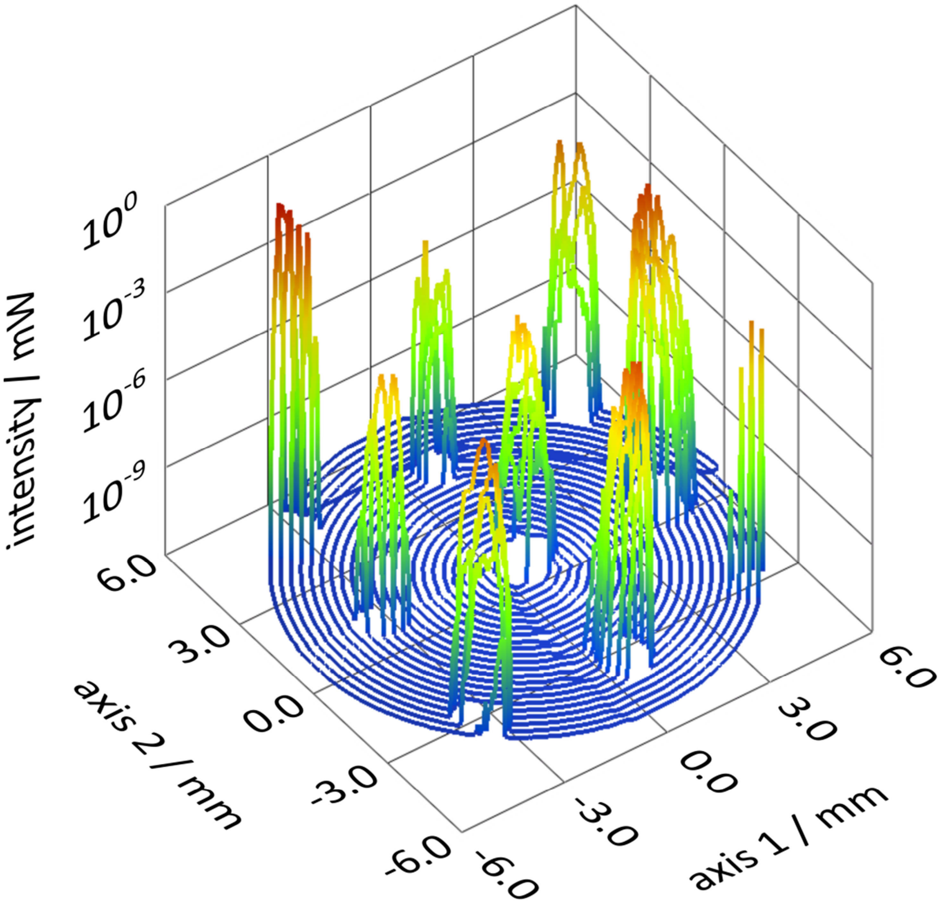
Advanced Positioning with PILine®

Positioning Capabilities of PILine® Components



Content

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Some of the procedures described in this whitepaper can have an impact on the stability and lifetime of the product.
Always make sure that the motor output stays within the limits described in the user manual of the product.
Contact your PI representative in case of questions and for further advice.

1 Overview

Over the past years there has been an increasingly high interest in piezoelectric motors, especially in the area of semiconductors, optics, photonics, medical and life science where precise motion and positioning is a prerequisite. PILine® positioning systems, which incorporate ultrasonic piezomotors, can achieve both accurate positioning in the nanometer range and fast motion, a combination that is not attained by many other drive technologies.

This whitepaper highlights some of the most demanding applications, in which PILine® motion and positioning systems can apply their strengths:

- positioning with nanometer resolution
- fast step-and-settle within milliseconds
- fast scanning of patterns
- motion at constant velocities
- ultraslow and smooth motion
- low position drift in standby mode
- motion along predefined paths (sine, circles, arcs)
- low latency triggering of motion and feedback
- low wear and minimized power consumption

2 Operating Principle of PILine® Motion Systems

PILine® positioning systems are based on ultrasonic piezomotors that are capable of direct-driven linear motion. A piezoelectric actuator, which vibrates at an ultrasonic frequency range, is preloaded against a runner using a coupling element (see Fig. 1).

Electrical excitement of the piezoelectric actuator at its resonance frequency causes oscillation. Due to the preload, the actuator oscillation is converted into continuous feed motion by the coupling element, which moves the runner. The preload also causes the drive to self-lock when the stage is not energized. The velocity of the motion can be adjusted by modifying the amplitude of the excitation and therefore the amount of power transferred to the runner.

Changes in position of the stage are detected accurately by an incremental, or in some cases, an absolute-measuring linear encoder. The number of counts recorded by the encoder is proportional to the distance travelled. Sub-nm resolution is possible using state-of-the-art sensors and gratings.

PILine® stages are usually operated in closed-loop mode, where a proportional-integral-derivative (PID) algorithm is used to minimize trajectory deviations. Comparing the actual position (obtained from the internal sensor) with a commanded position returns the following error which serves as a process variable for the PID algorithm.

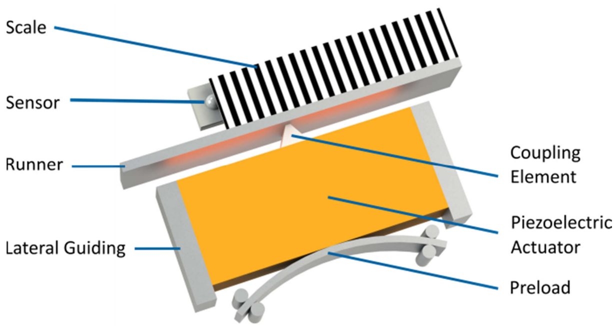

Fig. 1 Schematic diagram of a PILine® motor: The piezoelectric actuator is preloaded against the runner. Electrical excitement of the actuator causes oscillation. This oscillation is converted to forward motion, which is then transmitted to the runner using a coupling element. The position of the runner is recorded by a stationary sensor (encoder), which counts the periods of a grating attached to the runner. *Image: PI*

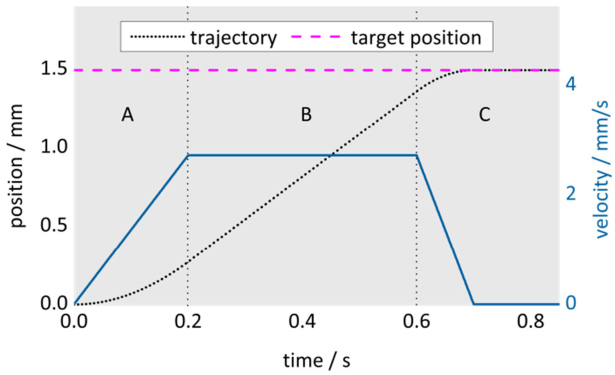

Fig. 2 Example of a position and velocity profile created by a PILine® controller for motion from 0 mm (start) to 1.5 mm (target position). It can be divided into three regions: acceleration (A), constant velocity (B), and deceleration and settling (C). *Image: PI*

When targeting a position, the inbuilt profile generator of the PILine® controller (e.g., C-867) creates a velocity profile for the motor, which consists of three regions (see Fig. 2): (**A**) acceleration, (**B**) constant velocity, and (**C**) deceleration and settling. Each of these regions can be tuned individually by adjusting the corresponding control (PID) parameters. The controller features up to five independent groups of control parameters (group 0 to 4). As depicted in Fig. 3, these control parameter groups are arranged concentrically around the commanded position or around the target position (default), depending on the servo window mode (parameter **0x4D**).

The values of the proportional, integral, and derivative parameters should decrease with an increasing control parameter group number. The number of groups to be used can be configured with parameter **0x400**. Operating with three control parameter groups is recommended. Each group of control parameters contains two windows: Window enter and window exit, specifying the activation area. As soon as the actual position of the stage reaches one of the entry windows, the corresponding control parameter group is activated automatically. The window exit parameter of the outermost parameter group is ignored by the PILine® controller, leaving this PID set active even when the stage exits the window.

The control parameter group 0 (**0x401** to **0x407**) plays the specific role of regulating the settling behavior – it is activated only after the commanded trajectory has finished (see Fig. 3). The other parameter groups (1 to 4, **0x411** to **0x447**) determine the behavior during stage motion.

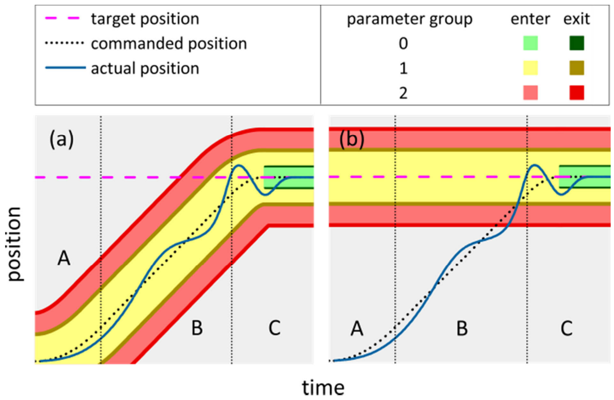

Fig. 3 The enter and exit windows of a configuration with three control parameter groups are represented by different colors. The windows can be centered around the commanded position (a) or around the target position (b; default setting). The innermost control parameter group (0, green) is activated only after settling begins; i.e., when the commanded position is equal to the target position. Note that in (b), the outermost control parameter group (2, red) is already active before the actual position of the stage reaches the corresponding enter window. *Image: PI*

3 Fast Motion and Settling

3.1 Increasing Acceleration (Region A)

In this region, the stage accelerates until it reaches the maximum velocity predetermined by the profile generator. The acceleration region can be minimized by

- increasing the acceleration parameter
- adjusting the drive offset parameters

As a quick and simple first measure, try increasing the motor's closed-loop acceleration (**0xB**), which by default, is set to a rather conservative value (see Fig. 4).

The second method of shortening the acceleration region involves adjusting the offset voltage parameters of the controller. Before the stage can start moving; stiction between the coupling element and runner has to be overcome. For that purpose, the controller gradually increases the motor output. The delay time associated with this process can be reduced by increasing the motor drive offset parameter (**0x48**), which sets the starting value of the motor output voltage (see Fig. 5).

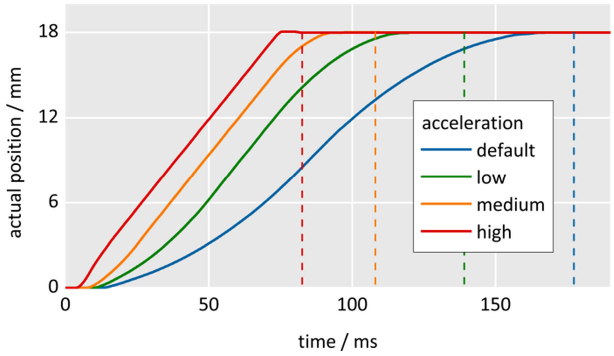

Fig. 4 The positioning time can be reduced using higher closed-loop acceleration (0xB) values. The dashed lines mark the time of settling for an example PILine® linear stage. *Image: PI*

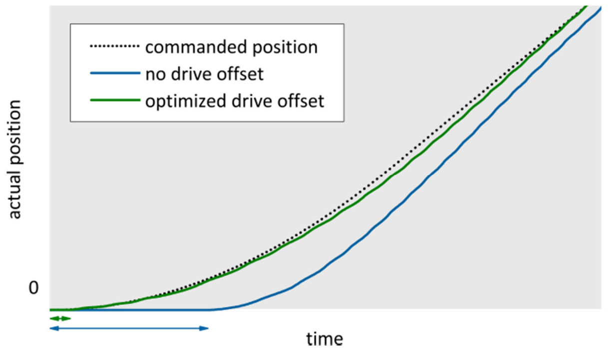

Fig. 5 Adjusting the motor drive offset parameter (0x48) reduces the time delay before starting (indicated by arrows), which is caused by initial stiction between coupling element and runner. *Image: PI*

Additionally, compensation for direction-dependent load of the stage (e.g., when mounted vertically), is achieved by tuning the parameters motor offset positive (**0x33**) and motor offset negative (**0x34**). These offsets are applied together with the motor drive offset. Suitable initial values can be found and set using the following host macro in PIMikroMove:

```
SVO 1 0
CPY CURPOS POS? 1
ADD THRESHOLD ${CURPOS} 0.01
VAR POSOFF 0
ADD POSOFF ${POSOFF} 25
SMO 1 ${POSOFF}
JRC -2 POS? 1 < ${THRESHOLD}
SMO 1 0
```

```
CPY CURPOS POS? 1
ADD THRESHOLD ${CURPOS} -0.01
VAR NEGOFF 0
ADD NEGOFF ${NEGOFF} 25
SMO 1 -${NEGOFF}
JRC -2 POS? 1 > ${THRESHOLD}
SMO 1 0
VAR CURPOS
VAR THRESHOLD
SPA 1 0X33 ${POSOFF}
SPA 1 0X34 ${NEGOFF}
```

Fig. 6 Running this host macro in PIMikroMove will determine the motor output required to drive off, both in a positive as well as a negative direction. These values are then stored as positive and negative motor offsets (0x33, 0x34) in the volatile memory of the controller.

3.2 Increasing the Velocity (Region B)

In this region, the stage has reached its constant velocity. The required time span can be shortened by increasing the stage's closed-loop velocity (**0x49**). In some cases, especially when covering short distances, the stage may go directly from acceleration (region A) to deceleration (region C), without reaching the maximum velocity. If so, try increasing the closed-loop acceleration (**0xB**) and deceleration (**0xC**) parameters.

3.3 Improving Settling (Region C)

In this region, the motor decelerates as it approaches the target position. The deceleration region can be minimized by

- increasing the deceleration parameter
- adjusting the integral term of control parameter group 1
- increasing window enter of control parameter group 0

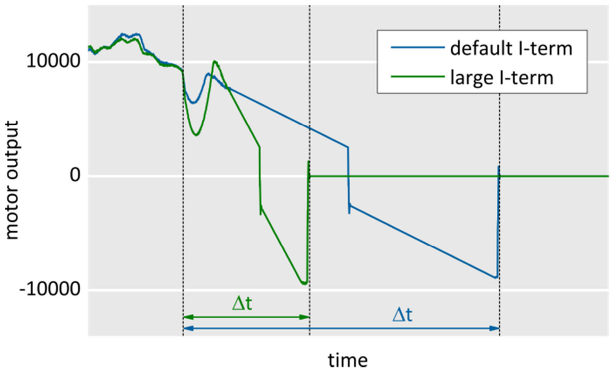

Fig. 7 Increasing the I term of control parameter group 1 reduces the time Δt the controller operates within this control parameter group. At the end of each Δt, the controller switches to settling mode (control parameter group 0). *Image: PI*

Increasing the closed-loop deceleration parameter (**0xC**) is similar to increasing the acceleration in region A, as explained in chapter 3.1. Faster deceleration can also be obtained by increasing the integral term of control parameter group 1 (**0x412**). This pulls the stage quicker into the settling window (control parameter group 0), as depicted in Fig. 7.

If accuracy is not of utmost importance, the window enter parameter of control parameter group 0 (referred to as "settling window", **0x406**) can be widened to achieve earlier settling, as shown in Fig. 8.

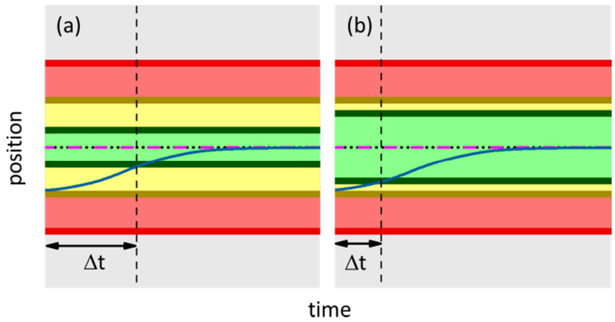

Fig. 8 Zoom-in to the settling region of Fig. 3. Default settling window (a) versus increased settling window (b) leading to earlier settling (for a legend see Fig. 3). *Image: PI*

3.4 Example I: Fast Step-And-Settle

Due to their dynamic response behavior, PILine® systems are able to take care of very fast step-and-settle tasks. When incremental motion of only a few micrometers is required, very short positioning times can be achieved.

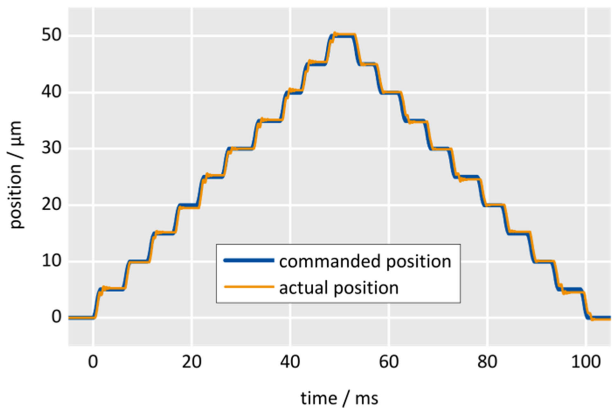

Fig. 9 Stepping motion profile by U-521.24 PILine® stage. Step size: 5 µm, deviation from target position: ≤ 0.5 µm, positioning time: <5 ms. Individual parameter optimization required. *Image: PI*

Fig. 9 shows a stepping motion with a step size of 5 µm. In this example application, ten steps were made in positive and then negative direction at an interval of approx. 5 ms for each step. This corresponds to 200 individual positioning steps per second. To ensure the fastest possible positioning, a deviation of up to 0.5 µm from the target position is tolerated. The stage was loaded with an additional mass of approx. 30 g to simulate a realistic application.

The PILine® stage needs less than 3 ms for one positioning step (acceleration, constant motion, deceleration, step-and-settle and overshoot subsidence). The stage is then completely at rest (any position deviation is lower than the sensor resolution), and a further 2 ms are available for example, for performing image recording with a camera. When the target has been reached, it is possible to transmit an impulse (TTL) via the digital output of the PILine® controller for triggering an external device. It is also possible to reverse the application so that the customer's equipment can trigger the next stepping motion via the digital input of the PILine® controller. This makes sense particularly when the time intervals between two positioning steps need to have different lengths. This configuration also allows an impulse to be transmitted after reaching the target position so that the fastest possible sequence can be ensured.

The technical implementation is achieved by optimizing the parameters as explained in the previous chapters. Above all, the acceleration and deceleration must be increased considerably to generate a steeper target trajectory. Furthermore, a higher motor offset needs be set to reduce the time breaking away from a standing position. Controller macros are used to evaluate the digital inputs.

3.5 Example II: Fast Scanning

Due to the large velocity spectrum and the lightweight design of PILine® positioning systems, they are particularly suitable for fast scanning applications that require high positioning accuracy. A typical customer application is depicted in Fig. 10. As a goal, the positioning system should be able to move back and forth between certain points as fast as possible (here: 0 mm and 1 mm) and achieve this as precisely as possible.

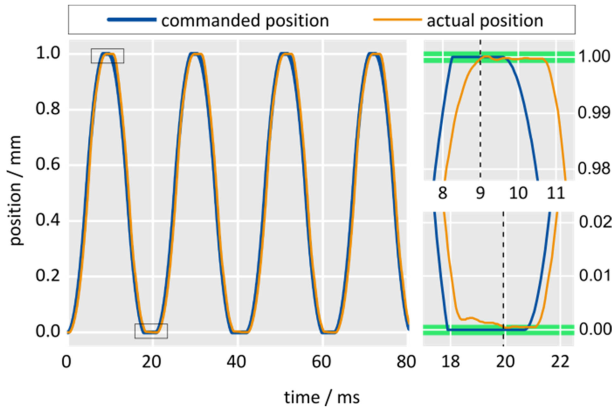

Fig. 10 Scanning application by U-521.24 PILine® stage. *Image: PI*

Enlargements of the target areas are shown on the right-hand side of the picture (a zoom into the rectangles on the left-hand side). The bidirectional repeatability was increased from ±0.2 µm to ±1.0 µm (demonstrated by the green areas) in favor of the positioning speed. As soon as the positioning system is inside this target window for a certain period of time - depicted here by the vertical dotted lines, the controller reports the arrival at the target via one of the interfaces (e.g., SPI, RS232, TTL digital outputs). After that, a measurement can be taken and the next positioning step can be triggered.

In the example above, the stage only requires 10 ms for a single positioning run (distance 1 mm). It therefore reaches 100 target positions per second (50 Hz) at an average velocity of 100 mm/s. The achievable velocity is reduced by approx. 15 % with an additional load of 10 g. Optimization of the control parameters is absolutely necessary for this application, particularly the increase in acceleration and deceleration as well as the use of individual motor offsets in order to reduce the time for getting out of a standing position.

These PILine® positioning systems achieved > 1300 h of uninterrupted scanning during an endurance test, which corresponds to an overall distance of more than 460 km or 230 million cycles before the ball bearing of the stage exceeded the tolerated play due to wear.

4 Fine Positioning

When accurate positioning in the nanometer range is required, reservations on positioning speed may have to be taken into account. Minimum incremental motion and high position resolution can be obtained by using a smaller settling window; i.e., by reducing the window enter 0 (**0x406**) and window exit 0 (**0x407**) parameters and optimizing the servo loop parameters.

Keep in mind that the true achievable positioning accuracy (in terms of deviation from a theoretical true position) is limited by other factors such as the grating pitch of the scale, accuracy of the sensor and signal conditioning of the sensor electronics. For higher accuracy consider acquiring:

- stages with a fine and accurate grating pitch of the scales
- controllers with improved interpolation systems
- stages with calibrated or mapped accuracy.

PILine® systems usually provide a resolution of 0.01 to 0.4 µm, which corresponds to bidirectional repeatability in the range of 0.05 to 2.0 µm, depending on the tolerated deviation from the target position (settling window). For applications that require higher accuracy, customized PILine® stages are available (Fig. 14). Fig. 11 shows an example of stepping motion by a modified U-521.24 PILine® stage. Compared to the standard stage, a ten-times higher interpolation was selected for this application, so a resolution of 10 nm is achieved instead of 100 nm. These settings make it possible to render the stepping motion specified here with a step size of 100 nm and with very high precision. The maximum deviation from the respective target position is only ±20 nm (standard value: ±800 nm). Nevertheless, positioning is done very fast – the entire stepping motion with 20 individual steps is achieved in under a second.

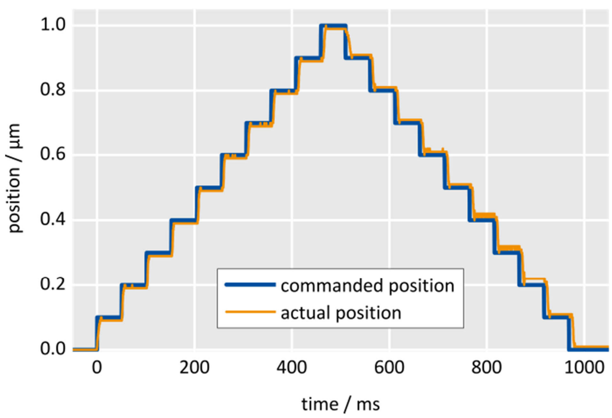

Fig. 11 Stepping motion by a U-521.24 PILine® stage. Step size: 100 nm, settling window: ±20 nm, positioning time: <50 ms. Individual parameter optimization required. *Image: PI*

5 Motion at Constant Velocity

Direct measurement of the velocity is usually not available in our standard products as we use position sensors. However, by measuring the time $\Delta t = t_2 - t_1$ required for the stage to travel a distance $\Delta s = s_2 - s_1$, the velocity can be obtained from the relation $v = \Delta s / \Delta t$. Bear in mind that the distance Δs varies depending on the sampling rate $1/\Delta t$ used, therefore different results are obtained for the constancy of velocity (= $v_{actual} / v_{set} - 1$), despite identical stage movement (Fig. 12).

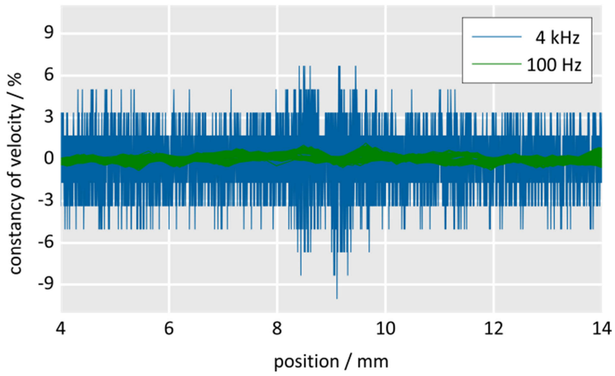

Fig. 12 Constancy of velocity versus position; recorded several times at two different sampling rates. Small local changes in velocity have significantly more impact at high sampling rates. *Image: PI*

PILine® motors feature a broad velocity range of 10 nm/s to over 100 mm/s. This range can be subdivided into three characteristic ranges:

- ultraslow motion (10 nm/s to 10 µm/s)
- slow motion (10 µm/s to 1 mm/s)
- fast motion (> 1 mm/s)

5.1 Ultraslow Motion

Positioning at ultraslow speeds is essential when scanning small objects; e.g., when using a microscope with a PILine® stage in manual mode. Customizing the PID and controller parameters according to the intended use is imperative for achieving optimum performance of the stage.

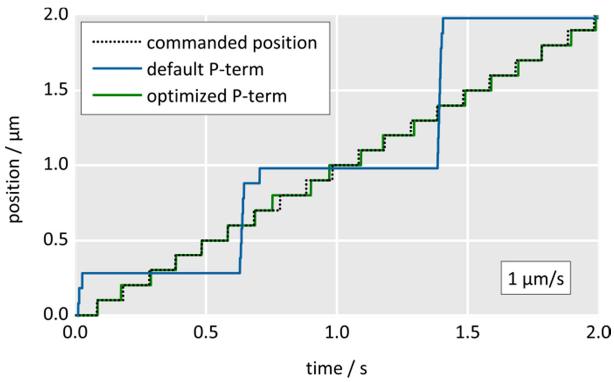

Fig. 13 Ultraslow motion at 1 µm/s before and after P-term optimization. The optimized proportional term causes the stage to closely reproduce the commanded position profile. *Image: PI*

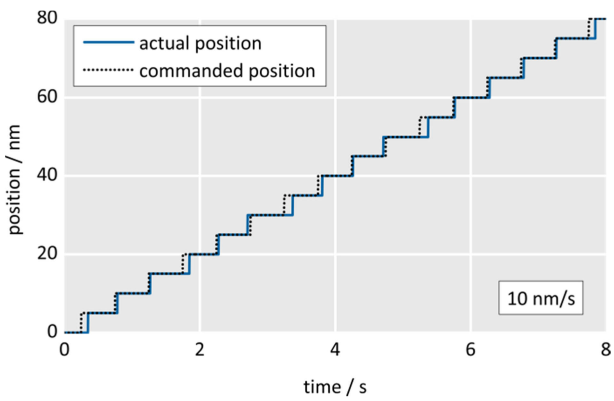

Fig. 14 Trajectory of a customized PILine® stage with a PIOne sensor, interpolated externally by a PILine® C-867.1U controller. The resolution is lowered to 5 nm, a 20-fold reduction compared to the standard resolution of 100 nm. The commanded position profile is reproduced very precisely. *Image: PI*

A key requirement for this velocity range is uniform motion. For this purpose, some of our high-end PILine® controllers (e.g., the C-867.2U2) offer a so-called second phase actuation. In this mode, one electrode of the motor is driven by a secondary output voltage; the amplitude can be set using the motor output two-phase magnitude parameter (**0x6F**). Doing so will adjust the forward feed vector of the coupling element, which decreases the breakaway torque. On the downside, forward force is reduced in this mode. The best results are achieved using motor offset values between 10 % and 40 % of the maximum motor output parameter (**0x9**).

Following errors, which occur particularly in this velocity range, have to be compensated by boosting the P term of the current PID set to a very high value (refer to chapter 1.1). Assuming that the stage is well tuned, the actual trajectory can closely reproduce the generated profile as depicted in Fig. 13 and Fig. 14.

PILine® controllers also feature a regulating circuit for automatic excitation frequency adjustment, which may interfere with the PID regulation. Before beginning with optimization of the P term, make sure that the dynamic frequency control (**0x52**) is switched off. Furthermore, a slight increase of the motor output frequency (**0x51**) can prove to be beneficial when driving slowly.

5.2 Slow Motion

Typical applications for this velocity range include triggered image capturing or laser-cutting cells.

A rattling noise, created by a periodic coupling mode switching of the coupling element, may occur in this speed range. The physics behind this noise are basically the same with a crayon rattling on a chalk board. It is not harmful to the motor and can be eliminated by driving the motor with a secondary phase using the motor offset parameter (**0x6F**), as explained in chapter 5.1. Using a secondary phase also reduces the following error.

5.3 Fast Motion

This velocity range is mostly used for fast step-and-settle applications. Typical use cases are positioning lenses in a beam path or shutter applications. Here, the main requirement is fast and accurate positioning; the shape of the trajectory plays a subordinate role. In most instances, the default settings of the controller can be adopted without the need for time-consuming customization. Furthermore, the use of two-phase actuation (motor offset) is not required and might in fact lead to slower final velocities and less forward force.

5.4 Minimizing Dynamic Following Error

When minimum position error is required, the P term of the active control parameter group has to be adjusted according to the current velocity of the stage. The I and D term do not need to be changed; however, decreasing them might be beneficial in some cases. Fig. 15 shows the empirically determined P terms of an example PILine® stage, for which the minimum following error is obtained.

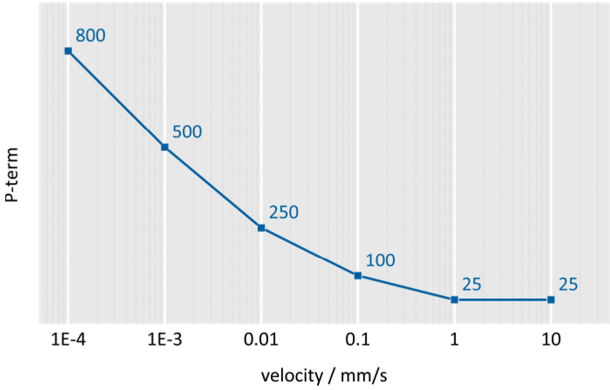

Fig. 15 Exemplary P-term vs. velocity diagram of a PILine® linear stage, plotted on a logarithmic scale. Different values may apply to your stage. *Image: PI*

To obtain the smallest possible following errors regardless of velocity, a function adjusting the P-term to the current velocity can be implemented in all supported software environments, e.g., by using an empirical formula or a lookup table.

6 Arbitrary Path Motion (APM)

This chapter is intended to explain how position trajectories like geometric shapes (circle, arc, and ellipse) can be generated and followed with PILine® stages and controllers. A circle is mathematically defined as a geometric shape that satisfies the following equations:

$$\mathrm{x}^2 + \mathrm{y}^2 = \mathrm{r}^2$$

$$x = a \cdot \sin(\omega t)$$

$$y = b \cdot \sin\left(\omega t + \frac{\pi}{2}\right),$$

where x and y are the coordinate points on the circle, r is the radius of the circle, a and b are the amplitudes of sinusoidal paths, ω is the angular frequency and t is the time. Two sinusoidal trajectories with the same amplitudes and 90° phase difference should be commanded to obtain a circle. Two sinus trajectories are excited synchronically from two channels of the controller to the two axes of the stages, so that a circular contour is generated. It is also possible to generate part of a circle or an arc which has a curved shape like a bow.

The equation of a circular arc can be written as a portion of a circle. Similarly, complex shapes such as an ellipse and a biarc (two adjacent arcs with the same rate of change at the conjunction point) can be commanded with the PILine® C-867.2U2 controller as well. An elliptical position path can be generated with two sinusoidal functions of different amplitudes:

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1$$

$$x = a \cdot \sin(\omega t)$$

$$y = b \cdot \sin\left(\omega t + \frac{\pi}{2}\right).$$

Some customers want to have a combination of these paths as a pattern to be commanded and followed which can be easily realized by PILine® C-867.2U2 controller and stages. In addition, arbitrary user-defined patterns can also be created. Keep in mind that the velocity of the sinusoidal path trajectories is also trigonometric. The velocity always varies between zero and the maximum value, which is dependent on the amplitude and the period or frequency of the generated trajectory. That is why intelligent and adaptive control concepts are required for such position and velocity profiles.

Since piezomotors are driven with a contact mechanism between runner and coupling element (refer to Fig. 1), there is always a dead zone which is a threshold voltage level to be exceeded to keep the motor moving (breakaway). Contact friction is a highly nonlinear phenomenon. The breakaway voltage should be compensated by offset values in the control mechanism (as described in chapter 3.1). A typical piezomotor open-loop voltage velocity characteristics curve is illustrated in Fig. 16.

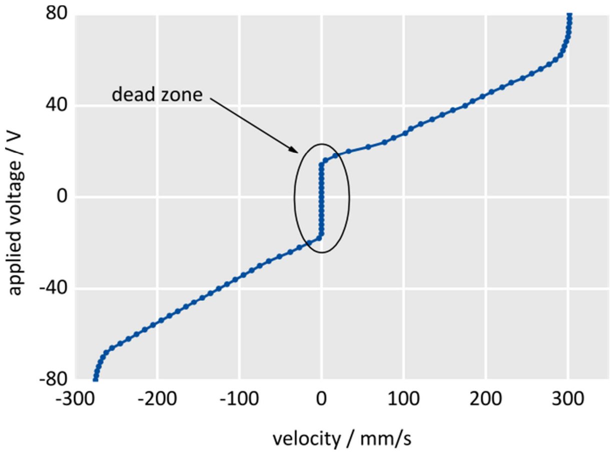

Fig. 16 Typical piezomotor open-loop voltage speed characteristics curve. There is no movement at operating voltages up to the breakaway level which is approximately 16-18 V for this stage. The dead zone is one of the main nonlinearities of piezomotors. Note: A motor output value of 32767 corresponds to the maximum motor output voltage (0x7C; here 80 V). *Image: PI*

The breakaway dead zone can be linearized by using an observer macro which measures offset values in both directions over the whole range of the stage. Minimum direction-dependent offset values are recorded in the control loop for the next trajectory path. The observer macro reduces the following error of the stages in the vicinity of direction changes and during startup. An example of such an observer macro with custom firmware is given below:

```
SVO 1 1
VAR MOUT 33000
MOV 1 -7
WAC ONT? 1 = 1
MOV 1 7
DEL 200
JRC 2 SMO? 1 > ${MOUT}
CPY MOUT SMO? 1
JRC -2 ONT? 1 = 0
ADD MOUT ${MOUT}
OTB 1 1 ${MOUT}
VAR MOUT -33000
MOV 1 7
WAC ONT? 1 = 1
MOV 1 -7
DEL 200
JRC 2 SMO? 1 < ${MOUT}
CPY MOUT SMO? 1
JRC -2 ONT? 1 = 0
MAT MOUT = ${MOUT} * -1
ADD MOUT ${MOUT}
OTB 1 2 ${MOUT}
```

6.1 Example III: Moving in Circles

Sinusoidal trajectories with arbitrary path motion (APM) using a U-751.24 two-axis PILine® stage and a C-867.2U2 two-channel, two-phase PILine® controller are presented in Fig. 17. The trajectories are generated by the controller via the following GCS commands:

`TGA {<Trajectory> <0 Value>}`	Append point to trajectory
`TGC [{<Trajectory>}]`	Clear all values of trajectories
`TGF [{<Trajectory>}]`	Finalize trajectories
`TGL? [{<Trajectory>}]`	Get number of values in trajectories
`TGS [{<Trajectory>}]`	Start trajectories
`TGT {<Timing>}`	Set trajectory timing
`TGT?`	Get trajectory timing

The circular trajectory is followed by a nonlinear adaptive control algorithm. During this test, not only adaptive PID control (APP) with respect to velocity was active but also two-phase piezomotor driving. An observer macro for dead zone linearization is operated before trajectory APM begins. The tracking and contour following error over the whole circle trajectory is less than 5 µm (Fig. 18).

The response of the stages near to the change of direction where the velocity is slower, is highly dynamic, silent and free of vibration. Movement of the stage near to direction change is continuous. Only minor stick-slip nonlinearity is observed.

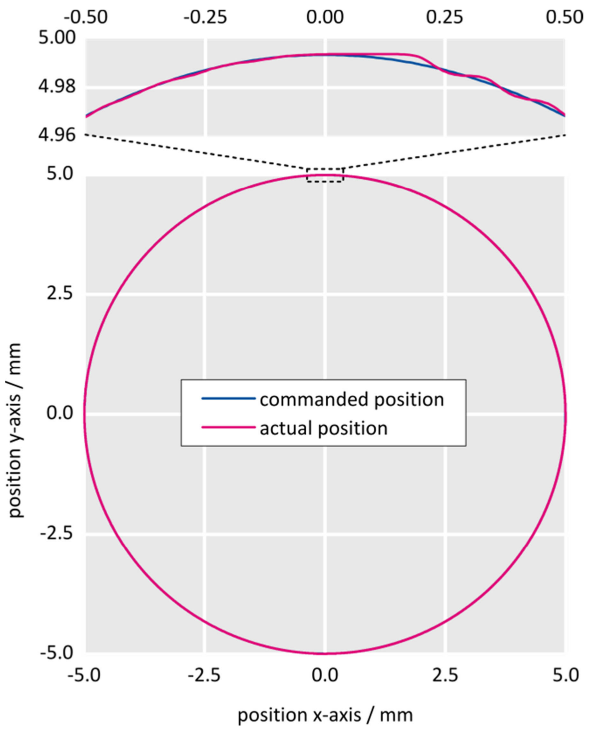

Fig. 17 Moving in a circle using an U-751.24 PILine® XY-stage and a C-867.2U2 controller. The zoom-in shows one of the four reversal points (here y-axis). When the direction is reversed, the maximum following error occurs due to stiction (here approx. 3 µm). *Image: PI*

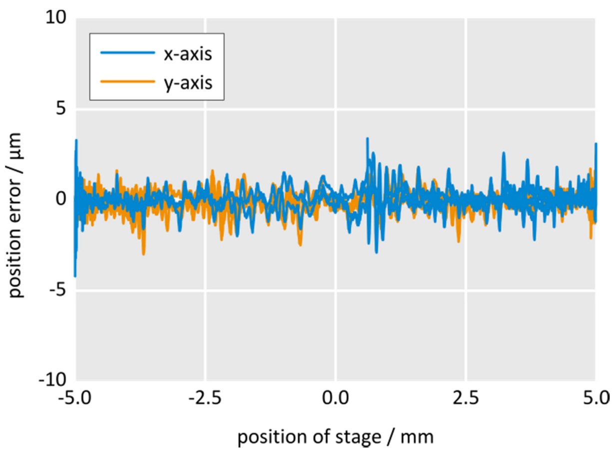

Fig. 18 Following error of both x-axis and y-axis with respect to the position of the stage. *Image: PI*

7 Position Drift at Standby

Precision positioning stages, especially in medical and metrology applications, are required to have not only accurate target positioning but must also remain at this target position over a long period of time, which is a very critical parameter for selecting positioning systems. Drift, which is the change of the stage position over time when it is in standby, can be defined as position stability over a period of time ranging from one minute to several days. It is a nonlinear phenomenon and therefore, it has random characteristics. Causes of position drift are mainly viscoelastic features of components such as polymers, epoxies and damping elements used in the stages. The figures below show a typical position drift of a piezomotor over a minute of relaxation.

PI designs its positioning systems to avoid using temperature-dependent materials in order to get lowest position drift. Because PILine® stages feature an excellent self-locking mechanism, they do not require extra electrical energy for holding their position. Fig. 20 illustrates the PILine® positioning system with anti-drift modification. The position drift is low and stable. Therefore, there is no need to activate the closed-loop control again to move the stage back to its original position. Position drift at rest is a result of the temperature deviation of the environment.

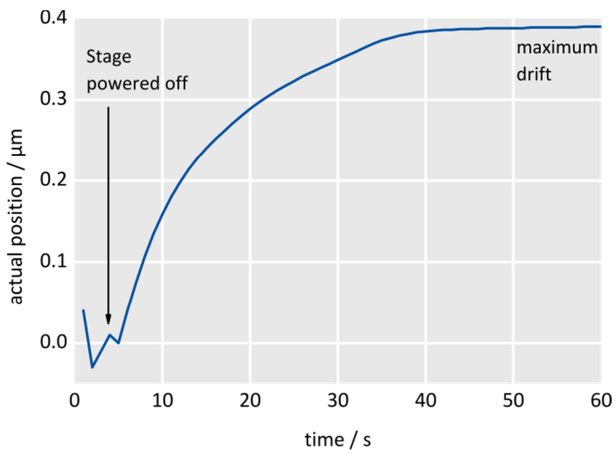

Fig. 19 Position drift example of a typical piezomotor. *Image: PI*

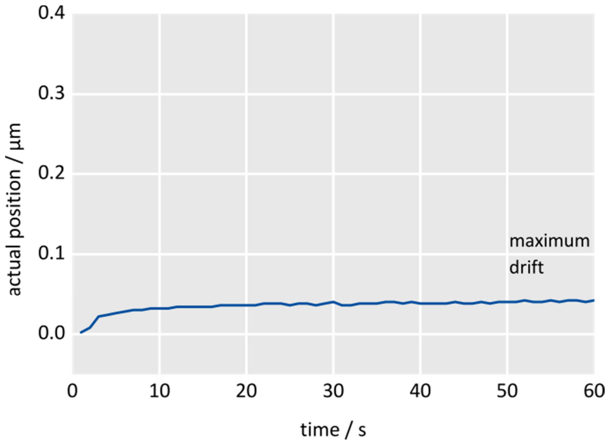

Fig. 20 Position drift of PILine® positioning system with anti-drift modification. *Image: PI*

8 System Modelling

For the most demanding applications, it is helpful to derive a transfer model of the actual system by methods of system identification. These models can be used to analyze control loop strategies more efficiently on a virtual system.

For most PILine® systems, the required data such as open-loop behavior in the frequency domain (Fig. 21) is available.

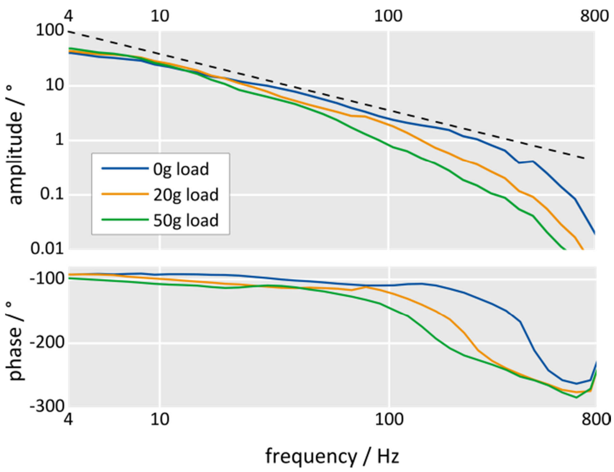

Fig. 21 Open-loop behavior of a PILine® rotary stage displayed in the frequency domain and with different loads. *Image: PI*

Authors

Dr. Christian Benz and Dr. Bülent Delibas are development engineers for piezomotor products at Physik Instrumente (PI) GmbH & Co. KG.

About PI

In the past four decades, PI (Physik Instrumente) with headquarters in Karlsruhe, Germany has become the leading manufacturer of nanopositioning systems with accuracies in the nanometer range. With four company sites in Germany and eleven sales and service offices abroad, the privately managed company operates globally.

Over 1000 highly qualified employees around the world enable the PI Group to meet almost any requirement in the field of innovative precision positioning technology. All key technologies are developed in-house. This allows the company to control every step of the process, from design right down to shipment: precision mechanics and electronics as well as position sensors.

The required piezoceramic elements are manufactured by its subsidiary PI Ceramic in Lederhose, Germany, one of the global leaders for piezo actuator and sensor products. PI miCos GmbH in Eschbach near Freiburg, Germany, is a specialist for positioning systems for ultrahigh vacuum applications as well as parallel-kinematic positioning systems with six degrees of freedom and custom-made designs.