Full characterisation of PZT actuators in quasi-static, large signal operation at elevated temperature

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Abstract:
Optimising a piezo-based application over a wide temperature range can be challenging. Currently the main obstacle is that multilayer actuators are not sufficiently characterised in temperature. To some extent, this is due to the lack of practical standards in this field. In this paper, a method is proposed to characterise the operating envelope of actuators over temperature. The approach is based on a series of simple measurements: dimensions, free displacement, stiffness and electrical measurements. The method was applied on multilayer actuators made of two different materials: one hard-doped PZT ceramic (NCE46) and one soft-doped (NCE51). Experimental results are presented, highlighting how the specification of a product evolves with temperature and providing a powerful tool for designers to verify and optimise their application.

Keywords: Piezoelectric; multilayer; actuator; temperature

Introduction

Quasi-static multilayer piezoelectric actuators are finding more and more applications, for example in the field of aerospace [1], however their properties are still not fully characterised, in particular at high temperature.
The present work is performed within the project AeroPZT, specifically funded under the Clean Sky Joint Technology Initiative (EU FP7). The project partners, TWI Ltd. (UK), Cedrat Technologies (France), Noliac (Denmark) and Politecnico di Torino (Italy) are targeting the development of materials and processes for the application of piezoelectric materials in aero engine controls, which implies harsh environmental conditions, particularly elevated temperature.
Some literature is available on large signal stress-strain behaviour [2-5], however these studies are often incomplete and difficult for end-users to exploit. This is in part due to the lack of standards in the field.

Standards

Currently available international standards focus mostly on material properties and small-signal measurements. Standards addressing large signals such as [6] still focus on transducers, not actuators, so both the parameters and methods of measurement are difficult to transpose.
[7] introduces the effect of temperature as a single slope coefficient as illustrated on Fig. 1. The standard recognises the presence of a sort of thermal hysteresis which makes the characterisation more difficult.
[8] introduces a series of linear coefficients, as defined in equation (1). $T^{(n)}$ is defined as the nth-order temperature coefficient of the quantity q at the reference temperature θ_0.

$$T^{(n)}(q) = \frac{1}{q_0 n!}\left(\frac{\partial^n q}{\partial \theta^n}\right)_{\theta=\theta_0} \quad (1)$$

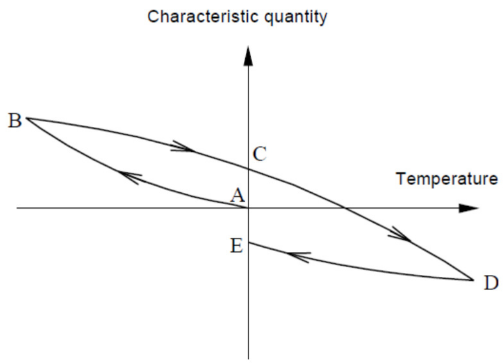

***Fig. 1:** Temperature dependency of a characteristic quantity according to [7]*

Although these two approaches can be relevant for transducers, they are not practical for quasi-static actuators. Furthermore, standards focus mostly on material properties, while these do not necessarily reflect the behaviour of multilayer actuators for several reasons:

- Multilayer actuators are operated under high electrical field, causing significant non-linearity, while material properties are usually measured under low field excitation.
- The end-user is often unaware of the internal construction of multilayer actuators, i.e. number and thickness of the active ceramic layers.

- Multilayer actuators can have a relatively complex design with inactive regions, electrodes and interconnection hardware, all of which can have an impact on performance.

Instead of these international standards, it has become customary within the industry to specify "macroscopic" parameters for multilayer actuators such as free displacement and blocking force instead of material properties.

When designing an application, the mechatronics engineer can use these macroscopic parameters in order to define the operating envelope of an actuator candidate. When the application requires operation over a wide temperature range, as it is the case for aerospace applications, the designer needs to know how these parameters vary with temperature to identify the worst case, which may be different from one application to another. The set of parameters that designers would need should include as a minimum: on the mechanical side, free displacement, stiffness or blocking force and thermal expansion; on the electrical side apparent capacitance and dielectric losses.

The present paper proposes a test protocol and methods for the measurement of these quantities. The method is applied to the full characterisation of two PZT materials (one soft-doped, NCE51, and one hard-doped, NCE46) up to 200°C using a pragmatic approach, for direct use by end-users. A simple set of methods and test results are presented.

Test methods

Approach

The measurement of the macroscopic properties of a multilayer actuator is a challenging task, particularly because it requires a change of the mechanical boundary conditions in order to measure both free displacement and stiffness or blocking force. The combination of displacements in the micron range and forces in the kilo-Newton range make the measurement challenging. Although specific setups exist [9], in the frame of this study it was decided to focus on performance in free conditions and estimate the evolution of stiffness through the measurement of resonance frequency.

For practical reasons, three independent measurements are proposed, however with the appropriate setup these could be combined:

- Displacement and thermal expansion
- Stiffness, leading to blocking force
- Electrical properties (capacitance and losses)

These measurements are presented in detail in the next paragraphs.

Displacement and thermal expansion

The measurement of free displacement is usually performed by monitoring the absolute length of an actuator using a differential interferometer. In the frame of this study, a Thermo-Mechanical Analysis (TMA) machine was used (fig. 2).

Fig. 2: *Sample in TMA equipment*

Ideally, free displacement should be measured for a sinusoidal excitation at full amplitude and a frequency representative of the operating conditions of the actuator. However this was not possible on the experimental setup since the sampling period was limited to 4s. Instead, the sample was submitted to a trapezoidal input signal from 0 to the maximum voltage, maintained for 2 minutes.

Thermal expansion is measured during the same test, so the effect of domain re-orientation (thermal hysteresis) is taken into account.

This method of measurement also allows the measurement of the creep effect. These results have already been presented and discussed in a previous publication [10].

Stiffness

The resonance frequency of a preloaded actuator is measured under small signal excitation using a spectrum analyser (Agilent 4194A). Relative stiffness is then estimated through Eq. (3).

$$\frac{K}{K_{(\theta=\theta_0)}} \cong \left(\frac{f_r}{f_{r(\theta=\theta_0)}}\right)^2 \qquad (3)$$

The measurement is performed on an actuator presenting a significant height compared to its width (fig 3) in order to make sure that a "thickness" resonance is measured, i.e. stiffness in the actuation direction is estimated.

Blocking force is calculated as the product of free displacement by stiffness.

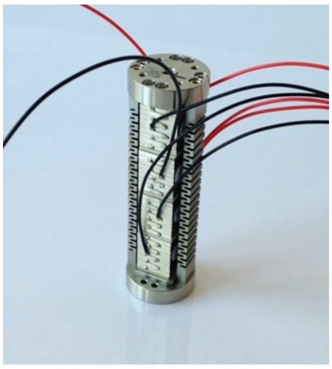

***Fig. 3:** Pre-stressed actuator (Picture courtesy of Cedrat Technologies)*

Electrical properties

Apparent capacitance and dielectric losses are measured under sinusoidal excitation at 1kHz for different voltage amplitudes. A Sawyer-Tower [11] circuit is used to monitor the charge absorbed by the sample while another acquisition channel is used to measure the applied voltage.
From these measurements, it is possible to calculate and plot the apparent capacitance C^*, which is related to the RMS reactive current drawn by the actuator (Eq. 4), and apparent losses tanδ^*, which are related to the energy dissipated within the actuator or the active current drawn by the actuator (Eq. 5).

$$C^* = \sqrt{2}.i_{RMS} \cdot \frac{1}{\pi.f.U_{pp}} \tag{4}$$

$$\tan\delta^* = P_{loss}.2.\sqrt{2}.\frac{1}{i_{RMS}.U_{pp}} \tag{5}$$

Test results

Free displacement and blocking force

As shown on Fig. 4, measurements indicate that free displacement increases up to 130 and 150°C respectively for NCE51 and NCE46. The additional displacement compared to room temperature is of respectively 25% and 15%. Above these temperatures, displacement levels and decreases.
Stiffness decreases slowly with temperature. As a result, blocking force (plotted on Fig. 5) increases less than free displacement, respectively +13% and +8% for the two tested materials.
For most applications, it is stroke at low temperature that will constitute a limiting factor, although for applications above 130°C, blocking force at high temperature can be a limitation.

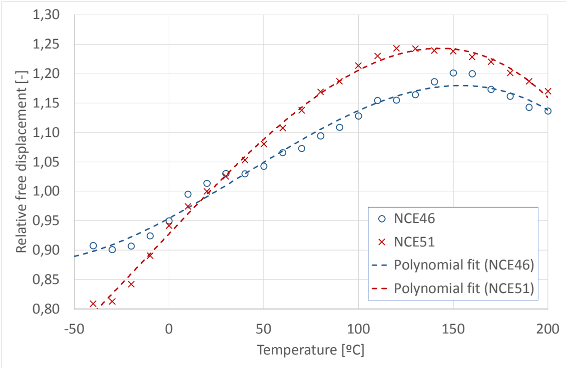

***Fig. 4:** Evolution of free displacement*

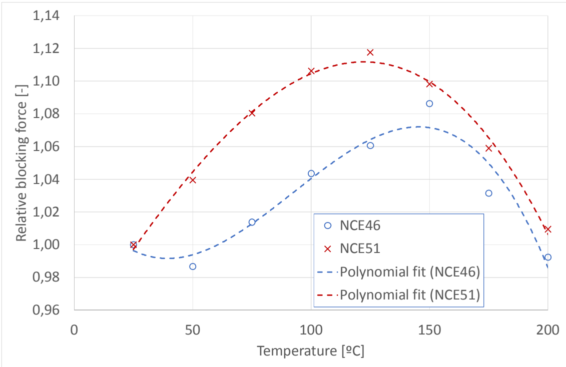

***Fig. 5:** Evolution of blocking force*

Capacitance and dielectric losses

Measurements indicate that apparent capacitance at maximum field increases almost linearly with temperature for both materials. The dependency is plotted on Fig. 6. At 200°C, the RMS current drawn by the actuators is 90% above the value calculated with the usual formula (Eq. 6) at room temperature.

$$i_{RMS} = \frac{1}{\sqrt{2}}.\pi.f.C.U_{pp} \tag{6}$$

As shown on Fig 7., dielectric losses under large signal excitation remain relatively stable (hard-doped) or decrease slightly (soft-doped) with temperature. However dissipated power increases in both cases due to the increase in apparent capacitance.
It can be mentioned that in particular the evolution of the dielectric loss factor can have a significant impact on the material choice at high temperature. A more detailed material comparison is presented in [12].
Also, the method allows a more refined analysis of the voltage-charge relationship. An analysis of the hysteresis behaviour of NCE51 is proposed in [13-14]. These results are not presented here as they do not concern the performance envelope.

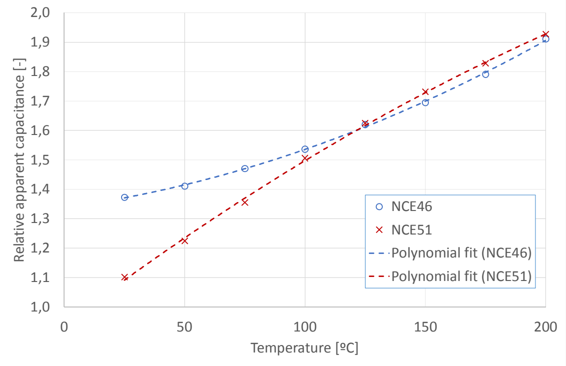

Fig. 6: *Evolution of capacitance*

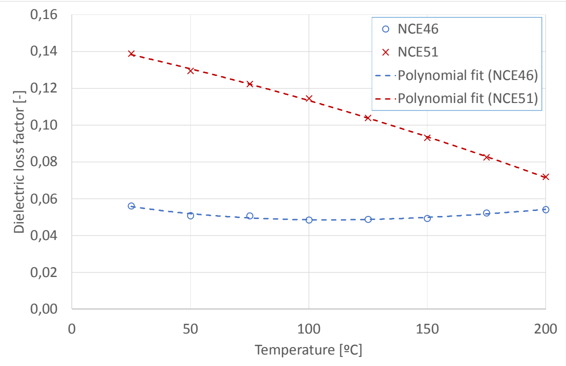

Fig. 7: *Evolution of dielectric losses*

Thermal expansion

Thermal expansion is difficult to characterise for PZT actuators because it is very low and depends on the poling state of the actuator. It is often observed and reported by manufacturers that there is a difference in the expansion of actuators between the first and subsequent heating cycles. It is also common to observe a non-recoverable strain at the first activation of an actuator after it has been cooled down.
The proposed interpretation is that upon heating, the piezoelectric actuator loses some amount of poling, which is not recovered when cooling again. In a practical application however, the actuator is constantly re-poled by an external field, so it makes sense to consider the "position at 0V" after a full activation of the sample. Or from another point of view: the non-recoverable displacement that is observed after the first activation cannot be used in the application, so it mustn't be included in the operating envelope of the actuator.
Results are presented on Fig. 8.

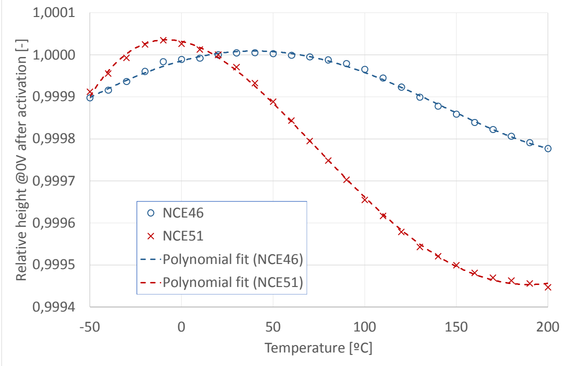

Fig. 8: *Thermal expansion*

Conclusions

Instead of focusing on material properties as described in the standards, this paper proposes a pragmatic approach focusing on the actual parameters of a typical specification. With the knowledge of how these parameters vary with temperature, the designer can more easily identify the limiting factors for a given application and therefore achieve a better optimisation of the design.

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