Reliability enhancement through the use of fusing technique

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Abstract:
Fusing is sometimes used for Multilayer Ceramic Capacitors in order to improve their tolerance to cracking, particularly under external stress. The approach can be applied to stacked "chip" multilayer actuators, where a fuse effectively allows further operation after one or more individual failures. Statistical analysis indicates that the probability of failure is greatly reduced. Experimentation confirmed the enhanced lifetime and independence of the failures with limited impact on the operational envelope of the actuators.

Keywords: Piezoelectric; multilayer; actuator; fuse; reliability

Introduction

Multilayer piezoelectric actuators are massively parallel capacitive devices, containing thousands of layers. If a short circuit occurs at any point through a layer, the whole device will not be able to hold an electrical field, therefore it will not be usable. Being mostly capacitive, multilayer piezo actuators share some similarities with multilayer ceramic capacitors (MLCC). In MLCC, a major reliability concern is crack propagation due to stress induced by deformation of the PCB substrate [1]. On standard MLCC, a crack will reduce the dielectric strength of the device, leading to internal arcing and ultimately failure in short-circuit. More advanced designs address this issue through different methods: increase of the electrode margins in order to locate the crack in inactive material (Open Mode Design); floating electrodes, i.e. effectively putting several capacitors in series; compliant termination in order to reduce the induced stress [2]; fusing [3].

Unfortunately, many of the usual approaches used in MLCC are not applicable to piezo actuators, for which they would cause a drop in performance or an increase of the required voltage. The fusing technique has however been proposed for piezoelectric actuators in the past [4], but without any known commercial application.

Analysis of failure modes

Manufacturers usually consider two different operating conditions for PZT multilayer actuators: DC and AC.

In DC operation, the actuator is submitted to a constant electrical field, leading to electro-chemical degradation. The most likely failure mode in this case is a loss of dielectric insulation, leading to short-circuit. This phenomenon is accelerated by the presence of humidity or contaminants [5].

In AC operation, the electro-chemical effects are greatly reduced. On the other hand, the structure is submitted to mechanical fatigue. In these conditions, several publications reported crack propagation at the interface between ceramic and internal electrodes [6, 7]. When this problem is avoided, it is common to see the first failure appear at the electrical interconnect, typically at the interface between the ceramic and the interconnection system (see Fig. 1). This type of failure is usually not detected, so operation of the actuator continues in degraded conditions. The intermittent contact and sparking under high voltage leads to dynamic loading and further degradation, such that the usual way the failure is observed is through short-circuit.

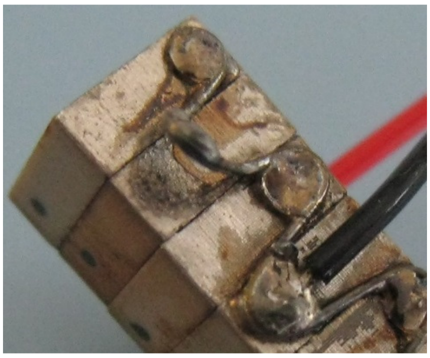

Fig. 1: *Loss of contact after 10^9 cycles at 150°C (contact lifted from surface to highlight the defect)*

In any case, the amplitude of the electrical field and temperature are major factors defining the reliability of piezoelectric devices [8, 9].

In addition to these failure modes, experience shows that external factors play a major role in the reliability of piezoelectric actuators. Uneven loading, dynamic stresses and contamination are some possible root causes. Although these causes are different from the ones observed on MLCC, in general for all those cases, the failure will manifest itself as an electrical short.

Furthermore, unlike capacitors, multilayer piezo elements are normally used over the full voltage range, so a failure will be visible as soon as the dielectric strength drops below the nominal rating.

Principle

The principle of fusing is to divide a piezoelectric actuator into independent sections, each connected to the power input through a fuse (Fig. 2).

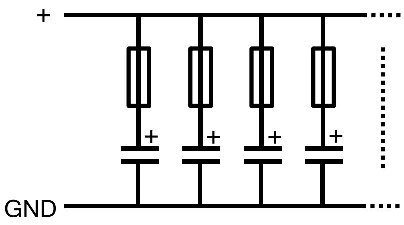

Fig. 2: *Principle of fusing of a stack actuator*

The fusing approach can easily be applied to “chip” (or “tile”) type stacked multilayer actuators.

Statistical analysis

From a statistical point of view, the effect of adding a fuse in series with each section of the multilayer stack is to transform a “series system”, where all components have to function to ensure proper function of the system, into a “m-out-of-n system”, where the system of n components only fail if m or more of them fail.

It is usual to consider [10] that the failure probability of a solid dielectric device follows a Weibull repartition [11]. The cumulated failure probability P_i over time t follows an equation of the type:

$$P_i(t) = 1 - e^{-\left(\frac{t}{\lambda_i}\right)^{k_i}} \tag{1}$$

The parameters k_i and λ_i can be described: k_i (Weibull modulus) represents the shape of the repartition, indicating the spread of the failures. λ_i is homogeneous with t and represents the scale of the repartition.

Assuming that all elements fail independently, the failure probability P_N of a stack of N elements follows Eq. (2), which can be combined with Eq. (1), leading Eq. (3).

$$P_N(t) = 1 - \prod_N \left(1 - P_i(t)\right) \tag{2}$$

$$P_N(t) = 1 - e^{-N\left(\frac{t}{\lambda_i}\right)^{k_i}} \tag{3}$$

In other words, the failure probability of an assembly of N elements follows a Weibull law of same modulus k_i and of scale $\lambda_i / N^{1/k_i}$.

If the actuator can tolerate a number m-1 of faulty elements before failing, then its cumulated failure rate can be expressed as a combination, as written in Eq. (4).

$$P_{m/N}(t) = 1 - \left(1 - P_i(t)\right)^{N-m+1} \cdot P_i(t)^{m-1} \cdot C_{m-1}^{N} \tag{4}$$

In that case, the distribution is no longer equivalent to a Weibull distribution. This can be illustrated by plotting P_i, P_N and $P_{m/N}$ for N=20 and m=2 and 3 as shown on Fig. 3. The simulation is performed with arbitrary values of k and λ_i, respectively 0,66 and 400000h.

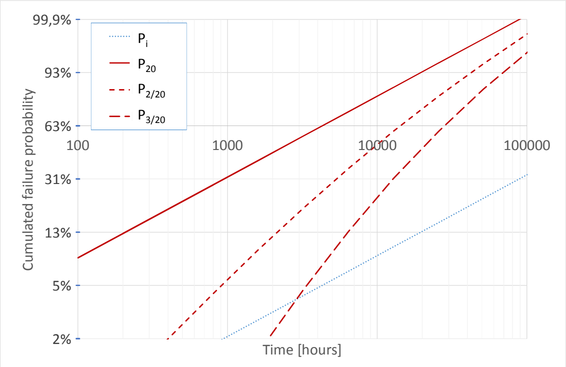

Fig. 3: *Weibull curves for an individual element and combinations*

As it can be seen, the statistical approach indicates that allowing one single failure multiplies the MTTF (P=50%) by a factor 4, while allowing 2 failures multiplies the MTTF by a factor over 8.

The gain is less for higher values of k_i. For example for k_i=2, the increase in MTTF is of respectively 50% and 100% for m=2 and 3.

Nevertheless, fusing increases significantly the lifetime of a piezoelectric stack. Particularly the early failures are avoided. In the first hours of operation, the stack actually becomes more reliable than an individual element.

Experiments

A series of stacks with fuses has been developed, manufactured and tested in Noliac’s laboratories. The stacks are composed of independent multilayer elements, each 2mm thick, with a common ground electrode and alternated positive electrodes. The positive electrodes are connected to a common positive electrode through a fuse. An example is shown on Fig. 4.

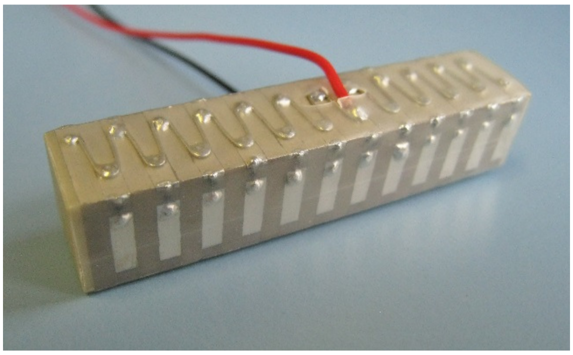

Fig. 4: *Stack with fuses*

For the purpose of the test, an amplified actuator totalling 200 individual elements was assembled and driven in harsh conditions (high electrical field, high frequency, generating high temperature and high mechanical load) in order to provoke failures. A picture of the actuator on its test bench is given in Fig. 5 and a more detailed description of the design of the actuator and its performance can be found in a previous publication [12].

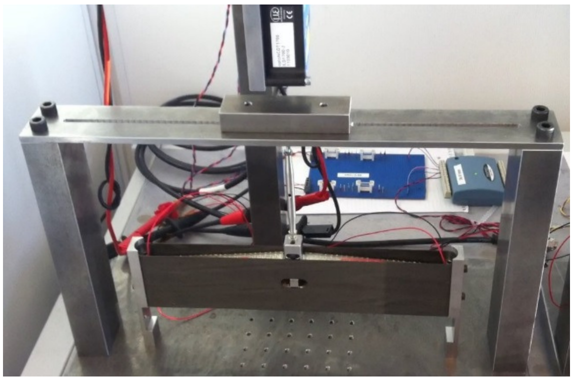

Fig. 5: *Amplified actuator with fuses*

The driving system was equipped with a current sensor, such that it could register the occurrence of an overcurrent, corresponding to the activation of a fuse. The remaining elements were allowed to continue. In parallel to that, using a laser displacement sensor, the system monitored the total peak-to-peak displacement of the actuator under load.
Measurements are presented on Fig. 6.

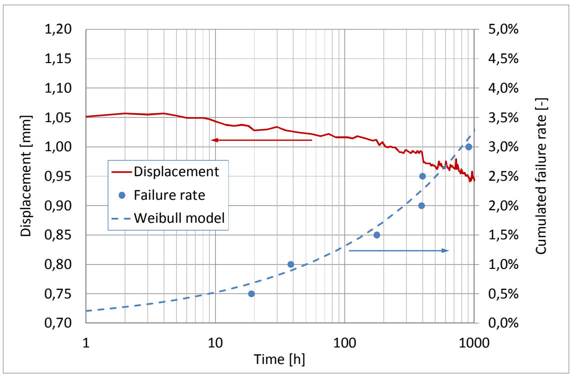

Fig. 6: *Experimental measurements of fuse stack*

Measurements indicate that, after a slight increase due to temperature stabilisation, displacement decreases following a normal ageing rate around 4% per decade. In addition to that, fuse events contribute to the decrease. Over the test duration of 1000 hours, 6 events were recorded, leading to a decrease of 3% of the displacement.
Experiments confirm that fusing effectively allows continued operation of the system even after successive failures. This requires however that the power supply can handle the current surge at the moment of the failure, before the fuse is activated. A small series resistor can help limit the surge.
The temporal repartition of the failures seems to follow a Weibull law, indicating that failures are independent, i.e. a first failure doesn't induce a second one in a neighbouring element. This was confirmed directly on the actuator where the spatial distribution of the failures was also found to be random.
Considering similar operating conditions, the MTTF of a system with fuses is superior to the classical parallel arrangement. This opens-up for the possibility to increase the stress levels (electrical, mechanical) and possibly achieve gains in terms of size, mass or cost. Alternatively, the designer can choose to increase the stress levels gradually as elements are fused-out in order to maintain a constant performance. The health of the stack can be monitored to trigger maintenance operations, avoiding an unexpected failure.

Limitations

The presence of a fuse can be a limitation for the operating envelope of a piezo stack, because each element cannot receive a current higher than the rating of the fuse. However in practice and with a rating of 1,5A, this limitation is usually far above other limitations of the system (current capability of the driver, self-heating, dynamic limit of the system…). Also, the temperature limitation of the fuses (>600°C) doesn't affect the operating range of the actuator (usually 150°C max).

The fusing technique protects effectively against the most common failure mode, short-circuit. It cannot ensure the mechanical integrity of the actuator, i.e. failure modes involving the loss of structural integrity. However this type of failure mode is less likely as it requires extremely high stress levels.

Conclusions

The fusing approach is applicable to multilayer piezoelectric stacks, particularly those made by stacking "chips". It can provide benefits for stacks of a certain size, for which the function is not affected by the loss of one or two elements.

Statistical analysis indicates that the MTTF of the system can be improved significantly, particularly if the failure rate of single elements follows a Weibull repartition with a low modulus (*k* coefficient).

The designer can also choose to "trade" this gain in reliability against performance by increasing the stress levels on the actuator.

Experimental results confirm that a fused stack can continue to operate even after multiple failures and that the failures are independent.

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