Energy Harvesting with Piezo Patch Transducers

Working Principle

The term *piezo* is derived from the Greek word for pressure. In 1880 Jacques and Pierre Curie discovered that an electric potential could be generated by applying pressure to quartz crystals; they named this phenomenon the *piezoelectric effect.* Later they ascertained that when exposed to an electric potential, piezoelectric materials change shape. This they named the *inverse piezoelectric effect.*

The piezo effect is used for sensor functionality, while actuator behavior uses the inverse piezo effect.

The piezoceramic plates in DuraAct™ patch transducers resemble a capacitor. The ceramic acts as a dielectric between its metallized surfaces. When voltage is applied, an electric field is created inside the ceramic. The field causes a uniform lateral contraction of the ceramic perpendicular to the direction of the electric field (Fig. 1). This behavior is called the transverse piezoelectric effect (d_{31} effect, Fig.2).

The electric field strength determines the magnitude of the lateral contraction. This is the key to simple control of the transducer modules. When the modules are glued to a substrate, they effectively transfer force over the whole surface, not only at selected points, as with conventional actuators. Conversely, DuraAct™ patch transducers transform changes in shape to electric current, thereby enabling their use as sensors or energy sources.

The piezoceramic response to a change of the electric field or to deformation is extremely fast. Vibrations in the kilohertz range can be produced or detected. Different excitation voltages are required and different contraction amounts possible, depending on the ceramic type and its dimensions. The correlation between displacement and applied voltage is not linear. A voltage-to-displacement curve with the typical hysteresis behavior is shown in Fig. 3.

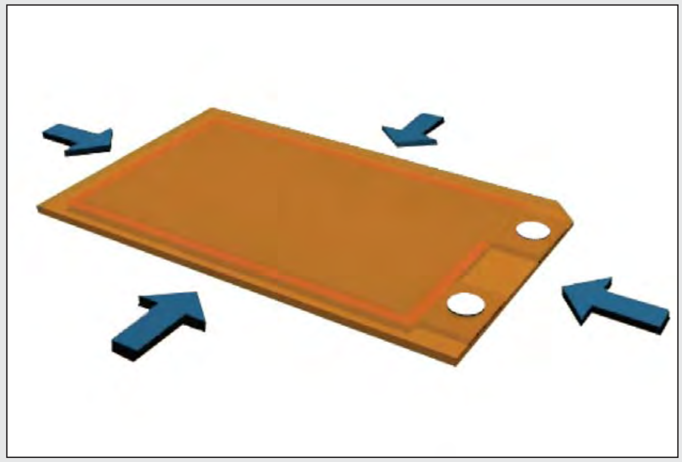


Fig. 1: Lateral contraction

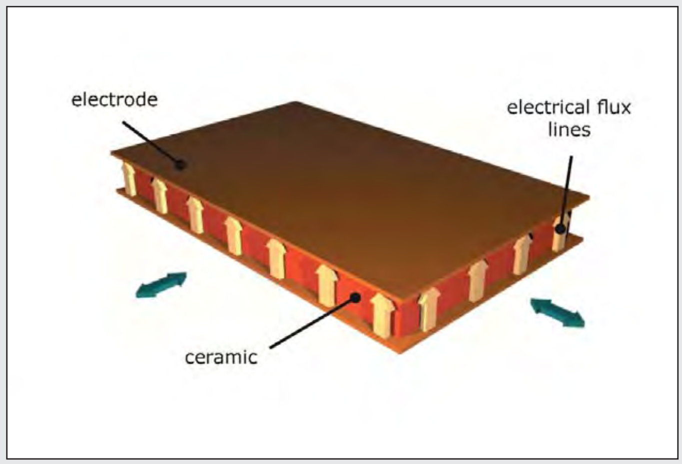


Fig. 2: d_{31} effect

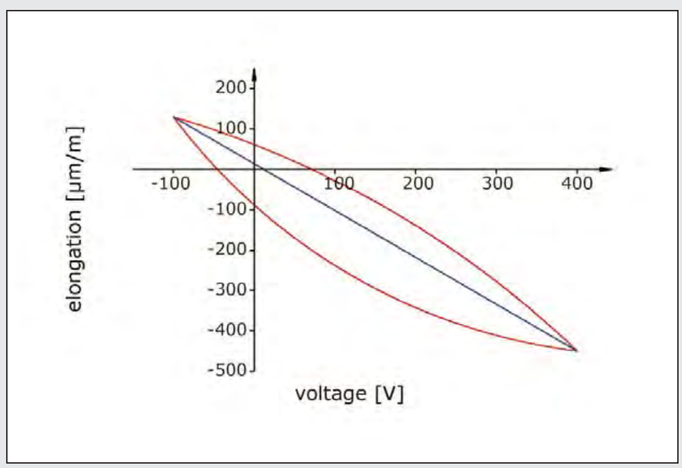


Fig. 3: Piezo hysteresis

Technology

DuraAct™ patch transducers operate as sensors with varying bandwidths—reacting to mechanical strain like impact, bending or pressure—and as high-precision positioning or bending actuators.

The standard transducer design features a piezoceramic foil with metalized surfaces for electrical contact (Fig. 4). The thickness of standard foils used is typically 100 to 500 µm, with even thinner layers possible. Without further processing, these piezoceramic elements are brittle and difficult to handle. Embedding them in a polymer structure provides electrical insulation and mechanical stability. The result is a module that is ductile and extremely robust.

An alternative design features multiple layer piezoceramics, enhancing force generation for the same operating voltage.

DuraAct™ patch transducers are solid state actuators and therefore have no moving parts. Wear and failure rates are low. Electrical contact is realized by soldering, clamping or gluing leads to two pads. Connecting multiple layers separately allows separation of the sensor and actuator functionality, meaning that the transducer can be used as sensor and actuator simultaneously.

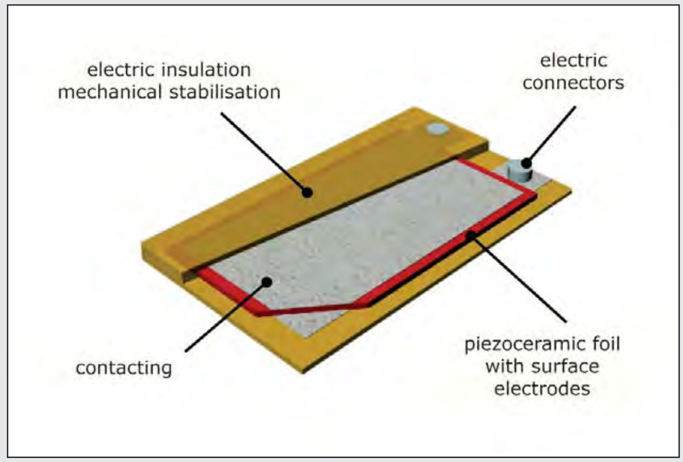


Fig. 4: DuraAct™ transducer design principle

Working Diagram

The actuator properties of piezoceramic transducers are essentially described by two parameters: the blocking force F_B and the free displacement, S_0. When a voltage U is applied to the free (unblocked) actuator, it reaches its maximum displacement S_0. The force required to prevent any length change at all is called the blocking force, F_B (Fig. 5).

A graph of applied force versus actuator displacement is called the actuator characteristic curve (Fig. 7). It basically follows the line passing through the points with 0 force and 0 displacement described above. In most cases the actuator acts against an elastic structure, e.g. when a spring or a metal sheet is deformed (Fig. 6). If the load is represented by a spring (characteristic curve of the spring) with stiffness of c_F, the resulting operating point is the intersection of the load line with the actuator characteristic curve (Fig. 7). The most effective operation occurs when the operating point is in the middle of the characteristic curve.

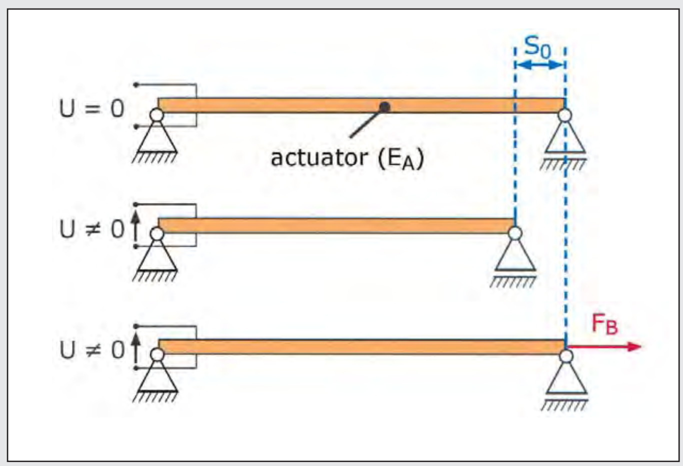


Fig. 5: Parameter definitions

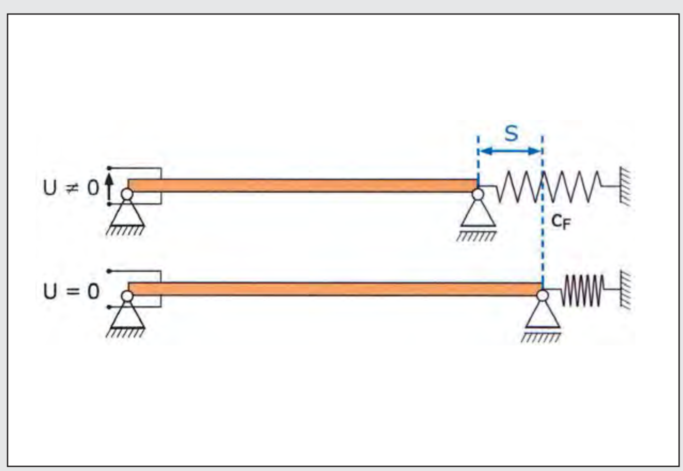


Fig. 6: Application of a spring force to an actuator

Parameters for Bender Actuators

DuraAct™ actuators are usually glued to a substrate and transfer the contraction not at a few attachment points, but over the whole surface. In such a configuration, the DuraAct™/substrate combination acts as a bender actuator. Bender actuators provide fast, high-precision and repeatable deflection and are used in a wide range of applications, e.g. in printers, valves, and in the textile industry. DuraAct™ patch transducers are based on the transverse piezo effect, and therefore contract with an electric field applied. The bender flexes and exerts a normal force as shown in Fig. 8. For the free, unblocked bender, the free deflection is W_0. The force required to reduce the deflection to zero is called the bender blocking force F_{BW}. It is significantly smaller than the actuator blocking force. The line through these two points, gives the characteristic curve for the bender. Fig. 9 and 10 show curves relating the maximum deflection W_0 and the maximum force F_{BW} to the substrate thickness and elasticity. These diagrams show the actual deflections and forces measured with 50 mm substrate samples made of different materials and a P-876.A15 DuraAct™ patch transducer. Together with the characteristic curve for the DuraAct™ alone, the bender characteristics form the basis for effectively estimating the actuator performance in a specific application. PI therefore includes these curves on all datasheets.

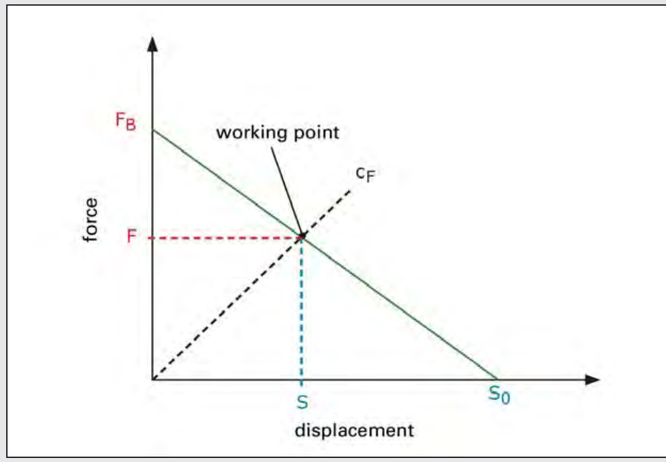


Fig. 7: Characteristic curve with spring load line

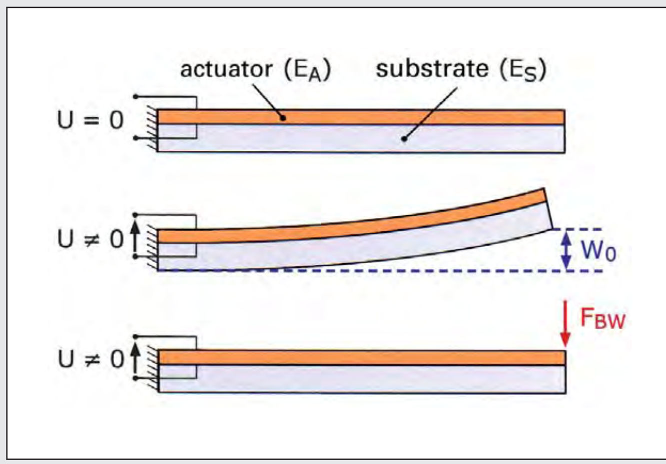


Fig. 8: Bender actuator characteristics

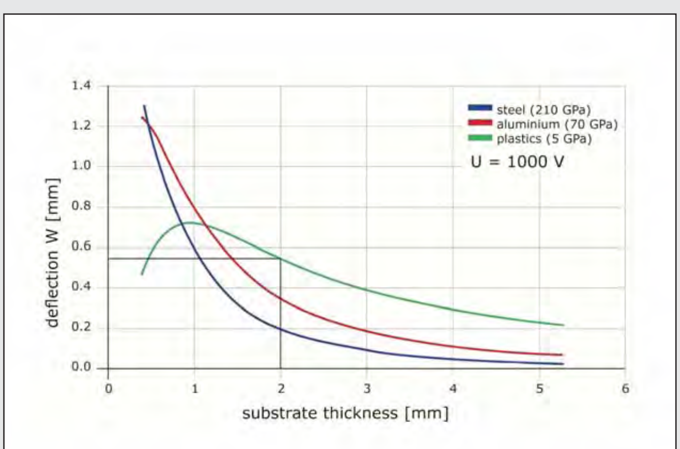


Fig. 9: Free deflection of bender actuators

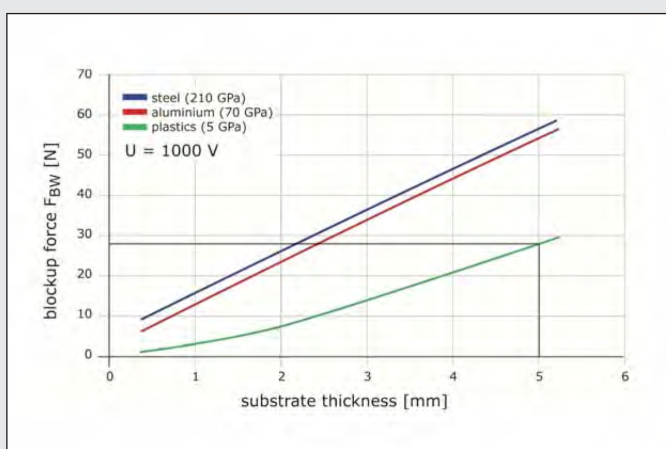


Fig. 10: Bender actuator blocking force

Power Requirements

To determine the required electrical power for successful actuator operation, the electrical capacitance must be known. Typical DuraAct™ capacitances are in the nanofarad range and can be found in the datasheets.

The electrical capacitance, C, depends on the piezoceramic type, thickness and area. For an estimation of the average electrical power, P_m, knowledge of the operating voltage range and the excitation frequency is necessary.

$$P_m = C \cdot f \cdot U_h^2$$

f: Frequency
U_h: Voltage swing

The maximum power required P_{max} is then just the average power times pi (π):

$$P_{max} = P_m \cdot \pi$$

Application Examples

Sensor Mode

- Vibration damping applications: good results can be achieved by combining a piezoelectric sensor with a servo-controller and having the sensor signal control an (external) damping mechanism.
- Structural Health Monitoring (SHM): DuraAct™ patch transducers can be used to monitor the functional and structural integrity; the patch transducers are either part of the structure itself, or embedded within it.
- Fast switching: DuraAct™ patch transducers provide fast response and long lifetime and are ideal actuators for these applications.

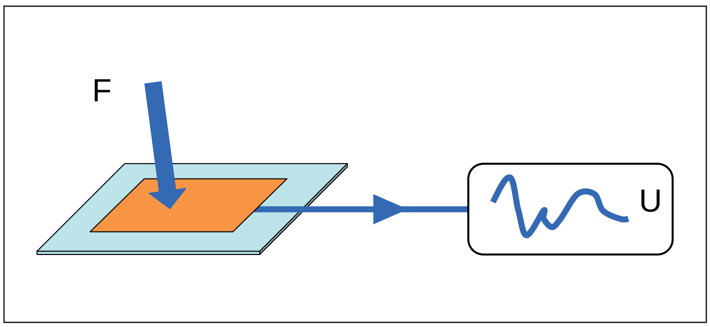


Fig. 1a: Classical application of the direct piezo effect. Minute deformations of the substrate cause displacements in the DuraAct™ patch transducer and produce an electric current proportional to the motion. DuraAct™ transducers can detect deformations—like those caused by bending strain or pressure—very precisely, even at high frequencies.

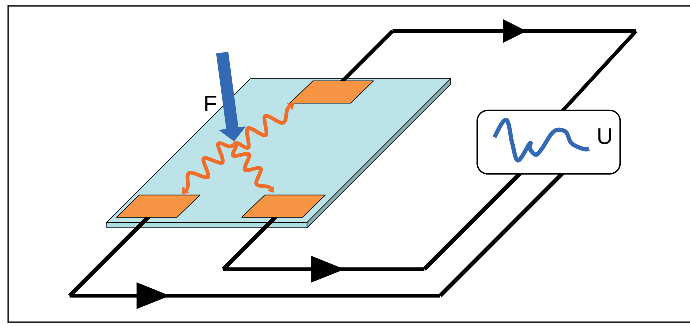


Fig. 1b: The same operating mode can be used with an array of several modules.

Actuator Mode

DuraAct™ patch transducers feature a very high bandwidth. In combination with suitable electronics (e.g. E-413.D2 from PI) they can be used as high-dynamics positioners with sub-micron precision.

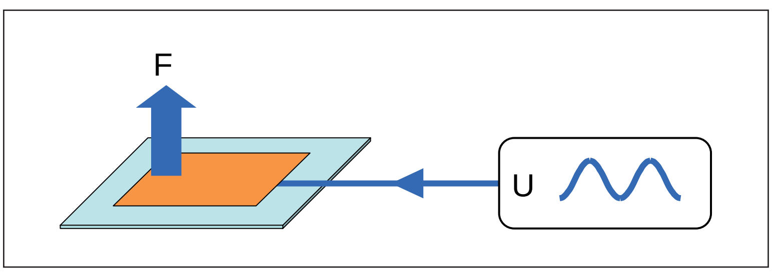


Fig. 2: In actuator mode, DuraAct™ patch transducers use the inverse piezo effect: they contract when voltage is applied. Affixed to a substrate material, a DuraAct™ patch transducer acts as a bender

Structural Health Monitoring (SHM)—Damage Diagnosis

Whole areas can be surveyed with an array of multiple modules attached to various points on the surface. Active monitoring, where some transducers are used as actuators while the others detect the waves they generate, is also possible. Faults in the structural material, like microcracks, are detected by comparing the signals with those from an undamaged system.

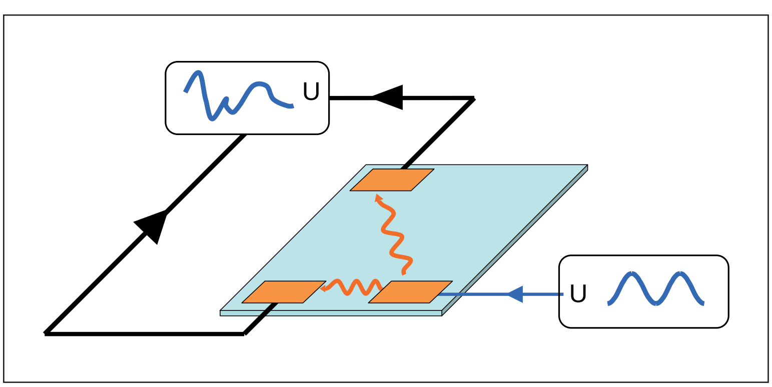


Fig. 3: Design principle for a health monitoring system: one DuraAct™ patch transducer is controlled by an electronic amplifier (actuator functionality) and induces vibrations in the substrate. An array of transducers detects the vibrations and transfers the signals to suitable control electronics. Comparison with the signal pattern from an undamaged system gives information concerning the condition of the substrate.

Application Examples (cont.)

Adaptive Systems Use Both Sensors and Actuators

- Active Vibration Damping: A DuraAct™ patch transducer is used as high-precision sensor and high-performance actuator, simultaneously detecting and damping or eliminating undesirable vibrations in, for example, rotating components. The DuraAct™ sensor signal may be used as power supply for the same module, where it is fed back in with a phase shift. Multilayer ceramic designs make for higher efficiency.
- Profile or shape control: The sensor functionality is used to detect a deformation, and the actuator function to counteract it. The resulting shape control is highly precise, down to the submicron range.

Adaptronics

The use in adaptive structures exploits both the sensor and actuator functionality of the DuraAct™ patch transducer. As smart materials, they can adapt to varying environmental conditions like impact, bending or pressure. Adaptive materials are used in particular for vibration reduction in vehicles, and their use in mechanical engineering is growing.

Energy Harvesting

- DuraAct™ patch transducers can provide power for low-power electronics like sensors, making the development of autonomous systems possible. A special branch of Structural Health Monitoring (SHM) is Wireless Health Monitoring. Here, a DuraAct™ patch transducer can serve simultaneously as shape-control sensor and supply energy to a radio transmitter for remote data transfer.
- DuraAct™ patch transducers may replace other power supply solutions in existing applications.

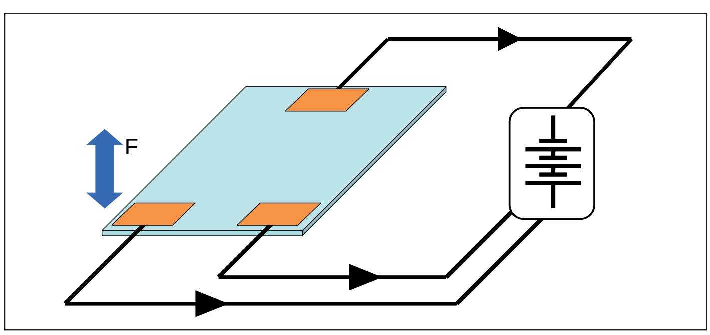


Fig. 4: The ability of DuraAct™ transducers to convert mechanical to electrical energy makes them ideal for satisfying power requirements of low-power electronics, and makes possible construction of energy-autonomous systems

Adaptronics—Industrial Applications of Tomorrow

The development of self-correcting, adaptive systems is receiving more and more attention in modern industrial research. Structures using "smart materials" which integrate sensor and actuator functions are taking on growing importance in this field. These systems are designed to detect and react to changes in their operating environment, like impact, pressure or bending forces.

With a long history as adaptive materials, piezo actuators have been especially popular for the monitoring and active damping of high-frequency vibration. The novel DuraAct™ patch transducers now offer a compact solution in this area.

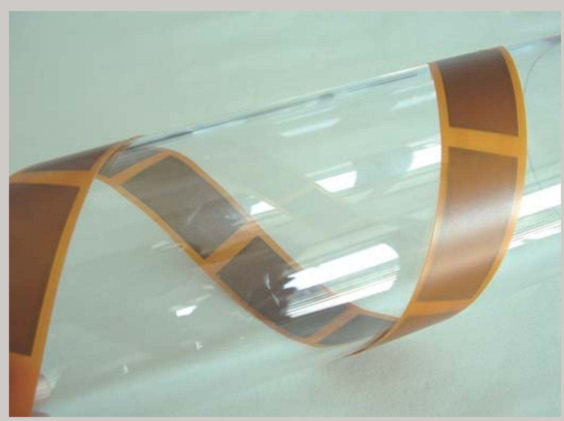
Applied directly to a substrate, or used as part of the structure itself, DuraAct™ patch tranducers can detect and produce vibrations or contour deformations at the source, inside the structure. The magnitude of usable deflection depends strongly on the substrate properties, and extends into the millimeter range.

Piezo-Electric All-Rounder—DuraAct™ Patch Tranducers

Piezoelectric components like the DuraAct™ patch transducer transform electrical to mechanical energy and vice versa. Possible applications are in high-precision bender actuators, high-dynamics sensors or as power sources.

DuraAct™ patch transducers are extremely compact units based on a thin piezoceramic foil between two conductive films, all embedded in a ductile composite-polymer structure. In this way, the brittle piezoceramic is mechanically prestressed and electrically insulated, which makes the transducers so robust that they can be applied on curved surfaces with a bending radius as low as 20 mm. The patch transducers are glued to the surface and can be used for various purposes.

Even in high-dynamics applications, the rugged design ensures reliability, high resistance to damage and a lifetime well over 10^9 cycles. Wear and failure rates are low, as the solid-state actuators contain no moving parts.



DuraAct™ patch transducers tolerate bending radii as low as 20 mm (3/4 in.)

Miniature Electric Generator for Autonomous Systems

DuraAct™ patch transducers can extract electric power from mechanical vibrations of up to several kilohertz, thus acting as energy harvesting devices. The power, in the milliwatt range, can supply miniature electronics like LEDs, sensors or mini RF transmitters for remote data transfer.

DuraAct™ technology allows high flexibility in actuator design. This means that DuraAct™ is also ideally suited for research and prototyping. In addition to the range of standard designs, highly individualized structural shapes can be realized to meet different requirements of geometry, flexibility, stiffness or operating temperature.

Standard DuraAct™ patch transducers consist of one piezoceramic layer only. For special applications, multilayer devices can be made available. In an actuator, multiple layers result in higher force generation with the same operating voltage. If the layers are wired separately, both sensor and actuator functionality can be used simultaneously.

The piezoelectric transducers can be designed to fit the application exactly, including even transducers with arrays of multiple ceramic elements. Such custom products can be produced very efficiently, even in low quantities.

Selection of custom modules

Control Electronics

Depending on the application, different demands are made on the electronics. To operate a high-precision, high-dynamics positioner, a low-noise, broadband amplifier is required. Active vibration damping requires fast servo-control with bandwidth sufficient for close-coupling the generated force to the structural mass to be damped. PI offers special, high-resolution amplifier modules for DuraAct™ patch transducers, and can always create custom versions to meet special requirements.

DuraAct™ Patch Transducers—Features and Advantages

- High damage immunity
- Choice of materials and geometries
- Well-defined mechanical and electrical properties
- Short lead-time availability
- Compact
- Long lifetime
- High bandwidth
- Customized solutions
- Can be applied to curved surfaces
- Cost-effective
- Constant & proven quality
- Easy to use
- Operation as actuator, sensor or power source
- Multilayer module, e.g. for actuator-sensor combination
- Highly flexible ceramic elements

P-876

DuraAct™ Piezoelectric Patch Transducers

P-876.A12 and .A15 actuators. Golf ball for size comparison

- **Actuator, Sensor or Energy Source**
- **Highly Formable Ceramics**
- **Can be Applied to Curved Surfaces**
- **Customized Solutions on Request**
- **Cost-Effective**

P-876 DuraAct™ patch transducers offer the functionality of piezoceramic materials as sensors and actuators as well as for electrical charge generation and storage. Used as bender actuators, they allow high deflections of up to 0.8 mm with high force and high precision. Other possible operation modes of DuraAct™ transducers are as high-dynamics sensors (e.g. for structural health monitoring) or for energy harvesting.

Application Examples

- High-dynamics actuators
- Adaptive systems
- Vibration and noise cancellation
- Deformation control and stabilization
- Damage monitoring
- Energy harvesting

Integration into Adaptive Systems

With their compact design, DuraAct™ transducers can be applied to structure areas where deformations are to be generated or detected. For this purpose the transducers can be affixed to the surfaces of structures or integrated as structural elements themselves. Whole areas can be monitored effectively by applying an array of several modules to a surface.

DuraAct™ patch transducers are ideally suited for active and adaptive systems. Embedded in a servo-control loop, they can reduce vibrations and control structures in the nanometer range.

Robust and Cost-Effective Design for Industrial Applications

The laminated design with piezoceramic plate and polymers provide a mechanically preloaded and electrically insulated device for easy handling. P-876 patch transducers feature a rugged design with the mechanical stability of a structural material.

Energy Harvesting: Self-Sustaining Systems in a Small Package

One possible application of DuraAct™ patch transducers is in the field of energy harvesting. Transformation of mechanical vibrations of up to some kilohertz into the corresponding potential difference can yield electrical power in the milliwatt range. This power can supply miniature electronic devices like diodes, sensors or even radio transmitters for remote data control.

DuraAct™ transducers can be offered in highly customized versions:

Ordering Information

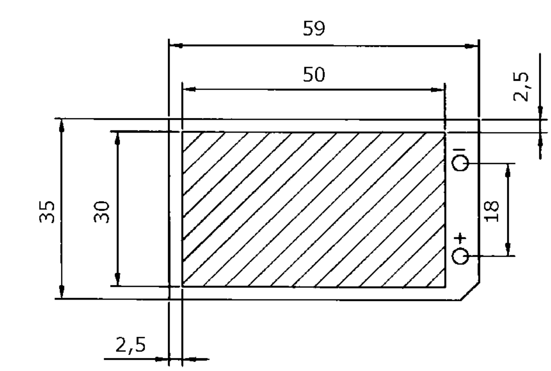
P-876.A11
DuraAct™ Patch Transducer,
61 x 35 x 0.4 mm

P-876.A12
DuraAct™ Patch Transducer,
61 x 35 x 0.5 mm

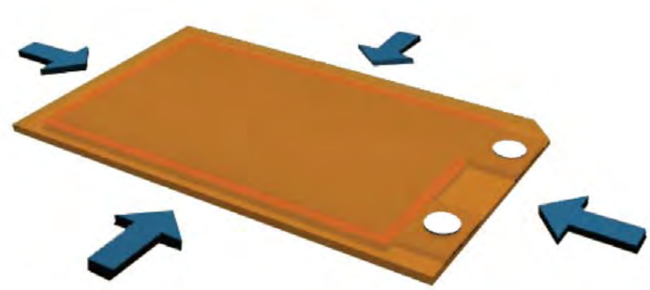
P-876.A15
DuraAct™ Patch Transducer,
61 x 35 x 0.8 mm

Ask for custom designs!

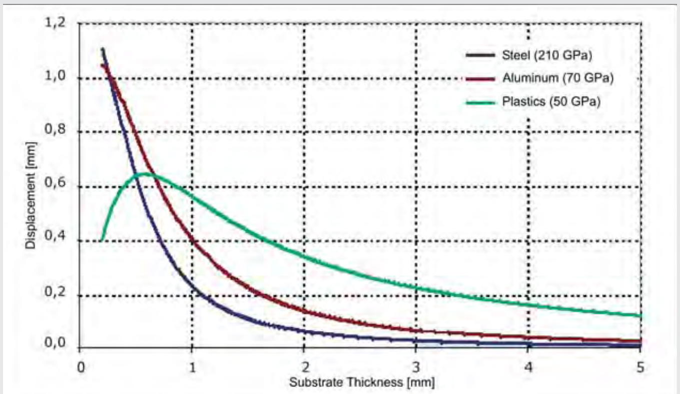
- Flexible choice of dimensions
- Flexible choice of thickness and bending properties
- Flexible choice of piezoceramic materials and operating temperature
- Various electrical connection designs
- Combining sensor and actuator functions (multiple ceramic layers)



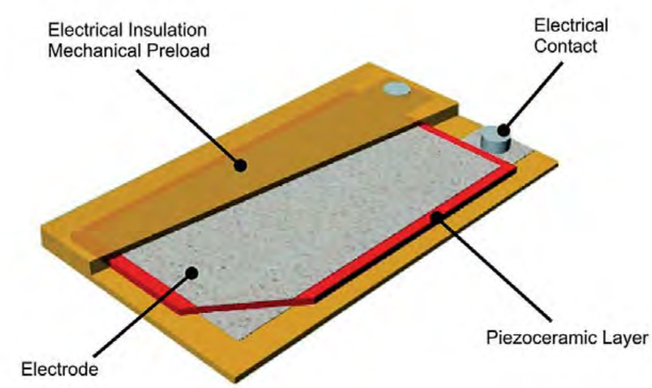
Dimensions of the P-876 in mm



Lateral contraction of a DuraAct™ patch transducer when voltage is applied



Deflection of a bending transducer as a function of the substrate thickness for different materials. A bending transducer consists of a substrate with a P-876 actuator (here: P-876.A15) glued to one side. A contraction of the actuator effects a deflection W



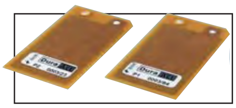
Design principle of the transducer

Technical Data

	P-876.A11	P-876.A12	P-876.A15	Tolerances
Operating voltage	-50 to +200 V	-100 to +400 V	-250 to +1000 V	
Motion and positioning				
Lateral contraction, open-loop	400 µm/m 1.6 µm/(H/m/V)	650 µm/m 1.3 µm/(H/m/V)	800 µm/m 0.64 µm/(H/m/V)	min.
Mechanical properties				
Holding force	90 N	265 N	775 N	
Length	61 mm	61 mm	61 mm	±0.5 mm
Width	35 mm	35 mm	35 mm	±0.5 mm
Thickness	0.4 mm	0.5 mm	0.8 mm	±0.5 mm
Bending radius	12 mm	20 mm	70 mm	max.
Drive properties				
Piezo ceramic type	PIC 252 Layer thickness: 100 µm	PIC 255 Layer thickness: 200 µm	PIC 255 Layer thickness: 500 µm	
Electrical capacitance	150 nF	90 nF	45 nF	±20 %
Miscellaneous				
Operating temperature range	-20 to +150 (180) °C	-20 to +150 (180) °C	-20 to +150 (180) °C	
Mass	2.1 g	3.5 g	7.2 g	±5 %
Voltage connection	Solder pads	Solder pads	Solder pads	
Recommended controller/driver	E-413.D2	E-413.D2	E-508	

Selection Guide

DuraAct™ Patch Transducers



Model	Dimensions (l x w x d) [mm]	Mass [g]	Active Area [cm²]	Capacitance [nF]	Supply Voltage (min/max) [V]	Lateral Contraction/ Voltage [(µm/m)/V]	Free Lateral Contraction S_0 [µm/m]	Blocking Force F_B [N]	Young's Modulus [GPa]
P-876.A11	61 x 35 x 0.4	2.1	15	150	-50 to 200	1.6	450	90	16.4
P-876.A12	61 x 35 x 0.5	3.5	15	90	-100 to 400	1.3	650	265	23.3
P-876.A15	61 x 35 x 0.8	7.2	15	45	-250 to 1000	0.64	800	775	34.7

Coming Soon

Model	Dimensions (l x w x d) [mm]	Mass [g]	Active Area [cm²]	Capacitance [nF]	Supply Voltage (min/max) [V]	Lateral Contraction/ Voltage [(µm/m)/V]	Free Lateral Contraction S_0 [µm/m]	Blocking Force F_B [N]	Young's Modulus [GPa]
P-876.A22	113 x 35 x 0.5	6.5	30	180	-100 to 400	1.3	650	265	23.3
P-876.A42	113 x 67 x 0.5	12.5	60	360	-100 to 400	1.3	650	527	24.2
P-876.A25	113 x 35 x 0.8	13.5	30	90	-250 to 1000	0.64	800	775	34.7
P-876.A45	113 x 67 x 0.8	27.0	60	180	-250 to 1000	0.64	800	1546	36.1
P-876.B12	61 x 55 x 0.5	5.5	25	150	-100 to 400	1.3	650	438	24.5
P-876.B22	113 x 55 x 0.5	10.0	50	300	-100 to 400	1.3	650	438	24.5
P-876.B42	113 x 107 x 0.5	20.0	100	600	-100 to 400	1.3	650	873	25.1
P-876.B15	61 x 55 x 0.8	11.5	25	75	-250 to 1000	0.64	800	1290	36.6
P-876.B25	113 x 55 x 0.8	21.5	50	150	-250 to 1000	0.64	800	1290	36.6
P-876.B45	113 x 107 x 0.8	43.0	100	300	-250 to 1000	0.64	800	2570	37.5
P-876.C12	81 x 30 x 0.5	4.0	17.5	10.5	-100 to 400	1.3	650	220	22.7
P-876.C22	153 x 30 x 0.5	7.5	35	210	-100 to 400	1.3	650	220	22.7
P-876.C42	153 x 57 x 0.5	15.0	70	420	-100 to 400	1.3	650	440	23.8
P-876.C15	81 x 30 x 0.8	8.2	17.5	53	-250 to 1000	0.64	800	650	33.8
P-876.C25	153 x 30 x 0.8	16.0	35	105	-250 to 1000	0.64	800	650	33.8
P-876.C45	153 x 57 x 0.8	31.5	70	210	-250 to 1000	0.64	800	1290	35.4
P-876.SP1	27 x 15 x 0.5	0.5	0.8	4.75	–	–	–	–	–

Custom Transducer Shapes

Custom modules

The modular design of the DuraAct™ technology opens a wide range of optimization possibilities concerning the following features:

- Transducer geometry
- Flexibility and bending
- Operating temperature
- Insulating material
- Electrodes, shape and material
- Connection points, shape and material

For more information on piezoceramic materials and components, see the PI Ceramic catalogs and Website (www.piceramic.de).

For more information on these and other PI product lines, see the Physik Instrumente (PI) Nanopositioning catalog and website (www.pi.ws).

Program Overview

- Piezoelectric Actuators
- Piezo Nanopositioning Systems and Scanners
- Active Optics / Tip-Tilt Platforms
- Capacitive Sensors
- Piezo Electronics: Amplifiers and Controllers
- Hexapods
- Micropositioners
- Positioning Systems for Fiber Optics, Photonics and Telecommunications
- Motor Controllers
- PILine® High-Speed Ceramic Linear Motors

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