Piezo-Based, Long-Travel Actuators For Special Environmental Conditions

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Abstract

New developments in the semiconductor industry and in the research areas of materials and life sciences are leading to greater and greater need for nanopositioning devices. Many applications like semiconductor testing require devices for UHV, helium atmospheres and with no magnetic materials. In this paper we shall present a high-load, six-axis, long-travel, UHV-compatible and non-magnetic piezoelectric stage as an example of equipment suitable for such nanopositioning requirements. Besides describing the actuator working principle, the piezo material and the mechanical joints will be discussed. In addition, a new hybrid system consisting of a leadscrew motor-drive with an integrated classical piezo actuator is presented.

Keywords: piezo, Nexline®, hybrid, nanopositioning, hexapod

Introduction

In this paper we present long-travel positioners with extremely high-resolution using piezoelectric actuators. The system can be made to function under difficult environmental conditions, like helium atmosphere, no residual magnetism (nanotesla levels after application of a magnetic field), vacuum compatibility or resistance to radiation. First the *Nexline*® actuators will be presented - their working principle explained and measurement data provided to show the typical behaviour. These actuators can be the basis for multi-axis stages - one of which, a non-magnetic six-degree-of-freedom hexapod, will be discussed. There, the mechanical joints were especially challenging because of the demand that the system not exhibit residual magnetism. Then we will give an overview of another long-travel-range, high-resolution system - one using so called *hybrid* technology. It consists of a motor leadscrew drive with an integrated piezo actuator between the nut and the platform.

Nexline® Technology

Operating Principle

The stroke of a conventional piezo actuator is typically limited to 0.15% of the length of the active material. This restriction can be overcome, however, by using a stepping mechanism. The first positioner we present uses two different kinds of piezo materials which are excited in coordinated sequences to obtain the desired mechanical behaviour.

The unit consists of four parts: two piezo modules, a mechanical housing with integrated mechanical preload and a moving part as mechanical interface (see Fig. 1). The moving part is restrained in one off-axis direction by being clamped between the two piezo modules. In the other off-axis direction (perpendicular to the page) additional guiding elements are required.

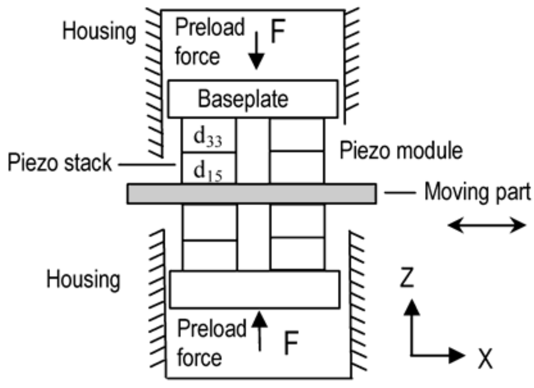

Fig. 1: *Nexline® actuator design*

Each piezo module consists of a base plate and a minimum of two piezo stacks (usually more). These stacks are made up of clamp unit working with a longitudinal piezoelectric effect (d_{33}), acting in the Z-direction, and a second drive unit working with the piezoelectric shear effect (d_{15}), acting in the X-direction [1,2] (see Fig. 1).

The first basic type of motion is *stepping mode*. A step is realised by the stacks alternately making clamping contact with the moving part. During the contact phase, the shear piezo section is activated to drive the moving part in the desired direction (see Fig. 2). During the retracted phase, the shear-piezo is moved back in the opposite direction. The piezos are electrically driven with voltages of ±250 V. This results in a low peak electric field of 0.5 kV/mm. Furthermore, the average applied voltage is zero, giving the longest possible piezo lifetimes. The step size can be varied by using different maximum shear voltage amplitudes.

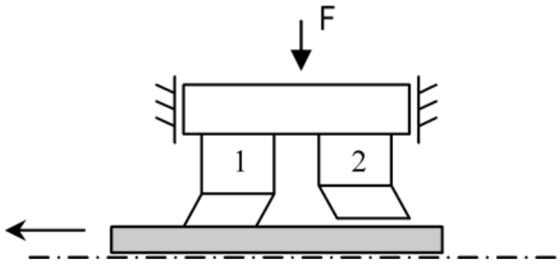

Fig.2: *Step mode*

The mechanical behaviour will be greatly influenced by the lift-off between stack 2 and the moving part, especially for smalls step sizes. The maximum actuating forces have to be adjusted keeping two design considerations in mind: 1.) the preload F, which determines the slipping force of the frictional interface and 2.) the stiffness of the stacks which can be varied by their cross sections. The geometry of the piezo module determines the desired stiffness of the actuator as whole. Typical values are in the range of some twenty newtons per micron. As a result, the first mechanical resonant frequency is in the kilohertz range. The maximum velocity is a function of the electrical current capacity of the power supply used for driving the piezos, of the mechanical resonance and of the amount of the shear stroke. Velocities of up to 2 mm/s can be achieved. An important advantage of Nexline® actuators is that they are self-locking, i.e. with no applied voltage they stay at a defined position in the nanometre range (under constant environmental conditions).

The second basic type of motion is *shear mode*. In shear mode, all piezo stacks make clamping contact with the moving part simultaneously, and all shear piezos move in concert (see Fig. 3).
Shear mode provides the highest stiffness because all piezos are in permanent contact to the moving part. The typical high-dynamics, shear-mode drive range is up to 6 µm. The limitation of the shear stroke is caused by the clamping section stiffness, the d_{33} stroke and the resulting lift-off behaviour. The stroke resolution in shear mode is limited by the noise of the drive electronics.

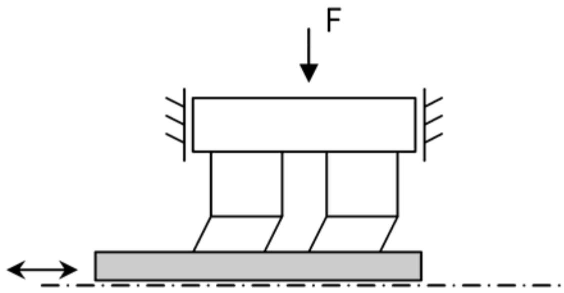

Fig. 3: *Shear mode*
(one of 2 piezo modules shown)

An additional motion mode is *continuous velocity driving*, featuring minimum acceleration forces. It is realised by modifying the stepping sequence slightly. In it, the retracted stacks begin shear motion just before they clamp to the moving part. The other stacks then release their clamping force before stopping their shear motion (all this must occur before the clamped stacks reach the end of their ±250 V shear stroke). The moving part does not stop between "steps".

For some applications it is necessary to operate under helium. The challenge for high-voltage actuators is that the breakdown voltage is reduced to nearly one-third that under normal conditions. This physical behaviour is described by the Paschen curve [3], which shows the breakdown voltage as a function of the product of gas pressure and the sparking gap. The breakdown voltage of helium for a gap size of 0.5 mm and one bar pressure is about 300 V. The electrical land patterns are isolated with a special plastic coating. Therefore an actuator with an applied voltage of less than 250 V can be used in such an environment.

Performance Results

At first we will focus on the Nexline® actuators themselves. The following diagram shows the step mode behaviour (see Fig. 4) of a single unit. Three steps of about 7 microns are shown.

The characteristics of shear mode motion are shown for different displacements, i.e. different voltages applied to the shear piezos (see Fig. 5). The nominal voltage for the maximum shear stroke in the positive direction is 250 V. The position measurements were made with a capacitive sensor.

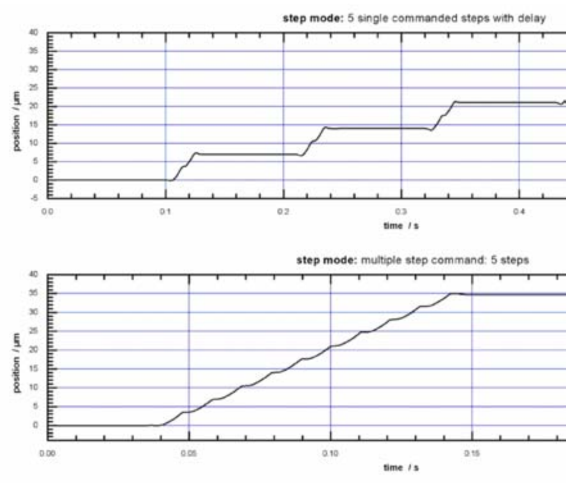

***Fig. 4:** Nexline® step mode*

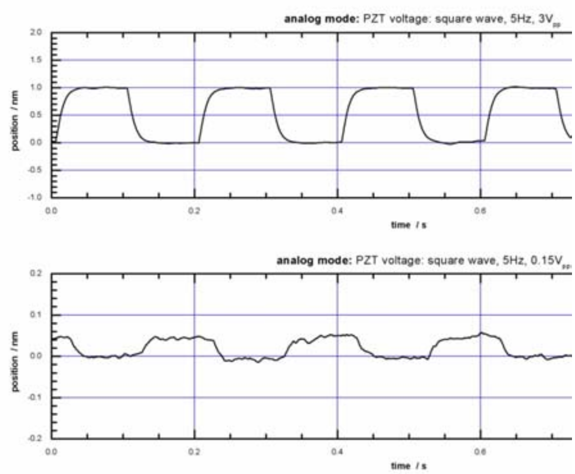

***Fig.5:** Nexline® shear mode*

The results show that a shear stroke of 1 nm can be achieved at 3 V_{pp} ; with 0.15 V_{pp} a minimum stroke of only 50 pm is detected. The detection of smaller stroke values, which are within the capability of the piezo itself, is limited by the resolution of the capacitive sensor.

The motor characteristic curve of the Nexline® actuators was also determined. For that purpose a variable external pushing force and different preload forces were applied, and the resulting step sizes were measured (see Fig. 6).
The measurements show that for this particular actuator a preload force of 430 N or less assures a full step size of 4 µm (without external pushing forces). If the preload value is increased to 550 N, the lift-off is affected so that the retracted stack has unintended contact with the moving part. As a result, the step size is smaller because of residual mechanical friction. An external pushing force acting against the moving direction leads to a reduction in step size because of the limited stiffness of the piezo module itself and the variation in stiffness during the stepping sequence.

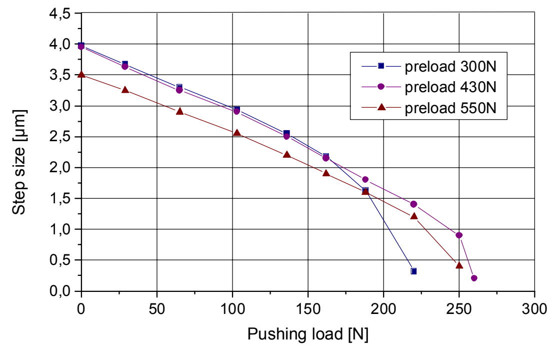

***Fig6:** Nexline® motor characteristic*

The slipping force is about 60% of the preload force, if relative motion between the moving part and the piezo modules occurs.
For the high-load, six-axis positioning device (Nexline® Hexapod), we used optimised Nexline® actuators with step sizes of 6.5 µm. The achieved actuator force is greater than 50 kg (see Fig. 7).

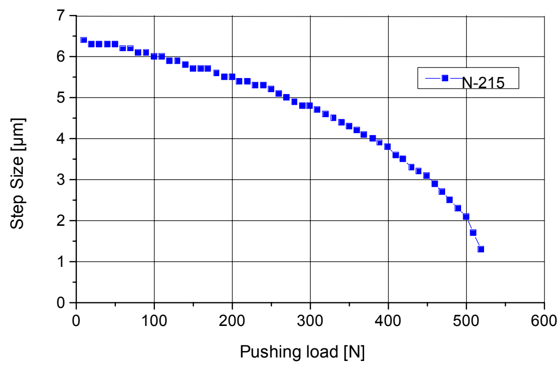

***Fig. 7:** Standard Nexline® motor characteristic*

Six-axis Positioning Device

The requirements which the multi-axis device had to meet include the complete absence of magnetic materials and operation in a high vacuum.

Piezoelectric Material

To meet low-residual-magnetism requirements, the piezo material must be optimised in regard to its iron and nickel content while the electrode material and the sputtered contact surface of each piezo layer must be made of non-magnetic materials. The ferromagnetic behaviour of Nexline® piezoceramics was tested by using an Fe-Nd-B magnet in combination with a Tesla meter. The resolution of the meter was 5 nT_{pp}. For the optimised piezo material samples, made of PIC255 [4], the residual magnetism is less than 10 nT after exposure to the high magnetic field.

Mechanical Joints

Multi-axis stages for high-magnetic-field applications must often be made from non-magnetic materials to prevent them from influencing other mechanical parts or - in testing applications - the samples or probes. For such applications, common stainless steel or brass is not allowable. Furthermore, aluminium and titanium are not suitable because of friction coefficient, surface hardness and mechanical abrasion considerations.

Ceramic materials, like Al_2O_3 (alumina), however, can meet the requirements for a mechanical joint. For the six-axis positioning device described, we use a special ball joint in which both the ball and socket, are made of alumina. The material has a grain size in the submicron range, which makes for an average surface roughness of less than 50 nm. The tolerances in the spherical parts of the geometry are less than 1 µm. Therefore, very high accuracy - in the micron range over a travel of some 20 mm - is obtainable. This ceramic material is highly tolerant of surface pressure, so that external forces of up to several hundred kilograms on a 28 mm diameter ball are acceptable. Furthermore this kind of mechanical joint is easy to handle because of its simple assembly from only two ceramic parts and its self-adjusting effect.

Each of the six Nexline® actuators is equipped with an integrated optical scale which also meets these requirements. The outside diameter of the stage is 300 mm, the height is 130 mm (see Fig. 8).

The stage must work against forces of up to 50 kg with an accuracy in the micron range.
Each of the six piezo actuators is separately calibrated and controlled. A dedicated controller performs the necessary coordinate transformations and commands the corresponding extension of each actuator according to the six-axis, Cartesian-coordinate command received from the user.
The hexapod was tested with an applied external force in +Z direction (see Fig. 5) of 20 kg. The lateral positioning accuracy within a travel range of ±10mm is better than 5 µm. The hysteresis of about 2 µm is caused by the friction in the mechanical joints at the backlash points. The preload inside these joints is about 50 kg. To provide an impression of the positioning characteristics, the results for Z-axis movement are shown (see Fig. 9).

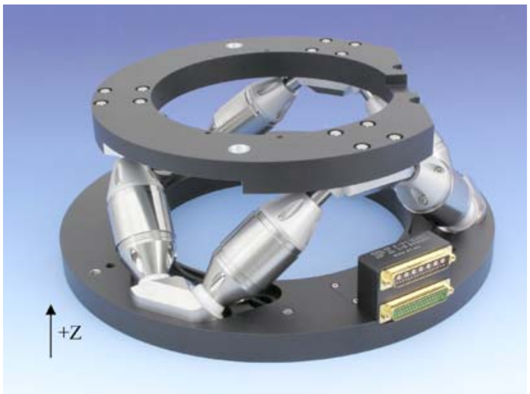

Fig. 8: *Nexline® Piezo Hexapod with 300 mm outside diameter; it provides travel ranges of ± 10 mm / ± 3 degree and a max. load capacity of 50 kg in all directions while moving*

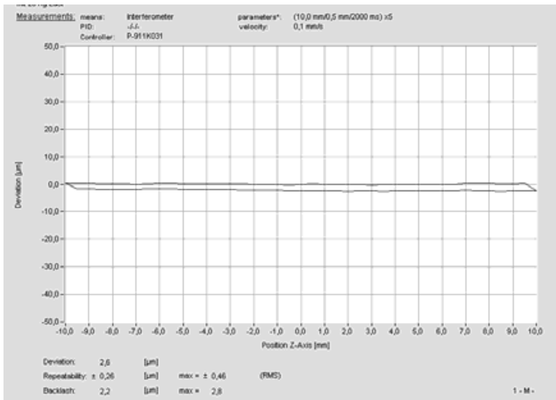

Fig.9: *Nexline® Hexapod Z-axis characteristic*

Hybid Technology

The new hybrid system uses a single extremely high-resolution incremental sensor (placed close to the moving platform) in a stage driven by both a flexure-guided piezo actuator and DC motor (or ultrasonic piezomotor) at the same time (see Fig. 10,11).
These stages can be realised in vacuum-compatible versions for pressures down to 10E-6 mbar.
The specially developed controller is based on a hardware clock; it buffers sensor inputs and synchronises the output buffer. The motor is controlled by a PWM signal and the piezo amplifier is driven by a 24-bit D/A converter. The sampling rates can be set between 1 kHz and 200 kHz. Because both drives - the piezo and the motor - are acting on the same stage, it is necessary to use widely separated control frequencies for the respective control loops.

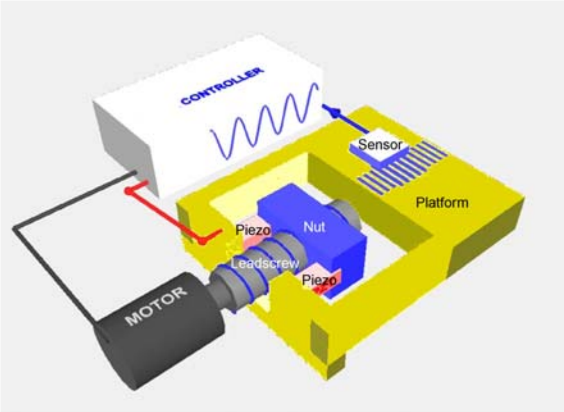

Fig. 10: *Hybrid system; The incremental sensor is located at the platform, piezo elements between the spindle and the nut within flexure design*

Fig. 11: *Hybrid stage for 2nm resolution and 100N load*

The piezo is used in a higher bandwidth than the motor. Tests show that the frequency separation should be larger than a factor of two. The piezo travel is only +/- 2 µm.

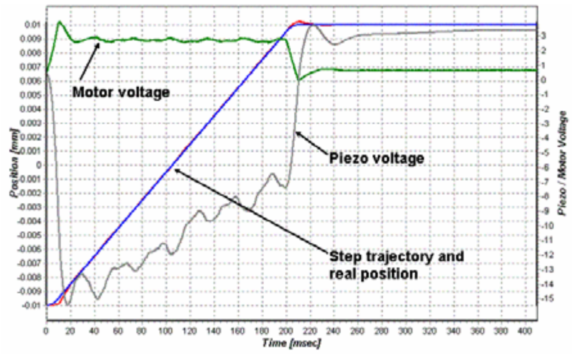

Fig.12*: 20 µm step with small overshoot to demonstrate the continuously driving mode of both actuators. The motor and the piezo are actuated at any time.*

Performance Results

The hybrid technology is used in two different stages, one with 8 mm and one with 100 mm travel range. For initial tests a 2 µm optical scale from Heidenhain GmbH and a specially designed 1000-times interpolation unit was used, giving a final resolution of 2 nm.

Fig. 13 shows the step performance with a series of 10 nm steps forward and backward. The motion was measured with an external interferometer. The hysteresis measured is considerably less than 1 nm. During motor motion the piezo actuator compensates for the influences of friction and roughness, as shown in figure 12.

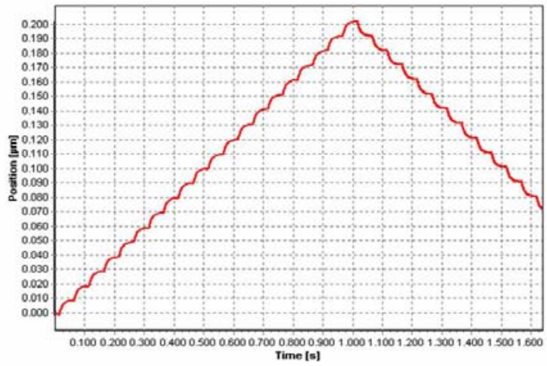

Fig. 13: *Step response of the hybrid stage for 10 nm steps, measured with external laser interferometer*

Conclusion

Both the positioner types presented enable a long travel range of over several hundred millimetres with resolutions in the picometre range. Especially for applications in cutting-edge technologies like the semiconductor industry, and in fundamental research, the Nexline®-based piezo stages are very flexible in terms of operation under different environmental conditions such as UHV, radiation, helium atmosphere and non-magnetic-materials requirements. The results show in detail the high positioning performance of the piezo-based actuators alone and in combination as a multi-axis stage.

References

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