Integrating piezo components in system solutions

The number and variety of piezo applications is growing in all industries, such as semicon, medical, aerospace, consumer and industrial. HEINMADE, based at the High Tech Campus in Eindhoven, the Netherlands, deals with the integration of piezo components into system solutions. After an introduction on piezo technology various examples will be discussed.

• ***Hein Schellens and Maikel Heeren*** •

The company HEINMADE was founded in 2005 by Hein Schellens as HEIN MAnagement and DEvelopment, underlining that succesfull integration should be properly managed right from the start of development. As a distributor of leading piezo components suppliers (Nanomotion, Noliac and Piezomechanik), HEINMADE is supported by a solid base of piezo knowledge and know-how, and can deliver any type of piezo solution. With its residence at the High Tech Campus in Eindhoven, virtually every analytical technology and scientist is at hand to assist during development. The testing and qualification is performed in a well-equipped lab and, if needed, in a class 1000 cleanroom.

PZT

The word piezo is derived from the Greek piezo or piezein, which means to press. In response to pressure the piezo material (PZT, i.e. lead zirconate titanate) generates an electrical field over the poling direction; see Figure 1. The reverse effect is seen when under an electric field a strain is produced. The maximum strain is about 0.15% at an electric field of 3 V per μm thickness (i.e. 3 kV/mm).

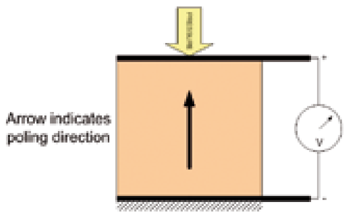


Figure 1. In response to pressure piezo material generates an electrical field.

High precision and high stiffness

The dominant use of piezo in nanotechnology is demonstrated by an example. The elongation of a single bulk element is calculated as the material constant d_{33} (piezo electric charge constant, ~ $500{\cdot}10^{-12}$) times the voltage. At a voltage of 1 V, the elongation becomes 0.5 nm. Thus at 1 mV, the elongation is 0.5 pm (= $0.5{\cdot}10^{-12}$ m), bringing subnanometer positioning ‘easily’ within reach; see Figure 2.

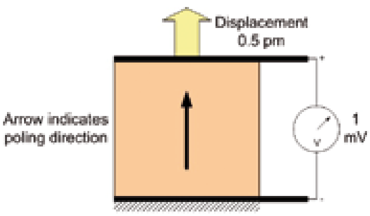


Figure 2. Piezo technology enables subnanometer positioning.

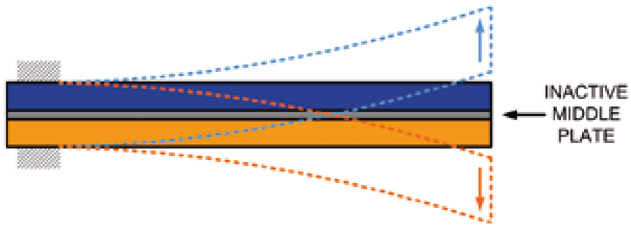


Figure 5. Bending mode of a piezo actuator.

The force required to push the actuated piezo element back to its nominal position is called the blocking force (~ 40 N per mm^2 at 0.15% strain). The relatively small strain in combination with this high blocking force, results in an extremely high stiffness. For example a 10x10 mm^2 element with a thickness of 4 mm gives a strain of 6 µm and a blocking force of 4000 N. The subsequent stiffness is 6,7·10^8 N/m, making high resonance frequencies on system level possible. Figure 3 shows the working area of a piezo actuator.

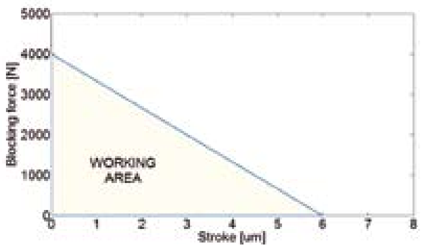


Figure 3. Working area of a piezo actuator.

Multi-layer to lower the voltage

The 4 mm height of the piezo crystal in the example would indicate a required voltage of 12 kV. Because of electrical breakdown risk such high voltages best be avoided. Alternatively, a piezo crystal can be built up from thin layers. At a layer thickness of 66 µm, the maximum voltage is reduced to 200 V for obtaining the maximum stroke. Figure 4 shows the configuration of a multi-layer component. The layer thickness can be freely chosen down to a thickness of 10-15 micron, reducing the voltage further to 30-45 V.

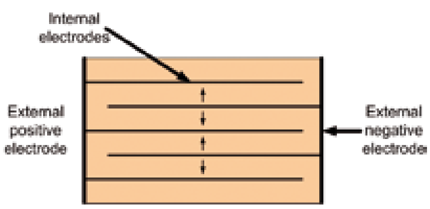


Figure 4. A multi-layer piezo component.

Increase of stroke

The limited displacement of a piezo component can be increased in three different ways: bending mode, cantilever multiplication and by means of a piezo motor. The term piezo actuator is used for the first two and links the applied voltage directly to a certain position. The term piezo motor is used in those cases where the stroke is in principle unlimited and where position is maintained at power shut down. The latter is one of the major advantages of a piezo motor compared to an electromagnetic motor. Maintaining position at standstill without power consumption does not generate any heat, and hence no additional position corrections are needed.

Bender

A well-known option for increasing the stroke is the bending mode. Two separate piezo elements are bonded, in some cases with an inactive middle plate. The bending is caused by a difference in shrinkage of the two piezo elements in the length direction due to a difference in the piezo actuation; see Figure 5.

For a multi-layer bender the active layers are split in a lower and upper section leading to the same bending option at again lower voltages. The strokes are at millimeter level and forces are around 1 N (i.e. stiffness at 1·10^3 N/m).

Multi-layer ring bender

As indicated in Figure 6, there is a large shift in stiffness from a piezo actuator to a piezo bender. To overcome this shift Noliac A/S developed the ring bender. The advantages of the ring bender are its low height in combination with its relative high stroke maintaining a high blocking force. Figure 7 shows a ring bender and how it works, which resembles a cupped spring washer. The stroke ranges from 20 to 200 µm at a force of around 50 N, leading to a stiffness in the range of 1·10^6 N/m.

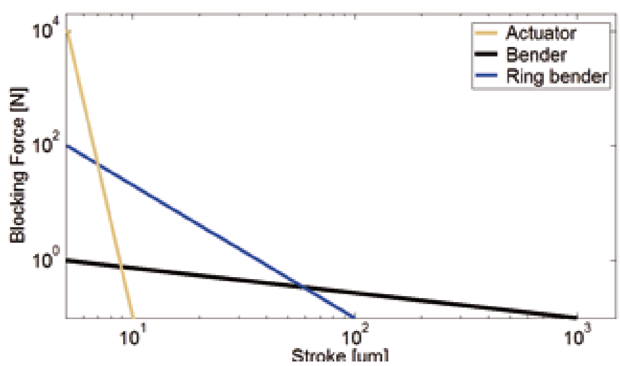


Figure 6. Comparison of blocking force vs stroke for piezo actuator, bender and ring bender.

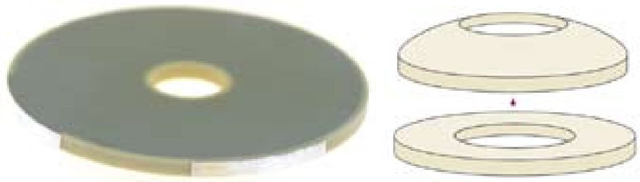
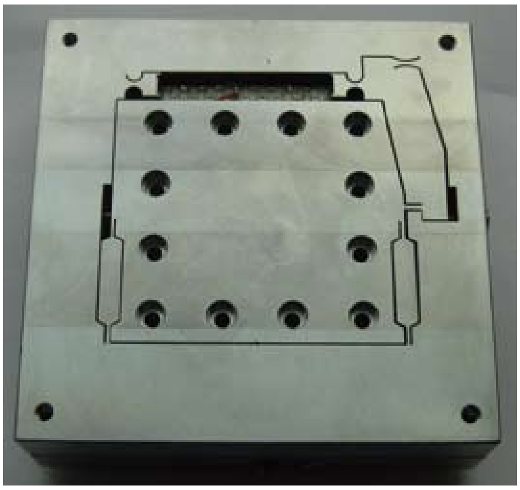


Figure 7. A ring bender and its principle of operation.

Cantilever multiplication

When placing a piezo stack in a cantilever hinge structure, the multiplication factor to increase the stroke can be chosen as needed. The multiplication factors in general range from 5 to 15. When combined with a piezo stack of 50 mm and thus 70 µm of stroke, this leads to strokes up to 1000 µm. The down side is the quadratic drop of the stiffness by a factor of 25 to 225. Figure 8 shows a solution designed and manufactured in cooperation with Brom Mechatronica using a Noliac multi-layer piezo stack.
The hinge structures are often chosen for high accuracy, absence of backlash and ease of drive.



Stroke = 50-250 µm; $C = \sim 5 \cdot 10^6$ N/m; $F_{res} = \sim 1$ kHz;
UHV compatible

Figure 8. A piezo stack in a cantilever hinge structure.

Piezo motor

Piezo motors can be diverse in shape and motion pattern. There are stepping solutions like the inch worm or the linear piezo motor by Philips. Similar solutions use a bending mode, a shear mode or saw tooth based on friction to make steps. All these versions have their own specific pros and cons, but non have reached high-volume quantities and/or can be easily designed into motion systems.

In other piezo motor solutions a tip, prestressed to a moving body, describes an ellipse at piezo resonance. The tip as such pushes the moving body in either direction, similar to Fred Flintstone driving his car by his feet. A subsequent option is to fix a piezo element to a body with tip, to bring the body in resonance and to find the optimum position for the tip. The ultrasonic motor by Nanomotion will be discussed to describe the way of working in more detail.

Nanomotion ultrasonic motor

Since the 90's Nanomotion designs and manufactures piezo motors which have proven their quality over many years of service in stringent environments. The simultaneous excitation of the longitudinal extension mode and the transverse bending mode creates a small elliptical movement of the ceramic edge, achieving the dual mode standing wave as shown in Figure 9. The principle is shown in Figure 10.
By coupling the ceramic edge to a precision stage, a resultant driving force is exerted on the stage under the spring prestress, causing stage movement. The excitation frequencies are much higher than the mechanical resonance of the stage allowing continuous smooth motion.

$F = 4$ N; $C = 1 \cdot 10^6$ N/m; $V_{min} = 1$ µm/sec; $V_{max} = 250$ mm/sec

Figure 9. A Nanomotion ultrasonic motor exhibiting a dual mode standing wave.

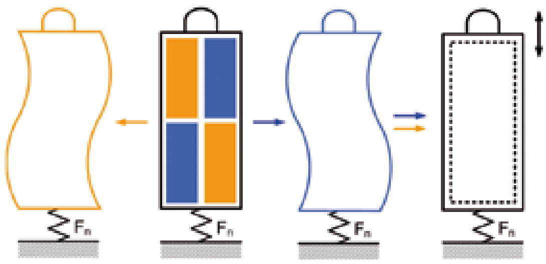
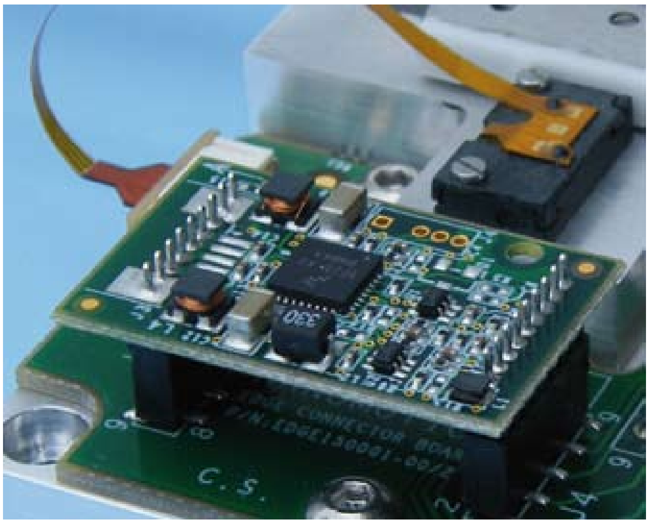


Figure 10. Principle of the dual mode standing wave.



F = 0.3 N; C = 0.07·10^6 N/m; V_{max} = 120 mm/sec; m = 0.55 gram

Figure 11. Edge motor (the black box with flex) with ASIC driver.

The size of the ellipse is determined by the height of the AC V_{pp} signal. Changing the V_{pp} level the speed can range from 1 µm/sec to 250 mm/sec. The force delivered by one Nanomotion standard HR element is 4 N. Standard motors have 1, 2, 4 or 8 elements, giving up to 32 N of force. Smaller and low-voltage versions are available. The so-called Edge motor has a size of 3.15x7.60x13.45 mm^3 and a driving force of 0.3 N at maximum driving voltages of 12 V_{rms}. Figure 11 shows the Edge motor with ASIC driver.

Three functions in one motor element

Three key characteristic functions have been incorporated in the design; see Figure 12. First, as already mentioned, the piezo element is pushed onto the stage and as such behaves like a break when power is cut off. Thus no power consumption and no heat generation. Secondly, driving the piezo at various AC V_{pp} levels the velocity can be controlled. With the wide dynamic range and velocities down to 1 µm/sec, submicron positioning is easily reached.

At standstill, the piezo can be used as a normal piezo actuator. This third key characteristic gives a stroke of +/- 0.3 µm. Although the stiffness of the HR element is limited to 1·10^6 N/m, the latter characteristic can be used for vibration damping. For example in diagnosis, a sample can be brought in position at a speed of 200 mm/s and submicron accuracy. In position, environmental vibrations are cancelled to allow precise diagnosis.

High-precision motion profile

To examine the limits of the Nanomotion piezo motor technology, HEINMADE built a stage with a stroke of 50 mm using the HR motors. The stage is equipped with an optical position encoder with a resolution of 5 nm. The

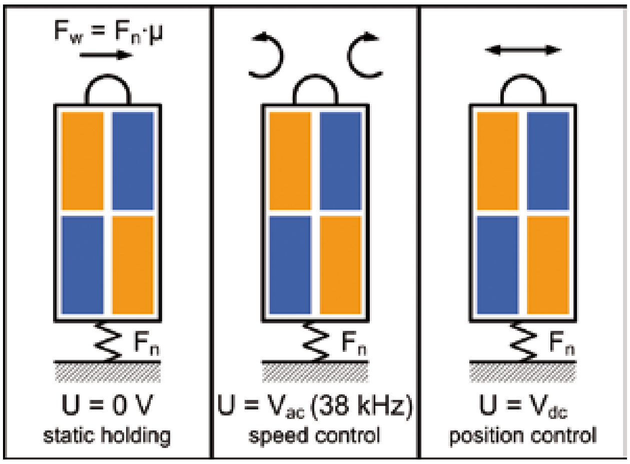


Figure 12. Three functions incorporated in one piezo motor element.

stage has a stiffness of 2·10^7 N/m. Figure 13 shows position profile steps of 200 nm made in both directions. Closed-loop operation is done using Nanomotion's Flex DC controller.
The position error while maintaining position is less than 2 increments, i.e. less than 10 nm. The position error peaks at acceleration and deceleration, to a maximum of 50 nm.

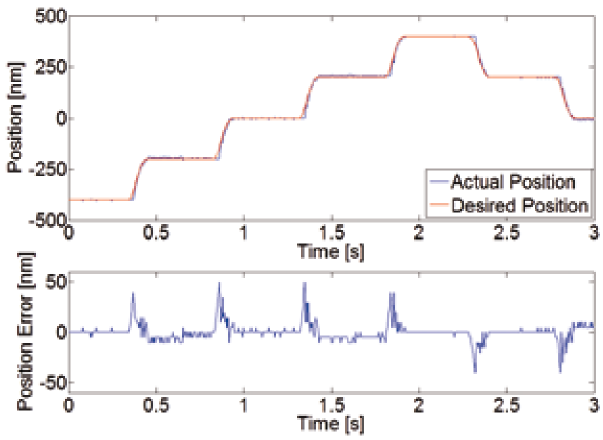


Figure 13. Position profile steps of 200 nm by a stage using Nanomotion piezo motor technology.

High-dynamic excitation

An interesting field of application for piezo is high-dynamic excitation. One example is diesel fuel injection where injection times of less than 50 µsec are required. This makes up to six injections per cylinder cycle possible, improving both the burning process (reduction of NO_x) and the performance. Further it shows that piezo meets 'under the hood' requirements: elevated temperature (> 100 °C), high accelerations (> 10.000 m/sec^2) and long lifetime (> 1·10^9 cycles).

From top to bottom:
- Stiff frame
- Hinge to compensate for tolerances and prestress of sample
- Sample position
- Hinge structure for alignment of forces
- High-dynamic piezo actuator
- Force sensor
- Stiff frame

Figure 14. Test set-up for impact testing of structural components.

For impact testing of stiff structural components HEINMADE used these high-dynamic capabilities of piezo. Figure 14 shows the test set-up designed in collaboration with Brom Mechatronica. In this configuration forces up to 10 kN and impact durations of less than 0.1 msec are feasible. The excitation itself is in most cases limited by the electronic driver. For testing a Piezomechanik high-power amplifier was used.

Sensors for active damping

Thus far, applications of piezo in the actuation mode have been discussed. In many applications, however, the piezo is used as a sensor to detect change of forces. As mentioned above, with a change of force an electrical field is generated. The electrical signal can simply be used for on/off switching (touch panels) or power harvesting. The sensor signal itself, however, contains a lot more information, which can be used to quantify the force and frequency used in all kinds of applications.

For making small structures feasible, machines have to hold position accurately. With proper isolation of the floor, vibrations down to 1 μm are under control. To reach and maintain nanometer accuracy, piezo components are used to actively damp submicron vibrations. For this application, the submicron vibrations are sensed by the piezo sensor and the collocated piezo actuator makes the opposite

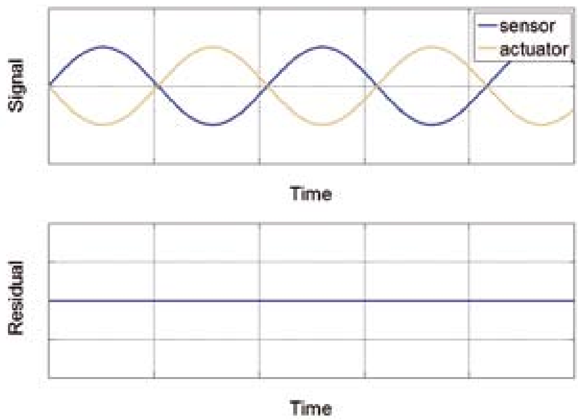


Figure 15. Active damping of (submicron) vibrations by piezo components.

movement as illustrated in Figure 15, thus damping the vibrations to subnanometer level.

In theory this seems a simple procedure, in practice several problems need to be overcome. This would cover another full article.

Summary

The above examples demonstrate the possibilities and advantages of piezo technology in precision engineering, which may be summarized as follows:
- Non-magnetic compatible
- Direct drive
- Small and powerfull
- Fast responses
- No power consumption at standstill
- Cryogenic temperatures
- Ultra-high precision
- Ultra-high vacuum compatible
- Accelerations up to 10.000 g
- Active damping
- Energy harvesting
- Ultrasonic applications
- Multi-axis stages

Authors' note

Hein Schellens is founder and owner of HEINMADE. Maikel Heeren works with High Tech Partners, a cooperation of self-employed, experienced high-tech people.

Information

www.heinmade.com