Design of Linear Ultrasonic Micro Piezo Motor for Precision Mechatronic Systems

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Abstract:
This paper presents a new design for a linear ultrasonic piezo motor for precision positioning developed by Physik Instrumente (PI). The stator of the ultrasonic motor consists of a rectangular piezoceramic plate. Two sliders, bonded to a spring which presses them against the stator, move along guides integrated in the stator. These motors are characterized by their extremely simple construction. Two prototypes of the motors using a 9x4x1.5 mm^3 and a 16x8x1.5 mm^3 piezoceramic plate have been designed and tested. With an external position sensor and servo-controller, the motors can be driven to positions in the 0.1 µm range. In open-loop mode, repeatable step size is in the micron range. Maximum speed of the motors is around 100 mm/s. In closed-loop mode, speeds in the millimeter per second range are possible. The design and operating characteristics of the prototypes in both open- and closed-loop modes are presented in this paper. To obtain the proper stator geometry, FEM software was used and the vibrational behavior of the system was analyzed with a 3D scanning vibrometer. The FEM simulations, as well as the results of the laser vibrometer measurements, will be presented as animations.

Keywords: piezo motor, PZT, ultrasonic motor, standing-wave, piezoelectric actuator, linear motor, piezo, non-magnetic, piezoceramic

Introduction

Piezoelectric ultrasonic motors (PUMs) have a number of advantages over electromagnetic motors. PUMs can achieve positioning accuracies in the range of several tens of nanometers. They hold their positions even when powered down and thus consume less energy. PUMs can be constructed with significantly fewer parts. The efficiency of electromagnetic motors falls as their dimensions are reduced, but that of PUMs stays virtually constant [1]. Linear electromagnetic motors are very difficult to design; in contrast linear PUMs are quite simple. Interest in PUMs is growing, especially for use as miniature drives in mass-produced consumer electronic products.

Miniaturized Ultrasonic Piezo Motors

Physik Instrumente (PI) has been active in piezoelectric ultrasonic motor R&D for many years. Minature PUMs have also been subject to investigation at PI. Several years ago PI developed a piezoelectric rotary traveling-wave motor with a stator measuring only 3x3 mm [2][3]. That motor uses what is known as the tangential-axial oscillation mode of the piezoelectric hollow cylinder. A traveling wave is set up in the stator with the help of three electrical signals which are 120° out of phase.
In addition to rotary ultrasonic motors, PI is also developing linear ultrasonic motors. The actuator elements in the PILine® series employ asymmetric excition of the (3,1) piezo-mode in a rectangular piezoceramic plate [4],[5],[6]. The actuators can be scaled at will and can be used for practically any mechatronics application. Figure 1 shows miniature rotary and linear piezomotors made at PI.

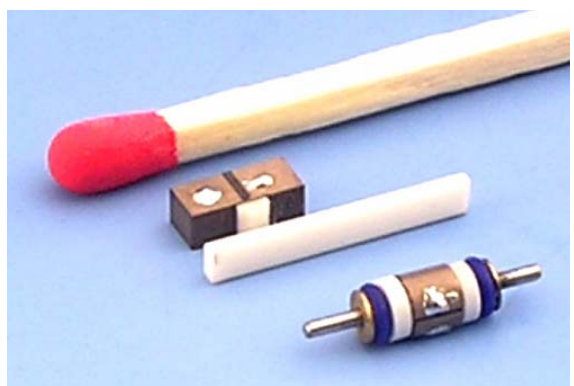

***Fig. 1**: Miniature ultrasonic piezo motors (match for size comparison)*

The latest developments from PI are miniature linear PUMs with stator dimensions of 9x4x1.5 mm^3 and 16x8x1.5 mm^3.

Working Principle and Design of the New Ultrasonic Motor

Fig. 2 shows a CAD model of the newly developed piezo motor [7]. These piezo motors are of very simple design, consisting of two basic parts: the actuator (stator) and the sled (spring bonded to two sliders), the moving part of the motor. The actuator consists of a rectangular piezo-ceramic plate of size L×W×0.5L polarized in the *thickness* direction. The two large faces of the plate are covered by electrodes. On one (top, in Fig. 2) are the two exciter electrodes, each covering half of the surface. The "bottom" surface (not visible) has a single electrode that serves as a common drain.

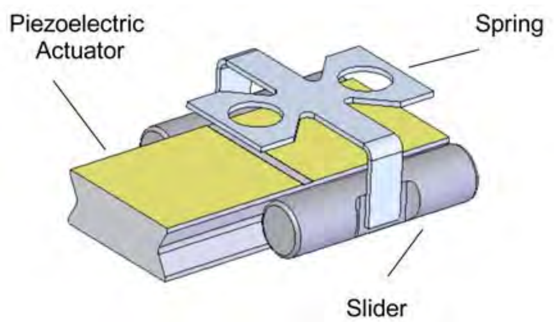

***Fig. 2:** CAD drawing of the newly developed miniature ultrasonic piezo motor*

The actuator plate has guide grooves cut in the long edges. The sled has two sliders which are pressed against the ceramic actuator by the integrated spring. The entire motor consists of the piezoceramic plate and the moving sled, guided along the integrated grooves in the plate.

Fig. 3 shows the E(3,1) oscillation mode of a piezoceramic plate.

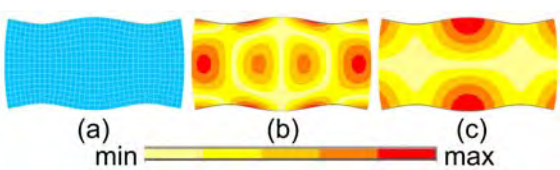

***Fig. 3:** E(3,1) Modes in a rectangular piezoceramic plate (a) Deformation. (b) Length oscillation velocity distribution (c)* height *oscillation velocity distribution (FEM simulation).*

The areas with the highest oscillation amplitudes in the height direction are on the long edges of the plate, at the exact center (Fig. 3c). The maxima for longitudinal oscillation are somewhat offset relative to the height maxima. The deformation of the plate is thus symmetrical relative to the length and width symmetry planes of plate. The operating principle of the new ultrasonic motor is based upon asymmetric resonant excitation in the piezoceramic plate in an E(3,1) mode. The asymmetric E(3,1) excitation is accomplished using the split electrode. In so doing, the actuator is excited with a sinewave voltage applied to one of the excitation electrodes while the other floats. Under the influence of such an asymmetric E(3,1) oscillation, the points of the guide grooves move along straight-line paths inclined at different angles relative to the surface. The motion amplitudes of the individual points differ as a function of position. There are even some locations, where the motion is in the opposite direction. The sliders, which are pressed into the guide grooves, receive tiny pushing impulses of varying amplitude from all the points they contact. The resultant force developed is one which moves the slider in the desired direction.

Fig. 4 shows the response of a piezoceramic plate to the asymmetric excitation used in this type of motor. Fig. 5 shows the distribution of the oscillation amplitudes in the longitudinal and height directions as well as the resulting point trajectories of points on the long edges of the plate.

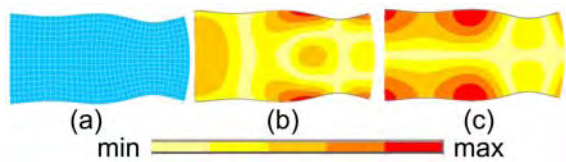

***Fig.4:** E(3,1) Modes in a rectangular piezoceramic plate (a) Deformation. (b) Length oscillation velocity distribution (c) height oscillation velocity distribution (FEM simulation).*

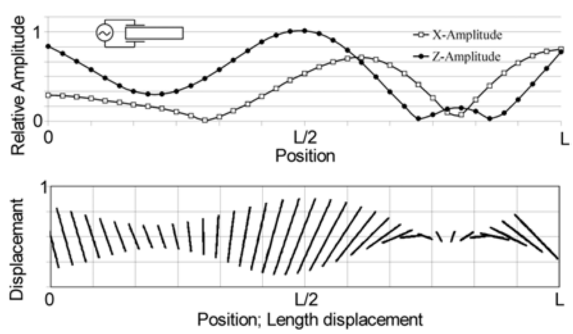

Fig. 5: *Displacement Amplitudes (top); motion trajectories of Points on the plate edge. (bottom)*

To change the direction of motion, the other electrode is excited and the first allowed to float. This changes the trajectory of the surface points by 90°, so that it impells the slider in the opposite direction.

Measurement with 3D Scanning Vibrometer

Finite Element Method (FEM) programs have proven to be essential tools for the development of ultrasonic motors. All the simulations, calculations and the optimization of ultrasonic motors were done with the help of ANSYS FEM software. Fig. 6 shows an FEM simulation of the stator of a 9 mm motor.

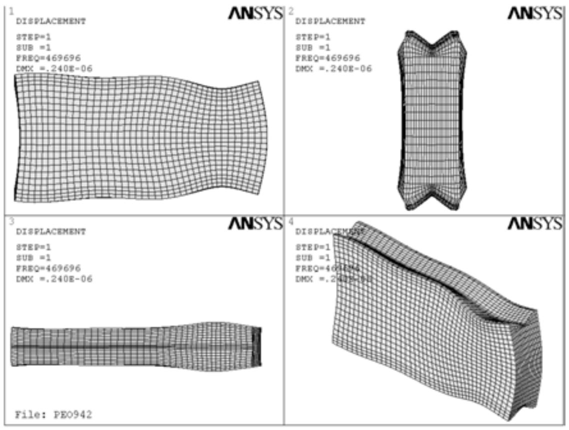

Fig. 6: *FEM simulation of the stator of the newly developed ultrasonic piezo motor*

Fig: 7 shows the magnitude of the vector sum of the displacement vectors for each point on the surface.

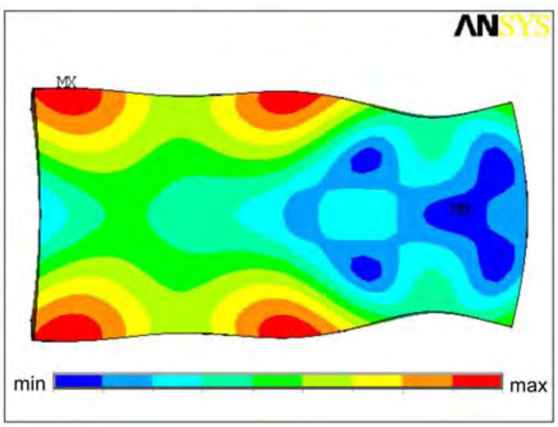

Fig. 7**:** *Displacement vector sum (ANSYS)*

To determine how well the calculated oscillation patterns and amplitudes correspond to those actually obtained, a number of measurements were permormed. Such measurements can be made on a point-by-point basis using a two-dimensional piezoelectric sensor [2]. The simplest method, however, is to use a scanning laser vibrometer. Optical scanning of the actuator surface also eliminates any influence the measuring system might have on the oscillation.

The PSV-300-3D laser measuring system from Polytec in Germany can scan an object and determine the vibratory motion of the individual surface points in three dimensions. Fig. 8 shows the results of vibration measurements of the stator of the 9 mm motor (without sliders); in the graphic the magnitude of the displacement vector (vector sum of all components) at each point is shown.

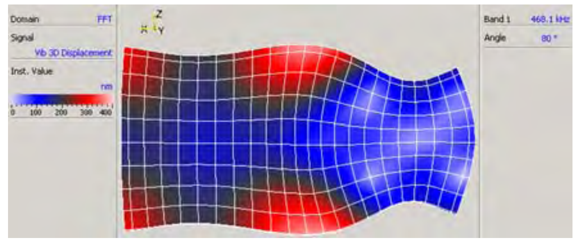

Fig. 8**:** *Displacement vector sum (measured with laser vibrometer*

It shows excellent agreement with the calculated values.

The maximum oscillation amplitudes of the unloaded stator reach 400 nm; those of the stator with the sliders pressed against it, 200 nm.

Drive Circuitry for the Piezo Motor

Fig. 9 shows the impedance characteristic curve of the motor with and without the sliders. The resonant frequency used was 470 kHz. The fact that the resonant frequency is influenced by external conditions like temperature, makes necessary the development of electronics that automatically adjusts to the motor's resonant frequency.

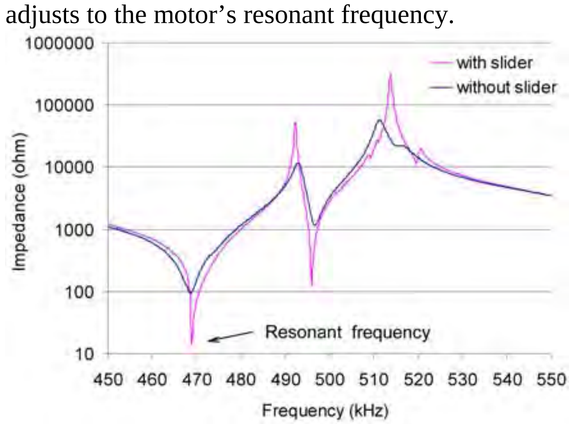

Fig. 9**:** *Impedance kurve of the 9-mm Piezo Motor*

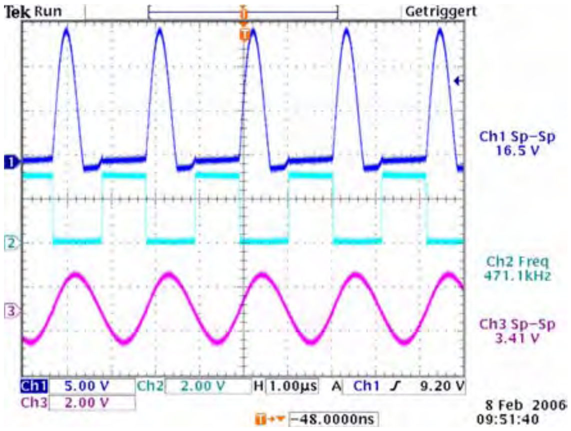

***Fig. 10**: Drive electronics signal. Ch1: voltage at the motor; Ch2: Signal at the switching transistor; Ch3: Current through the motor*

The drive electronics can operate on a supply voltage starting at 2 V. With a 3 V supply, it can generate an output voltage with an amplitude of 15 V. With this voltage, the 9 mm motor can generate a maximum force of about 4 millinewtons (mN). The associated maximum speed (unloaded) is about 100 mm/s. With a voltage of 25 V, the 9 mm motors can generate maximum forces of up to 15 mN. The maximum speed then reaches a value of 180 mm/s.

Drive Characteristics of the New Micromotors

Fig. 11 shows two prototypes of the new ultrasonic motors with stators measuring 9x4x1.5mm^3 and a 16x8x1.5mm^3, respectively.

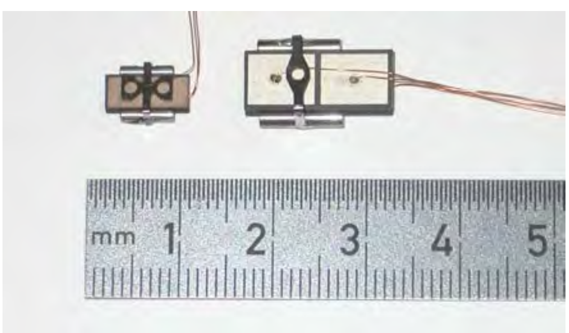

***Fig. 11**: Two prototypes of the piezo motors with 9x4x1.5mm^3 and a 16x8x1.5mm^3 piezoceramic plate as stator*

The typical drive characteristics of the 9 mm motor are shown in Figs. 12-16. In open-loop, the 9 mm motor attains a speed of up to 100 mm/s. The smallest possible steps in open-loop mode are 100 nm. This corresponds to the resolution of the position measurement system used (Numerik Jena, Germany). Figures 12 and 13 show the motor characteristic curves for open-loop operation.

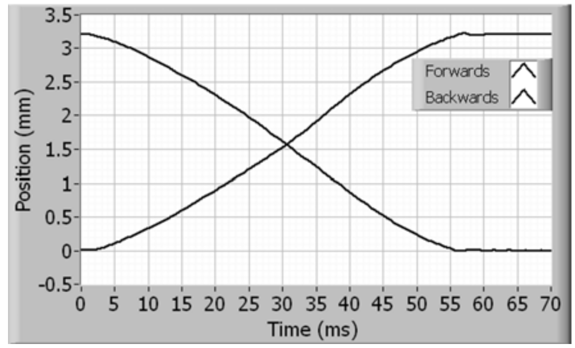

***Fig. 12:** Position vs. time characteristic curve of the motor with 9×4×1.5 mm^3 piezo actuator (open-loop)*

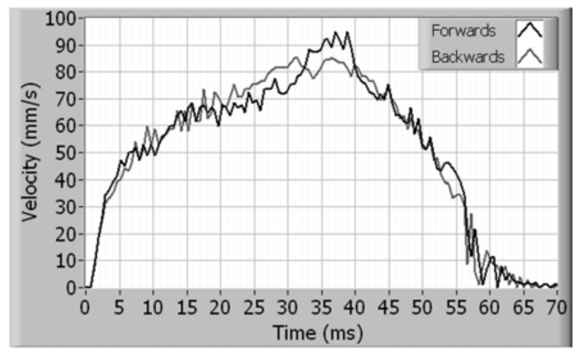

***Fig. 13**: Velocity vs time characteristic curve of motor with 9×4×1.5 mm^3 piezo actuator (open-loop)*

Figure 14 shows the curve of the 9 mm motor in open-loop pulsed operation. The motor was given a pulse train of 1 ms ON pulses at a rate of 60 per second.

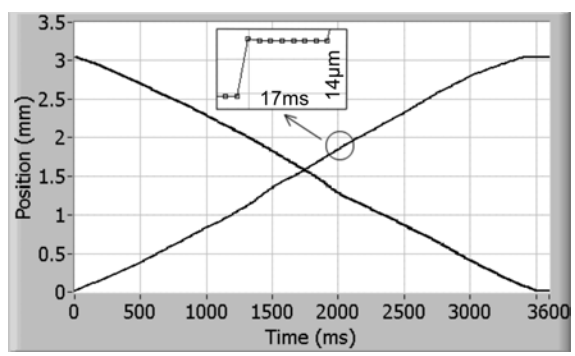

***Fig 14:** Pulsed operation of the motor with 9x4x1.5 mm piezo actuator (open-loop)*

Despite their extremely simple construction, these motors can be quite well servo-controlled. Closed-loop tests using a suitable motor controller, also from PI, in conjunction with an incremental optical position sensor attached to the motor, showed that speeds up to several millimeters per second could easily be obtained. The minimal incremental motion in closed-loop was also measured at 100 nm. This corresponds to the resolution of the measurement system used. The time required for a 1µm step is typically less than 15 ms. Fig. 15 shows a 1µm step of the motor. Fig 16 shows the position characteristic curve of the piezo motor in closed loop operation with a speed of 10 mm/s.

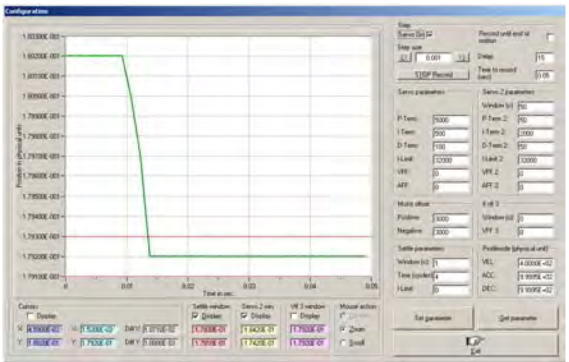

Fig. 15: *1µm step of the motor with 9×4×1.5mm^3 actuator (closed-loop)*

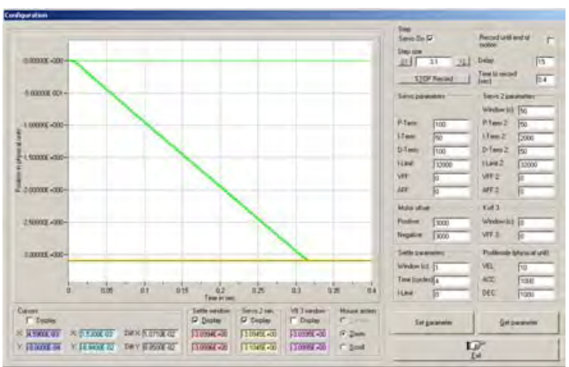

Fig. 16**:** *Closed-loop operation of the motor with 9x4x1.5mm^3 actuator with speed of 10 mm/s*

Conclusions

A new type of ultrasonic linear piezo motor has been developed which is most notably characterized by its very simple construction; it consists of a piezoceramic with integrated guide grooves and a slider. The dimensions can be easily reduced down to a few millimeters.
The travel ranges of these motors, while limited by the dimensions of the ceramic, are quite sufficient for many systems requiring only a few millimeters motion. Despite its simple construction, the motor is suitable for positioning tasks requiring accuracies in the submicron range. Endurance tests have shown that the motors can achieve 2 million cycles with no problems. The drive electronics can easily be implemented in ASIC technology.

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Simple New Ultrasonic Piezoelectric Actuator for Precision Linear Piezo Motor Drives

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Abstract:
Bimodal ultrasonic linear piezo motors using the superposition of the 1st longitudinal mode and the 2nd flexural mode of a piezoceramic plate have been known for a long time. They are widely used as direct-drive systems in micropositioning applications. Physik Instrumente (PI) has developed a new design for such ultrasonic actuators (patent pending) and is manufacturing a number of precision direct-drive models suitable for conventional and specialized micropositioning tasks (such as high-vacuum designs). The operating specifications have been considerably improved by employing a special technique for attaching the actuator, using two elastic double frames fastened along node lines of the actuator. This design makes possible a very stiff connection between the housing and the actuator while still allowing an elastic interface where it is pressed against the friction surface of the slider. In addition to resonant excitation, the new actuator designs also allow quasi-static operation wherein resolutions in the nanometer and subnanometer range can be obtained. To operate these precision devices with standard controllers for conventional DC motors, PI has developed its own controller electronics.

Keywords: piezo motor, PZT, ultrasonic linear motor, standing-wave, piezoelectric actuator

Introduction

Over the last ten years many studies have been made and much written about bimodal piezoelectric actuators and ultrasonic motors using them. To resume briefly, in a bimodal actuator, longitudinal and flexural deformations are excited in a rectangular piezoelectric plate resonator. Excitation is with four electrodes, which a switched in diagonal pairs, and which create simultaneous longitudinal and flexural standing waves in the plate. The waves have orthogonal oscillation components, so that points on the edge of the plate resonator move along eliptical trajectories. Arranged on one of the edges are pushers, which transfer motion to a slider pressed against them. Changing the electrode pairing shifts the phase between the two orthogonal oscillation components by 180°, causing reversal of the direction of motion. By choosing a resonator with appropriate dimensions, it is possible to bring the different oscillation modes into relation with one another. This working principle was first proposed in 1976 [1] (see Fig. 1) albeit for a rotary motor. That piezo electric motor design uses 1L2B ultrasonic excitation, i.e. 1st longitudinal mode, 2nd flexural (bending) mode. In 1977 an improved variation of such an ultrasonic motor was patented [2]. The basic principle of bimodal plate actuator has proved itself quite effective—so much so that the *Nanomotion* company patented several actuator designs [3],[4] and, around 1994, was the first company to begin industrial production of such actuators and micropositioning systems based on them.

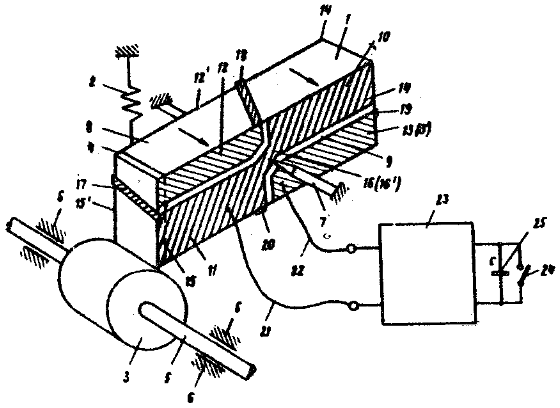

Fig. 1: *Piezoelectric motor [1]*

Attachment of 1L2B Actuators

When designing ultrasonic motors, the distribution of oscillation velocities must be taken into consideration. Especially important is the position of node lines, because it is obviously most reasonable to attach the actuator at points on its node lines.

Actuators with 1L2B-mode excitation have three node lines on the surface of the resonator (see): an absolute node in the center, and two relative nodes beside it. Along the absolute node line, both the longitudinal and the transversal oscillation velocities are zero. Along the relative node lines, only the transversal velocity is zero, not the longitudinal.

Many 1L2B actuator designs have their attachment points on the relative node lines, thus restraining not only the transversal but also the longitudinal motion there. Furthermore, the slider is pressed against the free edge with a force (of a spring) which reduces its motion at precisely the points where it has the maximum longitudinal velocities. Such mounting has a very pronounced damping effect on the longitudinal resonance of the actuator, leads to high acoustic losses, unnecessary warming, and an increase in the excitation voltage required.

1L2B Piezo Motor Actuator from PI

Physik Instrumente (PI) has developed a new 1L2B precision actuator, complete with a new attachment scheme [5]. The new mounting is very stiff in the direction of motion, but elastic in the direction in which the slider is pressed against the actuator, so it does not place excessive load on oscillations in the resonator. The new drive is in the form of small module $38 \times 22 \times 6.5$ (mm). The resonator is a rectangular piezoceramic plate of $37 \times 10 \times 3$ (mm), polarized normal to its faces.

The mounting that has been developed comprises two double-frame brackets. Each consists of an outer and an inner frame, connected by thin bridges (see Fig. 3). The thin inner frame is affixed to the long edges of the resonator at points on the relative node lines. The large outer frame is screwed to the housing of the drive unit.

When the drive is installed (see Fig. 4, top) the friction tip or pusher of the actuator (2) is pressed against the friction surface (3) of the slider (4). This pressure is such as to cause the module to move slightly, tensioning the elastic double frame (6). Then the fixation screws (7) can be tightened. When the drive is pretensioned in this way, the outer frame (8) and the inner frame (9) pull slightly apart, creating elastic forces all along the long sides of the outer frame. These forces are passed to the bridges (10) connecting the frames (8,9) and on to the inner frame (9) as Ft, and to the resonator, pressing the pusher elastically against the friction bar (see Fig. 4 top and bottom). This is the origin of the pretensioning.

The force Ft transmitted by each bridge element, is made up of Fd and Fh (Fig. 4 bottom). Fd tends to pull the inner frame (8) apart, Fh tends to push the sides of the frame against the resonator side surfaces. Fh presses the resonator together and thus ensures its reliable fixation.

In the direction of motion of the slider, the resonator is held firmly by the high lengthwise rigidity of the

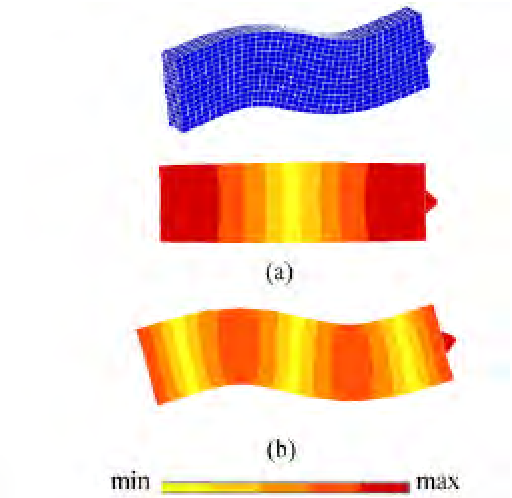

Fig. 2: *Oscillation velocity distributions (a) 1st longitudinal mode (b) 2nd flexural mode (FEM simulations)*

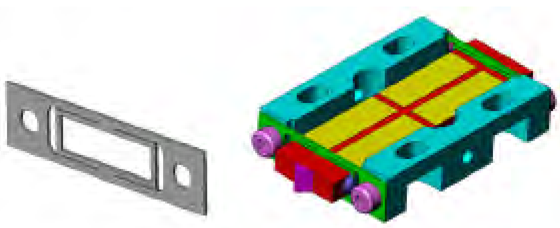

Fig. 3: *Piezo motor actuator and new mounting bracket*

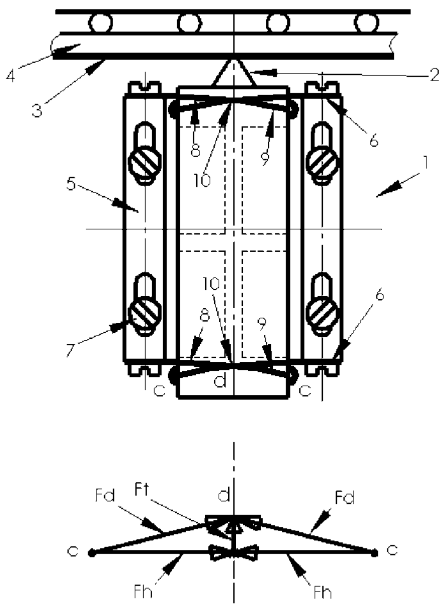

Fig. 4: *Mounting (top) and force diagram (bottom)*

double frame. In the direction normal to the friction surface, the resonator is loaded by only the very low acoustic resistance of the frame. This type of mounting eliminates all significant acoustic losses in the actuator during operation.
The new drive units are designed for use in high-precision positioning systems. Also vacuum-compatible versions have been developed. The new drive units can be obtained already installed in linear stages, or separately, the required friction bar included (see figures 6 and 5 respectively).

Driving the Piezo Motor Actuator

To excite the actuator, special drive electronics was developed. The drive electronics can in turn be controlled by either a linear control signal or with standard PWM (pulse-width modulation) signals. The versions developed can use either the resonant actuation mode described or a combination resonant/quasi-static mode.

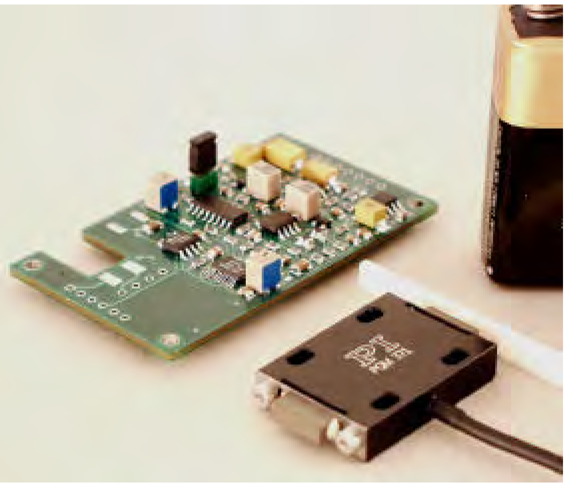

***Fig. 5:** Drive module, friction bar and drive electronics (9-V battery for size comparison)*

***Fig. 6:** PIline piezo stage with L1B2 piezo actuator*

In the resonant mode, the diagonally connected electrodes are subjected to a voltage signal whose frequency is equal to the resonant frequency of the resonator (approx. 43 kHz). The speed of motion of the actuator can be controlled by a variable control signal, which can run either from 0 to 10 V or from -10 to +10 V or, if PWM control is used, can consist of standard PWM signals with frequencies from 10 to 25 kHz.

Figures 7 to 9 show the most important characteristic curves for a PI micropositioning stage with an actuator in resonant operation. The typical positioning accuracy of the stage in this mode is 0.2 µm.

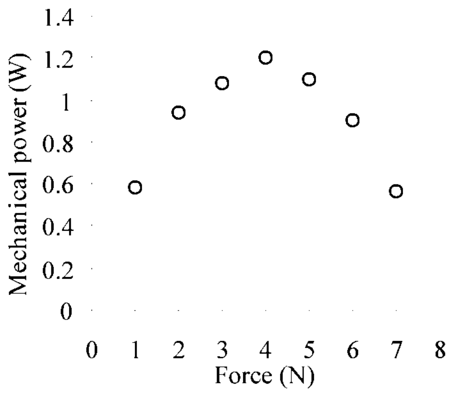

***Fig. 7:** Mechanical power vs force characteristic curve*

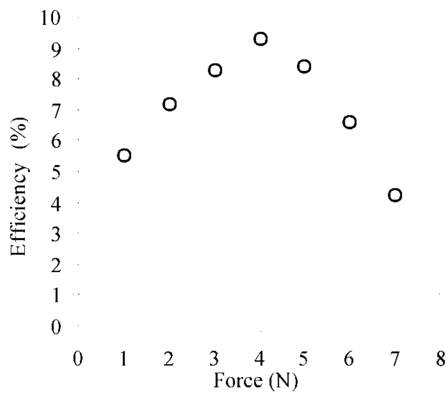

***Fig. 8:** Efficiency vs force characteristic curve*

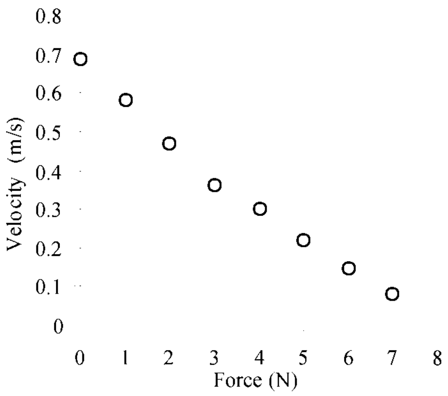

Fig. 9: *Velocity vs force characteristic curve*

The combination resonant/quasi-static mode makes possible positioning in the nanometer range. In the combination mode, the slider is first brought roughly to the target in resonant operation, then the exciter switches to quasi-static operation. In quasi-static operation, the actuator electrodes are fed a DC voltage of up to 1000 V, causing the actuator to bend along its long axis. Fig. 10 shows an FEM simulation of the actuator deformation (made without the mounting frames).

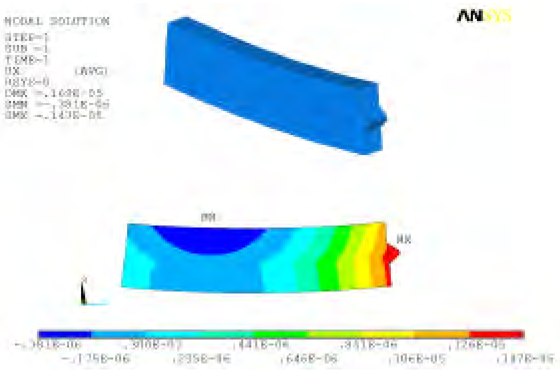

Fig. 10: *Static-mode piezo actuator deformation (FEM-Simulation)*

The simulation indicates a maximum pusher displacement of about 1.5 µm at a voltage of 1000V. The graphic reveals a flexural asymmetry due to the presence of the pusher. Fig. 11 shows the position characteristic curve of a linear stage with the actuator in quasi-static mode (open-loop).

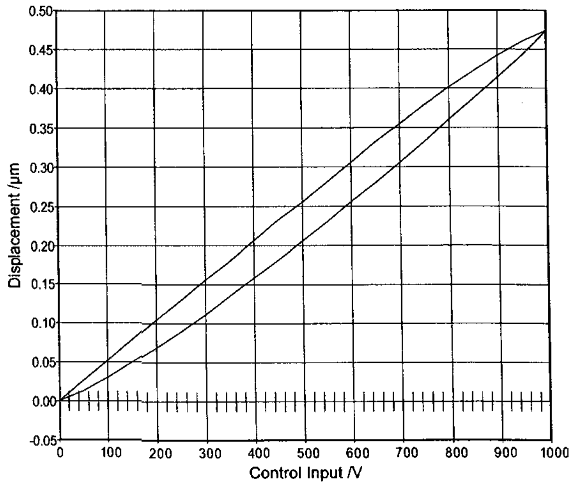

Fig. 11: *Linear displacement of piezo stage with actuator in static mode (measured values)*

The actuator sensitivity in quasi-static mode is about 0.2 nm/V. When 1000 V is reached, the slider has moved about 500 nm. The fact that the linear displacement measured with the stage is only one third that in the FEM simulation is primarily due to the stiffness of the mounting frame. The minimum measured displacement was 1-2 nm.

Conclusions

The parameters of the linear ultrasonic actuators depend also on there mounting. Especially for the ultra-precision applications the very stiff mounting is a must. This new mounting allows achieving the linear resolution up to 1 nm.

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New Type of Standing Wave Ultrasonic Rotary Piezo Motors with Cylindrical Actuators

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Abstract:
This article presents a new type of ultrasonic rotary piezoelectric motor from Physik Instrumente (PI). In this design, the stator is a monolithic hollow tube of piezoceramic material. To produce the rotary motion, a special two-dimensional standing wave is produced in this stator. Pushers attached at particular points on the end surface of the tube extract the motion and transfer it to the rotor against which they are pressed. The standing wave is excited with a single-phase electrical signal. When the stator is excited, the pushers oscillate at an angle to the frictional surface of the rotor and stator. Rotation occurs as a result of the minute impulses given to the rotor. The first part of the article both explains the working principle of such an ultrasonic motor operating under 5th mode excitation, and gives the results of FEM modeling of it. In the second part, three motor variations using different oscillation modes to produce the rotary motion are presented.

Keywords: piezomotor, PZT, ultrasonic motor, travelling-wave, standing-wave, piezoelectric actuator, hollow cylinder

Piezo Motor Introduction

Today electrodynamic and other electromagnetic forces dominate the drive mechanisms in machinery designs. Increasing accuracy requirements—in the µm and nm ranges—lead, however, to very complicated systems when implemented with conventional electromagnetic drives. Often the physical limits are reached in terms of miniaturization, accuracy, dynamics and interference immunity.

One principle alternative to conventional electromagnetic drives are ultrasonic, piezoelectrically driven motors. As is well known, piezoelectric ultrasonic motors are drive systems whose functionality is based on excitation of acoustic waves in an oscillating stator, or resonator. Functionally, piezoelectric ultrasonic motors can be divided into two categories: standing-wave ultrasonic motors (SWUM) and traveling-wave ultrasonic motors (TWUM). In traveling-wave motors, the superposition of standing waves in the stator is used to create a traveling wave. The surface points of the active stator travel in elliptical trajectories; they contact the rotor or slider in a way that drives it continuously.

The best-known design of a traveling-wave piezomotor is that of the Shinsei company [1], which uses a “rotating” bending wave. Physik Instrumente’s traveling-wave piezomotor [2] uses a quasi-longitudinal wave which travels along circumference of a hollow-tube resonator.

In contrast to the TWUM, in the SWUM, motion is obtained by giving the rotor a chain of angled microimpulses. On the active surface of the resonator in motors based on standing waves, one or more friction elements are attached at points with the same vibration direction and amplitude. The rotor in this type of motor has mechanical (frictional) contact with the oscillating stator only at these specific, active points. The sources of these impulses (the pushers) can follow eliptical or straight-line paths.

A well-known design of the SWUM is the piezoelectric multimode ultrasonic motors. In the resonator of these motors, two oscillation modes are excited. They can be of the same or different types, and have two orthogonal vibration components. The resonant frequencies of the two modes must be very close to each other. The phase relationship between the two orthogonal vibration components results in elliptical trajectories of just those surface points where the pushers are attached. In the 70’s, motors based on coupled longitudinal-bending waves of different orders in a rectangular piezoelectric plate gained some currency [3],[4]. Over the last few years, new design proposals incorporating this basic principle have continued to appear.

An additional type of SWUM is the single-mode ultrasonic motor [5]. In it, a single mode of resonant oscillation is used, e.g. bending mode in a piezoelectric plate or ring. Pushers are attached at points where the oscillation vectors have the same amplitudes and directions. In these motors, the pushers follow straight-line rather than elliptical trajectories.

Physik Instrumente (PI) GmbH & Co. KG, one of the leading manufacturers of piezoelectric actuators and positioning systems, has for many years been involved in the development and fabrication of ultrasonic piezomotors and positioning systems incorporating them. PI's newly developed ultrasonic piezomotors are based on excitation of a special eigenmode (2-D standing wave) in a piezoceramic resonator. The wave has two orthogonal vibration components which are coupled. This eigenmode can be excited both in piezoelectric hollow cylinders and in rectangular plaes, making possible fabrication of very simple, high-performance rotational and linear motors.

Design and Working Principle of PI Standing Wave Rotational Piezo Motor

Fig, 1 shows a CAD drawing of a PI rotary standing-wave ultrasonic piezo motor design.

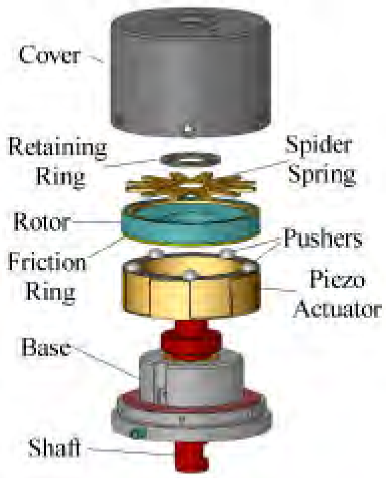

Fig. 1: *CAD drawing of rotary standing wave ultrasonic piezo motor design.*

The rotor and the stator are the main parts of the ultrasonic motor. The stator consists of a piezoelectric hollow cylinder. Aluminum oxide pushers are arranged along the end of the cylinder (as seen in Fig. 2), glued in place to the piezoceramic with a special epoxy resin.
The rotor is pressed against the pushers by means of a spider spring (not shown). At the center, the spring is attached to the shaft with six bolts, and at the outside it is in contact with the rotor through a rubber ring. The torque, generated with the spring pressure, is transmitted from the rotor to the shaft via the frictional contact with the spring. On the lower side of the rotor is an aluminum oxide friction ring.
The cylinder is polarized radially and the excitation electrodes are similar to those of the travelling-wave motor [2]: a common drain covering the entire inside surface and two separate groups covering the outside surface. These electrode groups permit excitation of the stator in a special eigenmode (coupled tangential axial mode) in which the pushers move back and forth at an angle to the end of the cylinder (see black arrows in Fig. 2). On the "upstroke" of each oscillation, the pushers impart a microimpulse to the rotor, while on the "downstroke" they slide relative to it.
The length of the excitation electrodes and the distance between electrodes of the same group is equal to one-half wavelength ($\lambda/2$) of the standing wave in the φ-direction (cylindrical coordinates). The number of electrodes in each group is equal to the number of wavelengths (λ) around the circumference of the cylinder. The two electrode groups are identical but shifted by $\lambda/2$.
Excitation of the required oscillation mode involves placing a single-phase sine wave voltage on one of the electrode groups. The other group is allowed to float. Rotation in the opposite direction is effected by interchanging the roles of the electrode groups, which shifts the standing wave in the φ-direction by $\lambda/2$ (because of the $\lambda/2$ difference in physical position of the electrode groups). This changes the phase of the tangential component of the pusher motion, causing their straightline oscillatory motion to "point" in the opposite rotational direction. Fig. 2 shows the arrangement of the pushers, electrode groups and the resulting deformation of the cylinder (exaggerated) for excitation of the 5th degenerate tangential-axial mode in the stator.

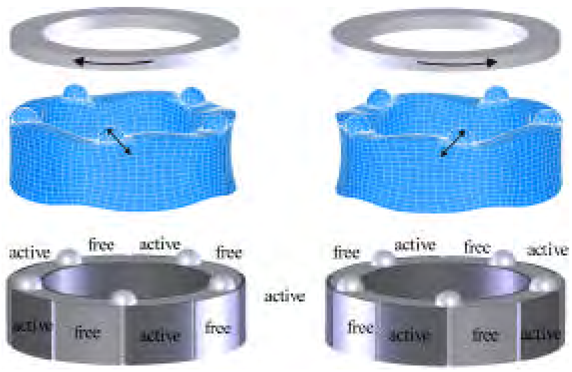

Fig. 2: *Stator excitation for counter-clockwise and clockwise rotation respectively*

The stator of the ultrasonic motor is supported by the motor casing. To reduce any undesired influences the casing body might have on the acoustic waves excited in the stator, and to absorb the reaction forces, an elastic separation layer is provided. The motor shaft rides on two ball bearing assemblies installed in the casing body. On the top of the casing are three threaded holes designed to allow installation of an incremental rotary encoder.

Oscillation Modes of a Piezoelectric Hollow Cylinder

Like any solid body, a piezoceramic hollow cylinder has an unlimited number of eigenforms. These vibration modes, generally three-dimensional standing waves, can be effectively characterized by the spacial representation of the vibration amplitudes. An example of one of the well-known eigenforms of a hollow cylinder is the longitudinal mode. When a hollow cylinder is excited in the longitudinal mode, it experiences oscillations in length. All points of the cylinder exhibit a predominantly longitudinal motion. The displacement amplitudes are sinusoidal. The oscillatory behavior of the cylinder can be described by the following standing wave formula:

$$U_z(z,t) = U_{\max} \sin(\frac{p}{H} z) \sin(wt) \qquad (1)$$

The next common eigenmode of a hollow cylinder is the longitudinal wave which can be established along the circumference of a piezoceramic hollow cylinder (traveling wave motor [2]). Similar to the longitudinal wave, the tangential wave (longitudinal wave along the circumference) can be described by an equation:

$$U_j(j,t) = U_{\max} \sin(\frac{np}{l} j) \sin(wt) \qquad (2)$$

Another oscillation mode of a piezoceramic cylinder is the coupled tangential-axial mode. This mode consists of a two-dimensional standing wave with components in the j- und Z-dimensions. (cylindrical coordinate system). The mode can be represented by the following equations:

$$U_j(j,z,t) = U_{j\max} \cos(\frac{np}{l} j) \left(\cos(\frac{p}{H} z) - 1 \right) \sin(wt) \qquad (3)$$

$$U_z(j,z,t) = U_{z\max} \left(\sin(\frac{np}{l} j) + 1 \right) \sin(\frac{p}{H} z) \sin(wt)$$

where:

Uj, Uz	are the displacements in the j and Z directions
H	is the cylinder length
n	is the number of wavelengths along the circumference (order of the oscillation mode)
l	is the circumference
U_{max}	is the maximum displacement
w	is the frequency

The height and circumference of the cylinder must obey the following approximation:

$$H \approx l/(2n+1).$$

FEM Modelling of the Piezo Motor Stator

The existence of particular eigenform of the stator is primarily a function of its geometry. The effectiveness with which the mode can be excited depends on the arrangement of the electrodes and from the polarization vectors in the piezoceramic. Due to their complexity, such problems can no longer be solved in analytic form. Instead, numeric methods and iterative procedures, such as Finite Element Modelling (FEM), are used. FEM software is found today in a number of commercial packages as well as in freely available tools. The ANSYS FEM package was used for the simulation of the ultrasonic piezomotors presented in this article.
Fig. 3 shows the mode analysis simulation results for three degenerate modes of coupled tangential-axial oscillation in hollow piezoceramic cylinders of different dimensions.

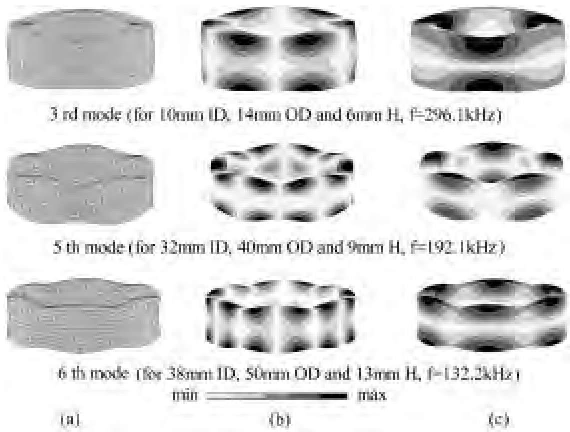

Fig. 3: *3rd, 5th and 6th degenerate coupled tangential-axial modes. (a) Deformation during oscillation. (b) Distribution of the tangential oscillating velocity components. (c) Distribution of the axial oscillating velocity components.*

The top row shows the 3rd-order mode, the middle row the 5th-order mode and the bottom row the 6th-order mode of coupled tangential-axial oscillation. As can be seen in Fig. 3, the maxima of both the tangential and the axial oscillations occur on the end surfaces of the cylinder.
Fig. 4 makes the motion of the points along the cylinder end clear: the top graph shows the amplidtude profiles of the axial and tangential oscillations, the middle graph their respective phases, and the representation at the bottom illustrates the resulting straight-line trajectories, again as a function of the position around the circumference of the cylinder end.

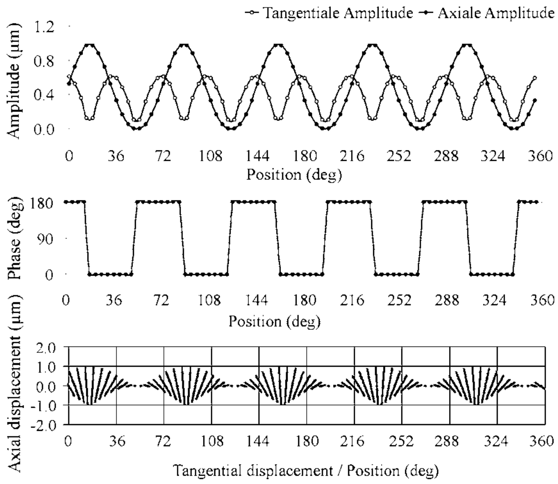

Fig. 4: *Displacement amplitudes, phases and motion of points on the ends of the cylinder as a function of j -position in degrees (FEM simulation).*

As seen by comparing Fig. 4 and Fig. 5, the maxima for the axial displacements occur at points centered relative to the five excitation electrodes. The tangential displacements, however, are zero at these points, making their trajectories parallel to the length of the cylinder. At the points centered relative to the floating electrodes, both the tangential and axial velocities are zero: no motion occurs at these points on the surface.

The cylinder-end points between the electrodes are of more interest. Here the tangential oscillations reach their maxima. In addition, the tangential and axial oscillation amplitudes are equal and the phase angle between them is either 0° or 180°. These points can thus be divided into two groups, one with its straight-line trajectory inclined at 45°, the other at 135°. Pushers are attached to the points in one of these groups. Fig. 5 makes the electrode arrangement and actuator deformation patterns for the 5th degenerate coupled tangential-axial mode clear. The vectors on the end surfaces represent the motion (exaggerated) of specific, associated points.

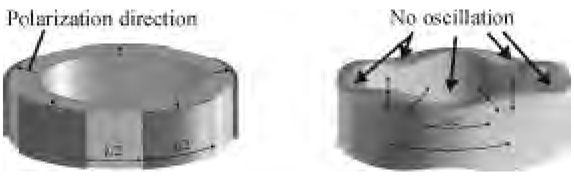

Fig. 5**:** *Piezo cylinder deformation, electrode arrangement, polarization and end-point motion for the 5th degenerate coupled axial-tangential mode*

For development work with ultrasonic motors, appropriate metrology equipment is required for analysing the mechanical oscillation and, in particular, the trajectories of points on the active surfaces of the actuator. For each point of interest, two oscillation components must be measured simultaneously—including determination of their relative phase relationship. Of primary interest are the components perpendicular to the friction surface and parallel to the direction of motion of the rotor. The shape of the trajectories followed by the actuator surface points depends on the relative phase angle between the oscillation components.

For the development of the ultrasonic motors presented here, a mechanical technique based on contact with a two-dimensional piezoceramic vibration sensor was used. The top graph in Fig. 6 shows the measured tangential and axial oscillation amplitude components for points on the ends of the cylinder. The lower portion of the figure is a representation of the measured trajectories of the same points (cf. Fig. 4).

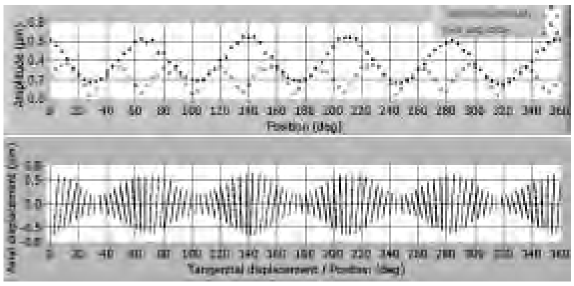

Fig. 6: *Displacement amplitudes and trajectories of points along the end of the actuator cylinder (measurement)*

The goal of the development project was to determine the feasibility of rotary motors using the same oscillation modes used in PI linear piezomotors. In the course of the development work, three different variations of rotary ultrasonic motors were developed. They differ in resonator dimensions and in the oscillation mode used. Fig. 7 shows the ultrasonic piezomotor prototypes developed, which use the 3rd, 5th and 6th degenerate modes of the coupled tangential-axial oscillation.

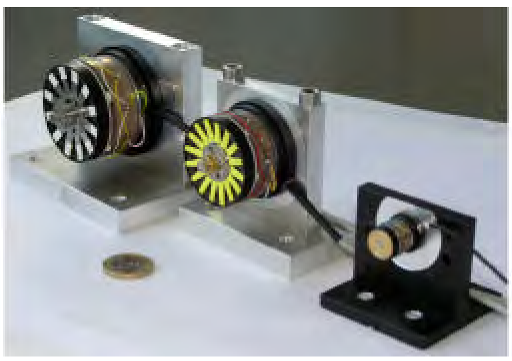

Fig. 7: *Prototype ultrasonic piezo motors using the 3rd, 5th and 6th degenerate coupled tangential-axial modes.*

Motor Characteristics

Fig. 9 shows examples of torque versus rpm for the motor with resonator 9 mm in length and ID 32 mm and OD 40 mm, excited in the 6th mode. Fig. 8 shows the efficiency curve for the same motor. Table 1 summarizes the characteristic values of the three motors.

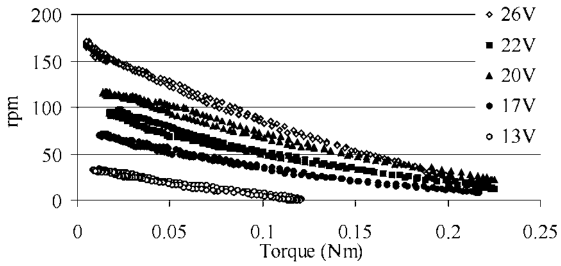

Fig. 9*: Rpm vs. torque characteristic curve of the piezo motor with Æ32´Æ40´9mm actuator*

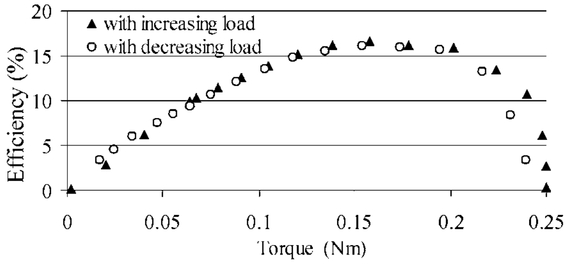

Fig. 8*: Efficiency vs. force characteristic of ther motor with Æ32´Æ40´9mm actuator.*

Stator dimensions ID/OD/height, in mm	Mode	Maximum torque in Nm	Maximum rpm	Efficiency	Oscillator resonant frequency in kHz	Nominal driving voltage, at resonator in V
38/50/13	5th	0.4	350	18	131	35
32/40/9	6th	0.25	170	16	191	25
14/10/6	3rd	0.009	900	20	300	20

Table 1: Characteristic values of the piezo motors developed

Conclusions

The insights into the oscillation behavior of the resonators obtained through the FEM simulations were investigated and confirmed by measurements of the motion of points on the ends of hollow-cylinder piezoelectric actuators. The ultrasonic piezomotors developed on this basis represent an alternative to traveling-wave motors. While traveling-wave motors require a two- or three-phase drive signal, the newly developed ultrasonic motors are run on a single signal, greatly simplifying the drive electronics.

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New Ultrasonic Piezo Motor Actuator for Nanopositioning

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Abstract:
Physik Instrumente (PI) has developed a new type of ultrasonic piezoelectric actuator which can be used effectively in direct linear drives. The actuators are of simple construction and allow design of very compact, fast and inexpensive micropositioning systems. The actuators consist of a rectangular piezoceramic plate with a common electrode on one surface and two symmetrical excitation electrodes on the opposing surface. A pusher, which makes frictional contact with a slider is attached to one long edge of the actuator at the gap between the excitation electrodes. During operation, a two-dimensional standing wave is created by exciting the piezoceramic plate asymmetrically. The resultant motion of the pusher is linear and inclined relative to the actuator. The slider moves as a result of the minute, high-frequency, angled impulses it receives from the pusher. The article explains the working principle of the new actuators using FEM simulation data, and presents the new linear precision drives from PI which operate on this principle.

Keywords: piezo motor, PZT, ultrasonic motor, standing-wave motor, piezo actuator

Introduction

In recent years industry has shown growing interest in linear ultrasonic piezoelectric actuators and ultrasonic drives. Well-known manufacturers of micropositioning systems have increasingly put micropositioning systems driven by ultrasonic actuators onto their product palette. Piezoelectric ultrasonic actuators make possible systems which are of simple design, and are thus finding wider and wider application in micropositioning systems. Especially advantageous and cost-efficient systems can be made with ultrasonic actuators having a rectangular piezoceramic plate as resonator and using eigenmodes associated with that shape. Probably the best-known design for such an ultrasonic motor uses what is called a bimodal ultrasonic actuator. Here the piezoelectric plate is excited simultaneously in a flexural mode and in a longitudinal mode. This operating principle, suggested in the 70's [1], [2] and first exploited industrially by Nanomotion, has proven so effective that actuators using it are encountered in most linear piezomotor micropositioners on the market today. Such actuators are also offerred by PI, both alone and in derived products [3].

Physik Instrumente (PI) GmbH & Co. KG, one of the leading manufacturers of piezoelectric actuators and positioning systems, has for many years been involved in the development and fabrication of ultrasonic piezomotors and positioning systems incorporating them. PI's newly developed ultrasonic piezomotors are based on excitation of a special eigenmode (2-D standing wave) in a piezoceramic resonator. The wave has two orthogonal vibration components which are coupled. This eigenmode can be excited both in piezoelectric hollow cylinders and in rectangular plates, making possible fabrication of very simple, high-performance rotational [4] and linear motors. In this article, the authors describe the operation of the new ultrasonic piezoelectric plate actuators.

Working Principle and Design of the New *PIline* Ultrasonic Piezo Motor Actuator

Fig. 1 shows the newly developed ultrasonic piezoceramic actuator and the basic design of a translation stage driven by it. The actuator consists of a piezo-ceramic plate of size L×W×0.5L (X, Y, Z), polarized in the Y-direction. The two large faces of the plate are covered by electrodes. On the front are the two exciter electrodes, each covering half of the surface. The rear surface has a single electrode that serves as a common drain. On one long edge of the plate is a pusher, made of aluminum oxide. The slider, the moving part of the motor, is pressed against this pusher.

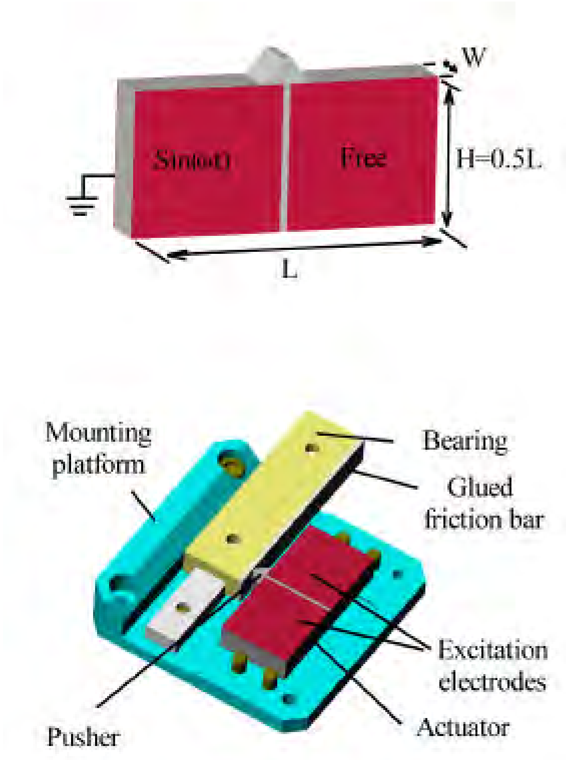


***Fig. 1**: Piezoceramic ultrasonic actuator (top) and basic design of piezo-motor-driven linear stage*

Operation of the new piezo motor is based upon asymmetric excitation of the piezoceramic plate in a special resonant mode consisting of a two-dimensional standing extension wave. Because of the asymmetric oscillation, the pusher moves along a straight-line trajectory that is inclined at either 45°—or with mirrored excitation—at 135° to the edge of the actuator. The actuator is excited with a sine wave voltage applied to one of the excitation electrodes while the other electrode floats (the potential on the second electrode could be used in a feedback loop for matching the excitation frequency with the resonant frequency of the actuator). As a result of this excitation, the pusher provides micro-impulses at very high frequency, driving the slider. To change the direction of motion, the other electrode is excited and the first allowed to float. This changes the trajectory of the pusher by 90°, so that it impells the slider in the opposite direction.
Fig. 2 shows the results of harmonic analysis in four specific oscillation phases using a FEM model (finite element method) of the actuator and FEM analysis software from ANSYS. The material properties used were those of the piezoelectric ceramic PIC-181 from PI Ceramic in Lederhose, Germany.

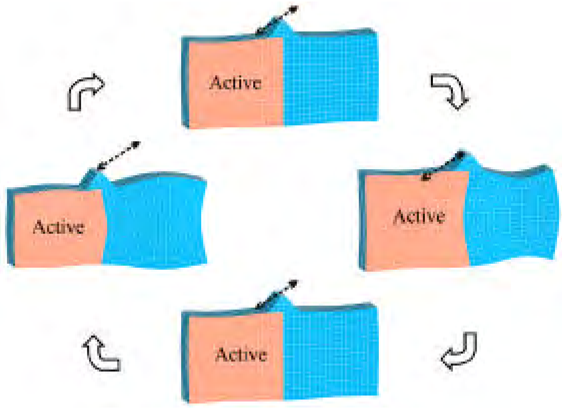


***Fig. 2:** FEM- Simulation*

FEM Simulation

As already explained, the new actuator works based on asymmetric excitation of a two-dimension standing extension wave in a piezoelectric plate. Similar to the designation usually used in the literature for 2-D flexural waves, we call the various modes of this type E(*k*, *l*), where “E” indicates “extensional” and *k* and *l* are the number of half wavelengths (λ/2) in the X- and Z-directions, respectively. The E(3,1) mode can be excited in a plate (polarized in Y, normal to the faces) if the length-to-height ratio is approximately 2 to 1, L/H≈2:1
With electrodes fully covering the two faces, the mode shape can be described mathematically as follows:

$$U_x(x,z,t) = -A\sin(\frac{3p}{L}x)(\cos(\frac{p}{H}z)-1)\sin(wt) \quad (1)$$

$$U_z(x,z,t) = B(1-C\cos(\frac{3p}{L}x))\sin(\frac{p}{H}z)\sin(wt) \quad (2)$$

where:

U_x, U_z are the distortional displacements in the X and Z directions at points *x*, *z* and time *t*

A, B, C are material and geometrical amplitude functions.

This oscillation mode is thus described by standing waves in the X- and Z-directions respectively, (Gl (1), (2)).
Fig. 3 shows the results of a modal analysis of a piezoceramic plate with X, Y, Z dimensions of 60×9×28 mm, polarized in the Y-direction (9mm) and with electrodes fully covering the two faces. Fig. 4 shows the amplitude and phase characteristics for points on the top edge of the plate (along the length) as a function of their X position (0 to L along

line L in the figure). The phase difference between the X and Z displacements alternates between 0° and 180° as a function of the X position. As a result, the points on a line along the top edge of the plate move along linear trajectories.

The highest oscillation velocities in the Z-direction are found at the center of the long sides (X-coordinate = length/2, Z-coordinate = H). The oscillation velocity in the X-direction at this point is zero, meaning that this midpoint oscillates in a vertical straight line. The resonant frequency of this mode is 62.9 kHz.

Fig. 5 (a) shows a FEM simulation of the oscillation amplitude distribution of the points, as well as a representation of their trajectories, as a function of position along the long side of the piezoceramic plate (Line L in Fig. 4). Fig. 5 (b) shows the same diagrams, but with measured values, for comparison. To obtain these values, the oscillation behavior of a piezoceramic plate was investigated using a vibration sensor (also of piezoceramic) material. The sensor captures surface vibrations of the plate in two dimensions over a single-point feeler [5].

The measurements were carried out on a piezoceramic plate with X, Y, Z dimensions of 60×9×30mm^3, polarized in the Y (9mm) direction and with electrodes fully covering the two faces. The resonant frequency is 60.1 kHz (61.6kHz measured value).

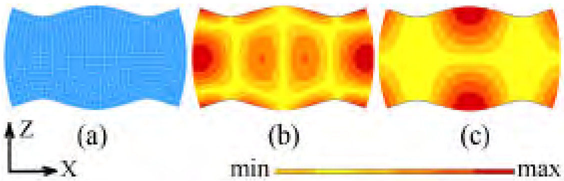


Fig. 3: *E(3,1) Modes in a 60´9´ 28 mm^3 (L, W, H) piezoceramic plate (a) Deformation. (b) X-oscillation velocity distribution (c) Z-oscillation velocity distribution (FEM simulation).*

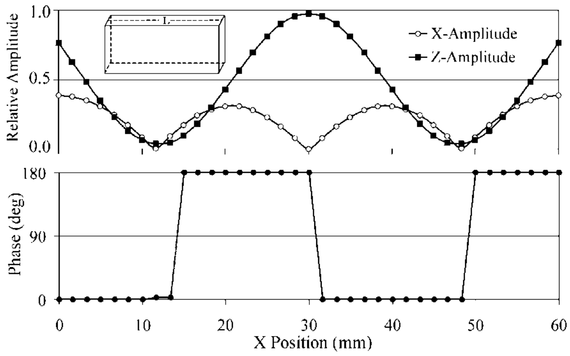
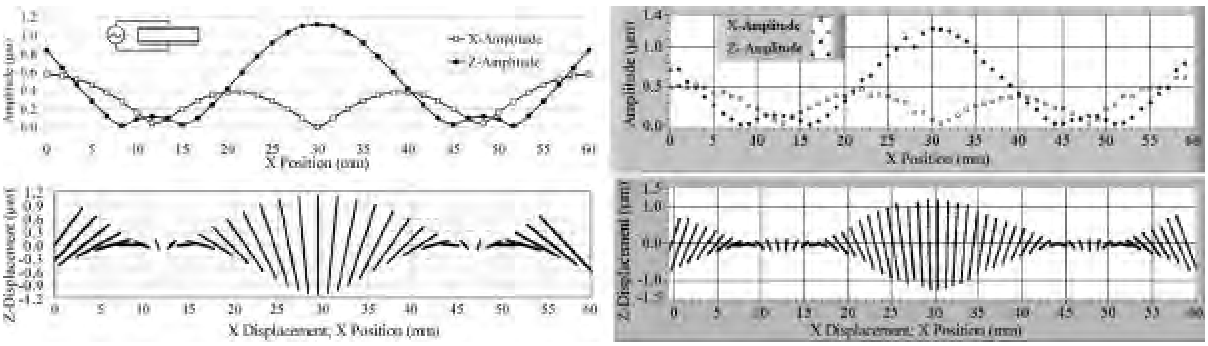


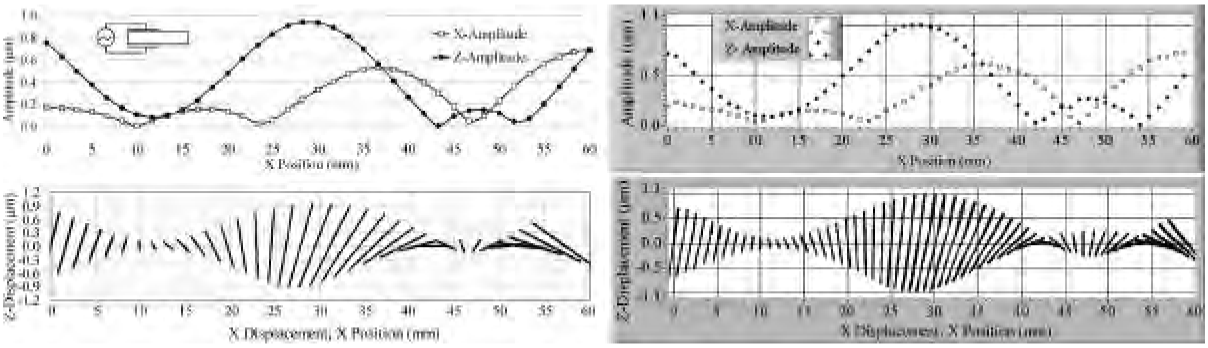
Fig. 4: *Amplitude and Phase diagram.*



(a) (b)

***Fig. 5**: Displacement motion of the piezo motor elements. (a) FEM simulation; (b) Measurement.*

To obtain slider motion with the pusher in the center (X coordinate = Length/2, Z coordinate = Height) it is necessary to increase the X displacement at that point, and a mechanism to reverse the phase between the X and Z displacement by 180° must be available. This is accomplished by exciting the X direction standing wave asymmetrically. To do so, the excitation electrode is cut vertically into two electrodes, each covering only half of the XZ surface. During operation, only one of these two electrodes is excited while the other is left to float. Fig. 6 show the FEM simulation and measured values resulting from this asymmetric excitation of the mode in a 60×9××30mm^3 piezoceramic plate. This is the excitation technique used for the newly developed actuator. The diagram shows the reduction of the X amplitudes in the excited side of the plate and their simultaneous augmentation on the other side. In addition, the standing wave in X-direction is shifted toward the excitation electrode, as seen by the shifted node lines (compare Fig. 5 and Fig. 6). The shifting of the X-direction standing wave results in increased X displacement amplitudes at the center of the plate.



(a) (b)

Fig. 6: *Displacement motion. (a) FEM simulation; (b) Measurement*

PI Linear Motors and Stages with New Actuators

The new actuators are being used in new linear motors and complete linear stages. These actuators make possible construction of very small linear stages with ideal parameters. Fig. 7 shows three such actuators and linear motor and stages in which they are used.

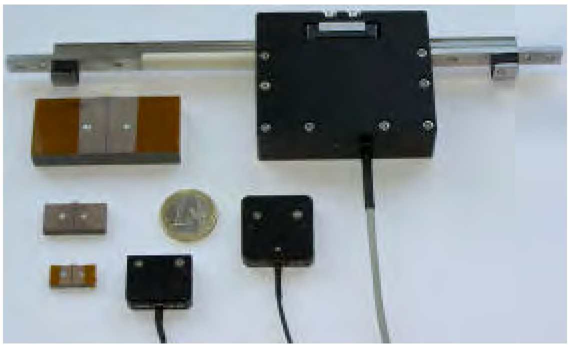


Fig. 7: *Linear actuators measuring 18´8´3mm, 25´12´4mm, and 60´9´28mm with the corresponding linear piezo motors*

The PIline™ M-661, M-662 stages are driven by a small external driver that converts controller signals into the ultrasonic oscillations required by the piezo actuator. Control is either electronic or through a manual pad. Electronic control is achieved through a PWM drive signal of 12 V. The smallest step is on the order of 50 nm and corresponds to an approx. 10 µs input. These units achieve velocities to 800 mm/s. By varying the length of the input-active period, the step length, and thus the velocity, can be controlled. The translation stages are equipped with integrated high-precision optical linear encoders for closed-loop operation with standard servo-motor controllers. For optimum closed-loop performance it is operated with a PID motion controller that allows setting of the full range of parameters tailored to piezo motor operation.
As an example, Fig. 8 shows the internal layout of a linear motor with a 60 x 9 x 28 mm actuator.

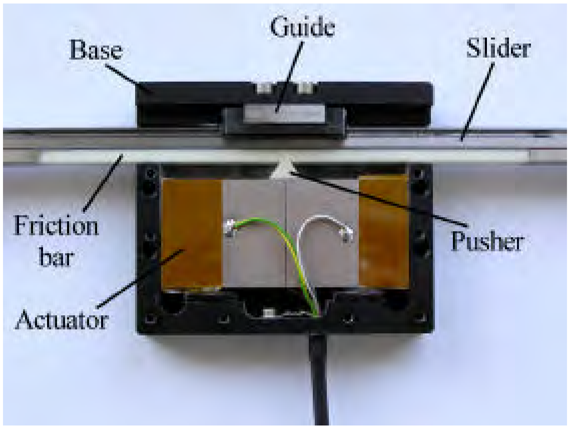


Fig. 8: *Linear motor with 60 ´ 9 ´ 28 mm actuator*

Figures 9 to 11 show the main characteristic curves of this linear piezo motor.

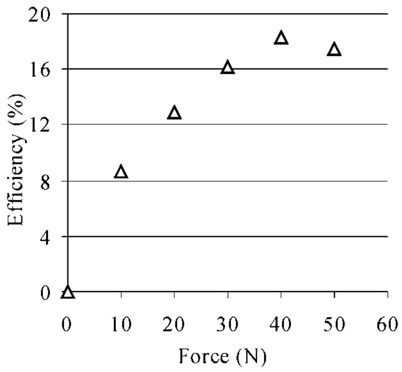


Fig. 9: *Efficiency vs force characteristic of linear motor with 60´9´28mm actuator*

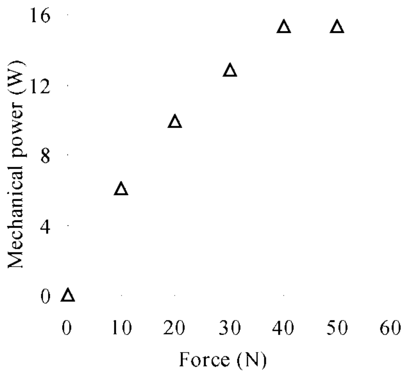


Fig. 10: *Power vs force characteristic curve of linear motor with 60´9´28mm actuator*

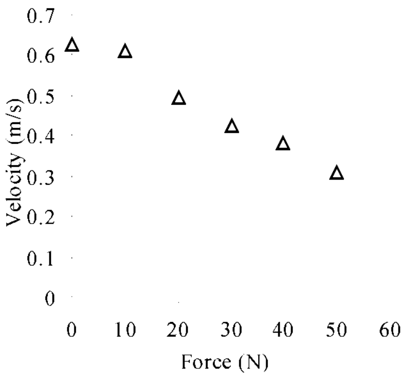


Fig. 11: *Velocity vs force characteristic curve of linear motor with 60´9´28mm actuator*

This linear piezo motor has the best performance of any built to date. Its maximum power output is 16 W, and the efficiency reaches 18%. The maximum (open-loop) velocity is 600 mm/s, and the maximum force developed, 60 N. The nominal voltage applied to the piezo actuator is $200V_{rms}$.
More information about PIline™ linear motor stages and piezo motors is available at www.pi.ws .

Conclusions

A new type of ultrasonic piezoelectric actuator for ultra-precision linear drives has been developed that features a very simple easy scalable mechanical design. The results of the FEM-simulations corresponding well with the measured oscillation profiles of the excited standing wave. The efficiency of this new actuator achives 18 % in the designed linear stages. Excellent dynamics is another fundamental feature of this new actuator.

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