Reliability of Multilayer Piezoelectric Actuators in Precise Positioning Applications

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Abstract

The piezoelectric multilayer actuator technology is an essential tool in ultra-precise nano-positioning. For the further spreading into new applications it is very important to exactly know and specify the driving limits of these actuators for different environmental conditions.

Recently we completed an extensive study on the DC-lifetime of PICMA® co-fired multilayer actuators were we used up to four climatic chambers at the same time to get a grid of 15 humidity and temperature conditions. At every condition we determined the DC-voltage dependent lifetime of the actuators by using Weibull-analysis. In total we used more than 1,000 actuator samples to get a DC-signal-lifetime model. We found a graphical method to present the results. This allows the user to calculate the lifetime for its voltage-, humidity- and temperature-conditions in a simple and fast manner.

For studying the AC-signal lifetime it is necessary to get high cycle numbers within a limited time. We found a way to drive the actuators at the nominal peak to peak voltage with more than 1 kHz repetition rate and slew rates down to 50 µs by different cooling measures to control the self heating. This allowed us to get 10^{10} cycles within just 100 days of testing and opens the opportunity for rather comprehensive investigations. We present the AC-results for different driving signals and pre-stress- as well as temperature-conditions.

1 DC-signal lifetime

DC-signal driving of the actuators is typical for nano-positioning applications were the actuators have to keep a position over long time and just get minor AC-signals to control disturbances.

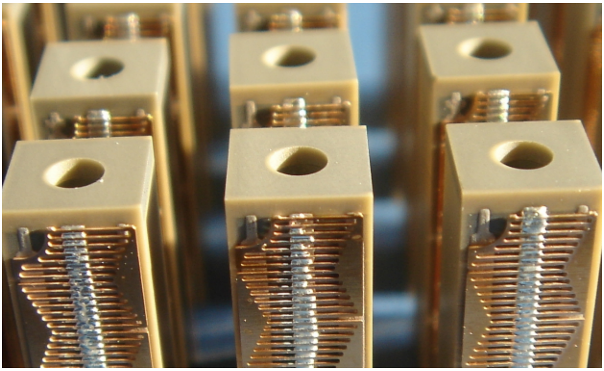

Figure 1: PICMA® actuator with a cross section of 5x5 mm² and an aperture of 2 mm diameter. Outer and inner surfaces are ceramic protected.

The reliability of piezoceramic actuators under large DC-signals is influenced by the size of the electric field, the temperature and the environmental humidity. Especially the humidity is promoting the degradation because electrolysis of water results in free moving ions on the surface of the actuator. Hence, different migration as well as protonic destruction processes finally reduce the insulation resistance of the actuator [1, 2]. The only possibility to inhibit these processes is to insulate the inner electrode structure of the actuator by an inorganic ceramic coating because no polymer coating is dense for humidity. A unique thin but dense ceramic coating is applied on PICMA® actuators (Fig. 1) [3].

The superior DC-signal lifetime of ceramic protected PICMA® actuators was demonstrated in several long running tests where they were tested versus standard polymer coated samples. Nevertheless application engineers always express a strong request for a tool which allows the calculation of the PICMA®-DC-lifetime for different voltage, temperature and humidity conditions. Therefore a comprehensive lifetime investigation was started, were PICMA® 5x5x18 mm³ actuators were tested at different climatic conditions. Five different voltages with 8 samples each were tested at every climatic condition.

Afterwards Weibull-analysis was carried out for the determination of the single experiment mean time to failures (MTTF’s). Then interpolations were performed to get individual relations for the lifetime versus the three determining factors. A power law was utilized for the voltage, an Arrhenius type of equation for the temperature and an exponential law for the relative humidity. Finally, the different interpolation equations were averaged and the time factors were implemented to get the graphical PICMA®-DC-lifetime calculation tool (Fig. 2).

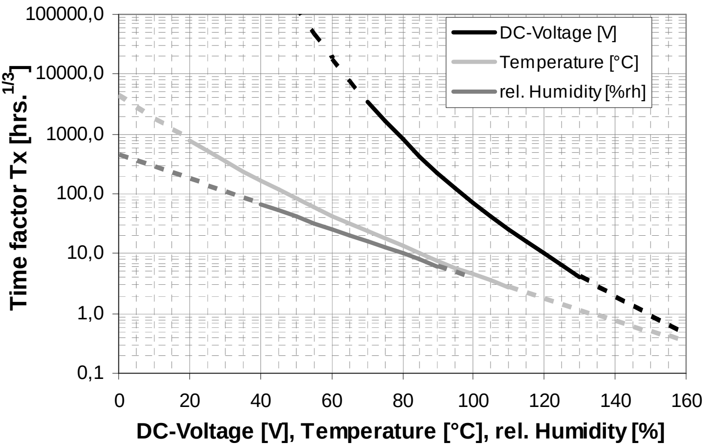

Figure 2: PICMA®-DC-lifetime calculation tool: the three time factors for the relevant DC-voltage, temperature and relative humidity condition have to be determined and multiplied to get the PICMA® DC-MTTF.

The tool can be used in a very simple way: just determine and multiply the time factors for the three application conditions DC-voltage, temperature and relative humidity to get the PICMA® DC-MTTF.

Especially the voltage has a very distinct influence on the lifetime as can be seen from the steepest slope of the graph in the logarithmic scale diagram in Fig. 2. The following example supports this observation: for the conditions 150 V, 80% relative humidity and 40°C a MTTF of 1 x 10 x 130 hours = 1,300 hours or 2 month can be calculated. If, however, the voltage of 150 V, which is above the rated nominal voltage of 120 V, is reduced to 100 V, then the MTTF is increased to 70 x 10 x 130 hours = 91,000 hours or more than 10 years!

The PICMA®-DC-lifetime calculation tool in Fig. 2 is very helpful in the challenging process to match the customer request for high displacement or rather voltage at specified driving and environmental conditions with the requirement to deliver a very reliable system.

2 AC-signal lifetime

Applications like intelligent tooling, jet dosing or very fast scanning mirrors use the ability of piezoelectric actuators to induce extremely high accelerations at large AC-signals. Under permanent large signal AC-operation, water based destruction is not the dominating degradation effect of the actuators, because usually self heating due to dielectric losses prevents the local humidity effect. Then the internal mechanical stresses and the related cracking in the passive actuator volume are more pronounced. AC-signal-reliability is therefore specified in cycles.

A test on 5 PICMA® 5x5x36 mm³ was run at 0…120 V unipolar sine wave, 15 MPa pre-stress with forced air cooling (high flow rate of 25 l/min) at 1.16 kHz. All samples suvived 10^{10} cycles under these conditions.

Further results of extreme tests with voltages above the rated nominal voltage comprise:

– 3 samples of PICMA® 7x7x36 mm³ at 0…150 V unipolar, rectangular signal with 80 µs slew rate and 50 µm displacement at 150°C to 5×10^9 cycles;
– 10 samples of PICMA® 2x3x18 mm³ at 0...200 V unipolar, triangular signal, 464 Hz, 30°C, silicone oil, no pre-stress, 1×10^9 cycles.

All tests were successful in a way that no actuator lost more than 10% of its initial displacement.

These results were possible because of two patented design features of the PICMA®-actuators [4]: 1) the segmentation of the stack by artificial cracks prevents stress accumulation and high energy axial cracking and 2) the bypassing of these artificial cracks by a special outer contact stripe avoids the decoupling of stack segments [3].

References:

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