Impacts of environmental factors and installation on the lifetime of Piezoelectric stages

Introduction

Queensgate Instruments has decades of experience in the design and manufacture of piezo-actuated nanopositioning stages[1]. We are committed to providing the highest performing and most reliable precision positioning equipment.

The low voltage PZT piezo actuators we use in our stages are suitable for operation in a broad range of environmental conditions, however, some factors may reduce the overall lifetime of the product.

This document explores the major environmental considerations when installing a stage in a typical 'quasi-static' DC positioning application such as a microscope sample positioning stage and gives some mitigation techniques to optimize lifetime.

Reliability of Piezo Actuators

There are three major 'aging' factors that accelerate the failure rate of **all** PZT piezo actuators in DC (quasi-static) operation:

1. DC drive voltage (V)
2. Relative humidity (RH%)
3. Ambient temperature (ºC)

When humidity, temperature and voltage values are elevated there is an increased likelihood of chemical reactions occurring within the ceramic material. These include creation of Silver Hydroxide (AgHO) ions from a reaction between the Silver-Palladium (Ag-Pd) electrodes and water molecules. The Ag+ ions migrate from the anode to cathode through the active PZT layer. This causes silver metal deposits to grow along the ceramic grain boundaries (Figure 1) eventually resulting in an electrical short.

Furthermore, the remaining hydrogen atom from the water molecules can cause microcracking along the grain boundaries, a process similar to hydrogen embrittlement in metals.

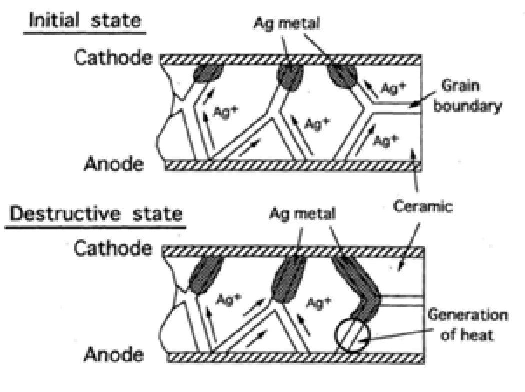

Figure 1: Ion Migration in Piezo ceramics[2].

[1] Queensgate Instruments has been a leading supplier of nanopositioning devices since the company was established in 1979.

[2] Thoungrueng, J,. Tsuchiya, T, et al. (1998) 'Lifetime and degradation mechanism of multilayer ceramic actuators' Journal of applied physics 37, 5306-5310.

Through extensive experimentation the supplier of our actuators has defined the following formula (Figure 2) to calculate the influence each factor has on the mean time to failure (MTTF) of a single actuator.

$$MTTF_r = MTTF_s \times A_v \times A_h \times A_t \quad \cdots \quad (1)$$

$MTTF_r$: Estimated value

$MTTF_s$: Reference value (=500h)

A_v : Acceleration factor for drive voltage $= \left(\frac{150}{V_r}\right)^{3.2}$ — V_r : Actual voltage (V)

A_h : Acceleration factor for relative humidity $= \left(\frac{90}{H_r}\right)^{4.9}$ — H_r : Actual relative humidity (RH%)

A_t : Acceleration factor for ambient temperature $= 1.5^{\frac{40-T_r}{10}}$ — T_r : Actual ambient temperature(℃)

Figure 2: MTTF calculation for piezo actuators

Each of these can also be plotted on a graph to illustrate their impact as per Figure 3. Here it should be noted that the Y-axis is a logarithmic scale and that the humidity and temperature factors are highly non-linear. It is also worth mentioning that negative DC voltages applied to a piezo electric actuator have no detrimental impact on lifetime (provided they are with the accepted operation range typically up to -30 Volts).

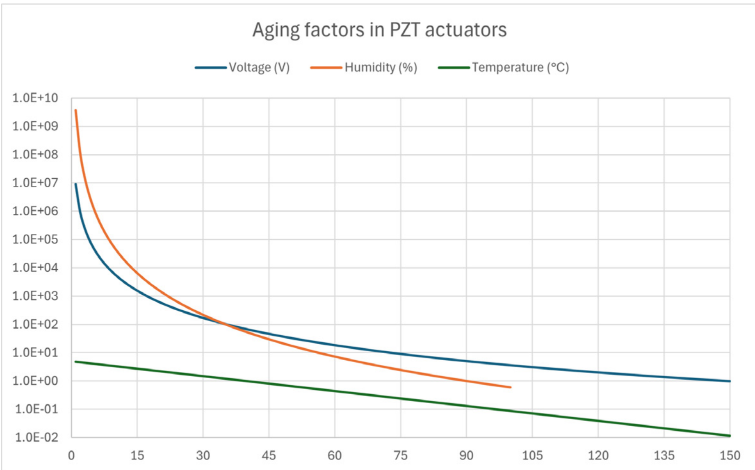

Figure 3: Aging factors of PZT actuators

Due to the complex interaction of these aging factors and the diversity of applications, it is nearly impossible for the manufacturers of the piezo electric actuators to give absolute operating limits for temperature or humidity in isolation and subsequently neither can Queensgate for our stages. The operating limits for voltage are defined at a system level and are typically between -30 to +150 volts.

Mitigating Impact for Increased Lifetime

Given the above considerations regarding the aging factors that impact lifetime of piezoelectric actuators there are mitigation steps that Queensgate have taken in the design of our systems and best practices that users can follow to ensure longevity of their systems. If care is taken the MTTF of a piezo system should be many years.

High Palladium Content Electrodes

To help limit the impact of silver ion migration Queensgate exclusively use piezo stack actuators which come from reputable sources and are guaranteed to have a high palladium (Pd) content of greater than 25%. Palladium is less reactive with water molecules than silver and subsequently there is decreased the ion formation rate in comparison to inner electrodes with a higher silver concentration[3].

Negative High-Voltage (HV) Offset

To ensure that our stages always achieve the specified closed-loop travel range the mechanism is typically designed to deliver an open-loop range at least 20% greater when the actuator is driven over the full operating voltage of -30 to 150 V_{dc}.

On start-up Queensgate's 6000 series controller will run an auto-balance routine to measure the open-loop travel available. Where possible the system will then set the closed-loop travel range biased towards the negative and lower voltage range as shown in Figure 4.

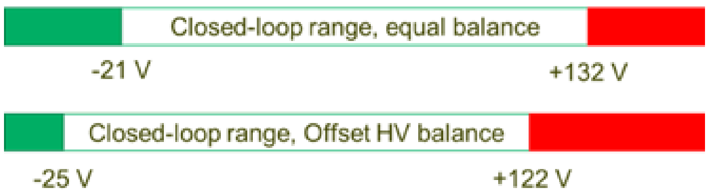

Figure 4: Offset auto balance

Using drive voltage data gathered from a sample of our NanoScan SP400 and SP600 sample positioners customers it is estimated that biasing toward lower voltages can increase system life up to 30% over setting the closed-loop range to the middle of the available travel.

User Actions to Mitigate Aging of Piezo Actuators

There are several steps that users and system integrators can take to help mitigate aging of the piezo actuators.

Drive and Idle Voltage

As discussed, higher continuous DC voltages applied to the actuators will have a non-linear detrimental impact on the life-time. It is of course acceptable to use the entire travel range of the stage including the maximum position commands. Consideration should be given to the duty cycle and care taken to minimize the amount of time in these regions.

Furthermore, it is sensible to ensure that when the system is left idle it should be in a position where the aging effect is minimized, typically in the lower third of the travel range.

For systems-controlled via analogue input this would typically be <3V for 0-10V inputs and < - 6V for ± 10V systems. For integrators commanding the system digitally it is recommended to command the system as close to 0 µm position or highest acceptable negative travel position for equally balanced systems (I.e. - 50 µm for ± 50 µm stages).

Use in Elevated Humidity and Temperatures

In ideal circumstances the piezo stages would all be implemented in climate-controlled laboratory with low temperatures and humidity; however, it accepted that this is not always practical.

Temperature

Where the stage is integrated in a bench-top OEM system or used in a microscope cage-heater elevated temperatures are inevitable and will reduce the lifetime of the system to some degree.

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[3] Note: Palladium is significantly more expensive than silver (25-30x) and so care should be given to the Ag-Pd ratio of the actuators used when comparing cost between piezo systems where reliability is a concern.

Care must be taken in such circumstances to mitigate the impact of the operating temperatures as best as possible.

A powered closed-loop piezo actuated positioning system actively compensates for thermal expansion/contraction of the system with temperature changes. For example, the NanoScan SP will increase the drive voltage to maintain the same nominal position of the sample with positive increases in temperature.

A temperature increases from ~20°C to the ~40°C needed for applications such as live-cell imaging can result in more than a +10 V HV offset on the actuators.

It is **highly recommended** that the piezo system is left powered off whilst the overall system comes up to operating temperature. If it is necessary for it to be powered, then once stabilized the auto-balance routine detailed above should be run to restore the beneficial low voltages. This scan either be commanded digitally (see command manual) or by power cycling the controller.

This is also good practice where stage-top heaters/incubators are used whilst the impact is typically less, they can increase piezo stage temperature via conduction.

Humidity

Humidity is perhaps the hardest of the aging factors to proactively mitigate against given it is related to climatic conditions and ambient temperature. There are hermetically sealed piezo actuators on the market, but their form factor makes them impractical for implementation in most piezo nanopositioning systems.

It is up to the user to ensure that the piezo stage is used in as dry conditions as is practical, ideally when used in air conditioned environments the humidity should be set as low as possible. The piezo systems should be implemented as far away from any 'wet' processes that may increase local humidity as is possible.

Where a stage-top incubator is used then measures should be taken to ensure these are not ventilated directly on to the piezo stage, any leaks or poor sealing should be addressed as a matter of high importance.

The piezo stage should **never** be place within an enclosure at very high humidity, I.e. the >90%RH as required for live-cell imaging.

It is important to note the above comments are with respect to non-condensing water vapor. Liquid water (or other aqueous fluids) can cause instantaneous failures of piezo actuators. Subsequently rapid changes in temperature or introduction of objects below the dew point of the ambient air near the piezo stage that could cause condensation must be avoided. For example the dew point, the temperature at which water droplets will begin to condense, of air at 37 °C and 90%RH is approximately 35°C.

Furthermore, in the case of a spillage the piezo system should be powered off immediately and sufficient time allowed for it to dry completely.

Summary

The lifetime of piezo actuated nanopositioning stages can be many years provided correct consideration is given to their operation and environment. It is unavoidable that the piezo actuators will 'age' in typical nanopositioning quasi-static operation due to high DC drive voltages, temperature and humidity.

Queensgate use quality piezo actuators with high palladium to silver ratios and implement smart control strategies such as low voltage offset auto-balance to mitigate some of these impacts. However, users can maximize the lifetime of their systems by:

1. Considering control/motion strategies that limit the amount of time high drive voltages are used (typically the upper end of the travel range).
2. Ensure that when the system is idle a low drive voltage such a 0 µm command or 3 volts analogue input is applied.
3. Where the stage is used at an elevated temperature power cycle the controller once the temperature has stabilized to ensure the optimum drive voltages are used.
4. Taking care about the ambient environment to ensure the lowest relative humidity as possible, i.e. eliminating local sources of water vapor such as venting from cell incubators.
5. Avoid exposing the piezo stage to condensing water vapor, or any other aqueous liquids, at all times.

If there are any doubts about the suitability of an environment for the use of a piezoelectric positioning system, then please contact your local Prior/Queensgate representative who will be happy to discuss the application in more detail.