrical power generation (energy harvesting) and power conversion (transformers). In precision mechanics and mechatronics, piezo actuators are key components in mechanisms used for precision valves in applications such as lathe control, micromachining, micro dispensing, embossing, and engraving.

Voltage transformers

Piezoelectric transformers are highly effective for generating high voltages. A piezoelectric transformer consists of a ceramic block with two functional sections, each equipped with its own electrode structure. The first section serves as the input, while the second provides the output. The spacing of the electrodes in each section differs and determines the transformation ratio.

The device operates in mechanical resonance at relatively high frequencies to maximize power density. The energy undergoes two conversion steps: electrical input power is first transformed into mechanical energy in the input section, which excites the resonance of the entire ceramic body. In the output section, the mechanical energy is then converted back into electrical energy. The output voltage is extracted from electrodes with significantly wider spacing than those on the input side.

These components demonstrate both piezoelectric effects: the direct and the inverse. Their key advantages are compact size and high efficiency in generating high voltages in the watt-range.

Energy harvesting

The piezoelectric effect describes the generation of electrical energy from mechanical deformation. When oscillations are present, piezoelectric elements can be attached to vibrating structures (e.g., machines) to harvest electrical energy.

The output power of such piezo generators depends on:

- the mechanical deformation,
- the vibration frequency,
- and the efficiency of the electromechanical coupling of the piezo material.

Piezostack actuators from Piezotechnics are ideally suited for designing such energy harvesting elements. The achievable output power is determined by the available mechanical energy, the strain experienced by the piezo element, and the operating frequency.

Piezo generators are suitable for powering small electrical loads for low-power applications such as wireless or remote sensors.

Sensors

Piezo are perfect for dynamic sensor applications such as acceleration and force measurement. Forces, which act on a piezo stack, cause the displacement of the charges in the crystal structure of the material and a voltage signal across the terminals is generated. Piezo stacks from Piezotechnics generate quite high usable voltage output and allow direct measurement without amplifiers is possible. The limits of these excellent sensors are the low frequency response. In this situation quartz materials are preferable.

Piezo Actuator Fundamentals

Piezo actuators are linear motors based on electrically controllable deformation of a solid body. The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical and the electrical state in certain crystalline. The piezoelectric effect is a reversible electro-mechanical mechanism:

- the direct piezoelectric effect describe the internal generation of electrical charge resulting from an applied mechanical force)
- the reverse piezoelectric effect (the internal generation of a mechanical strain resulting from an applied electrical field).

The inverse piezoelectric is deployed for actuators and is used for static positioning as well as dynamic actuation up to the production of ultrasonic sound waves.

The key advantages of a piezo actuator are the capability to generate

- extraordinary high force,
- immediate reaction, and
- precise stroke behaviour.

The displacement of a piezo actuator is in first instance proportional to the voltage input. Forces are much higher than that of any other electrical device of comparable size such as a linear voice coil motor. It is extremely important to notice, that the force capability is associated with fairly small stroke.

Piezo Materials

Piezo actuators are solid-state components which are made of a special class of ceramics material. This ceramics have a perovskit structure. The actuators from Piezotechnics are high perfomance compositions bases on formulations of PZT, Pb (lead)-Zr (zirconium)-Ti (Titanium) mixed-oxides. The properties of the PZT material for Piezotechnics actuators are optimized by dopants and manufacturing process. The materials were developed for actuator applications and are world-class performance. The materials were engineered for optimized electrical behaviour, high displacement, force generation, low losses and stability, life and reliability. Actuators of Piezotechnics demonstrated long life and reliability and proved to perform more than 10^{10}cycles with full voltage amplitude at high speed.

The actuators are electrically polarized components. The analogy to piezo is a permanent magnet, which has also the property of being polarized when an external field is applied. During the polarisation process the internal structure (the so-called domains) were oriented and the material obtain a predominant direction. The polarization process increases significantly the strain capability of the component. Piezo materials have physical coupling effects and such as electro-striction (deformation in electric fields) is analogue to the magneto-striction effects present in magnetic materials.

Ceramic Multi-layer Actuators CMA

The benchmark solution for piezoelectric actuators is the co-fired Multilayer Actuator (CMA) technology. The state-of-the–art technology actuator is a prismatic block. The actuator body is a stack of thin (typically less than 100 μm) ceramics layers with intermediate layers of electrically conducting material, which represent the electrode structure. The electrodes of the individual layers are connected alternately with two external conductors so that all layers are designed to generate a perfectly homogenous electric field when a voltage source is connected with the terminals of the external electrodes. The layer technology allows operation of actuators at low maximum voltage of 150 V. The electrode pattern generates high internal electrical fields of the order of 2 kV/mm. Prior to this art ceramics plates and electrode sheets were glued to a cylindrical block. In the CMA production process the whole actuator stack structure including internal electrodes and functional ceramics material is produced in one step. Electrode and ceramics raw materials were formed to a "green" block and sintered at high temperatures to a monolithic block. This process is named co-firing.

Optimized Electrode Structure

On key design aspect of Piezotechnics actuators is the homogeneity of the internal field and an adequately optimized electrode structure. The applied electrical field directly produce internal mechanical stress in the ceramics. For best performance and efficiency uniform deformation of the stack is most desirable. Also, inhomogeneous field distribution cause high tensile stress components in a piezoelectric stack, which is detrimental to the mechanical integrity of ceramics body. Thus, homogenous field distribution is of fundamental importance for performance and life of a piezo stack actuator. Piezotechnics stacks offers actuators with full stack-through electrodes which cover the whole area of the active layers. The stacks have external insulation on the sides to insulate the connector which links the electrodes of same polarity. This geometry is the only solution for an ideal homogeneous field distribution.

Overview on actuator designs

There are two principal classes of piezoelectric actuator designs:

- direct actuation with CMA, multi-layer stack atuators with comprise a large number of stacked thin layers (displacement typ. 9 – 20 μm, Assemblies with less than typ. 400 μm),
- amplified piezoelectric actuators with special gear designs or structural amplification of displacement e.g. with bender designs.

Bending Actuators

Stroke of bender actuators are relatively high and can easily reach 1mm. Acoustic applications of benders are widespread. Telephone capsules for speaker and microphone functions, ultrasonic cleaner, valves driver, pump driver are known

Bending actuators deploy stress-induced deformation and generate displacement like bimetal strips. Bender consists of several layers e.g. a piezo (P) and a metal sheet (M). The layers are glued together. Common bender variants are P-M, P-P, and P^+-M-P^-. The superscript +/- indicates opposite phases of displacement (expansion, contraction). The piezo layer can also be a thin multilayer actuator (low profile multilayer stack actuator). The common piezo bender deploys d_{31} contraction effect whereas the d_{33} effect is effective in multilayer benders for higher performance. When the piezo layer is activated, the adjacent layers of the bender are subject to different stress levels. A torque is generated which deforms the bender.

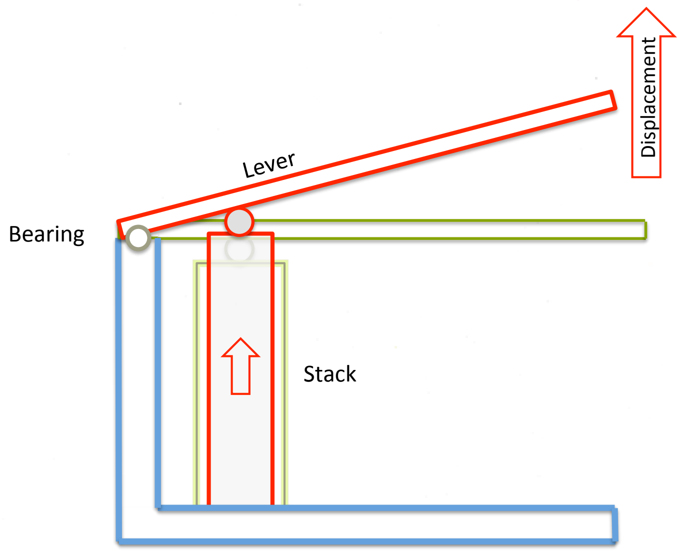
Smart Materials and Multifunctional Structures.

In the 90s of last century an international scene established and smart structures technology emerged. The research stream focussed on the development of advanced multi-functional structures. Structures were studied and realized, which has in addition to load carrying functionality features of actuation, sensing and energy harvesting. Active materials such as piezo and shape memory alloys were prepared and integrated into fibre reinforced plastics. For actuation in smart structures strain induced structural actuation mechanism was developed. Solid-state actuator components such as piezo plates, low profile stacks, or shape memory alloy wires were implemented into composite structures together with electrical wires and sensors. The structures are able to generate twist or bend and significantly deform. Active structures were developed to prototype status for aeronautic applications such as active vibration damping and aerodynamic control purposes. The latter application is highly attractive for gapless smooth aerodynamic elements. The motivation for these novel technologies is about to alter the conventional way of engineering with segregation of structures and systems. Also embedded sensors and systems were developed for health monitoring, self-diagnosis of the structure and some of theses approaches were already implemented in civil buildings and tested in aircraft applications.

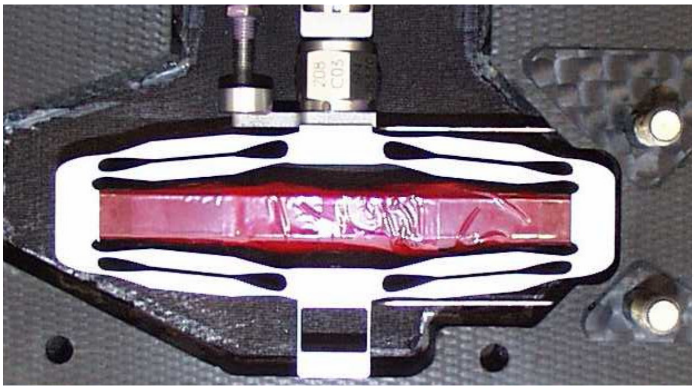
The actuation approaches are manifold and distributed as well as concentrated piezoelectric actuators were integrated in structural configurations. Just to name a few, bending as well as strain-twist-coupling effects were elaborated.

Amplified Actuators

Piezotechnics stack actuators provide active strain of 1000 micro-strain (0.1%) and the standard range of displacement is 10 – 100 micrometer. This is perfect for precision positioning and many other actuation applications like valve control, vibration management. When larger displacements are required a gear may be used to meet application needs. The quality and effectiveness of a gear for piezo is characterized by the preservation of the elastic energy. The elastic energy is ½ free stroke x blocking force. Deformations of the load transmission elements cause losses of the elastic energy and the potential to perform work at a load is reduced. Thus, gears for piezo stack actuators are special designs. Flexural hinges are deployed to minimize play and wear. The next figure shows the principle mechanism of a amplified actuator.



Deformation of the lever under load is an obvious disadvantage of a lever-type design approaches. Any deformation in the mechanism reduces the work potential and the output force of amplified actuators. An elaborated model is presented in the next figure. The device is installed in the outer area of a rotor blades of an helicopter withstand very high mechanical loads and g-forces. The mechanism is numerically optimized for lowest weight and has very high stiffness of the levers as well as flexibility.



Source: ICAS 2008, PIEZO ACTIVE VIBRATION AND NOISE CONTROL IN HELICOPTERS

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The ultimate design approach employs fibre reinforced plastic materials, which provide anisotropic properties to optimize flexibility as well as stiffness to those devices.

Physics and constitutive equations

Internal electrode structure and electro-mechanical coupling effect

Piezo materials are highly dielectric insulators. The body of a Piezotechnics actuator is equipped with an inter-digital electrode structure, which provides a homogenous electrical field to the active material. The electrode structure of piezo stack actuators is similar to MLC (multi layer capacitors). When an electrical voltage is applied to the actuator an internal electrical field is generated which exert electrostrictive forces on the crystal structure of the piezo material. The actuator body deforms and generate stroke. The mechanic-electric coupling mechanism is reversible: When a force is applied to a piezo the deformation of the body is associated with displacement of internal charges and a voltage is generated at the electrodes. This sensor effect was discovered by Pierre and Jacques Curie in 1880 and called piezo effect.

This, the inverse piezoelectric effect describes actuation, the deformation of a body when an electrical field is applied.

Constitutive Equations

A linear theory of piezoelectric phenomena effect was developed which describes small signal behaviour (for further reading see *1 *2). This theory does not comprise nonlinear effect and hysteresis. For actuator effective large signal parameters have to be applied. Piezo actuation (inverse effect) can be described mathematically in matrix notation as:

$$S_j = d_{ij} E_i$$

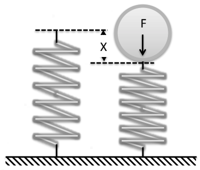
S_j is the strain (in m per m), d_{ij} is the piezoelectric charge coefficient (m/V) E_i is the electric field (in V/m). Typical values for maximum strain is 2000 micro strain or 0.2% and electric field is 2 kV/mm. The subscripts i and j indicate the direction. The "d_{33} effect" is used for piezo stacks. The axes 2 and 3 are the transversal direction and describe the contraction of the material in transversal direction to the applied voltage. The d31 effect is used for bender elements. The values of strain d_{31} and d_{32} are equal. The axes 4, 5 and 6 represent the axes of rotation turn around the axis of the coordinate system. For stack actuators the direction of applied field as well as strain is the stack axis, which are indicated by the subscript 3. Thus the relevant material parameter is the d_{33} coefficient and strain S_3 is equal $d_{33} \times E_3$. In the further discussion the matrix notation is simplified to scalar equations.

It is evident, that piezoelectric actuators couple two phenomena: the mechanics of a solid and dielectric behaviour of a capacitor. In the first instance both aspects will be described uncoupled. That means, that either the electrical state (e.g. terminals of piezo stack shorted) or the mechanical state is kept constant (e.g. ideally clamped). The mechanical constitutive equation that applies for piezo materials is known as Hooke's Law.

$$S = s\, T$$

In words, this equation states: Strain = Compliance × Stress This formula can be transformed to an actuator body:

$$x = s\, A/l\, F$$



In words, this equation states: displacement x = compliance × base area / height x Force

Piezoelectric materials are concerned with electrical properties too. We must also consider the constitutive equation for common dielectrics:

$$D = \varepsilon E$$

In words, this equation states: Charge Density = Permittivity × Electric Field.

This formula can be transformed to an actuator body:

Q = ε [illegible] = C U

In words, this equation states: Charge = Permittivity x base Area / height x Electric Field equal electrical capacity x Voltage.

Piezoelectric materials combine these two constitutive equations into one coupled equation, written as:

$$S = s\,T + d\,E$$

$$D = d\,T + \varepsilon\,E$$

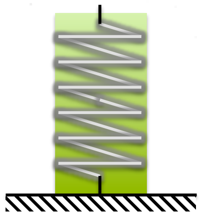
The parameter of a piezo component: mechanical stiffness k, force F, charge Q can be calculated from these equations. The observable quantities at the terminals of the actuator are electrical voltage U, length, displacement, force and electrical current. The electrical charge Q, which is fundamental important for the piezo effect, is observable by the time integral of electrical current.

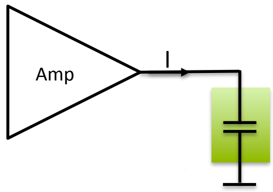
$$Q = \int I \, dt$$

In consequence, the electro-mechanical coupling mechanism results in a linear relation between speed of displacement and electrical current.

The coupling of electrical and mechanical phenomena by the piezo effect is illustrated in the next figure. The elastic behaviour of the body (contraction as a reaction of compressive forces) is superimposed by the piezoelectric strain effect (internal electric forces cause strain). Also, the electrical charge of the piezo, which is represented by a capacitor, is the sum of two terms: 1) charging a capacitor C by an applied electrical voltage U and 2) a charge, which result of the deformation of piezoelectric crystals by the applied force. The next figure summarizes the coupling of mechanical and electrical phenomena:

$x = k\,F + d\,U$ $\Longleftrightarrow$ $Q = d^{*}\,F + C\,U$





The piezoelectric coupling terms can be formulated in comprehensive matrix representation d when a three-dimensional analysis is required. In this frame, the description of a piezoelectric material requires knowledge about the material's mechanical properties (compliance or stiffness), its electrical properties (permittivity), and its piezoelectric coupling properties.

Strain-Charge Relation

$$S = s_E\,T + d^T\,E$$
$$D = dT + \varepsilon_{\square}\,E$$

Strain Voltage Relation

$$S = s_D\,T + g^t\,D$$

$$E = -g\,T + \varepsilon_{\square}^{-1}\,D$$

Stress Voltage Relation

$$T = c_D\,S - q^t\,D$$

$$E = -\theta\,S + \varepsilon_{\square}^{-1}\,D$$

Stress-Charge Relation

$$T = c_E\,S - e^t\,E$$

$$D = -q\,S + \varepsilon_{\square}^{-1}\,D$$

Meaning

T	vector	6 x 1	[N/m^2]	stress components (e.g. σ_1)
S	vector	6 x 1	[m/m]	strain components (e.g. S_3)
E	vector	3 x 1	[V/m]	electric field components
D	vector	3 x 1	[C/m^2]	electric charge density displacement components
s	matrix	6 x 6	[m^2/N]	compliance coefficients
c	matrix	6 x 6	[N/m^2]	stiffness coefficients
ε	matrix	3 x 3	[F/m]	electric permittivity
d	matrix	3 x 6	[N/m^2]	piezoelectric coupling coefficients for Strain-Charge form
e	matrix	3 x 6	[C/m^2]	piezoelectric coupling coefficients for Stress-Charge form
g	matrix	3 x 6	[m^2 /C]	piezoelectric coupling coefficients for Strain-Voltage form
q	matrix	3 x 6	[C/N]	piezoelectric coupling coefficients for Stress-Voltage form

Literature

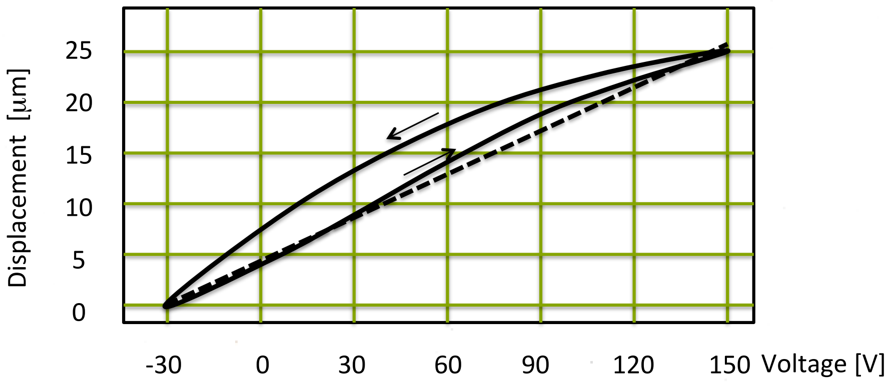
*1 Cady, W G, Piezoelectricity, McGraw Hill, New York (1946)

*2 Cook & H Jaffe , Piezoelectric Ceramics, Academic Press, London (1971)

Nonlinear Displacement Behaviour

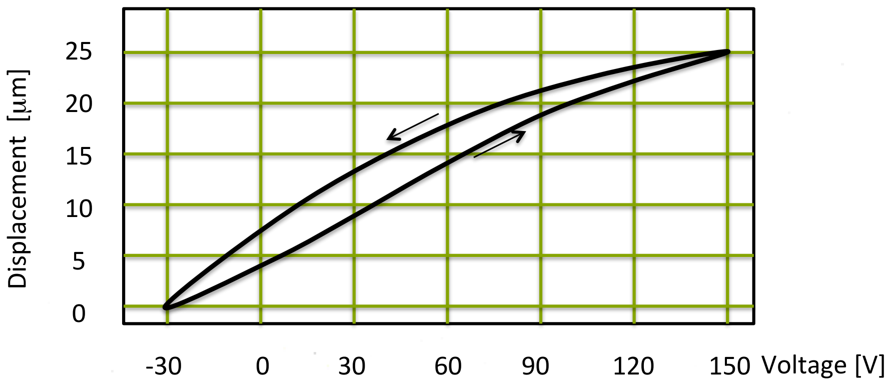
Real piezoelectric actuators exhibit divergent behaviour from pure linear constitutive equations. They show nonlinearity and hysteresis. Also, time- and temperature dependent effects are present. All these effects can be controlled by proper electronics. In closed-loop operation with feedback of displacement / strain measurement the hysteresis of the actuator can be well reduced.

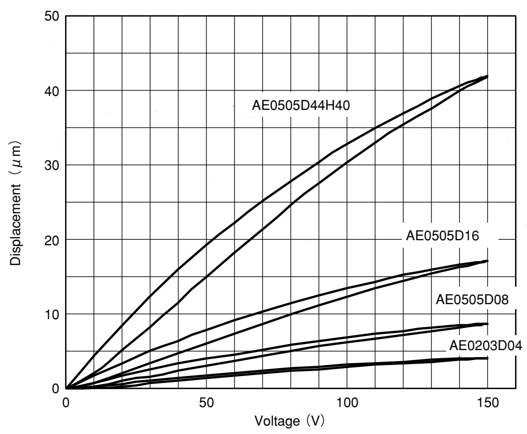
An illustration of displacement versus applied voltage for a piezo actuator stack, is shown in next figure. The hysteresis of the piezo stack actuator is indicated. With position control the hysteresis will effectively be reduced (dotted line).



Active strain performance

The active strain of standard actuators is 0.1% strain in unipolar driving mode (the voltage applied to the – and + terminals is ramped up from zero to the maximum positive value) and 0.14% in bipolar mode (the voltage applied between the – and + terminal is ramped between the allowed negative -30V to the most positive value 150 V). The strain depends on the pre-stress level. Appropriate pre-stress level increases the strain performance of the actuator.





Poisson ratio of the actuator material is about 0.3. Thus, the elongation of a piezo in field direction (the stack axis) is associated with 30% contraction in perpendicular directions (transversal contraction). The phenomena of transversal contraction cause tensile stress at the interface of the stack in the mounting material and may require special consideration in the design of actuator mechanism. Please contact Piezotechnics for consulting services.

Young´s modulus. The modulus of piezo materials is in the range of 30 to 60 GPa. The elastic modulus depends on the electrical boundary condition, as electro-mechanical coupling is effective. The effective modulus in an electrically open state is higher than that of a short-circuited state.

Generative stress (blocking force capability)

The generated stress is Young's modulus Y x active strain S.

$$\sigma = Y S$$

The stress generation capability of piezo stacks is in the order of 3.500 N (unipolar) and 500 N (semi-bipolar) per cm^2 stack base area. This is a large value for any actuator principle! The high stress capability is highly valuable for the design of actuator application. The actuators are mechanically stiff elements. One can only transfer this capability into large active forces effectively, if the load at the interfaces to the actuator represents a mechanically stiff element.

Humidity

Piezo ceramics are sensitive to humidity. Moisture on the ceramics surfaces can cause leak currents. These currents reduce life of the stack as stated in the life model equations. Special coatings are applied on the actuator surfaces of Piezotechnics stacks. The coating effectively shield the piezo against humidity and to effectively prolong life of the actuator. Operation at 60% or lower RH environments is preferred as it helps further prolong the life of the actuator. Also it is noted, that in dynamic operation, when the surfaces of the piezo become warmer than the environment, the actuator will be more robust to humidity.

Special solutions are available from Piezotechnics for applications in high humidity or in environment where fluids are be present. Metal sealed type multilayer piezoelectric actuators series actuators are much less influenced by ambient humidity because of complete insulation from the atmosphere. As a result, long service life and high performances never experienced in the past have been attained to allow use in various applications such as semiconductor device production equipment and optical communication equipment, which require high reliability.

Temperature

Piezotechnics actuators are designed to work in a broad range of temperatures from extremely low, cryogenic temperatures up to elevated temperatures up to 125 °C. The maximum temperature is limited by a fundamental material property which is the Curie temperature. Like magnetic materials the piezo effect is disappearing when a certain temperature point, the Curie temperature, is exceeded. In case the Curie temperature is exceeded in operation or storage, the actuator has to be polarized. This procdure is explained in the chapter on handling.

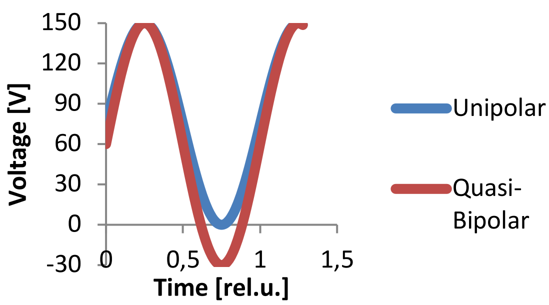
Limits are set by the piezo material itself, the coating, thermal expansion, and interfaces such as adhesives, electrical wires and insulation. The actuators from Piezotechnics are perfectly suitable for the whole temperature range. Standard Piezotechnics stack actuators operate down to –25 °C without any problems. For cryogenic applications specially adapted stack are available on request.

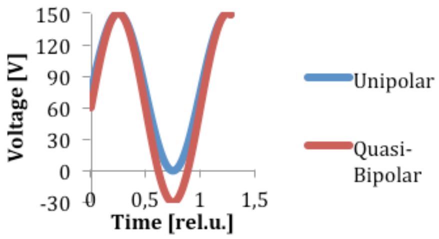
Creep and Drift

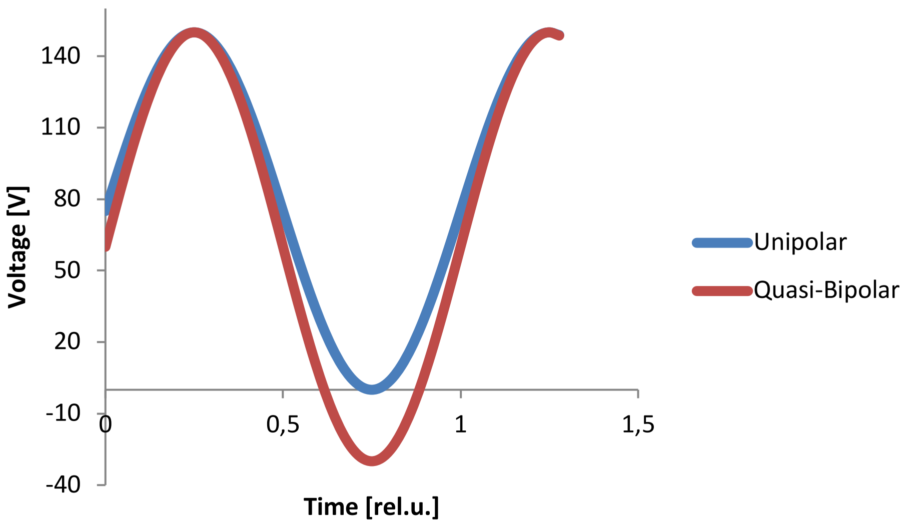
Piezo actuation effect is partly subjected to time-dependent phenomena of the orientation of dipoles in the material. After change of voltage the stack immediately react and a force is generated by the interaction of the field and the dipoles of the piezo material. The piezo stack deforms and produces useful displacement. In analogy to magnetic materials the the microscopic structure of piezo comprises electric dipoles that are coupled and manifest in domains. The orientation of the dipole of the domains is influenced by electric field and mechanical stress. These couplings cause secondary effects. Afterward fast settling of the electric field cause further reorientation of the dipoles and the stack creeps slowly until reaching equilibrium. Of course, these effects are much smaller than the immediate reaction. Those effects can be corrected by feed-back of position.

Unipolar and Quasi-Bipolar Operation

Piezotechnics actuators are designed for unipolar as well as bipolar voltage operation. The standard operation is from 0 to 150 V (unipolar). Quasi-bipolar operation from -30 V to +150 V brings the advantage of up to 40% higher displacement.







Quasi-bipolar operation is an extremely powerful method to enhance actuator performance. Piezotechnics actuators have the necessary characteristics the quasi-bipolar operation requires. Nevertheless, it may be noted, that this that this driving method increases the specific mechanical and electrical loads of the material. Also, with the power conversion throughput losses increase.

Electrical Behaviour - Current

To gain an overview of the electrical power requirement, a simple calculation with a constant electrical capacity is sufficient.

The well-known equation for the current through a capacitor is

$$I = C\dot{U}$$

For a sinus wave with amplitude $\hat{U}$ and frequency f, the amplitude of the current $\hat{I}$ is

$$\hat{I} = 2\pi f C \hat{U}$$

This formula is most fundamental and should be considered for selecting the right amplifier. The influence of temperature and large signal is significant and thumbs of rules are needed to practically estimate current rating. The large signal behaviour of actuator –grade ceramics is non-linear and an increase of the current by a factor of two provides a good guess. Piezo actuators are electrical capacitors with superimposed effects related with of electro-mechanical coupling mechanism. Practically, the deformation of the piezo is linked with the superimposition of charges in the capacitor and the deformation rate (speed of displacement) is linked with an additional electrical current. Thus, the detailed analysis requires setting up and solving the equations with the couplings terms for the mechanics of piezo and loads.

Electrical Power Need

To select the right amplifier and to design the electrical supply, it is necessary to define the peak current need I_{peak} and the average P_{ave}. The current depend on the required maximum dynamic operation of the piezo and of course by the maximum voltage. The maximum speed of the displacement requires a maximum current I_p, which the amplifier has to supply. In the previous chapter the current has already been calculated for sine wave form operation. More generally, the as displacement of a piezo is in first approximation proportional to the voltage U

$$X = d_{eff} U$$

$$X = d_{eff} U$$

where d_{eff} is the effective factor for displacement of the piezo actuator in analogy to the piezoelectric constant for material. The speed of displacement V is proportional to the time derivative of the voltage

$$V = \dot{X} = d_{eff} \dot{U}$$

$$V = d_{eff} \, d/dt \, U$$

The current flowing through a capacitor is proportional to time derivative of the voltage

$$I = C\dot{U} = C \frac{\Delta U}{\Delta t}$$

The current, which is needed for a required rate of displacement of a piezo actuator is

$$I = C \frac{\dot{V}}{d_{eff}} = \frac{C}{d_{eff}} \frac{\Delta X}{\Delta t}$$

Example

The stack 5x5x20mm has a maximum displacement of 17µm at 150 V. The capacitance C is 1.4 µF.

When the piezo is driven to 150 V it takes a charge

$$Q = 1.4\ \mu F \times 150\ V = 1.4\ 10^{-6}\ As/V\ 150\ V = 0{,}21\ mAs.$$

The current needed to position the stack in 5 ms to the maximum length is:

$$I = 0{,}210\ mAs/\ 5\ 10^{-3}\ s = 42\ mA$$

A standard Piezotechnics amplifier is sufficient including margins to consider the so-called large-signal effect. The large signal effect describes the capacity for a large voltage swing. Whereas the nominal capacity is a small signal value which is derived with standard measurement equipment and this work with signals in the range of some tens of millivolt.

If higher dynamics is needed e.g. driving the same piezo in 500 µs to 150V a higher current is needed:

$$I = 0{,}210\ \text{mAs}/\ 500\ 10^{-6}\text{s} = 420\ \text{mA}$$

The high power amplifier version is needed.

Electrical Behaviour – Power Losses

As in any electric component piezoelectric actuators causes some losses of electric energy. Usually, the calculation of the losses is carried out with a loss factor tan d or by an **equivalent serial resistance (ESR).** In alternating current AC theory a dielectric loss factor is introduced as:

$$tan\,\delta = ESR\ \omega\ C$$

tan delta = ESR 2 Pi f C

where ω is the angular frequency (ω = 2πf). tanδ is called loss tangent. For piezo the loss tangent depends from the voltage amplitude. For small amplitudes, e.g. some Volts, the damping effect is very small and the loss factor tanδ [illegible] typically [illegible]. For large signal operation, e.g. full amplitude swing from -30 to 150 V, the loss tangent is typically 10%. Rectangular wave operation causes losses up to 20%. It is noted that for static operation (constant voltage or position) the losses are extremely small. This is a fundamental advantage against electromagnetic actuators.

Mathematical Solution for Controlling the Position of a Piezoelectric Actuator Under Load

As described the electric field cause mechanical stress which induce a deformation of the actuator body. The generative force F_g is the product of actuator area A and the piezoelectric stress sigma:

$$F_g = A\ \sigma$$

F = A sigma

The generated stress σ is proportional to the piezoelectric constant d, which is a material property, and the applied electrical voltage. The maximum generative force is provided in the actuator specification. The proper actuator size can be selected by choosing the actuator base area.

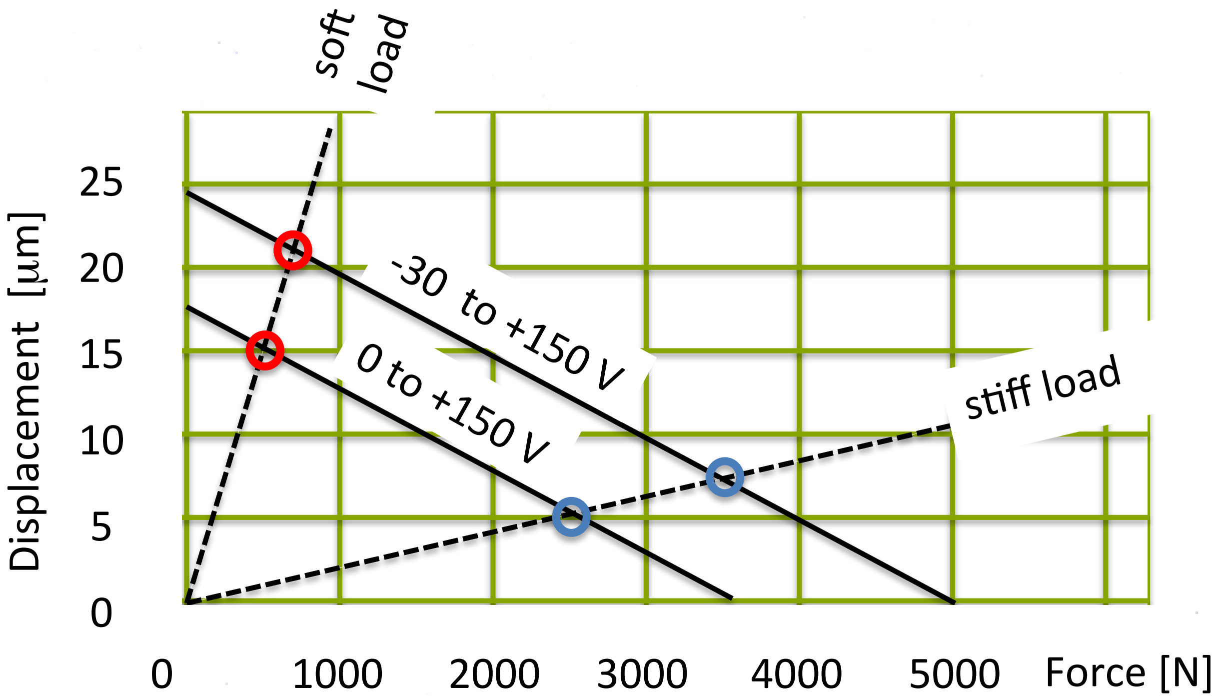
It is important to consider that piezo actuators are solid bodies and feature much higher mechanical stiffness than any other actuator of same size. In mechanical equilibrium the generative force is equal the sum of the useful load force and the internal elastic force which is associated with the actuator deformation. This means that the useful force F under load reduces linearly with displacement X. X_0 denotes the free displacement (no lad situation.

$$F_{load} = Fg\,\frac{1 - X}{X_0}$$

$$F_{load} = Fg\,\frac{1 - X}{X_0}$$

Geben Sie hier eine Formel ein.An illustration of the force versus displacement behavior of a piezoelectric actuator at various applied voltages is shown in the next figure. This graph enables analysis of the actuator's performance under load. The force-displacement characteristics of both the actuator and the load are plotted on the same graph. The points where the curves intersect represent the equilibrium positions — the displacements at which the actuator’s force balances the load force.

$$F_{Piezo} = F_{load}$$



The mechanical equilibrium between the spring load and the elastic deformation of the piezoelectric actuator is indicated in the diagram by the circular markers. As expected, a stiffer load (blue circles) results in lower displacement, since a greater force is required to deform it compared to a softer, spring-like load (red circles).
The origin of the graph represents the actuator at rest, with 0 V applied. In the case of bipolar operation, this corresponds to the lowest driving voltage, which is –30 V in the example shown in previous figure..

Fig-3 Generated force vs. Displacement-1

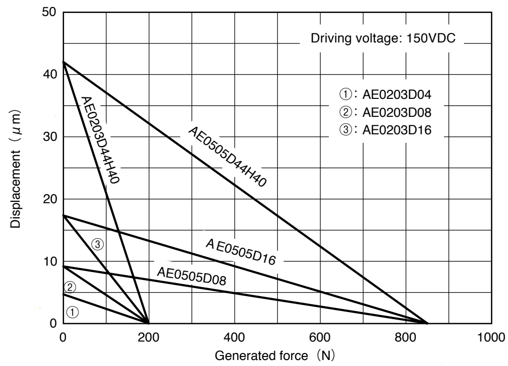
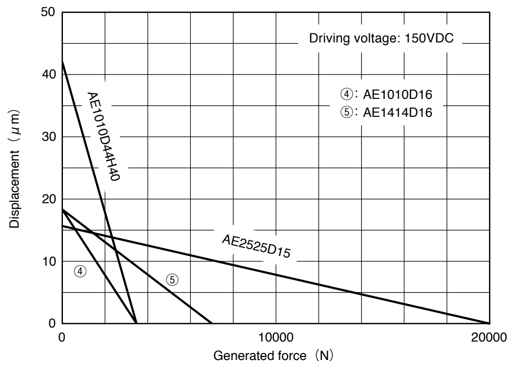


Fig-4 Generated force vs. Displacement-2



The images above show the elastic characteristics (force vs. displacement) of various piezoelectric actuators. The plots demonstrate that the output force is proportional to the actuator’s cross-sectional area

$$F \propto A \text{ and } \Delta L \propto L.$$

while the displacement is proportional to the actuator's length. These relationships reflect the fundamental mechanical behavior of piezoelectric stack actuators under load.

Major load cases.

The linear constitutive equation describes a linear elastic material with the superimposed effect of electrically induced force, which is linear to the applied electrical field. Second, a piezo actuator represents a capacitor with the superimposed effect of induced charge linear with the applied force. In conclusion, piezo actuation is based on electrically controlled deformation of a solid body. When a voltage is applied to a piezoelelectric actuator piezoelectric forces are generated instantaneously inside the solid body, which deform it and move the load to reach mechanical equilibrium.

From the above noted equations, **important load cases** can be examined:

No load (free stroke case):

The displacement X of a piezo actuator X is equal piezoelectric (charge) constant d x voltage U.

$$X = d\,U$$

Multilayer actuators use a multitude of thin layers and the total achievable displacement is the value of the individual layer multiplied by the number of layers. The layer thickness is in the order of 100 um, voltages are 150 V and field strength is 1 – 2 kV/mm.

Mass load.

T = constant. The displacement X of the actuator does not change and is still equal piezoelectric (charge) constant d x U. The mass force statically deforms the actuator

Spring type load.

The displacement of the actuator is reduced by the ratio of stiffness of the load spring k_{load} and actuator k_a.

$$X = X_0\,\frac{k_a}{k_a + k_{load}}$$

(free displacement $X_0 = d\,U$)
$k_a/(k_a + k_{load})$

Blocked Actuator (blocking force case).

The generated force is equal base area x piezoelectric constant d x electric field divided by compliance s.

$$F_b = \frac{A\,d\,E}{s}$$

$$F_b = A\,d\,E/s$$

Abrupt application of voltage

If the voltage source is abruptly switched on, the actuator will experience a step function excitation. The electric behaviour of the actuator is that of a capacitor and will pull large currents I form the amplifier to ramp up the voltage during rise time ΔT.

$$I = C\frac{\Delta U}{\Delta t}$$

If the amplifier is capable to provide high currents, the actuator will overshoot in this situation and internal tensile stress results. The actuator stack is in danger to be damaged if not sufficient measures are taken:

First, current limiting is reliable method to reduce rise time and to avoid overshoot. Second, a pre-stress mechanism can be installed which compensate transient tensile stress amplitude.

Dynamic actuation of loads

In dynamic actuation mode periodic (sine, square waves) or non-periodic waveforms (e.g. compensation of disturbances in a feedback control loop) are applied to the actuator. In modern car engines high-pressure fuel injectors are used to spray very precisely fuel into the combustion chamber. Piezo is the superior actuator principle to control the injection process and superseded electromagnets. The piezo in a fuel injector is used to generate several fast pulses during each combustion cycle.

The dynamic response of a piezo actuator and connected mechanical load to the electrically controlled piezoelectric force is determined by masses, stiffness's, and damping rates. The actuator itself represents a spring mass system with low damping rate. The low frequency response of that basic actuator system is given by the free stroke. At higher frequencies the stroke is limited by the inertia of the effective actuator mass. The realizable displacement of an actuator in sinusoidal operation is given by the equilibrium of the piezoelectric force and the force needed to accelerate the effective mass. The following equations illustrates the mechanical response quite below and beyond the mechanical resonance frequency f_r:

a) $f < f_r \qquad X = d\,U$

b) $f > f_r \qquad X = F_b / (m_{load}\,(2\pi\square)^2)$

Highly dynamic operation of a piezoelectric actuator results in high levels of mechanical (force x speed) and electrical power (voltage x current). Damping is effective in piezoelectric materials and in dynamic operation losses occurs with resulting heating of the material. Continuous dynamic operation can generate high losses and the piezo stack may rapidly heat up. Sufficient measures has be taken to avoid excessive temperatures:

- limit the amplitude (travel, voltage),
- limit frequency,
- limit the duration of operation, and
- adequate cooling.

Contact Piezotechnics if high power levels are required. Piezotechnics is experienced in highly dynamic actuation.

Guide for Dimensioning a Piezo Actuator System

Stack actuator key performance data

The comparison of the requirements with key performance data of Piezotechnics stack actuators can provide a first feasibility assessment of an envisaged piezo actuator application.

The two most important key performance indicators of piezo stack actuator are stroke and force. These data are directly related with the size of the stack:

- The force generation capability is proportional to the base area of the stack.
- The displacement capability is proportional to the length of the stack.

The capacity C and the maximum operating voltage U are the key electrical data. The electrical capacity is related with the size of the stack.

In the following table key data are summarized and represent the range of actuator stacks.

Symbol	Meaning	Minimum	Maximum	Special Design
X	displacement	2 µm	100 µm	1 µm - 400 µm
F_b	blocking force	200N	4 kN	50 kN
A	base area	2 x 3mm^2	10 x10 mm^2	25 kN
σ	active stress	3500N/cm^2		
S	active strain	0,1%	0,2%	
L	length	2mm	100mm	1mm, 400 mm
C	capacity	typ. 3 µF/cm^3 per active stack volume		
U	voltage	-30 to +150 V	0 to 150 V	300 V, 600 V
T	temperature	-25 °C	+ 85 °C	cryogenic
rH	humidity	< 60% rel. Humidity		100%

Standard sizes and performances are summarized in the following matrix:

Bare Stacks	Dimensions		Displacement		Electrical		Mechanical		
	Base Area	Length	Unipolar	Semi-Bipol	Capacity	Insulation	Resonanz	Stiffness	Force
Type	[mm²]	[mm]	[micro meter]		[nF]	[MOhm]	[kHz]	kN/mm	[N]
PB 3.9	3,5 x 3,5	9	9	13	350	50	152	50	400
PB 3.18	3,5 x 3,5	18	20	28	800	10	76	25	400
PB 5.9	5 x 5	9	9	13	800	50	152	100	850
PB 5.18	5 x 5	18	20	28	1600	10	76	50	850
PB 5.40	5 x 5	40	42	58	3400	5	34	22	850
PB 7.18	7 x 7	18	20	28	3400	5	76	100	1700
PB 7.40	7 x 7	40	42	58	6700	5	34	40	1700
PB 10.18	10 x 10	18	20	28	6600	5	76	200	3500
PB 10.40	10 x 10	40	42	58	13600	2	34	80	3500
PB 14.18	14 x 14	18	20	28	11000	2	68	400	7000
PB 25.15	25 x 25	15	16	21	31000	0,4	68	1300	20000

	Dimensions		Displacement		Electrical		Mechanical		
	Base Area	Length	Unipolar*	Bipolar**	Cap. C	R	Resonanz	Stiffness	Force
Type	[mm²]	[mm]	[micro meter]		[nF]	[MOhm]	[kHz]	kN/mm	[N]
PB 3.9	3,5 x 3,5	9	9	13	350	50	152	50	400
PB 3.18	3,5 x 3,5	18	20	28	800	10	76	25	400
PB 5.9	5 x 5	9	9	13	800	50	152	100	850
PB 5.18	5 x 5	18	20	28	1600	10	76	50	850
PB 5.40	5 x 5	40	42	58	1600	5	34	22	850
PB 7.9	7 x 7	9	9	13	3400	5	152	200	1700
PB 7.18	7 x 7	18	20	28	3400	5	76	100	1700
PB 7.40	7 x 7	40	42	58	6700	5	34	40	1700
PB 10.9	10 x 10	9	9	13	3300	5	152	400	3500
PB 10.18	10 x 10	18	20	28	6600	5	76	200	3500

*Unipolar U 0 … 150 V

**Bipolar U -30V … 150 V

In addition to the standard product range, customized solutions for piezoelectric actuators are available:

- Actuators for extended temperature ranges up to 150 °C
- Actuators with increased strain and work capacity
- Assemblies with end pieces, wiring, and lengths up to 280 mm
- Mechanically amplified actuators
- Preloaded assemblies ("piezo rods")
- Actuators with integrated strain gauges
- And more on request

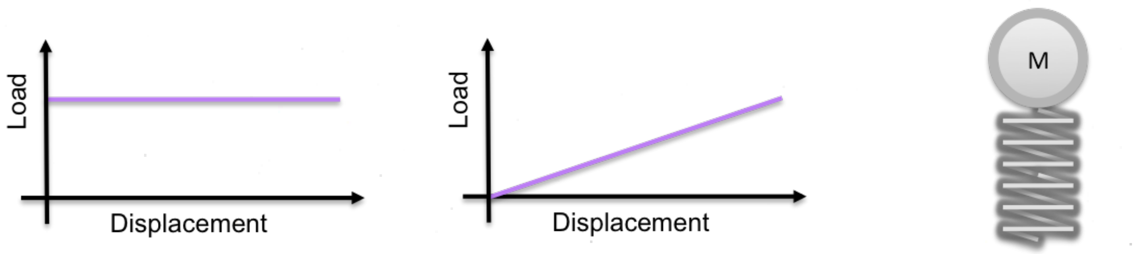
Analysis of actuator concepts

The analysis follows a three-step procedure:

1) Stack selection and sizing from load case
2) Dimensioning and selection of power supply, peak current, average current or power output, thermal management
3) Environmental protection and casing, coating, pre-stress.

Sizing of piezo stacks

The force-displacement relation of the given load case is essential for selection of a piezo stack. The maximum force and displacement requirements have to be determined. Form these data the required free displacement and blocking force can be calculated. The next figure outlines the most important load cases.



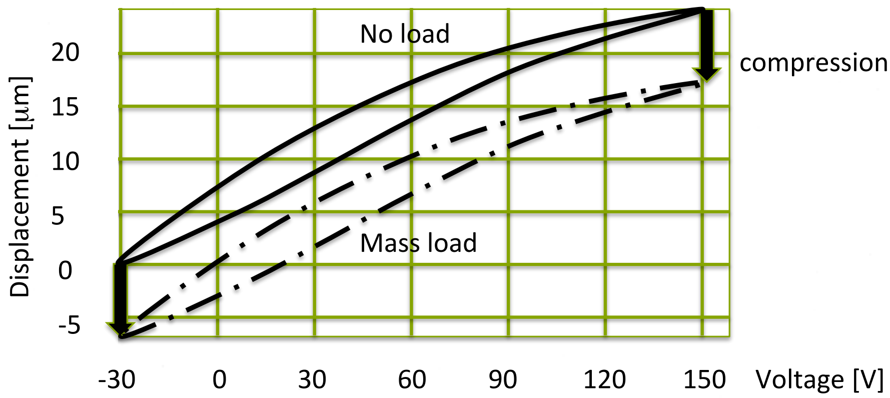
mass-type spring-type spring-mass-type

Constant load force.

This describes the situation, where the load force F_{load} is constant (or varies negligibly with regard to the blocking force of the selected stack) and independent for displacement. This situation is given in case of

- Mass load,
- Constant pneumatic or hydraulic pressure,
- Widely compressed soft spring.

Under constant compression force a piezo does not suffer the loss of its displacement capability. Within the acceptable load force given in data table of the stack, the actuator can provide full performance. This behaviour is shown in the next figure.



To select the right actuator you simply need to determine

- the maximum required displacement X_{max}
- the maximum required force F_{load}.

In consequence of the constancy of the displacement, the actuator can be chosen by its two main performance data blocking force F_{block} and free displacement X_0 :

$$X_0 = X_{max} + \text{margin (e.g. 20\%)}$$

$$F_{block} = F_{load} + \text{margin (e.g. 20\%)}.$$

The load force shall not exceed the blocking force.

Example. The piezo has to position a mass of 75 kg over a range of 35 µm. The load force F_{load} is

- F_{load} = 75 kg x 9,81 m s^{-2} = 736 N, and
- X_0 = 35 µm

A stack with base area of 5x5 mm^2 generates 850 N and would be sufficient. A stack with a length of 40 mm delivers in unipolar mode 42 µm. This would provide a sufficient margin of 7 µm, which is 20% on top of the required displacement. Therefore, a stack 5x5x40 mm is a right choice. Dependent on the mechanical system design, a larger stack area e.g. 7 x 7 mm may be selected.

- F_b = 850 N
- X_0 = 42 m
- A = 5x5 mm^2 (or 7x7 mm^2 may be chosen)
- Height = 40 mm

Spring type loads

In case of a spring type load the displacement of the stack will be reduced with regard to the initial free displacement X_0. The achievable displacement is determined by the elastic equilibrium of the counteracting compression of the spring and the piezo stack which are represented by the stiffness factors k_{stack} and k_{load}. The free travel X_0 is reduced by a factor dominated by the ratio of the stiffness of stack k_a and load k_{load}.

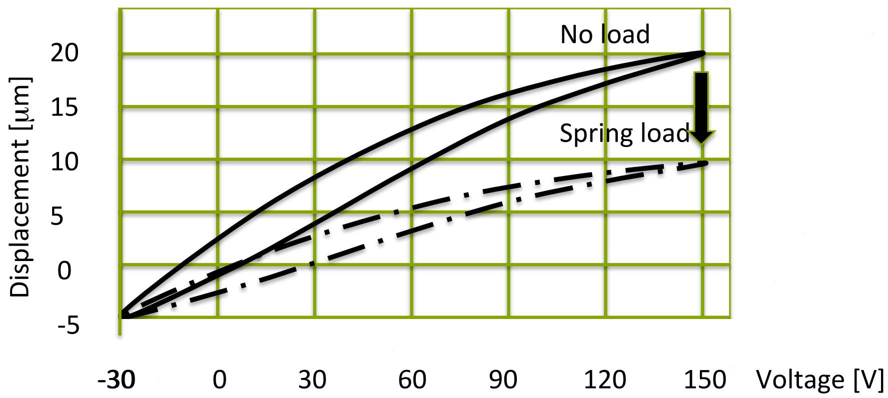
$$X = X_0 \frac{k_a}{k_a + k_{load}}$$

The formula suggests, that the actuator stiffness has to be high in comparison with the load to in order to maximize the useable displacement of a piezo stack.

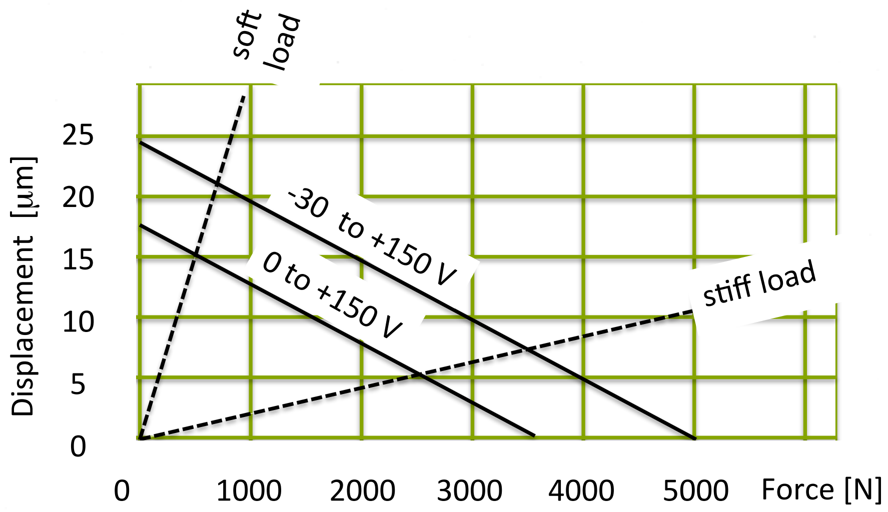
In case of a spring-type load an actuator stack has to chosen which free displacement is larger by a factor than the maximum given displacement X:

$$X_0 = X_{max} \frac{k_a + k_{load}}{k_a} + margin$$

The blocking force of the actuator stack has also to be chosen by the same factor larger than the max load force.



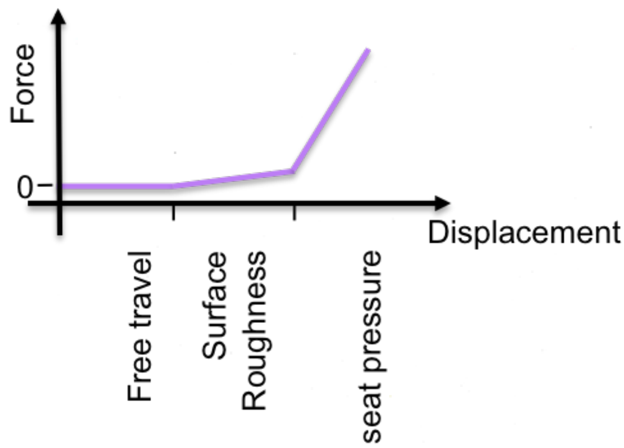
The equilibrium can also be determined graphically in a displacement-force diagram. The following figure explains the case of a soft spring load as well as a stiff load, where resulting displacements are much smaller.



The diagram explains the reduction of the free displacement X_0 in case of a soft (I) and a stiff (II) spring-type load.

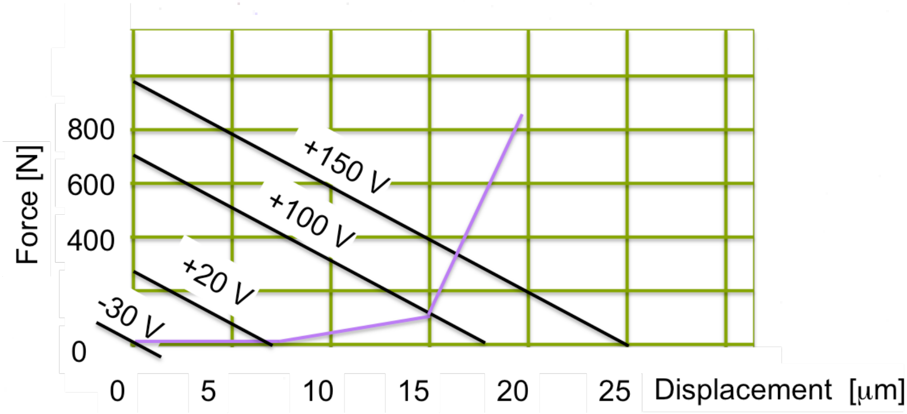
Example

An actuator, which closes a valve needle, is chosen for spring type loads. The selected load curve has section wise different stiffness. In the first phase, the needle moves freely. Then, the needle gets into contact with the seat and forces increases steeper when compressing the surface roughness. In the third phase, the needle is pressed increasingly into the seat and closes the valve.



In the next figure a displacement-force diagram of a selected piezo stack is shown, where different states of the actuator (-30V, +20V, 100V and 150 V) are indicated. Forces are in compressive direction. Each line represents the elastic mechanical behaviour of a piezo at a constant voltage condition.

When the voltage applied across the piezo terminals increases, the needle moves. At 20V the needle reaches the seat and compress the material in the surface roughness region. At 100V the needle is completely driven into the seat and further voltage increase compresses the valve seat. The chosen actuator is a 5x5x20mm Piezotechnics stack. The valve force reaches 350 N, which fit with a high-pressure valve.



Mass spring loads

All real mechanical system has mass and spring characteristics. In a dynamic analysis the inertia forces must be considered with a mass dependent term. The simplest case is a stack itself in highly dynamic operation. In the next differential equation of motion the Newton's law are expressed in a lumped parameter model:

$$m\ddot{x} + b\dot{x} + kx = F_p + F_{ext}$$

F_p is the piezoelectric force controlled by the voltage, x is the displacement, m the effective inertial mass of the piezo, and k is a term for damping.

This equation represents a damped spring-mass system, which will perform damped oscillation when excited by a voltage step function. The following data are exemplarily presented for a Piezotechnics PB5.8 stack:

- f_{res} 76 kHz
- m_{eff} 3,4 grams
- stiffness k 6 000 N/m equivalent to a effective Young's modulus of 44 GPa
- damping parameter b 150 Ns/m

It is well known that this dynamic system have a resonance effect and will overshoot and ring when excited with a voltage step function. The actuator has a large initial acceleration a_0

$$a_0 = \frac{F_b}{m_{eff}}$$

In the chosen example the initial acceleration of the stack a_0 is 250 000 m/s^2 or 25 500 g. In a practical case there will be a load mass and resonance frequency would be reduced of course.

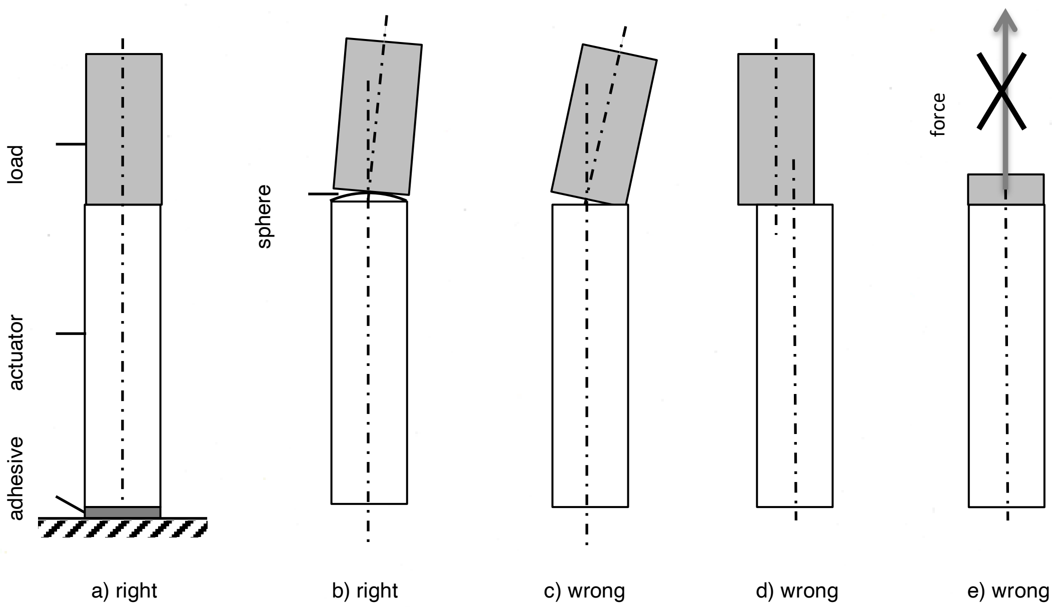
Rise time for spring-mass system is usually approximated by $t_r = 1/3f_{res}$. In the given example t = 5 µs. Please notice, that for faster dynamic operation a dynamic overshoot reaction occurs. An overshoot over the maximum static displacement cause internal stress in the ceramics in tensile direction. As ceramics is sensitive to tensile stress compensation by pre-stress is required to avoid cracking and failure of the piezo. Those pre-stress mechanism cause mass effort and will reduce reaction speed of the actuator.

Installation and Handling

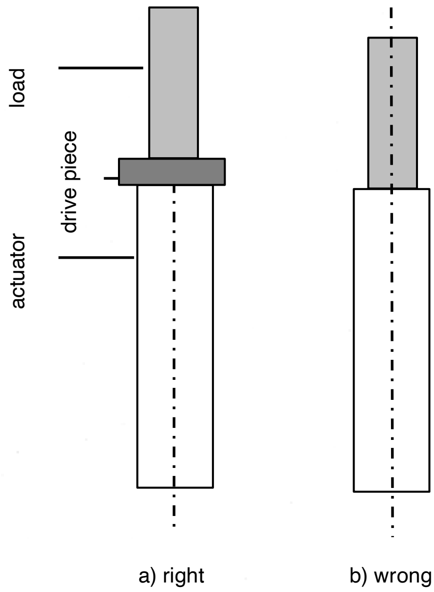
Bare stacks

Piezoelectric stacks are designed to generate uniaxial displacement. The best performance and life of the actuator will be achieved when a pre-stress mechanism is installed. The ideal pre-stress mechanism provides a constant compressive force to the piezo stack. Compression is effective against mechanical damage e.g. cracking. Pre-stress data are recommended for Piezotechnics stack products.

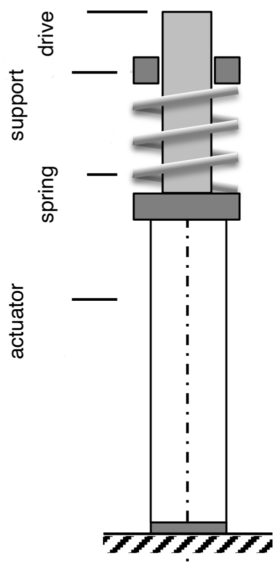
It is important to accurately align load and actuator axis. Misalignment cause bending or shear forces in he actuator for which it is not designed. Align the actuator and the load axis precisely, so that the centre axis of the piezo stack as well as the axis of displacement is vertical to the mounting surface. Avoid any tensile forces on the stack during installation and operation. Ceramics are sensitive to tensile forces whereas they are vey robust with regard to aligned compressive stress. For structural applications e.g. attaching piezo stacks to composite structures for integrated actuation or sensing please contact Piezotechnik. Piezotechnics has comprehensive experience in those applications.



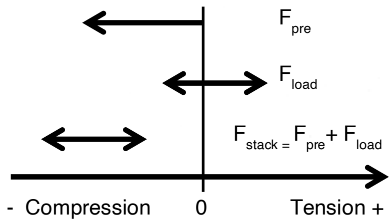
The above figure explains the mechanical integration of a bare piezo stacks actuator. The load axis is aligned with that of the load and the stack is fixed with a thin layer of adhesive (figure a). Minor deviations of load and actuator are acceptable. The end faces of the base plate as well as the load face shall be plane. Any punctual load would cause high stresses and could cause cracks and subsequent failure. A spherical end piece can compensate slight misalignment of stack and load axis (figure b). The tilt of the load must be avoided (figure c). Partial coverage of load and stack end faces will lead to nonhomogeneous stress distribution in the stack and may lead to failure (d). Tensile forces have to be avoided (e). Also consider inertial forces in dynamic operation (e).



The actuator can be clamped or bonded to the load mechanism. Epoxy-based adhesives are recommended for bonding. Do not apply adhesives to the sides of the stack. Plane faces with full coverage of the end face of the stack are good practice. A plane drive piece could be used for mechanical interface (b).



a) pre-stress mechanism



b) resultanting force on the stack

A preferred method to provide sufficient pre-stress is shown in the above figure (a). A spring is mounted between a support and the drive piece and compresses the stack. The pre-stress arrangement allows safe and reliable operation. Applying a bias of compressive stress on the stack is a proper solution to handle tensile load forces. In above figure (b) the superposition of pre-stress F_{pre} and load force F_{load} with the resulting force F_{stack} on the stack is shown. Choose the right pre-stress level to meet with the maximum tensile force! The resulting force on the stack should always be in compressive direction.

Housed stack actuators

Stacks are available with housing and pre-stress mechanism. For integration into applications load screw threads are available. The housing protects the sensitive ceramics material provide mechanical interfaces.

Life and reliability

Piezotechnics supplies high-quality, reliable piezoelectric actuators.
These components offer outstanding performance and long service life. However, as electrically active elements, piezo actuators—like capacitors—are subject to various degradation mechanisms. The failure rates depend significantly on the type of operation. A distinction must be made between static operation (DC voltage) and dynamic operation (pulsed excitation).

In positioning applications, stacks may be exposed to constant voltages over extended periods. In contrast, dynamic applications such as switching or valve control involve short, high-acceleration pulses with substantial mechanical forces.

In static applications, the most critical factors affecting lifetime are the **applied voltage level** and **ambient temperature**. In addition, **humidity** poses a major risk, as it can lead to severe degradation over time.

When operation in a humid environment is expected, the use of sealed actuators—especially those with **full metallic encapsulation**—is a rational and proven design choice. Metal housings provide effective protection against moisture and ensure high reliability by isolating the actuator from the surrounding atmosphere.

Humidity promotes destructive surface-related mechanisms, as water molecules are attracted to the stack surface and can initiate degradation in the external domain of the actuator.

When operated with rectangular pulse voltages, the resulting temperature rise due to dielectric loss significantly reduces the influence of humidity and can greatly extend the service life. However, the lifetime depends on the waveform, frequency, and actuator geometry and cannot be calculated as precisely as in the case of DC operation.

Nevertheless, an extensive data base confirms the excellent durability of piezo stacks. In long-term tests with rectangular pulses, the actuators achieved **more than one billion cycles** under full excursion of the nominal voltage range.

Note: Be aware of possible mechanical damage caused by ringing effects, especially in relation to the mounting method and voltage rise time. Proper pre-stress must be applied to avoid tensile stress during the contraction phase of the stack.

Precautions

Before using our products or designing a system using our products, read the precautions and specifications for the products you intend to use.

The products are extremely reliable with proven life of more than 10^{10} cycles. Nevertheless, environmental influence and misconceptions in the design phase of a specific application may lead to failures in operation. The main failures with piezoelectric actuators are cracking of the ceramics monolithic block, short-circuit, and open-circuit. Before using the products, also consider safe design praxis of electrical engineering. Carefully ensure prevent electric shock, cause and spread of fire. Use the products after checking the working conditions and rated performance of each of the multilayer piezoelectric actuator series. Stay within mechanical, thermal and electrical, and environmental limits.

Mechanical precautions

- Be careful with the mechanical handling
- Do avoid tensile, torsion, shear and bending stress.
- Do not exceed rated voltage limits. Be careful in bipolar electrical operation mode and recognize reverse voltage limits.
- Do not handle the product by picking up or moving the lead wire.
- Align the center axis of displacement of the actuator with the centre axis of the mechanical load.
- Avoid tensile, twist, shear and bending stress.
- Do not disassemble the case of the housed or metal sealed type.
- Machining of the actuator element and replacement of the lead wire are prohibited.
- Avoid excessive physical shock resulting from, for example, dropping. Otherwise, the internal piezoelectric ceramic element may be damaged.

- Store actuators where there is no vibration.

Thermal precautions and ambient conditions

- Note the ambient conditions
- Do not overheat.
- If the actuator is exposed to high temperature above 100°C or if it is used after long storage period (more than three months), it should be polarized by using the circuit configuration and conditions shown in the paragraph "Polarization".
- Do not handle the resin-coated type with bare hands. In that case carefully clean the stack with pure Isopropanol alcohol. Otherwise, the reliability of the element would be degraded.
- Do not wash stacks with organic solvents.
- Do not use the actuator in high concentration of highly inflammable gas. Otherwise, ignition may occur. Use the actuator so as not to cause bending, twisting or tension.
- Store actuator preferably in a dry atmosphere (desirably below 40% RH) at ordinary temperatures (- 5 to + 40℃).
- Avoid condensation on the product surface.
- These products must be handled properly as industrial waste. When disposing, please contact your local waste disposal service. Piezo actuator is industrial wastes, make sure disposal method under the laws.

Electrical handling

- Carefully setting up the electric power supply. Avoid abrupt voltage jump during switch-on.
- Do not rapidly charge and discharge the actuator. These might lead to degradation of the reliability or mechanical fracture.
- Connect the red lead wire to the positive (+) terminal of the power supply. Connect the black lead wire with the negative terminal (-).
- Carefully avoid electric shock since a high voltage is in use. Never apply excessive mechanical tension to a lead wire.
- Operational procedures
- Drive the actuator so that the rising speed is more than three times as much as the resonance period (stack plus load) in order to prevent the device from damaging by mechanical overshoot.
- This, do avoid steep voltage transients e.g. during switching the amplifier on or off. Check carefully the switch-on behaviour of your circuit whether the power supply steep voltage transients to the actuator. Steep voltage steps cause high acceleration, which cause high internal tensile stress amplitudes to the actuator material. Dynamic operation of piezo actuators requires proper mechanics to provide sufficient pre-stress (see previous chapter). The pre-stress shall be sufficiently dimensioned to fully compensate tensile stress static and dynamic loads.

Polarization

In case the actuator was exposed to higher temperature during storage or operation clos or above the Curie temperature, the piezo material may lose its polarization. In this state, the piezo effect is weakened or non-existent. The polarisation procedure requires a voltage source. A standard Piezotechnics amplifier can be used in combination with a signal source to set the output voltage. The voltage should be ramped up to 150 $\mp$ 0.2V and retained for 10s and than ramped down to 0V.