Hysteresis cancellation using self-sensing actuation in a multistack actuator

Gael SEBALD and Jinhao QIU
Institute of Fluid Science, TOHOKU University, Katahira 2-1-1, Aoba-Ku, Sendai, 980-8577, Japan
TEL: x81-22-217-5249 FAX: x81-22-217-5249 e-mail: gaels.ebald@insa-lyon.fr

Daniel GUYOMAR
Laboratoire de Genie Electrique et de Ferroelectricite, INSA de Lyon, 8 rue de la physique, 69621 Villeurbanne cedex, France
TEL: x33-4-7243-8158 FAX: x33-4-7243-8875 e-mail: daniel.guyomar@insa-lyon.fr

Tohru SUKIGARA
TEL: x81-28-677-7313 FAX: x81-28-677-7310 e-mail: tohru.sukigara@n.t.rd.honda.co.jp
(Received 30, September 2005 Accepted 31, January 2006)

For high voltages, large hystereses are usually observed in multi-stack actuators. To cancel it, either hysteresis modeling or closed loop system can be used. To overcome the limitations of both techniques, we present here an application of the correlation of the strain and polarization to build a self-sensing hysteresis cancellation. The advantage of this technique is to remain efficient for various voltage profiles and doesn’t require additional sensor.

Keywords: Hysteresis, Creep, Ferroelectric, Multistack actuator

I. INTRODUCTION
This work addresses the problem of eliminating the hysteresis of a piezoelectric actuator. Reaching high electric fields (around coercive fields), the induced displacement exhibits large hysteresis. It was shown in previous works ¹ that the hysteresis of the polarization versus electric field and the hysteresis of the strain versus electric field have the same origin (motion of domain walls, pinning depinning processes...). Moreover it was shown that it was possible to write strain as a non-hysteretic function of the polarization.

In this work, it is considered a multistack actuator used in diesel fuel injection device for which the precision of displacement is a key-issue to control precisely the injected fuel quantity. This latter performance is the prerequisite for reducing gaz-emissions and reduce the fuel consumption of engines.

This paper presents experimental results showing that strain versus polarization exhibit no-hysteresis, or highly reduced hysteresis.

In a second time, it will be shown an example of closed-loop response of the piezoelectric actuator using a simple proportionnal-integral controller.
Nomenclature:

- $P =$ Polarization (C/m$^2$)
- $S =$ Strain (m/m)
- $E =$ Electric field (V/m)
- $T =$ Mechanical stress (Pa)
- $Q =$ Electric charge (C)
- $V =$ Voltage (V)
- $U =$ Displacement (m)
- $\theta =$ Temperature ($^\circ$C)

II. NONLINEAR CHARACTERIZATION

The characteristics of the piezostack under test are given in Table 1.

Table 1. Characteristics of the piezoelectric stack under test.

<table>
<thead>
<tr>
<th>Type</th>
<th>TOKIN (A1010D16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>10x10x20mm$^3$</td>
</tr>
<tr>
<td>Capacitance</td>
<td>5.4\mu F</td>
</tr>
<tr>
<td>Curie Temperature</td>
<td>180$^\circ$C</td>
</tr>
<tr>
<td>Displacement @ 100V</td>
<td>12.3\mu m</td>
</tr>
<tr>
<td>Force @ 100V</td>
<td>3500N</td>
</tr>
<tr>
<td>Maximum Voltage</td>
<td>150V</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>4.4x10$^{10}$N/m$^2$</td>
</tr>
</tbody>
</table>

The piezoelectric stack actuator is characterized in no-load case. Both displacement and electric current are recorded for different voltages as shown in Fig.1. It can be seen the perfect correlation between displacement and electric charge.

From the model described in ref 1, it was shown that whatever the electric field or stress levels:

$$S = \frac{\alpha}{2} P^2$$

Converting $S$ and $P$ into displacement $U$ and electric charge $Q$ gives simply:

$$U = \beta Q^2$$

When applying a positive voltage on a poled ceramic, we can decompose strain and polarization as a static value and a varying value.

Hence, we write $U$ and $Q$ as following.

$$U = U_r + \overline{U}$$

$$Q = Q_r + \overline{Q}$$

Consequently,

$$U_r + \overline{U} = \beta Q_r^2 + 2\beta Q_r \overline{Q} + \beta \overline{Q}^2$$

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$$U = U_r + \overline{U}$$

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Consequently,

$$U_r + \overline{U} = \beta Q_r^2 + 2\beta Q_r \overline{Q} + \beta \overline{Q}^2$$

Fig.1. Correlation between electric charge and displacement.
Taking into account only the varying quantities when applying the voltage,
\[ \bar{U} = 2\beta \bar{Q} + \beta \bar{Q}^2 \]  (5)

It is thus shown that the displacement is a quadratic function of the electric charge. Considering the experimental results, it is obvious that the quadratic component remains very small in that range of voltages. As a consequence, we calculate by linear regression the coefficient \( \gamma \) defined as:
\[ \gamma = 2\beta \bar{Q} \]  (6)

Further experiments are necessary to get the variation of this coefficient as a function of higher frequencies, stress and temperature.

As a consequence, it is shown that the displacement as a function of the polarization is a non-hysteretic function, in other words, it is possible to deduce the displacement by measuring the polarization.

In this case (room temperature, no stress), the coefficient is found to be:
\[ \gamma = 2.072 \times 10^{-3} \text{m/C} \]  (7)

We then finally compare the deduced displacement using this relationship with direct measurement as shown in Fig 2.

![Graph showing measured and deduced displacement](image)

Fig.2. Comparison between direct measured displacement and deduced displacement from the polarization.

The nonlinear effects are as following:
- Non static displacement when holding the voltage to its maximum value (creep)
- Delay of the decrease of the displacement compared to the voltage (hysteresis)
- Non-zero displacement for a zero voltage state (creep)

These phenomena are seen on both the deduced and measured displacement, thus showing that all the nonlinear behaviors are already included in the polarization.

III. SELF-SENSING DISPLACEMENT CONTROL

The good accuracy of determination of the displacement from the polarization has been shown. It should be noticed that the spectrum of the signal depicted in Fig.2 exhibit a flat frequency spectrum until a frequency of 200Hz (non-zero length pulse). Consequently, the correlation shown in Fig. 1 remains exact for every frequency below.

Starting from this deduced displacement, a displacement control system is designed in order to remove hysteresis and creep from the displacement.

The structure (Fig. 3) implemented using Simulink and Dspace include signal generation, and integrators resetting triggered on the signal in order to avoid static flow problems.

![Control system diagram](image)

Fig.3. Experimental setup.

The open-loop and closed-loop results are shown in Fig. 4 for different voltage amplitudes. It can be seen the complete cancellation of the hysteresis and also a linearization of the maximum amplitude of the displacement as a function of the voltage.
This corresponds to the following equations:

\[ P = f_{\text{hyst}}(E, T, \theta) \]  
\[ S = g_{\text{hyst}}(E, T, \theta) \]

where \( f_{\text{hyst}} \) and \( g_{\text{hyst}} \) are hysteretic functions of electric field \( E \), mechanical stress \( T \) and temperature \( \theta \).

The further experiments should check if the following equation is a reasonable assumption to deduce the displacement:

\[ S = h_{\text{hyst}}(E, T, \theta) \]
\[ S = h_{\text{non-hyst}}(P) \]

If the strain can be written as a function of the polarization only whatever the stress level and temperature, then a displacement control is possible without modeling or adding any displacement sensor.

V. CONCLUSION

We report in this paper a self-sensing technique to control the displacement of a piezoelectric stack actuator driven in its nonlinear regime. It has been shown that both creep and hysteresis are well cancelled whatever the frequency or the voltage amplitude, leading to an efficient and low-cost technique to precisely control the field induced displacement.

REFERENCES


Presented at 6th Japan France Seminar on Intelligent Materials and Structures (October 29-31, 2005)