# Reliability of PILine® Components

**Lifetime, Wear and Reliability of PILine® Systems**

# 1 Overview

PILine® positioning systems are based on a direct drive using ultrasonic piezo motors. Therefore, very low response times as well as accurate positioning can be accomplished. Due to the particular operating principle, PILine® motors are self-locking even when switched off. However, the drive is prone to a certain degree of wear.

This white paper is intended to provide a better understanding of what this wear is and what it means in terms of product lifetime. Furthermore, it focuses on showing why and under which circumstances neither lifetime nor general reliability is an issue when using PILine® motors.

# 2 Operating Principle of PILine® Positioning Systems

At the core of every PILine® system, a piezoelectric actuator is preloaded against a runner using a coupling element (see Fig. 1).

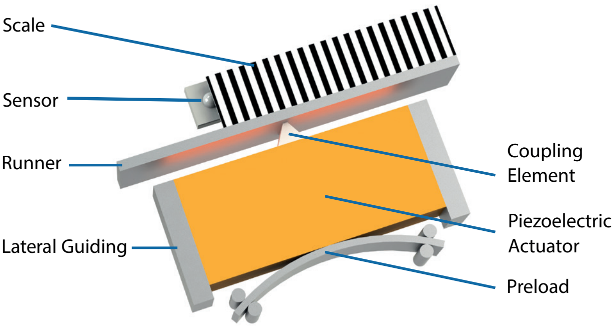


Fig. 1 Schematic design of a PILine® motor: A piezoelectric actuator is preloaded against a runner. Exciting the actuator electrically causes it to oscillate. This oscillation is transformed into forward motion, which is transmitted to the runner via a coupling element (Image: PI)

The actuator is excited electrically to generate highfrequency oscillations. In conjunction with preloading, continuous fast-feed motion results. The oscillation of the piezoelectric actuator is based on crystalline effects and is therefore completely free of wear.

The contact between the coupling element and the runner on the other hand, is subject to friction. Since this contact can account for up to 40 % of the system's total energy loss, great effort is made to determine the optimum composition of materials used.

Runners and coupling elements made of alumina ($Al_2O_3$) or zirconia-toughened alumina ($Al_2O_3/ZrO_2$, ZTA) have proven to be most effective.

# 3 Implications of Wear

Due to the friction-related power transfer between the coupling element and the runner, abraded particles accumulate in the housing of the motor (see Fig. 2).

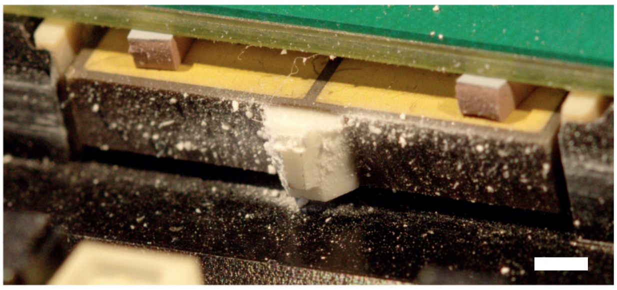

Fig. 2 Motor of a PILine® M-663.5U linear stage after 19,000 hours of operation. Abraded particles accumulate on the coupling element and piezoelectric actuator due to electrostatic effects. Scale bar: 2 mm (Image: PI)

However, the use of ceramic coupling elements keeps the degree of abrasion to a minimum. Furthermore, the coupling elements are dimensioned to prevent critical abrasion levels from being reached within the specified lifetime. Due to electrostatic effects, a large quantity of abraded particles remains in the housing because they are attracted directly to the piezoelectric actuator and coupling element.

## 3.1 Wear over Time

During the run-in period (approximately 100 h), unevenness caused by minor imperfections in the alignment between the coupling element and the runner are smoothed. After this initial process, the volume loss decreases to a low, constant value as visualized exemplarily in Fig. 3.

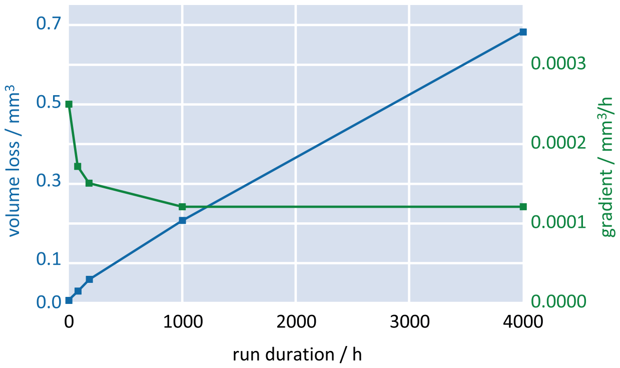


Fig. 3 Volume loss of a coupling element and corresponding gradient versus operating time. The gradient decreases considerably after the initial run-in period. In this exemplary test (described in more detail in chapter 4.1) the amount of abraded material per hour levels off below $10^{-4}$ mm³/h (0.5 µg/h) (Image: PI)

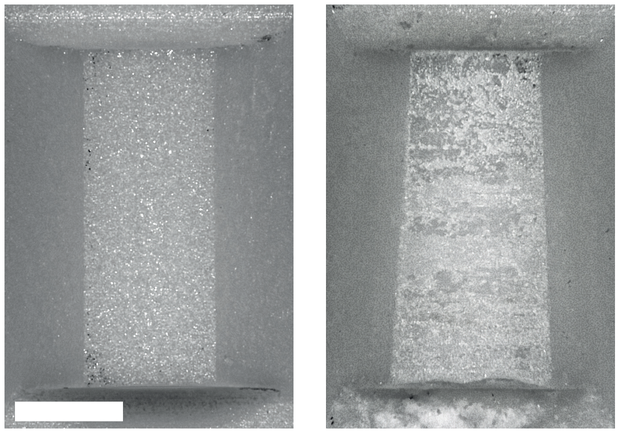

Fig. 4 Top view of two coupling elements: As manufactured (left) and after 19,000 h of operation (right). The asymmetric wear (cf. width top to width bottom) results from slightly uneven alignment between the coupling element and the runner, caused by nonuniform preload and/or inhomogeneous load on the stage. On average, the height of the coupling element was reduced by approx. 60 µm during the test cycle, as determined by laser microscopy. Scale bar: 0.5 mm (Image: PI)

## 3.2 Surfaces

On delivery, the surfaces of the ceramic coupling element and runner are smoothly polished. During the run-in procedure, asymmetry of the alignment is compensated by material abrasion. Over the course of a lifetime, signs of wear as well as effects of asymmetric alignment are visible on the surfaces of the coupling element and the runner.

The outcome of a 19,000 h lifecycle test of a PILine® M-663.5U linear stage test is discussed below, where these impacts can be readily observed. For more details on the test, refer to chapter 4.2. Wear and degree of abrasion on the coupling element and the runner are analyzed in Fig. 4 and Fig. 5, respectively. During the lifecycle test, the average height of the coupling element decreased by about 60 µm, with more than 85 % of the original height (400 µm) remaining. The removed volume amounts to approximately 0.05 mm³ (0.2 mg) of the abraded material.

The mean abrasion depth of the runner was estimated to be approximately 1 µm in the contact area of the coupling element, as described in Fig. 5. From profile scans, an abrasion volume of 0.03 mm³ (0.11 mg) can be estimated.

In total, this particular PILine® linear stage has produced approximately 0.08 mm³ (0.31 mg) abrasion. Therefore, after an initial run-in period, an abrasion volume of less than 0.02 µg/h can be expected, assuming constant wear.

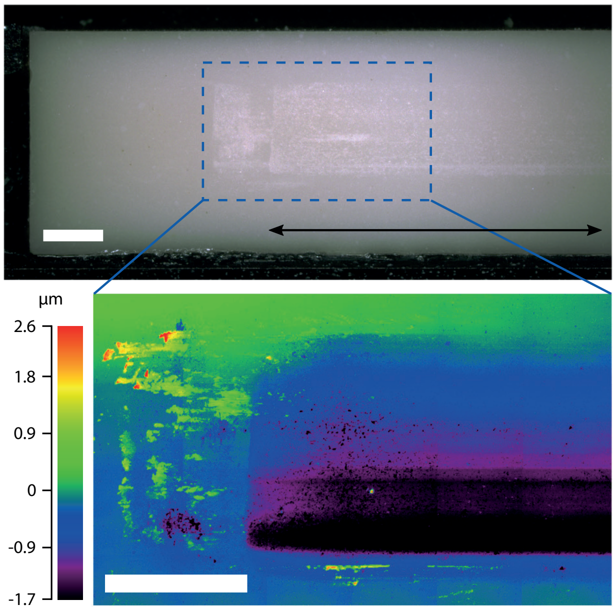


Fig. 5 Top: Optical microscope image of the runner, scale bars 1 mm. In the contact area of the coupling element, signs of wear can be identified. The trajectory of the runner versus coupling element is indicated by the black arrow. Bottom: Further analysis with a laser microscope provides information on the surface profile of the runner. Accumulation of abraded material is visible on the left-hand side. The mean abrasion depth within the contact area of the coupling element can be estimated to be ≈ 1 µm (image: PI)

## 3.3 Grain Size and Composition of Abrasion

The grain size of the abraded material was determined to be below 1 µm, as shown in Fig. 6.

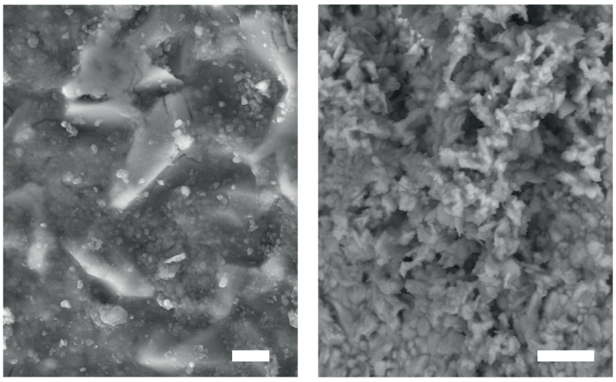

Fig. 6 Scanning electron microscope (SEM) images of the runner surface. Scale bars: 2 µm (left), and 10 µm (right). Individual abraded particles can be identified (the small bright particles < 1 µm). The vast majority of particles however, form tightly stacked clusters, as can be seen in the image on the right-hand side (Image: PI)

However, the appearance of single, isolated particles is rare; most particles agglomerate to large clusters.

The composition of the abraded particles was analyzed using electron diffraction x-ray (EDX). It corresponds to that of the ceramic coupling element and runner; therefore these can be identified as the sole source materials. As such, the abraded particles are electrically nonconductive, chemically inert and should not pose any danger to your electronic components. Furthermore, they have no impact on the performance of the PILine® motors.

## 4 Case Studies

During product development, numerous tests are conducted which are designed to meet customer requirements as well as attain the anticipated lifetime. The following representative case studies highlight some of our products.

## 4.1 Total Stations – Leica Geosystems

Leica Geosystems, a leading manufacturer of high-precision surveying instruments, relies on PILine® direct drive technology in their new total station product line (see Fig. 7).

Fig. 7 Leica Nova TS60 total station with PILine® direct drive (Image: Leica Geosystems)

Total stations are used for angle and distance measurement in geodesy. Customer requirements included an extensive increase of the rotation speed and the angular resolution compared to the previously used conventional drive. To verify the fulfillment of these requirements, a test recreating the typical usage of the device was conducted. It consisted of rotating a mass of 6 kg (15,000 kg/m²) in alternating directions. After completion of the test with a total of 7,000 h or 2,500 km of operation, all customer specifications continued to be fulfilled. The corresponding test with the analysis of the wear on the motor is shown in Fig. 3.

## 4.2 PILine® M-663.5U Translation Stage

The PILine® M-663.5U is a very fast and versatile linear translation stage. Due to its versatility, customers are expected to use it in unconventional situations or, more specific, suboptimal mounting orientations.

However, the mounting orientation has a significant impact on product wear due to the varying load on the coupling element and bearings. Fulfillment of the requirements on product lifetime was validated during a long-term test, where the stage was mounted at the least-favorable mounting orientation as depicted in Fig. 8.

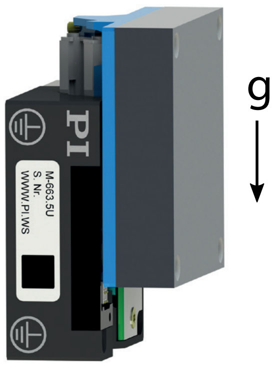


Fig. 8 M-663.5U linear stage, mounted in vertical orientation of the motion axis. The load on the stage was varied from 0.5 N to 2 N (Image: PI)

During this test, the stage travelled continuously across the full available travel range of 18 mm at a speed of 20 mm/s. A maximum applicable load of 2 N was determined as one of the test results. All stages remained in good condition during the trial period of over 19,000 h or 600 km, fulfilling the specifications as stated in the data sheet. Further analysis of the coupling elements and runners in these stages is discussed in chapters 3.2 and 3.3.

## 4.3 Customized PILine® M-663 Stage

This case study deals with a specifically customized PILine® M-663 stage. The customer requested a maximum permissible target deviation of ±1.2 µm and a settling time less than 250 ms. Both requirements were verified in longterm tests as presented in Fig. 9.

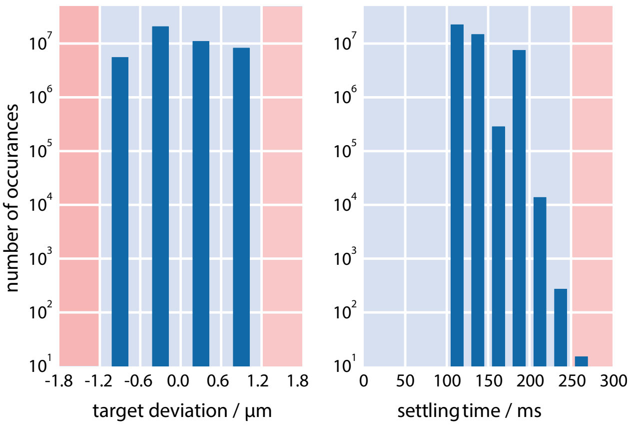


Fig. 9 Test results of a customized PILine® M-663 stage. Both target deviation (failure: none) and settling time (failure: 0.33 per million) are well within customer requirements (visualized by the light blue background). Note the logarithmic scaling of the y-axis (Image: PI)

After performing 45.6 million positioning cycles (380 km), the stage only failed to reach the target 15 times within the requested settling time, which is equivalent to 0.33 failures per million. The target deviation always remained below the threshold of ±1.2 µm.

## 5 Factors Influencing Wear

Depending on the ambient conditions, under which PILine® motors are operated, impact on wear may vary (see Tab. 1). This chapter intends to give you advice on how to maximize the lifetime of your PILine® positioning systems.

| Condition | Wear | Comment |
|---|---|---|
| Vacuum | ↑↑ | Max. power transfer |
| Dry environment | ↑ | High power transfer |
| Humid environment | ↓ | Lower power transfer |
| Frequency slightly higher than optimum | ↓ | Slightly slower positioning |
| Temperature >40 °C | ↑ | Risk of overheating increases |
| High acceleration or deceleration | ↑↑ | |
| High load | ↑ | |

Tab. 1 Impact of different ambient conditions on the lifetime of PILine® positioning systems

## 5.1 Humidity

The degree of abrasion depends on the power transmitted via the coupling element, which in turn depends on environmental conditions. Dry environments enable higher power transmission at the cost of increased wear. This is especially true under vacuum conditions, where maximum power transmission can be achieved. However, in humid environments, power transmission between the coupling element and the runner is reduced due to lower friction.

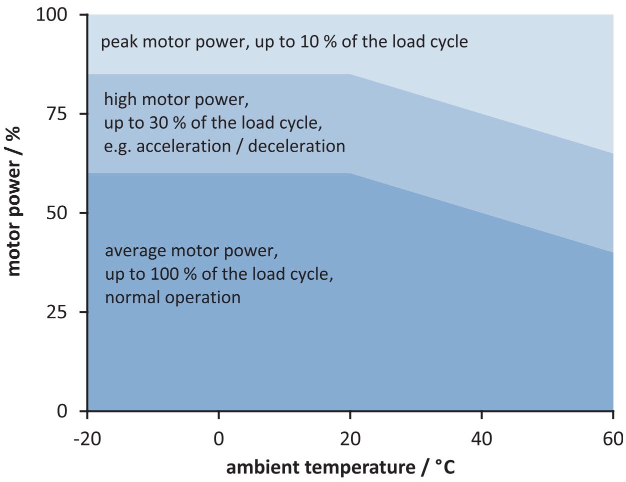


Fig. 10 Recommended duty cycle and motor power depending on the ambient temperature. In order to prevent overheating and increased wear, the motor power and the duty cycle should not exceed the limits specified in this graph (Image: PI)

## 5.2 Temperature

The ideal operating temperature for PILine® motors is between 10 °C to 40 °C. At lower temperatures, power transmission and maximum achievable speed are reduced due to the decreased inverse piezoelectric effect. For operation at temperatures above 40 °C, a reduction of motor power is advised to prevent overheating (see Fig. 10).

## 5.3 Load

Extended operation at high motor power leads to overheating and causes wear that could be prevented.

- It is recommended to keep the motor output below 60 %. The remaining 40 % is dedicated to acceleration, deceleration and use as a control reserve.
- PILine® motors undergo the heaviest load during acceleration and deceleration, while overcoming stiction. Try keeping them as low as possible, especially when moving heavy masses. Generally, 1,000 mm/s² is a good value, although a PILine® motor can easily achieve 10,000 mm/s².
- When targeting the same destinations repetitively, bumps may form on the runner. From time-to-time, try targeting a destination further away to promote smoothening of the runner surface.

# 6 Conclusion

Despite the wear-related drive principle, PILine® piezo motors are perfectly fit for applications where continuous operation is required.

As a general rule of thumb, PILine® systems typically reach 2,000 h of operation, 2,000 km or 20 million cycles, whichever occurs first. The operating time of 2,000 h corresponds to the actual duty time of the stage.

## Author

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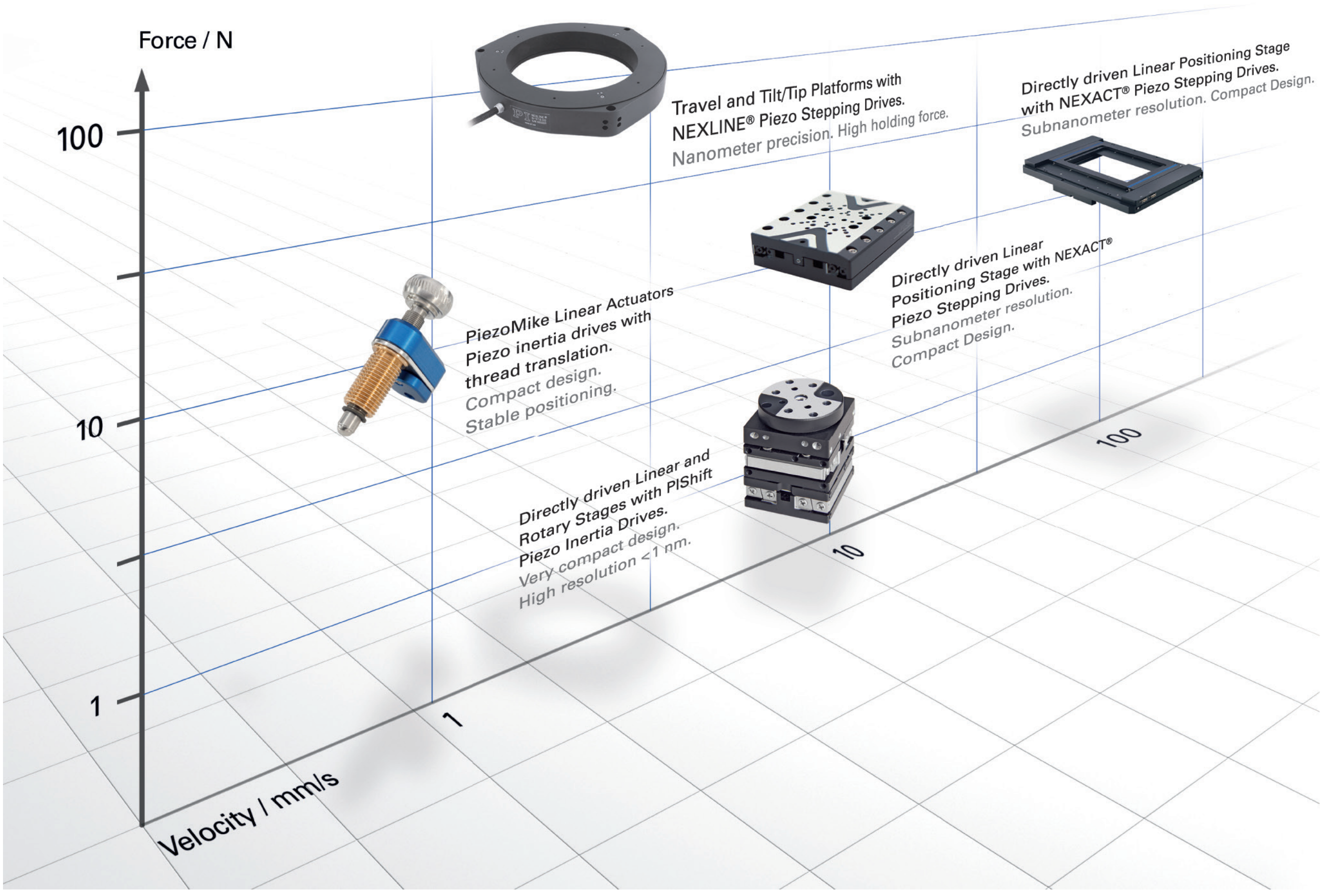
## About PI

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 850 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.



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