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Piezoelectric stack actuator parameter extraction with hysteresis compensation

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Keywords

<<Piezo actuators>>, <<Non-standard electrical machine>>, <<Servo-drive>>, <<Regulation>>, <<Measurement>>.

Abstract

The Piezoelectric Actuator Drive (PAD) is a type of rotary motor that transforms the linear motion of piezoelectric stack actuators into a precise rotational motion. The very high stiffness of the actuators employed make this type of motor suited for open-loop control, but the inherent hysteresis exhibited by piezoelectric ceramics causes losses.

Therefore, this paper presents a straightforward method to measure piezoelectric stack actuator equivalent parameters that includes nonlinearities. By folding the nonlinearities into a newly-defined coupling coefficient, the inherent hysteretic behavior of piezoelectric stack actuators can be greatly reduced through precompensation. Experimental results show a fitting accuracy of 98.8 % between the model and measurements and a peak absolute error reduction by a factor of 10 compared to the manufacturer-provided parameter. This method improves both the static and dynamic performance of the Piezoelectric Actuator Drive (PAD) while still permitting open-loop control.

Introduction

Piezoelectric stack actuators are widely used in applications ranging from rotary motors [1] and micropumps [2] to structural vibration damping [3]. Their advantage lies in very high stiffness and larger deflections (100 μm range), while reducing applied voltage levels compared to their bulk ceramic counterparts.

Often, the stack datasheets only provide information limited to free displacement and blocking force, maximum applied voltage range, travel range and piezoelectric material constants such as d coefficients,

s coefficients and coupling (k) coefficient. This gives no indication about the highly hysteretic behavior present between the mechanical and electrical parameters that the stacks exhibit [4]. This behavior limits usage of piezoelectric stacks in applications where precise dynamic operation is required without positional feedback possibilities.

A type of rotary motor that converts periodic elongation of piezoelectric stack actuators into precise rotational motion of a rotor is the Piezoelectric Actuator Drive (PAD). The operating principle is illustrated in Figure 1. The micro-mechanical toothing present in the ring and shaft enables high positioning accuracy and output torque. This type of toothing combined with the inherent large stiffness of the piezoelectric stack actuators makes the PAD appropriate for voltage-driven open-loop control [5]. Nonetheless, the hysteresis effects inherently present in the stack actuators are detrimental to efficient open-loop operation.

Therefore the paper presents a simple method for measurement and identification of the nonlinear piezoelectric one-dimensional bulk equivalent parameters in a piezoelectric stack actuator along its actuation dimension. The piezoelectric parameters' extraction is based on the quasi-static measurement method, due to its simplicity and comparable accuracy to other methods [6]. The accuracy of the achieved nonlinearity compensation is verified against measurements.

Piezoelectric stack actuator and model

Figure 2 shows the typical structure of a piezoelectric stack actuator. The stack can be considered to comprise hundreds of individual piezoelectric layers separated by thin electrodes. These layers are in a parallel configuration electrically, enabling a reduced voltage level to produce the necessary electric field. Mechanically, they are in a series configuration and therefore the elongation of each layer adds up to produce larger displacement than a single element would.

A widely-used model for piezoelectric structures is described in the IEEE Standard on Piezoelectricity [7], but this model does not inherently take nonlinear behavior into consideration. Other models exist that take nonlinearities into consideration [8], [9], but these separate the linear piezoelectric and hysteretic components. Moreover, these models require intimate knowledge of all the physical properties of the stacked actuator such as number and thickness of the layers, active area and number of inactive layers. This information is usually not provided by manufacturers.

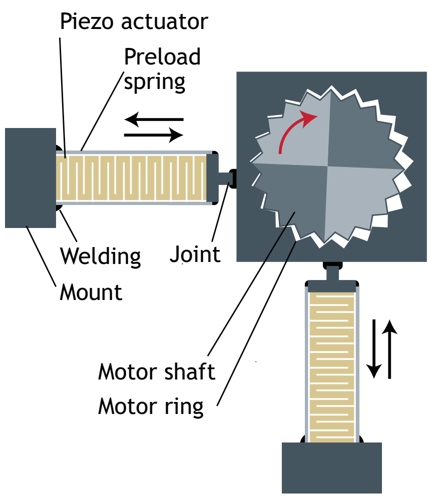

Fig. 1: Piezo Actuator Drive (PAD) principle [1]

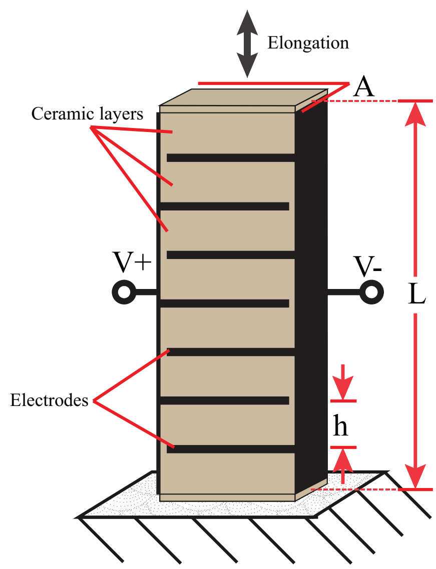

Fig. 2: Diagram of a piezoelectric stack actuator. A, L and h represent the stack's surface area, length and layer height, respectively

Equations (1) and (2) represent the second alternative form of the constitutive equations given by the IEEE Standard [7], particularized for direction 3, which is the dimension of actuation for a stack actuator, assuming no stress in other directions. Table I shows the quantities, their names and their units of measurement.

$$S_3 = d_{33} \cdot E_3 + s_{33}^{E} \cdot T_3 \tag{1}$$

$$D_3 = d_{33} \cdot T_3 + \epsilon_{33}^{T} \cdot E_3 \tag{2}$$

Although the constitutive equations presented in (1) and (2) are widely recognized [7], they can be rewritten to couple easily measurable quantities by substituting S, D, E and T with their definition in (3) – (6).

$$S = \frac{\Delta x}{L} \tag{3}$$

$$D = \frac{q}{A} \tag{4}$$

$$E = \frac{V}{h} \tag{5}$$

$$T = \frac{F}{A} \tag{6}$$

Table II presents the redefinition of the quantities presented in the constitutive equations. Based on these and (3) – (6) and considering that strain is measured in conditions of no stress and that dielectric displacement (charge) is measured with no applied electrical field, the constitutive piezoelectric equations can be simplified to (7) – (8).

$$\Delta x = n \cdot d_{33} \cdot V \quad |_{T_3=0} \tag{7}$$

$$Q = n \cdot d_{33} \cdot F \quad |_{E_3=0} \tag{8}$$

Where $n = L/h$ is the number of piezoelectric layers inside the stack and $Q = n \cdot q$ denotes the total stack charge. While the physical quantities of surface area and stack length can be easily measured, the number

Table I: List of constitutive equation symbols and their units

Symbol	Name	SI Unit
S_3	Strain component	
D_3	Electric displacement component	C/m^2
E_3	Electric field component	V/m
T_3	Stress component	N/m^2
d_{33}	Piezoelectric constant	m/V or C/N
s_{33}	Elastic comliance constant	m^2/N
ϵ_{33}	Permittivity constant	F/m

Table II: Redefined constitutive equation symbols and their units

Symbol	Name	SI Unit
Δx	Displacement	m
q	Layer charge	C
V	Applied voltage	V
F	Applied force	N
A	Stack active surface area	m^2
L	Stack active height	m
h	Stack layer height	m

of active piezoelectric layers inside the stacks is not usually disclosed. The only way to find the internal layer structure is by destructive dissection, which renders the stack useless. The method proposed in this paper circumvents this problem by folding the actuator physical properties into the coupling factor d_{33}. Therefore, a new piezoelectric coefficient is defined in (9).

$$D_{33} = n \cdot d_{33} \tag{9}$$

This coefficient is now directly measurable and better represents the electrical-mechanical or mechanical-electrical coupling inside a given piezoelectric stack. The disadvantage of this redefinition is that unlike d_{33}, which is material-specific, D_{33} is now specific to material and structural composition. Moreover, access to the stack is required before it is embedded in an application. In a small-scale usage scenario, this drawback is negligible when only a few stacks need to be characterized.

Measurement setup

In order to measure the piezoelectric equivalent parameters, the piezoelectric stack under test is connected to a power amplifier with a reference signal input. The amplifier is fed by a signal generator with a 0.1 Hz sine wave reference. The output of the amplifier is a sinusoidal voltage with a 110 V_{DC} bias and 90 V amplitude. This produces a quasi-sinusoidal displacement ranging between 3 μm and 35 μm, measured by an LVDT probe connected to a gage amplifier. All data is acquired through data acquisition card to a PC and post-processed using MATLAB. The mock-up of the measurement setup can be seen

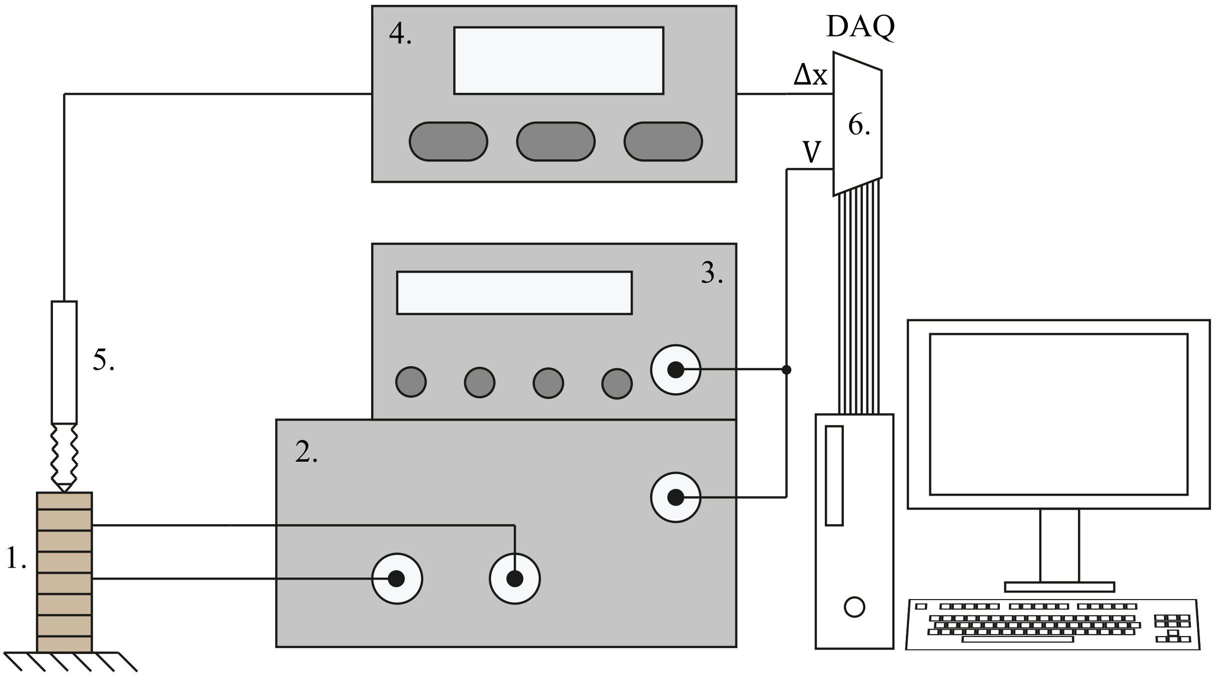

Fig. 3: Mock-up of the measurement setup

Table III: Devices in the measurement setup

Item	Name	Model
1	Piezoelectric stack under test	-
2	Power amplifier	Noliac NDR6880
3	Signal generator	Agilent 33250A
4	Gauge amplifier	TESA Tesatronic TT60
5	LVDT probe	TESA S32080861
6	Data acquisition board	Measurement Computing PCI-DAS6014

in Figure 3, while Table III provides the names and manufacturer models of the devices used.

Hysteresis compensation and experimental results

Figure 4 illustrates a typical piezoelectric stack hysteretic behavior between applied voltage and measured free displacement. This means that the $\Delta x - V$ characteristic is nonlinear and open loop positioning repeatability cannot be guaranteed without nonlinearity compensation.

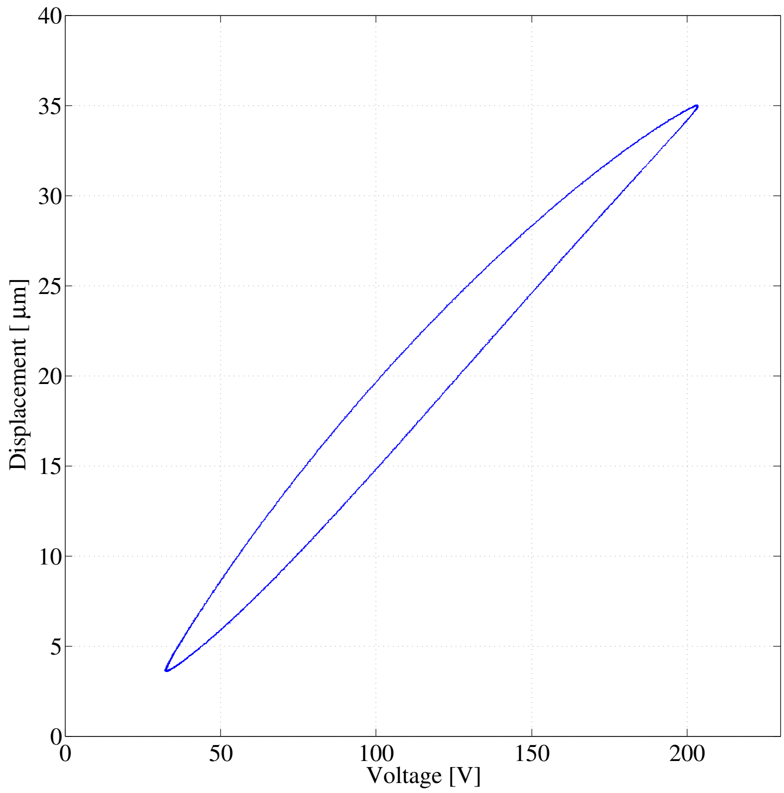

Fig. 4: Stack hysteretic behavior between applied voltage and measured displacement

The proposed solution for this compensation consists in encapsulation of the nonlinearities into the defined D_{33} coefficient. The quasi-static measurement method is used by applying a sinusoidal voltage input and measuring the output displacement. Piecewise discretization and differentiation of the obtained hysteresis curve yields a vector of slopes representing D_{33} in a nonlinear form, as shown in (10). Linear interpolation of the obtained vector gives a piecewise linear approximation of the hysteretic behavior.

$$D_{33} = \frac{\mathrm{d}(\Delta x)}{\mathrm{d}V} \tag{10}$$

Figure 5 shows good matching between the measured and compensated displacement values, as opposed to the uncompensated response which shows large deviation from measured values. The detail view shows slight mismatching at the waveform minima, attributed to presence of a small friction in the displacement measurement probe. The effect of the compensation on the hysteresis loop can be seen in Figure 6. The compensated behavior is approximately linear compared to the uncompensated one.
The relative error graph, calculated as the ratio between the absolute error and instantaneous measured value, is shown in Figure 7. While the uncompensated response shows a peak relative error of 21.3 %, this peak is reduced through compensation to 9.1 %. Moreover, the nonlinear model fits the measurements in proportion of 98.9% on average. As shown in Figure 8, the maximum absolute error sees a reduction by a factor of 10, from 3.6 μm to 0.36 μm.

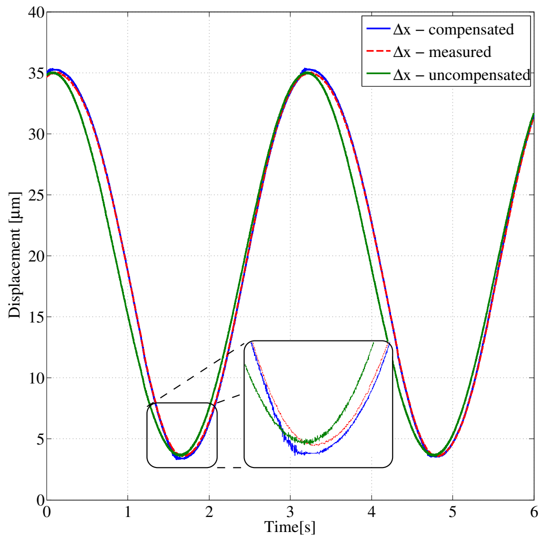

Fig. 5: Dynamic behavior of compensated, uncompensated and measured displacements

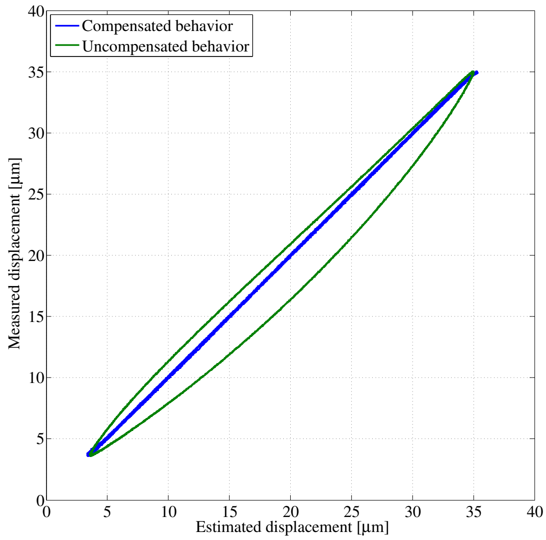

Fig. 6: Hysteresis compensation

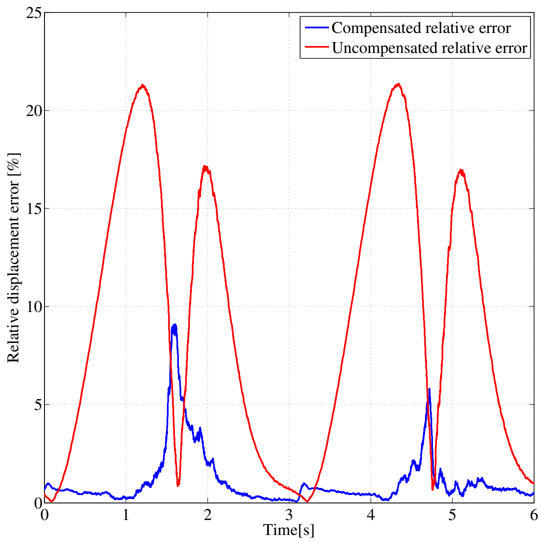

Fig. 7: Relative error comparison

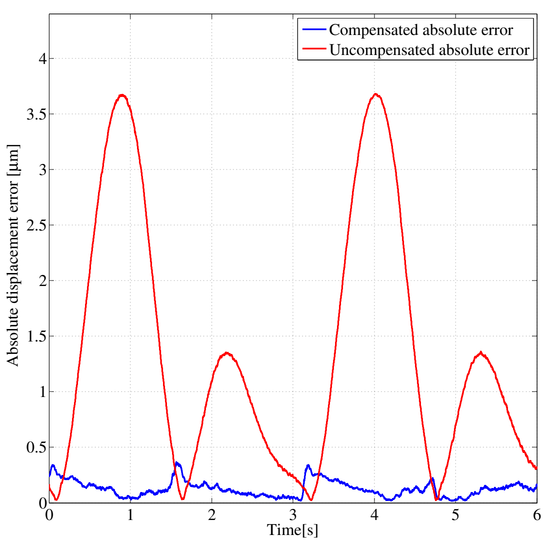

Fig. 8: Absolute error comparison

Conclusion

This paper presents a straightforward method for piezoelectric equivalent parameters measurement for a multilayer piezoelectric stack. The effective piezoelectric constant is redefined to include both nonlinearities and stack structural information. The nature of this result enables real-time hysteresis compensation after initial characterization. By inherently acting as a look-up table, this approach is both fast and requires little to no processing power and is therefore embedded processor friendly. Therefore, the proposed method is ideal for use in conjunction with the PAD, yielding an improved static and dynamic behavior of the motor during open-loop operation.

The results obtained show a good fit with experimental measurements and a large improvement over the parameters provided on the datasheet. The maximum absolute error is reduced through nonlinear compensation by a factor of 10 compared to the uncompensated case. Therefore, the dynamic performance of the piezoelectric stack is greatly increased and performance in piezoelectric applications where feedback is not available is improved.

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