Temperature dependency of the hysteresis behaviour of PZT actuators using Preisach model

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Abstract:
The Preisach model is a powerful tool for modelling the hysteresis phenomenon on multilayer piezo actuators under large signal excitation. In this paper, measurements at different temperatures are presented, showing the effect on the density of the Preisach matrix. An interpretation is presented, aiming at defining a temperature-dependent phenomenological model of hysteresis for a better understanding of the non-linear effects in piezo actuators.

Keywords: Piezoelectric; multilayer; actuator; Preisach; model; temperature

Introduction

Quasi-static multilayer piezoelectric actuators are generally used in quasi-static applications under large signal excitation. In these conditions, the hysteresis effect is pronounced and can become a limitation, in particular for positioning applications.
To address this, two main approaches are possible: sensor-based or model-based. In the sensor-based approach, a sensor (displacement, force…) is used to close the loop and effectively linearize the piezoelectric effect. Although it provides excellent results, this approach is not always preferred or even possible, because of cost, size or performance. In the model-based approach, the behaviour of the actuator is characterised and this model is inverted to provide open-loop control of the actuator. This approach has become very popular with the availability of powerful real-time controllers. Several models have been proposed [1, 2], among others Ishlinskii hysteresis model [3], Maxwell resistive capacitor-based lumped-parameter model [4], variable time relay hysteresis model [5] and Preisach model [6].
The Preisach model [7, 8] is a phenomenological approach that can accurately describe any hysteresis behaviour. It is often the preferred approach for piezoelectric actuators and its large number of degrees of freedom makes it possible to adjust very precisely to experimental data.

The Preisach model

In a simple Preisach model, the hysteresis effect is decomposed into an infinity of individual elements called hysterons. These elements act as relays with an activation threshold α and a de-activation threshold β.
A geometrical interpretation of the hysteron plane greatly facilitates the understanding of the Preisach model in general. In this plane, a so-called Preisach triangle T_0 is defined, which represents the region of operation of the actuator, bordered by $\alpha_{max}, \alpha_{min}, \beta_{max}$ and β_{min}. Only the surface above the diagonal given by $\alpha = \beta$ has any physical meaning and therefore T_0 is an upper triangular surface. The elementary hysterons have a direct correlation to the half-plane in such a way that at any point in time T_0 is divided into two surfaces S^+ and S^- representing the (α, β) pairs for which the relay elements are active or inactive, respectively.
Thereby, for a monotonic increase of an input $u(t)$, the input-output plane shows an ascending hysteresis branch, while the T_0 half-plane 'fills up' from the bottom to the horizontal line defined by $\alpha = \{\alpha_1 \mid \alpha_1 \leq u(t)\}$. Similarly, a monotonic decrease in input will then determine the surface to 'empty', but this process is orthogonal to the one for increasing input. Therefore the 'filled' space T_0 will empty starting from the right towards the vertical line defined by $\beta = \{\beta_1 \mid \beta_1 \geq u(t)\}$. Thereby, a stochastic input signal with several extrema will be represented as a combination of 'filled' and 'emptied' areas on the triangle, delimited by a boundary staircase layer, denoted L. The problem then boils down to finding the area under the obtained staircase curve. This is illustrated in Fig. 1.

The standard equation for this type of model is:

$$x(t) = \iint_{\alpha \geq \beta} \mu(\alpha, \beta) \gamma_{\alpha\beta}[u, \gamma_0](t)\, d\beta\, d\alpha$$

Where x is the model output, μ represents a weighting matrix that mathematically particularizes the model to fit different hysteresis shapes and $\gamma_{\alpha\beta}$ represents the hysteron elements that can take values from the set $\{-1, 1\}$.
Terms on the diagonal ($\alpha = \beta$) dictate the general trend of the curve without hysteresis while the density

within the triangle ($\alpha > \beta$) corresponds to hysteresis effects.

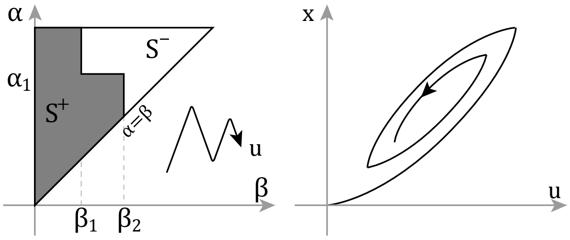

***Fig. 1:** Illustration of Preisach model*

In many applications, the actuator will be required to operate over a wide temperature range, which will affect the Preisach triangle. In such case, working with a constant Preisach model will induce errors in the open-loop control of the actuator.
In the present paper, a Preisach model is applied to the hysteresis relationship between dielectric charge and voltage (electric field). This set of parameters was chosen because it can be further processed in an electrostrictive behaviour model [9, 10]. However other parameter sets such as displacement versus voltage can be considered directly.

Experiment design

In our experiments, a multilayer piezoelectric element was submitted to a variable voltage while its dielectric charge was measured using a Sawyer-Tower circuit [11]. The element was placed in an oven (Fig. 2), allowing measurement between 25 and 200°C by steps of 25°C.

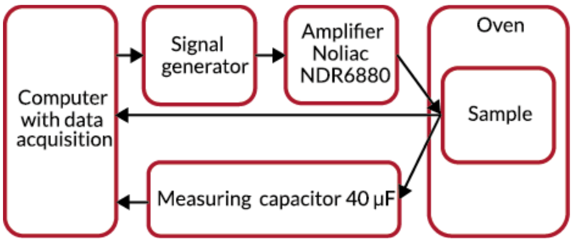

***Fig. 2:** Experiment setup*

Experimentation was performed using different input signals. In the end we selected a sinusoidal signal at 100Hz with a DC offset of 50V (corresponding to 1,5kV/mm, half the maximum peak-peak amplitude) and an amplitude decreasing by steps. Each wave is repeated to provide a statistical basis. The input signal is illustrated on Fig. 3. The first activation cycle at maximum voltage effectively “resets” the initial state of the Preisach matrix.

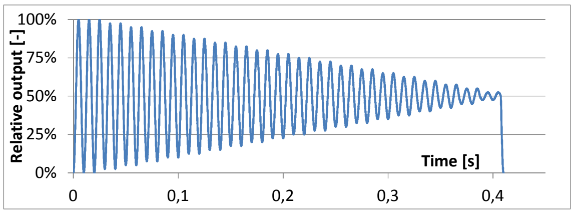

***Fig. 3:** Voltage input signal*

From these measurements we used two different methods to evaluate the Preisach matrices: analytical and recursive.
The analytical method is based on the following process:

- Identification of voltage reversal points. These define separation lines within the α - β plane, creating subdivisions of the plane. The selected input signal presents 40 reversal points, therefore a 39*39 discrete Preisach matrix can be built.
- Interpolation of charge values when the input signal crosses the separation lines.
- Starting from the smallest loop, charge differences can be calculated. The charge value in the Preisach matrix corresponds to the measured charge increase minus the charge increase measured over the same range in smaller loops (in other words the sum of the terms already identified in the same line for increasing voltage or in the same column for decreasing voltage).
- Charge density values (in C/V^2) are calculated by dividing each charge value by the area of the subdivision.

The recursive method relies on setting up a constrained least-squares minimization problem of the form:

$$\mu(\alpha,\beta) = \min_{\mu(\alpha,\beta)} \|\, \Gamma[u,\gamma_0](t) - x(t) \,\|^2,$$

Where μ represents the weight matrix, Γ is the Preisach operator, u is the current input, γ_0 represents the initial relay state vector while x is the measured system output.
Thereby, the square of the difference between modelled and measured outputs is iteratively minimized until the error lies below a set threshold. A weight matrix $\mu(\alpha,\beta)$ is obtained, which contains the hysteretic nonlinearities specific to the modelled system. This method is implemented in MATLAB.
The two methods give comparable results.

Results

The graphs on Figs. 4 to 6 are 3D representations of the identified Preisach matrix at respectively 25, 100 and 200°C (using the analytical method). The scaling is identical for comparison and the colour scale is deliberately finer in the lower values.

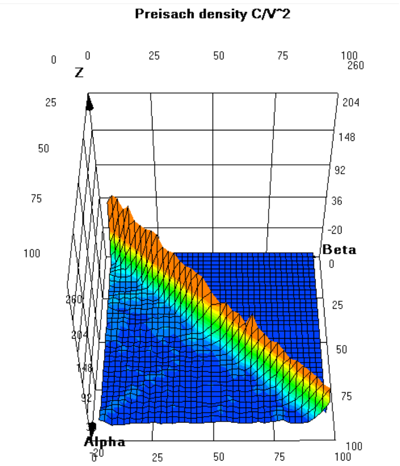

Fig. 4: Hysteresis matrix at 25°C

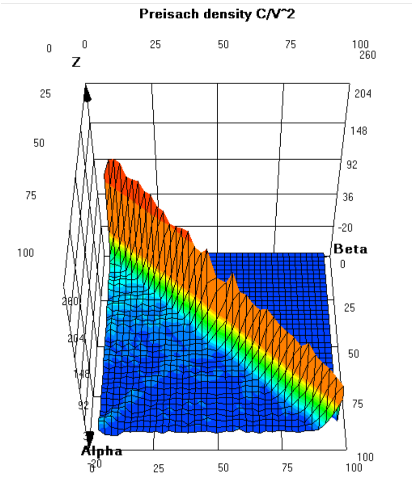

Fig. 5: Hysteresis matrix at 100°C

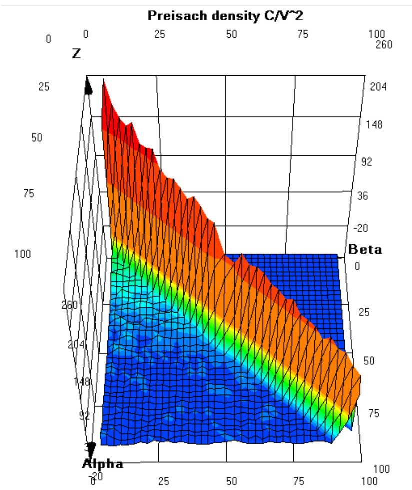

Fig. 6: Hysteresis matrix at 200°C

The density is characteristic of soft-doped PZT actuators, with most of the hysteresis present at low α values. These correspond to the "belly" of the hysteresis curve. In other words the P-E curves tend to get more elongated at high field as previously observed in [12].

Considering how the density evolves with temperature, two observations can be made:

- The density along the diagonal increases rapidly with temperature. This corresponds to the well-known increase of capacitance with temperature and is analysed in more details in [13].
- The density within the triangle increases only marginally with temperature. This indicates that, in proportion, hysteresis decreases at high temperature.

Analysis

The Preisach model can also be interpreted in terms of energy, where a given hysterion needs an activation energy corresponding to a voltage α to change state and returns to its original state if energy falls below a level corresponding to a voltage β. In a physical approach, the "switching" can correspond to domain re-orientation or domain wall movement; however the Preisach approach being phenomenological, the cause of the hysteresis is not relevant. Still, the effect of high temperature will be to facilitate the activation and de-activation of these "switches". In other words, hysterons shift towards the origin in the Preisach matrix.

This phenomenon has been studied for electromagnetics, for which it was proposed to use temperature-dependent scale factors for α and β [14]. However in the case of piezoelectric actuators, the relationship still needs to be formalised.

Nevertheless, it can be considered that both the Preisach density and the state line are affected by temperature. Using the same example as in Fig 1, if the element is subsequently submitted to a temperature change from θ_0 to θ_1, the state line will shift (Fig 7). Therefore the poling state of the element will change since a certain area (a) will switch to S^-.

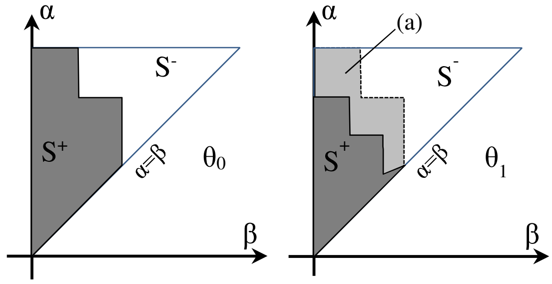

Fig. 7: Illustration of the impact of temperature on the state line

Also, it would make sense to extend the Preisach plane in the $\beta < 0$ range. This range would correspond to remanent poling. Obviously, the behaviour at θ_1 will be different from θ_0. But in addition, after return to θ_0 the initial state of the element will not be the same. Some remanent poling may be "lost" (S^-). However it can be easily recovered at the first activation. This phenomenon is often observed on soft-doped PZT, often in the fact that an actuator will provide a large free displacement at the first activation.

Extension of the model

Due to the adoption of a simple Preisach model, the proposed approach cannot include time-dependent phenomena such as frequency dependency and creep. This is contrary to observations. More advanced variants of the Preisach model have been proposed that include frequency dependency by adding $\frac{dx}{dt}$ as a parameter for the weighing function μ. Also the model can be extended to describe "viscous" effects such as creep by adding a random noise on the input signal [6].
However these implementations are complex and do not catch the full extent of poling dynamics as described for example by [15]. It is proposed to apply such behaviour models to individual hysterons, leading to time-dependency both in terms of creep and frequency dependency.

Control aspects

A temperature-dependent Preisach model is a very useful element of a reliable control circuit for a piezoelectric actuator. Several configurations can be considered:
In a sensor-less configuration (temperature unknown), this model is however of little interest. The controller will have to assume a certain temperature in order to estimate the state of the actuator.
If the temperature information is available, the controller would be capable of constantly adapting the Preisach matrix, thereby keeping an image of the state of the actuator, for example its free displacement.
It is also possible to sense the charge absorbed by the actuator. In such a case, the controller can compare the actual charge to the model and deduct the temperature of the actuator.
Finally, a combination (temperature + charge measurement) would allow the controller to deduct two variables such as position and external force. Combinations with displacement or force sensors are of course also possible, each additional parameter allowing the estimation of a variable or a consolidation of the estimates.

Conclusions

The target of this paper is to propose a temperature-dependent phenomenological model of hysteresis. Depending on the adopted sensor configuration, this model can be used within a control loop in order to determine the state of an actuator (free displacement), its temperature or the generated force.
Essentially, the target is to reach a better characterisation of the non-linearity of piezoelectric actuators and a better understanding of non-linear effects, leading to improved control capabilities.
Measurements give an indication of how the Preisach density evolves with temperature, with a general scaling as well as a shift of the hysterons towards the origin.
The adoption of a simple Preisach model implies rate-independent behaviour, however it would be possible to extend it to a rate-dependent model.

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