Piezocomposite Actuators

Cofired Multilayer Actuators

For the past few decades "cofired" multilayer stacks has been the state of the art method used for constructing piezo actuators. However there are a variety of applications where multilayer stacks reach their natural limitations.

Multilayer stacks consist of many ceramic layers (each approx. 100 µm in thickness) with thin (1 µm) electrodes between them. After stacking these layers the compound is then sintered at high temperatures (cofiring).

Multilayer actuators are operated with low voltages up to 200 V.

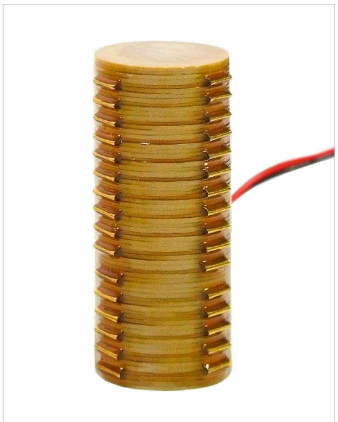

Figure 1: Piezocomposite stack actuator made from single piezoceramic discs and intermediate metal electrodes

Design of Piezocomposite Actuators

Piezocomposite actuators are made from completely sintered single PZT discs (thickness 0.3 to 0.5 mm) and separate intermediate metal foil electrodes which are held together by special high quality adhesives. Therefore these discretely stacked actuators are a composite material with some outstanding properties.

Piezocomposite actuators should be used to generate:

- High forces up to 50 kN
- High accelerations up to 100'000 m/s^2
- Short pulses
- To withstand loads up to 70 kN

Piezocomposite Ring Actuators are preferred for

- Optical applications
- Applications with high frequencies requiring effective cooling and special thermal behavior
- Applications with high bending stability

Stiffness

According to $C_T^E = \dfrac{A}{S_{33}^E \cdot L_0}$, the stiffness of Piezocomposite Actuators increases with the cross section and decreases with the length of the actuator. Piezocomposite Actuators with a preload show an elastic modulus nearly as high as that of multilayer stacks.

	Piezocomposite Actuators	Low Voltage Multilayer Stacks
preferred use	large cross sections generating high forces	small, medium cross sections for low volume elements
applications	high dynamic applications, shock generations, shakers, vibration generation short impulse excitation	positioning, scanning, integration into more dimensional positioning systems
operating voltage	500 V - 1000 V	up to 200 V
max. electrical field strength	approx. 2 kV/mm	
max. strain	0.1 to 0.15 % related to the stack length	
force generation	same order related to the same cross section	
positioning accuracy	same for both types: depending on the electrical supply and environmental conditions	
electrical capacitance / volume	approx. 10 nF/cm^3	approx. 2,5 µF/cm^3
production technology	stacking of sintered ceramic plates	stacking of non sintered ceramic layers and cofiring
material variety	large	small
operating temperature range	up to 200 °C	up to 100 °C
electrical current for dynamic applications / per volume	low current	high current
cross section of ceramics	diameters up to 35 mm	up to 14 x 14 mm^2

Dynamic Operation of Piezocomposite Actuators

In comparison to piezo actuators and piezo stages based on multilayer stacks, Piezocomposite Actuators are utilized more often in dynamic applications as opposed to positioning tasks.

The high stiffness of Piezocomposite Actuators directly leads to an increased resonance frequency making it possible to work at higher frequencies and driving larger external masses.

$$f_{res}^{0} = \frac{1}{2\pi} \cdot \sqrt{\frac{c_T}{m_{eff}}}$$

$$f_{res}^{1} = \frac{1}{2\pi} \cdot \sqrt{\frac{c_T}{m_{eff} + M}} = f_{res}^{0} \cdot \sqrt{\frac{m_{eff}}{m_{eff} + M}}$$

Furthermore the relatively low capacitance results in reduced current consumption.

Piezocomposite Actuators can be used in high dynamic operation with frequencies up to several kHz, such as high frequency vibration excitation or material testing (fretting tests or super high cycle fatigue tests).

Specially designed piezo shakers or shock generators can work near or above the resonance frequency. Low voltage multilayer actuators are not suited for this kind of operation.

In dynamic operations 5% - 20% of the electric input power dissipates into heat. The resulting temperature change of the dynamic working actuator can exceed its Curie temperature easily and result in damage or the malfunction of the actuator.

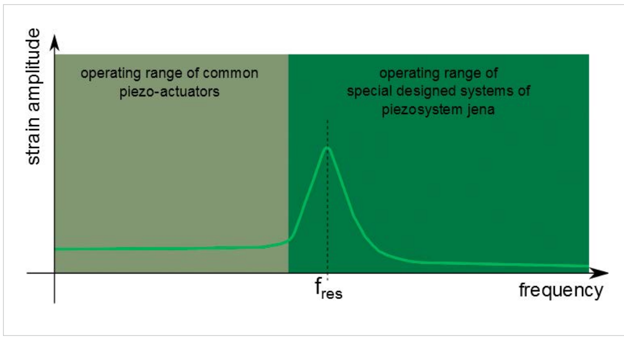

Figure 2: *frequency range of piezo shakers and standard piezo actuators*

Hence for long-term dynamic operation with Piezocomposite Actuators a heat management option is recommended to prevent overheating (compare ***chapter 3.10*** piezoline). ***piezosystem jena*** offers a "thermostable" option for Piezocomposite Actuators with casing and the use of high-temperature ceramic material for enhanced temperature ranges.

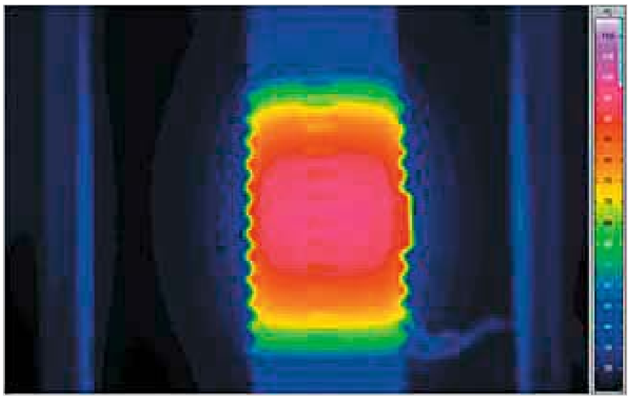

Figure 3: *Thermal image of a dynamically driven Piezocomposite Actuator, clamped at its end plates*

Piezo Shakers PiSha

In certain dynamic applications the requirements can easily exceed the capabilities of standard piezo actuators. Extreme accelerations in the range of several 1000 g and the resulting high power consumption require a specially adapted sophisticated design to withstand the high mechanical and thermal stresses. The solutions to these problems are special designed piezoelectric shakers (piezo shaker).

Key Features of Piezo Shakers

- High stiffness
- High forces, pressure forces up to several 10 kN
- Generation of kHz frequencies up to 100 kHz
- Amplitudes from sub-µm to several 100 µm
- High accelerations up to several 1000 g

*Please note, that these values cannot be achieved simultaneously

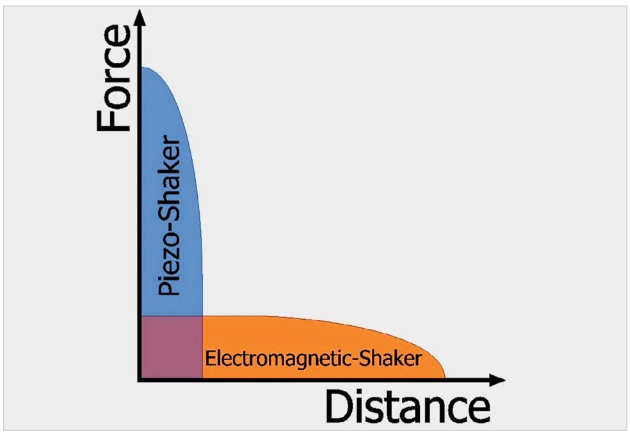

Figure 4: *Operating ranges of electromagnetic and piezoelectric shakers*

Piezo shakers show a higher stiffness and higher force potential than electromagnetic shakers. Therefore they usually cover different applications, especially those with higher frequencies. Due to the high power density of the piezoelectric material piezo shakers are ideally suited for miniaturized components.

Piezo Shakers versus Ultrasonic Transducers

There is a huge difference between piezo shakers and ultrasonic transducers. Ultrasonic generators use hard PZT materials with a high resonance magnification. Hence they operate at one specific frequency but consume a relatively small amount of electrical power.

Piezo shakers are tunable and work in a wide frequency range. In some cases they can also operate near or even above their natural frequency.

Piezo shakers are made from softer PZT material with a much smaller resonance magnification. In comparison to ultrasonic generators the power consumption is much higher.

Applications

With their high stiffness and high force potential piezo shakers are perfect for applications that require high frequencies up to 100 kHz tunable over a wide frequency range. Examples for such applications are:

- Acceleration tests
- Material characterization
- Defect detection
- Fatigue testing
- Modal analysis
- Non-destructive testing
- Vibration excitation

Functional Principle of Piezo Shakers

Piezo shakers are specially adapted piezo stack actuators. The driving voltage determines the amplitude of motion whereas the current determines the velocity. The internal design of the piezo shaker has to ensure that the shaker withstands the occurring high acceleration forces and thermal stress.

Operation Modes for Piezo Shakers

An efficient vibration excitation of an object strongly depends on the quality of coupling between shaker and the object. Depending on the application, different coupling arrangements can be achieved:

1. Bottom-Fixed Setup:

The bottom side of the piezo shaker is mounted to a heavy, non-moving base. The object is fixed at the shaker's moving end. In this case the motion is completely transferred to the object.

The maximum acceleration a is:

$$a = x \cdot (2\pi f)^2$$

x: amplitude,
f: frequency

Hence the resulting maximum force generation F is:

$$F = m \cdot a$$

m: mass of the object

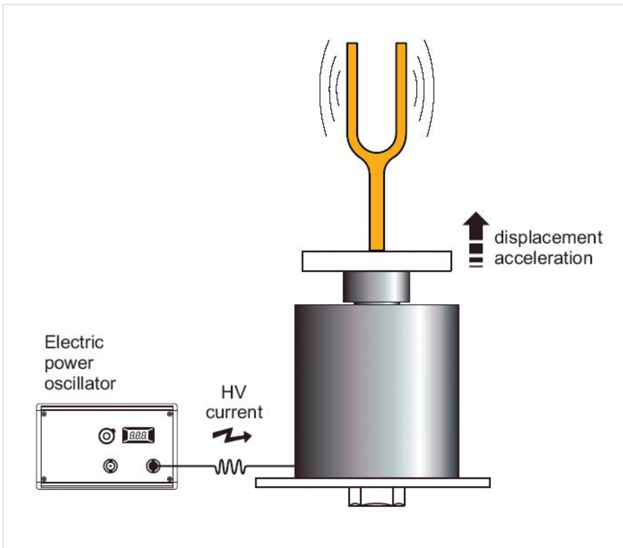

Figure 5: *Schematic of an inflexible setup of a piezo shaker*

2. Inertial Mass Setup

In this arrangement the shaker is freely mounted to the test object via its moving end. Operating the shaker generates an oscillation over the whole shaker body.

The achievable forces depend on the moving masses and the specimen's stiffness. Maximum forces and deformations

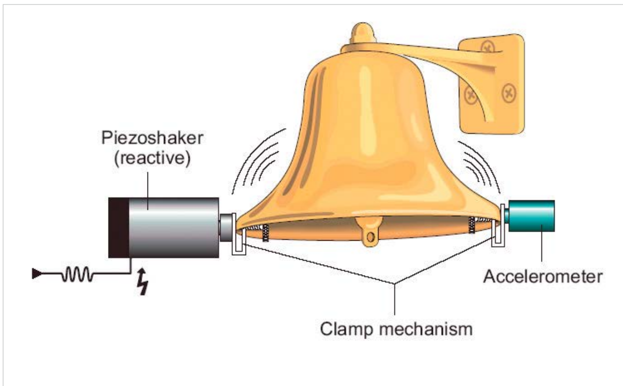

Figure 6: *Schematic of an inertial arrangement of a piezo shaker*

of the object will be generated, if the object is clamped tight (blocking condition). Adding seismic masses to the shaker allows a tuning of the system for frequency and forces. The vibration is detected via an accelerometer.

3. Clamped Setup:
The piezo shaker and the test object are mounted in a stiff clamping mechanism. The resulting amplitudes and forces depend on the shaker's and the test object's stiffness. The vibrations can be measured with a force sensor.

Depending on the setup the shaker can be integrated so that an additional clamping mechanism is not necessary.

Such kind of setup is often used for experiments for structure-borne sound investigations.

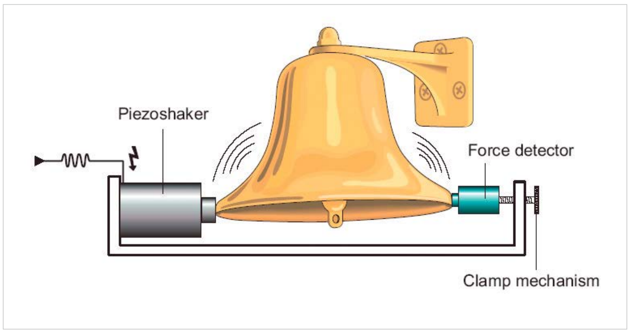

***Figure 7:** Clamping arrangement of a piezo shaker*

Piezo Shock Generators PIA

Shock generators are used to transfer short pulses to objects, to investigate their properties.

Shock Generator versus Shaker

In comparison to shakers, shock generators are operated by short electrical pulses or rectangular signals to achieve single pulses with high acceleration rates. These accelerations are independent of the repetition rate which can reach values in the kHz range.

Shakers usually work with a steady sine wave form. The frequency and amplitude of this oscillation determines the accelerations and forces reached.
Both systems are used for material and structure research; however the type of excitation is different: Shakers generate an oscillation of the material; shock generators realize single pulses to the material.

Conventional Shock Generators

Classic shock generation is usually realized by accelerating a specific mass (for example a hammerhead) which then hits its collision partner. During that short contact phase energy and momentum are transferred (the so – called impulse). Time and shape of the impulse strongly depend on the acoustical and elastic properties of the involved bodies. Due to the uncertainties during acceleration and contact phase it is extremely difficult to achieve reproducible shocks. Furthermore, the achievable repetition rates of these ballistic methods are strongly limited. A precise triggering (timing in µs-range) of the shock event which is needed in metrology is not possible. All these restrictions can be overcome with the use of piezo shock generators.

Piezo Shock Generators

Piezo shock generators overcome disadvantages of conventional generators. They provide:

- Adjustable shock parameters:
  energy (< 4 Joule); acceleration (> 10'000 g); amplitude (> 100 µm)
- High repeatability of the pulse parameters
- Precise time behavior — triggering in the µsec range
- Variable repetition rates — up to several kHz (burst)
- Fast rise time: — down to µs values
- Adjustable pulse width — down to 10 µs

Synchronization of several pulse generators is possible!

Piezo shock generators have to be specially designed to survive the high mechanical stress occurring during shock generation. Extreme preloads are necessary to withstand the high accelerations and resulting forces. Standard actuators are not sufficiently preloaded and would be immediately damaged under these conditions.

Please contact our team for more Technical Advice!

Applications

- Acceleration tests Shock experiments
- Shockwave propagation
- Material characterization (for example in Split-Hopkinson-Bar arrangements)
- Hardness testing
- Modal analysis
- Impact based measurements (like solid-borne sound investigations)
- Impact-echo-measurements (for example in geological and structural investigations)
- Sonic logging

The Piezo Stack as Shock Generator

If a piezo stack is charged with a very short rise time, the mechanical axial pressure in the ceramic material immediately increases to a high value. This so-called blocking pressure is generated over the full length of the piezo stack and leads to an accelerated expansion of the piezo bar. In this way a propagating pressure front can be created in the coupled shock-partner. Hence, the piezo represents an "active-bar", which then produces mechanical shocks.

The Physical Shock

In metrology usually bars are used for shock wave propagation, due to the easier mathematical modeling. The compression can be measured using strain-gages whereas Laser-Doppler anemometers can be used to determine the particle velocity. Changes in the bar's cross section lead to a splitting of the shock wave into a transmitted and a reflected part. This behavior is used in the Split-Hopkinson-Bar experiment (Fig. 8) to determine material characteristics subjected to high strain-rates.

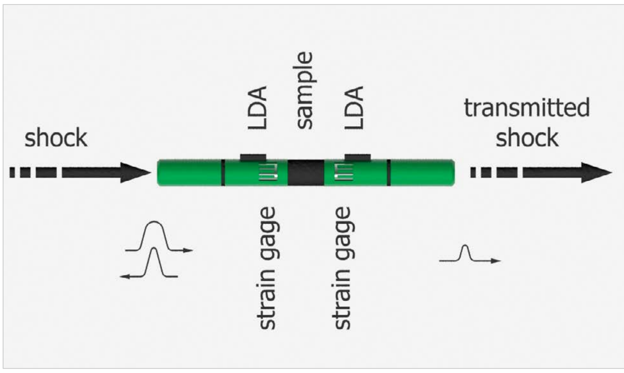

Figure 8: Hopkinson-Bar for material testing. By strain gauge and laser-Doppler anemometer the triggered and the reflected shock can be compared.

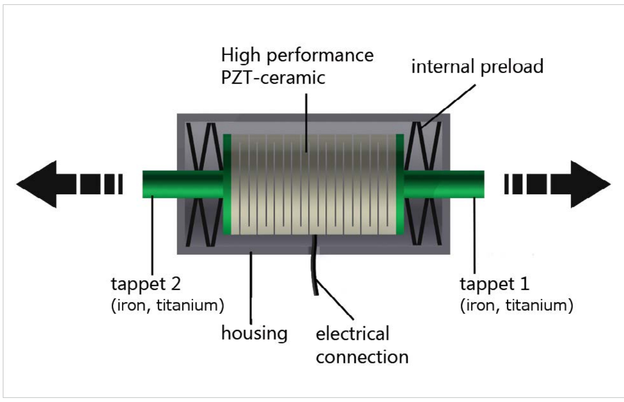

Figure 9: Schematic representation of a symmetric piezo shock-wave generator.

Layout of Piezo Shock Generators

Symmetric Shockwave Generators

Due to conservation of momentum, a piezo shock generator always creates two shocks propagating in opposite directions. This is used for the design of symmetric shockwave generators. (Fig. 9)

Single Sided Shockwave Generators

By applying a seismic mass on one side of the shock generator the backward running pulse can be reflected, resulting in a superposition of both pulses. The resulting pulse has nearly twice the energy and has an increased pulse duration showing a typical double-pulse profile. This concept is used for single-sided shock generators.

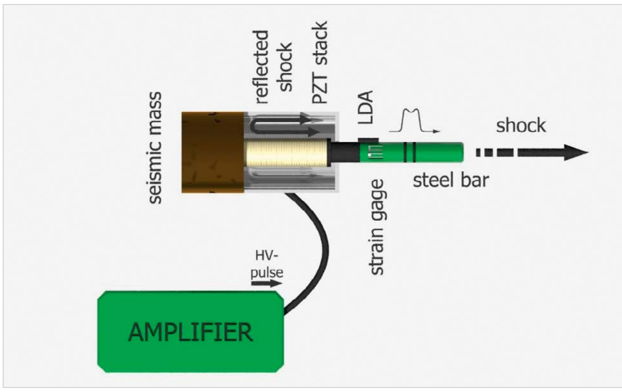

Figure 10: Schematic representation of a single-sided shock generator with a seismic mass. The double pulse is build by the overlay of reflected and forward pulse

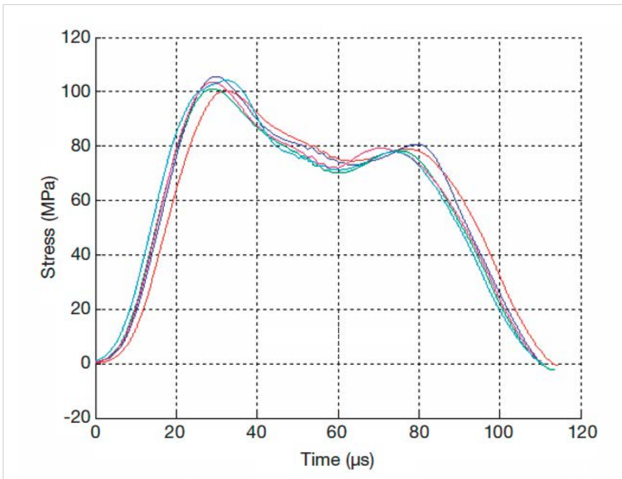

Figure 11: Typical pulse shape of a shock-wave generator with a seismic mass.

Electrical Operation of Piezo Shock Generators

For piezoelectric shock generation the piezo's capacitance has to be charged very fast. Considerations about position accuracy or voltage noise are irrelevant in such applications.

To reach electrical rise times in the microseconds range extremely high currents are necessary. These currents are provided using high power pulse switches as shown in Figure 12.

A capacitor bank (several 100 µF) is charged to the selected voltage (up to 1000 V). The piezo is then rapidly charged to the selected voltage via a small resistor leading to the actual mechanical shock. The piezo is then slowly discharged again. With the sufficient power of the amplifier pulse repetitions up to 100 Hz are possible. Due to the limited cooling of the actuators high repetition rates should be done in burst-mode.

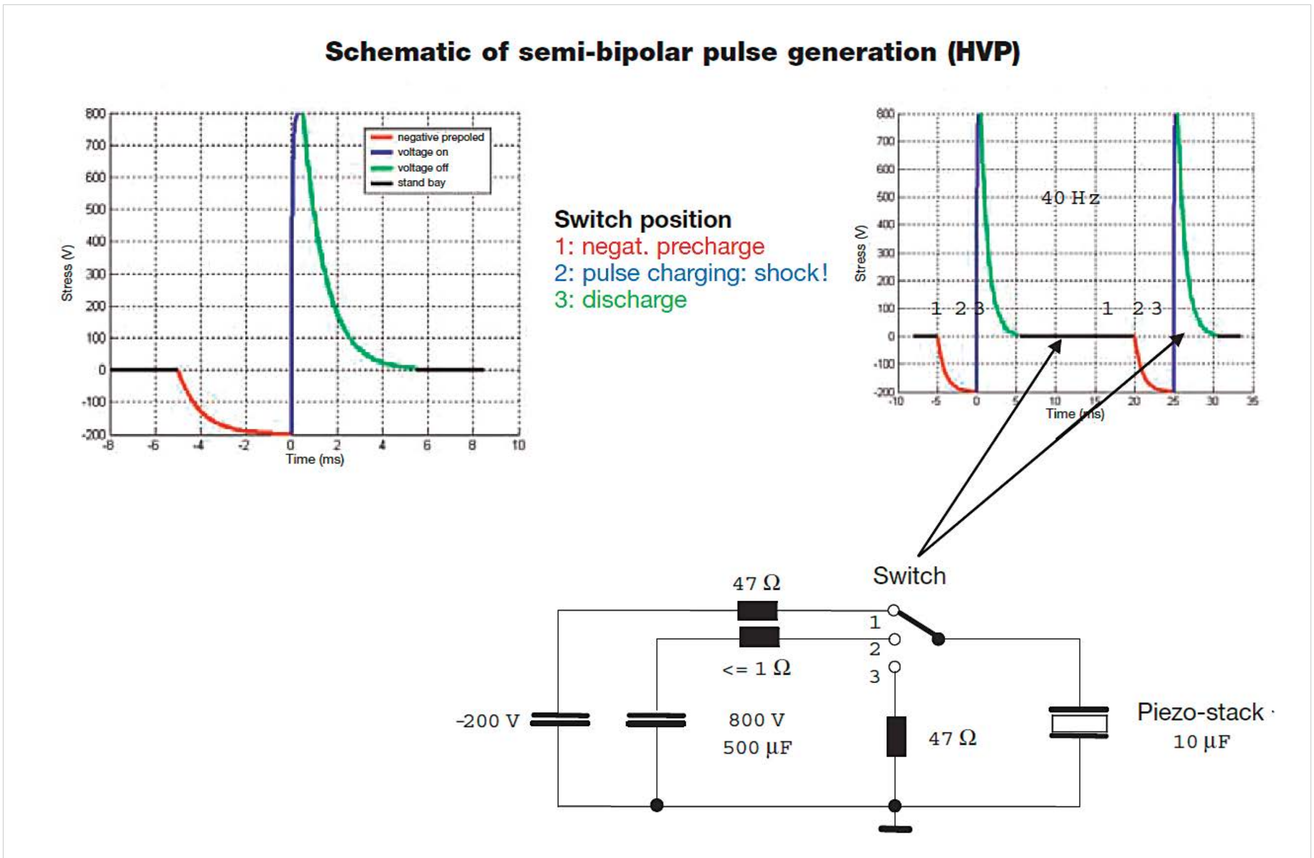

Figure 12: *Semi bipolar control with a high voltage pulser. The switch with three settings represents a combination of high power transistors, which are driven by a logic device.*
1. Negative charging to -200 V, 2. Shock like charging to +800 V, 3. Discharge to 0 V

Piezosystem Jena provides a wide range of Power Supplies for Piezo Shaker as well as for Shock Wave Generators:

amplifier	output voltage	peak output current	bandwith	description
for Piezo Shaker				
RCV 1000/7	1000 V	7 A	2 kHz	high power switching amplifier
LE 150/100 EBW	150 V	1 A	70 kHz	linear amplifier with enhanced bandwidth
for Shock Generator				
HVP 1000	1000 V	200 A	-	high voltage pulse switch amplifier
HVP 300/20	300 V	20 A	-	pulse switch amplifier

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]
$E = \frac{U}{L_0}$	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 $L_0 \approx 1_z$ [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 or 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 often it can be taken: $m_{eff} \approx m/2$ [g]
M	additional mass load to an actuator [g]
n	number of piezoelectric 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_{ii}	elasticity or compliance tensor (reciprocal value of the “Young´s modulus”) [m²/N]
S_{33}	elasticity for the longitudinal effect [m²/N]
T_c	Curie temperature [C]
$T = \frac{F}{A}$	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 ∂	tangent of the loss angle; ∂-loss angle [without dimension]
Φ	phase angle of an oscillation [without dimension]
ε	relative strain [without dimension]
ε_{33}^T	absolute dielectricity constant (typ. $\varepsilon_{33}^T \approx 5400$; $\varepsilon_0 = 8{,}85 \times 10^{-12}$ F/N) for piezo ceramic materials

Conversion Metrical/English Units

Table 1 Conversion MKS / English Units

25.4 mm = 1 inch
1 mm = 0.03937 inch
1 m = 39.37 inch

mm	in
1…	0.039
5…	0.197
10…	0.394
15…	0.591
18…	0.709
20…	0.787
22…	0.866
25…	0.984
32…	1.260
40…	1.575
50…	1.969
69…	2.717

m	Inch
1…	39.4
8…	315.0
16…	629.9
25…	984.3
35…	1378.0
38…	1496.1
40…	1574.8
50…	1968.5
100…	3937.0
200…	7874.0
300…	11811.0
400…	15748.0

Table 2 Common MKS / English

length	
1 meter	39.37 inches
1 inch	2.54×10^{-2} meters
area	
1 meters²	1.55×10^{3} inches²
1 inches²	6.452×10^{-4} meters²
volume	
1 meters³	6.102×10^{4} inches³
1 inches³	1.639×10^{-5} meters³
force	
1 kilopound	9.807 newtons
1 newton	1.020×10^{-1} kilopounds
mass	
1 kilogram	2.205 pounds
1 pound	4.536×10^{-1} kilograms
pressure	
1 atm = 1.105 N/m² = 760 Torr = 1.01 bar	
capacitance	
1 picofarad	1×10^{-12} farad
1 nanofarad	1×10^{-9} farad

pressure	= 1 PA	1 Mpa	1 bar	1 mbar	1 mmHg	1 Torr	1 psi	1 kp/cm²
1PA = 1N/m²	= 1	10^{-6}	10^{-5}	10^{-2}	7.5×10^{-3}	7.5×10^{-3}	1.45×10^{-4}	1.02×10^{-5}
1 Mpa = 1MN/m²	= 10^{6}	1	10	10^{4}	7500	7500	145	10.2
1 bar	= 10^{5}	10^{-1}	1	10^{3}	750	750	14.5	1.02
1 mbar	= 10^{2}	10^{-4}	10^{-3}	1	7.5×10^{-1}	7.5×10^{-1}	1.45×10^{-2}	1.02×10^{-3}
1 mWS	= 9.81×10^{3}	9.81×10^{-3}	9.81×10^{-2}	9.81×10^{1}	7.36×10^{1}	7.36×10^{1}	1.42	10^{-1}
1 mmWS	= 9.81	9.81×10^{-6}	9.81×10^{-5}	9.81×10^{-2}	7.36×10^{-2}	7.36×10^{-2}	1.42×10^{-3}	10^{-4}
1 mmHg (Torr)	= 1.33×10^{2}	1.33×10^{-4}	1.33×10^{-3}	1.33	1	1	1.93×10^{-2}	1.36×10^{-3}
1 psi	= 6.89×10^{3}	6.89×10^{-3}	6.89×10^{-2}	6.89×10^{1}	5.17×10^{1}	5.17×10^{1}	1	7.03×10^{-2}
1 kp/cm² = 1 at	= 9.81×10^{4}	9.81×10^{-2}	9.81×10^{-1}	9.81×10^{2}	7.36×10^{2}	7.36×10^{2}	1.42×10^{1}	1

Example (last row):

1 at = 1 kp/cm²
= 9.81×10^{4} PA
= 981 mbar 9.81×10^{4} N/m²
= 736 Torr
= 14 psi (psi = pound per square inch)

angle	=	degree	arc sec	mrad	µrad
1 degree	=	1	3600	17.45	17.4×10^{3}
1 arc sec	=	2.77×10^{-4}	1	4.85×10^{-3}	4.85
1 mrad	=	0.057	206.3	1	10^{3}
1 microradian	=	57×10^{-6}	0.206	10^{-3}	1

Mechanical noise as a function of voltage noise

mech. noise in nm	motion in µm	noise in mV	max. voltage range in V
0.04	15	0.4	150
0.10	40	0.4	150
0.25	100	0.4	150
0.50	200	0.4	150
0.75	300	0.4	150
1.00	400	0.4	150

Temperature change of the length for different materials

$\Delta l = \alpha \times 10^{-6} \times \Delta T \times L$ (in mm) x 1000

expansion Δl in µm	length in mm	temperature ΔT T2-T1	temp. coefficient $\alpha \times 10^{-5}\ K^{-1}$	material
- 6	50	20	-6	multilayer stack
- 1.2	20	10	-6	multilayer stack
+2.4	10	20	12	stainless steel
+0.15	10	10	1.5	invar
+2.38	10	10	23.8	aluminium
+0.94	10	10	9.4	titanium

+ expansion
- shrinkage