Multibody System Simulation of Hysteresis Effect by Micro Textile-Reinforced Compliant Mechanisms with Piezo-electric Actuators

D. Mărgineanu, E.-C. Lovasz, and N. Modler

Abstract The function integration in textile reinforced compliant structures requires integrated actuation besides mobility and sensors. Especially in micro-mechanisms, the piezo-actors are very useful due to their compactness, high forces and electrical control. However, the actuation hysteresis may be a problem in designing such structures aiming specific movements. Some procedures for multibody simulation taking into account the piezo-electric hysteresis effect are presented in this paper.

Keywords Piezo-actuators • Hysteresis • Micro-mechanisms • Multi body system simulation

1 Introduction

Compliant mechanisms (CM) consist of elements with higher rigidity and compliant elements, with higher elasticity according to their functional purpose (Howell 2001). Also, classic rotational joints in hybrid structures or elastic joints in monolithic structures may be used. CM can fulfill desired functions with minimum number of elements and joints. Textile reinforced structures are especially suited for building CM, as they may have variable rigidity.

By integrating sensors and actuators in the composite structure, active textile reinforced compliant mechanisms (A-TCM) are obtained, further reducing the product complexity and costs. Piezo-electric actuators, with their compactness and high actuating forces, have certain advantages by using them in ATCM, as allowing direct electrical control (Elspass and Flemming 1998; Hufenbach et al. 2006b).

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The A-CM transmission function and the trajectories, depending both on elements geometry and on the loads, and are strongly influenced by the elastic and inertial properties of the materials used (Hufenbach et al. 2006a; Modler 2008; Midha et al. 2000), thus the desired accurate motion can be obtained only after tests, re-design and adjustments, implying high costs and consuming precious time (Modler et al. 2009).

The increasing number of compliant mechanisms industrial applications led to researches on design approaches for developing compliant mechanisms for required motion and force-deflection characteristics (Hufenbach and Gude 2002; Hufenbach et al. 2007). The Pseudo-Rigid-Body Model (PRBM) allows compliant mechanisms to be modeled and analyzed as rigid-body mechanisms and significantly reduces the analysis complexity.

Parallel mechanisms, a bicycle derailleur and parallel-motion bicycle brakes are presented in (Mattson et al. 2004). Compliance comparison between multi-spring model and finite-element analysis for multidimensional acceleration sensors are done in (Gao and Zhang 2010). Analysis and design of an under-actuated compliant variable stroke mechanism by employing PRBM is studied in (Tanık and Söylemez 2010).

A-CM with various functioning principles are also extending their application range. On-chip sensing of bi-stable mechanism state using the piezo-resistive properties of poly-silicon (Anderson et al. 2006), is made by detection of changes in position by changes in resistance across the mechanism.

A piezoelectric driven compliant-based micro-gripper mechanism for manipulation of micro objects, shown by (Nashrul et al. 2009) address the nonlinearities associated with the application of conventional rigid hinges.

By A-TCM, analytical calculations can only give rough approaches because the calculus models include partial differential equations systems, the initial and limit condition depending on the parts geometry, yet to be determined. Or, the calculus model is simplified thoroughly, thus the results are not accurate enough.

A simulation procedure should be carried out between the analytic dimensioning and the FEM modeling step.

This simulation should observe some basic requirements:

- all the initial simulation parameters should be defined according to the dimensions, materials and loads of the simulated system;
- the simulation results should estimate with an accepted limit error the behavior of the real system;
- the simulation parameters should be easily changed, also according to optimization procedures;

The simulation procedure should be fast, reliable and repeatable.

2 Modeling A-TCM for Simulation

Piezoelectric energy converters provide high forces, response times of a few milliseconds and a positioning accuracy of a few nanometers, but only at more than one to two thousand Volt. In Eq. (1), by inverse piezoelectric effect used for actuation, the mechanical strain S depends on mechanical load T and electric field strength E. If the tensor of mechanical parameters on the surface of a crystal is considered, the linear equation in vector form is, in Voigt's notation is:

$$\{S\} = \left[s^E\right] \cdot \{T\} + [d^t] \cdot \{E\} \tag{1}$$

where:

$[d^t]$ is the matrix for the reverse piezoelectric effect,
ε^T – permitivity Matrix for T = 0,
s^E – compliance matrix for E = 0.

So, an accurate simulation model for an A-TCM should ensure both an adequate compliance and an actuation depending both on the input signal and on the effort in the actuator.

As the stroke of a piezo-actuator is very small, bending actuators with two layers: one passive and one active (see Fig. 1) are used. In this paper, an actuator with carbon fiber composite (CFC) as passive base layer and micro fiber composite (MFC) as actuator layer is considered.

The compliant RBS simulation model proposed for the actuator is composed of some simulation cells linked base-to-end to one another.

In order to better describe the piezoelectric actuation which adds the actuating and elastic deformations, the model presented in Fig. 2 is introduced. The 3 DOF simulation cell is a 6-bar mechanism with 4 revolute joints and 2 prismatic joints.

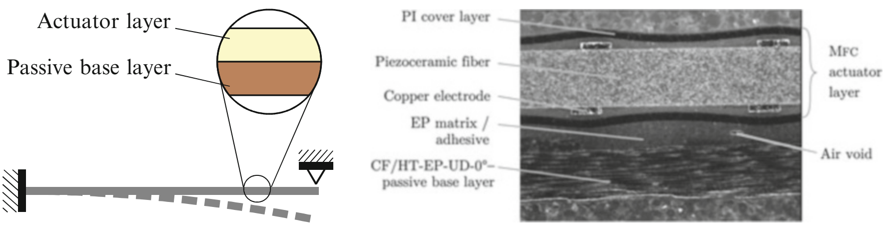
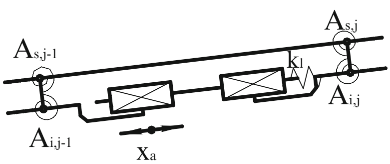


Fig. 1 The active element layers

Fig. 2 Active element cell kinematical model with 3 DOF and 2 prismatic joints simulating the piezo-actuating effect



The active equivalent layer $A_{i,j}A_{i,j+1}$ is composed of 3 elements, linked by 2 prismatic joints. The actuation x_a in the active joint obtained by applying the voltage U will be:

$$x_a = \Lambda \cdot L_j \tag{2}$$

with the actuating deformation Λ given in Eq. (3) with respect to input voltage U:

$$\Lambda = d_{33} \cdot E = d_{33} \cdot \frac{U}{t_{IDE}} \tag{3}$$

with d_{33}- piezoelectric constant, and t_{IDE} – distance between electrodes.

The elastic deformation of the actuator piezo-ceramic layer is simulated by the helical compression spring with the rigidity k_l:

$$k_l = E_2 \cdot \frac{b_2 \cdot h_a}{L_j} \tag{4}$$

The active layer is joined to the interface element in the rotational joints $A_{i,j}$ and $A_{i,j+1}$. In order to simulate the bending compliance of the two layer actuator, torsion springs are inserted in the upper and lower $A_{s,i;j}$ rotational joints. As two springs are connected on each side of the interface to ensure equal angles with the current an the previous layer element, the rigidity of these springs is calculated as the double of the equivalent bending rigidity of the CFK and MFC layers:

$$k_{\theta s,i} = \frac{M_j}{\theta_{s,i;j}} = E_{1,2} \cdot \frac{I_{z_{1,2}}}{L_j}, \tag{5}$$

where

– $I_{z1,2}$ – the area moment of inertia of each of the two layers cross-section:

$$I_{z_{1,2}} = \frac{b_{1,2} \cdot {h_{1,2}}^3}{12}, \tag{6}$$

with $b_{1,2}$, the width and $h_{1,2}$, the thickness of the active and passive layers.

The modeling and simulation was performed using the Solidworks software with Motion Analysis. In Fig. 3, the model of the bending piezo-actuator built according to this procedure is shown.

The actuation x_a of the linear motor in the simulation cell as a time-dependent function to be used in simulations will be determined in the following, taking into consideration the hysteresis effect.

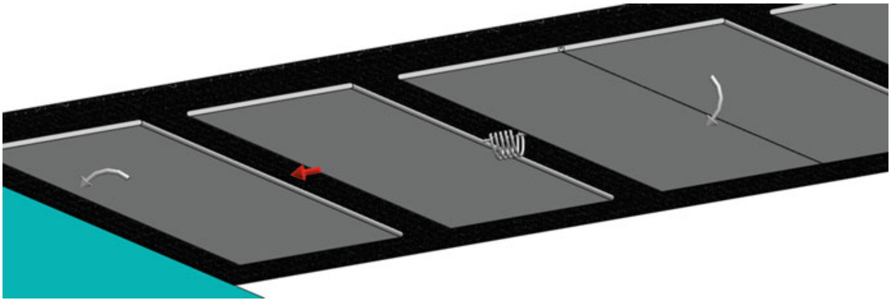


Fig. 3 The 3d model of the simulation cell for the bending piezo-actuator

3 Continuous Preisach Model Simulation of Piezo-electric Hysteresis

In order to simulate the hysteresis of the piezo-actuator, a procedure to convert the input voltage signal in the displacement output with hysteresis is needed.

The continuous Preisach model for hysteresis describes the output function as:

$$y(t) = \Gamma \cdot x(t) = \iint_{\beta \geq \alpha} \mu(\alpha, \beta)\ R_{\alpha,\beta}\ x(t)\ d\alpha\ d\beta. \tag{7}$$

where y(t) is the output signal, x(t) is the input signal, μ(α,β) is the density function and R(α,β) is the hysteron (see Figs. 4 and 5).

For equal density continuous Preisach operator, the integral reduces to the aria of a triangle in the Preisach plane, i.e. a 2nd degree input/output dependency.

So, for a continuous variation of the input voltage from the minimum to the maximum value and back, the output deformation may be approximated with Eq. (8), as the voltage rises from U_{min} to U_{max} (see also Fig. 5),

$$x_1(U) = x_{min} + (x_{max} - x_{min}) \cdot \left(\frac{U - U_{min}}{U_{max} - U_{min}}\right)^{r_1} \tag{8}$$

and, for the voltage falling from U_{max} to U_{min}, with Eq. (9)

$$x_2(U) = x_{max} - (x_{max} - x_{min}) \cdot \left(\frac{U_{max} - U}{U_{max} - U_{min}}\right)^{r_2} \tag{9}$$

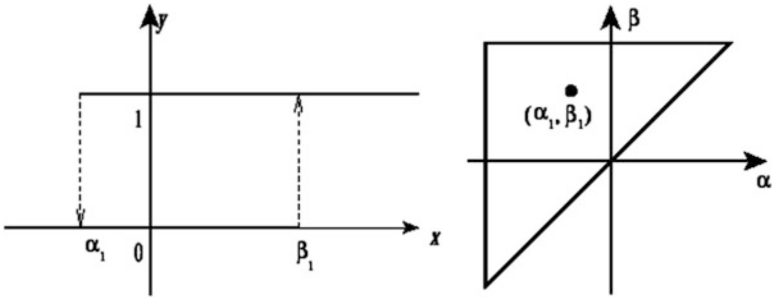


Fig. 4 Non-ideal relay and its corresponding point on the Preisach plane

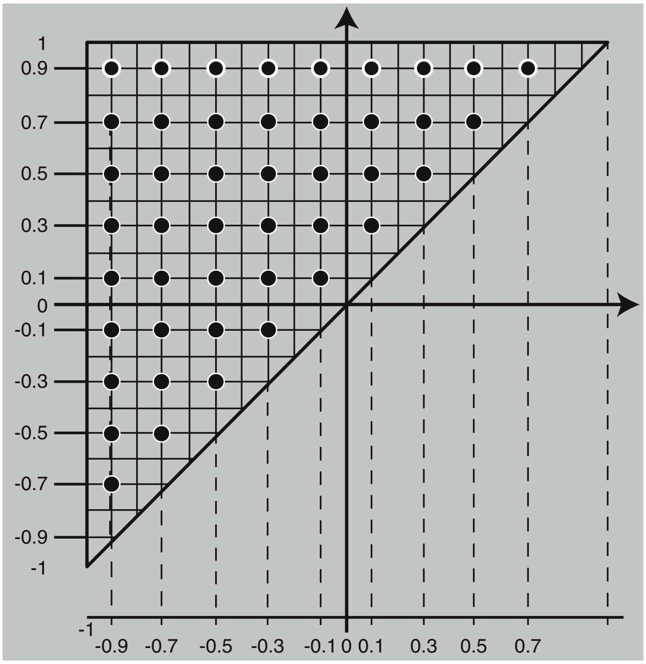


Fig. 5 Geometrical interpretation of Preisach nonlinearity with standard discrete support

The exponents $r_{1,2}$, calculated with Eq. (10), are used to adjust the approximation curves to fit better to the experimental ones by passing through the third precision point ($U_{m1,2}$; $x_{m1,2}$):

$$r_1 = \frac{\ln \frac{x_{m1} - x_{min}}{x_{max} - x_{min}}}{\ln \frac{U_{m1} - U_{min}}{U_{max} - U_{min}}};\ r_2 = \frac{\ln \frac{x_{max} - x_{m2}}{x_{max} - x_{min}}}{\ln \frac{U_{max} - U_{m2}}{U_{max} - U_{min}}} \quad (10)$$

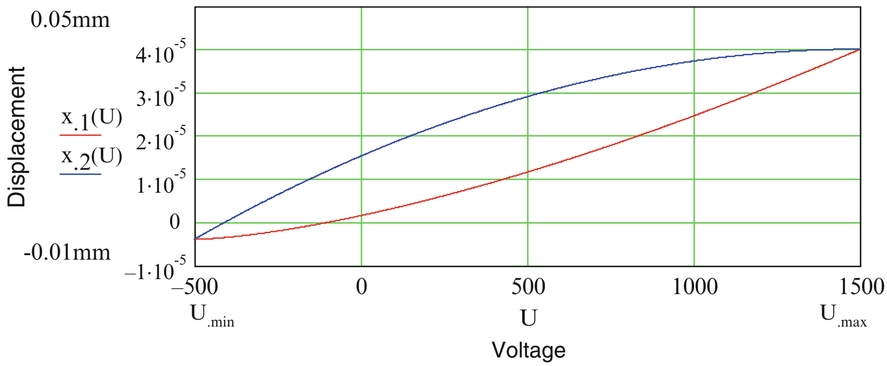


Fig. 6 The hysteresis cycle approximated with the continuous Preisach model

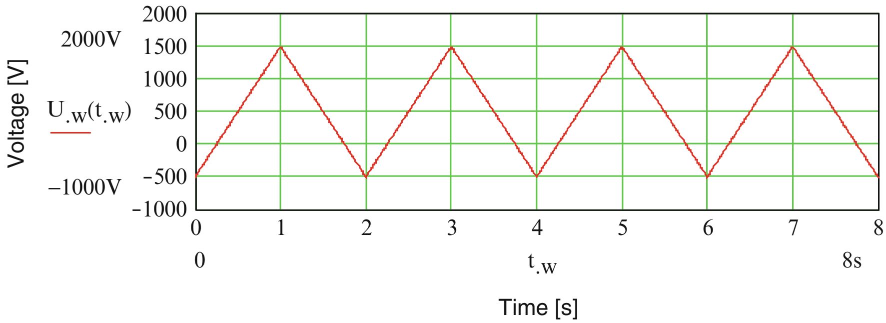


Fig. 7 Saw tooth input signal

For a simulating cell 29 mm long, $U_{max} = 1{,}500$ V max voltage, $d_{33} = 4.6\ 10^2$ pC/N piezoelectric constant and $t_{IDE} = 0.5$ mm distance between electrodes, the total actuator stroke calculated with Eqs. (2) and (3) is 40 μm. The negative displacement at $U_{min} = -500$ V is – 4 μm, i.e. 10 % of the maximal displacement. Approximation curves with $r_1 = 1.5$ and $r_2 = 2$ calculated for $U_m = 500$ V, $x_{m1} = 12$ μm and $x_{m2} = 28$ μm are presented in Fig. 6.

For a saw tooth voltage input signal in Eq. (11) and Fig. 7, the output piezoelectric displacement cycle of the active layer with hysteresis effect with Eqs. (11) and (12) will be as in Fig. 8.

$$U(t) = U_{med} + U_{am\,p} \cdot \left(\frac{4t}{T} - 1 - 2\mathrm{int}\left(\frac{2t}{T}\right)\right) \cdot (-1)^{\mathrm{int}\left(\frac{2t}{T}\right)} \tag{11}$$

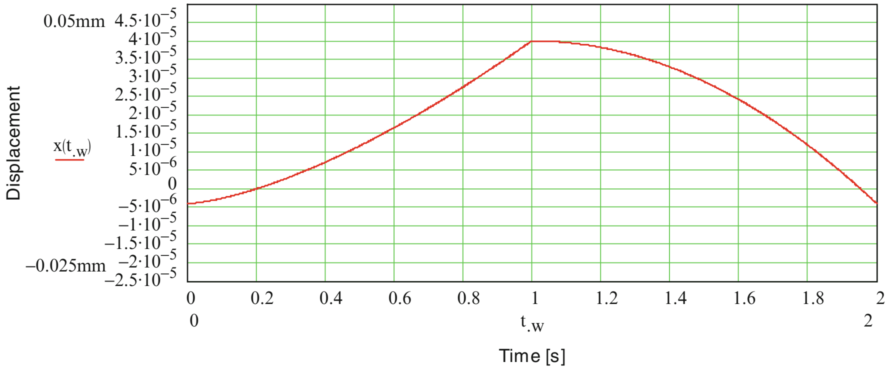


Fig. 8 Approximated piezo-electric displacement output signal for saw tooth input signal

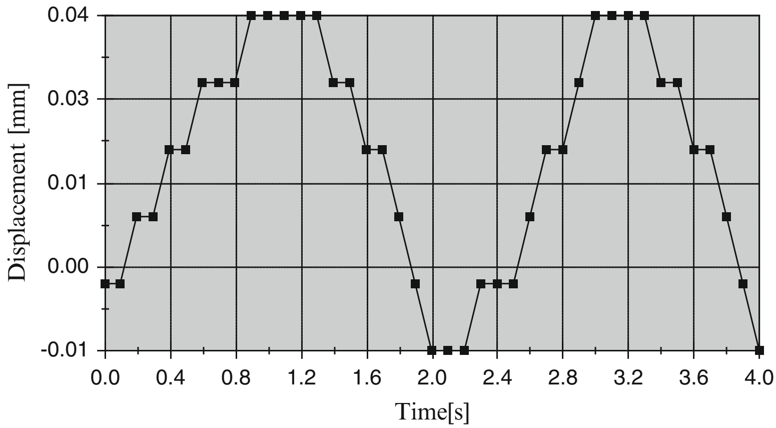


Fig. 9 Displacement versus time points for approximated piezo-electric displacement output signal for saw tooth input signal

For simulations, a table of displacements versus time is generated to be used by controlling the linear motor in the simulation cell by interpolation, as in Fig. 9. The command window for the linear motor of the simulating cell is presented in Fig. 10.

The simulation model for the bending actuator built with the proposed simulation cells is presented in Fig. 11, and the simulation results are shown in Fig. 12.

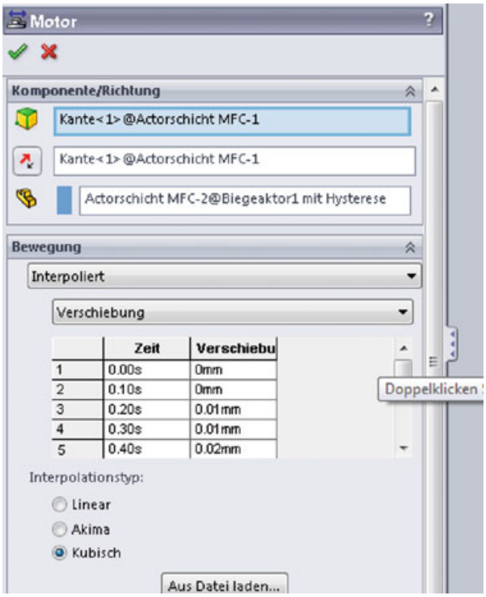


Fig. 10 The command window for the linear motor of the simulating cell

Fig. 11 Bending actuator simulation model

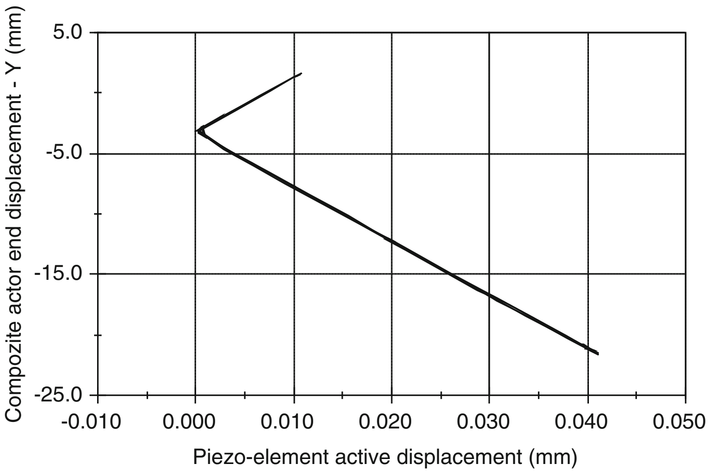


Fig. 12 Simulation results for the bending actuator with hysteresis

The simulation is more accurate as more precision points on the action table are used. Because the active deformation of linear piezo actuators is very small, the resolution of the simulation software is important. Resolutions of 0.01 mm may result in insufficient accuracy of the model.

4 Discrete Preisach Model Simulation of Piezo-electric Hysteresis

The continuous model may be used for simulating A-TCM behavior in complete cycles, from minimum to maximum input voltage. As to simulate mechanisms with intermediate positions controlled by piezo actuators, where the hysteresis gives more complicated output displacements, a simulation procedure using a discrete Preisach model is proposed (see Fig. 13).

The discrete model is composed of a group of non ideal relays and adjustable gains parallel connected.

Modeling the piezo-electric deformation Output signal with hysteresis is done by adjusting the switch on and the switch off points of the Relays 1–6 and the Gains 1–6.

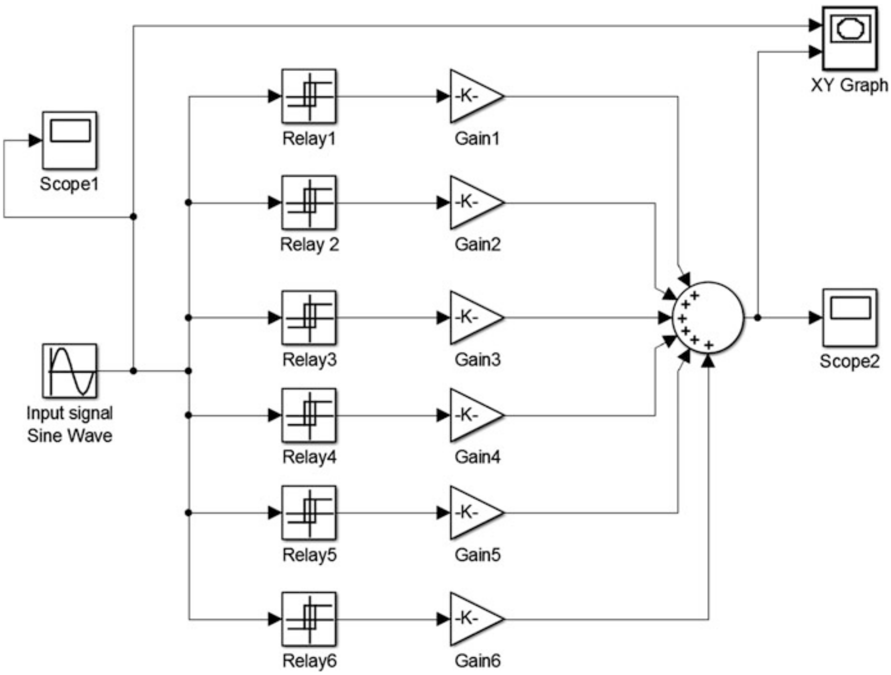


Fig. 13 Matlab Simulink model for discrete Preisach piezo-electric hysteresis simulation

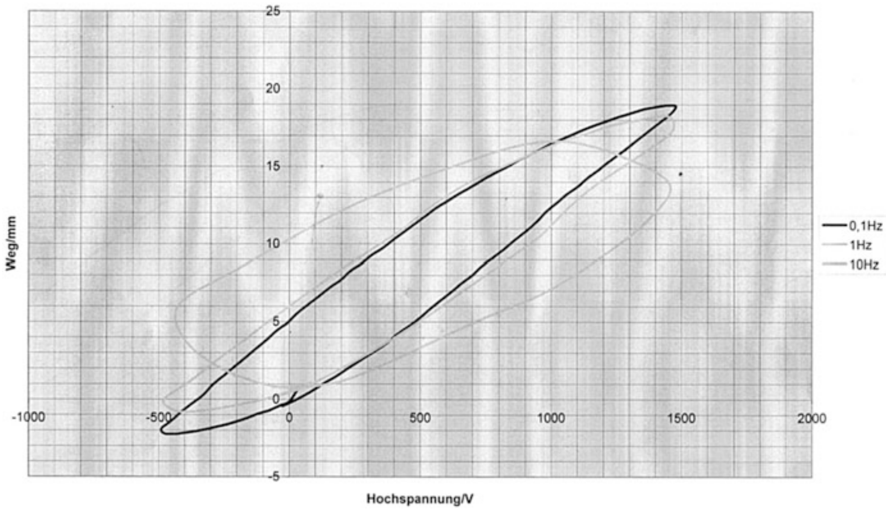


Fig. 14 Experimentally determined piezo-electric hysteresis

There strategy for determining the switch on/switch off points and gains is to have equal gains Δy for the n relays.

$$\Delta y = \frac{y_{max} - y_{min}}{n} \tag{12}$$

The switch on/switch off points are determined from the experimental hysteresis curve (Fig. 14) as the abscissa of the intersection points between the curve and horizontal lines at $y_i = i\ \Delta y$. The left point abscissa is the switch off point and the right point abscissa is switch on point of the relay.

This procedure insures a good approximation for the steep parts of the hysteresis curve, but lower accuracy for zones with lower slope.

In order to optimize the approximation without increasing the number of switches, a procedure with variable gains according to the local slope of the curve is to be developed.

The hysteresis cycle approximated with the discrete Preisach model is presented in Fig. 15.

The approximated input/output dependency is used to control the linear motor in the simulation cell. This model may be used in case of an input signal variable within the input range, with ups and downs not necessarily to limits.

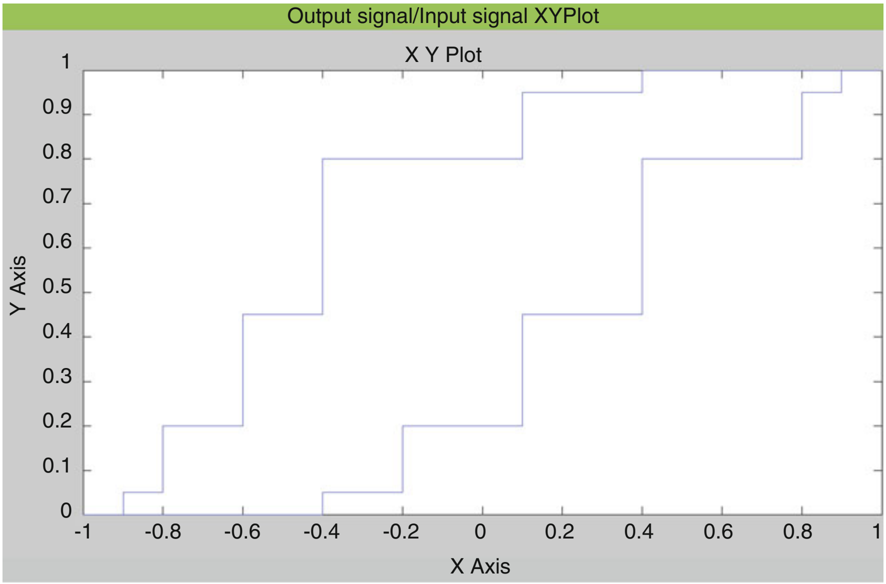


Fig. 15 X-Y plot of an input/output dependency generated with the discrete Preisach model for simulation of piezo-electric hysteresis

5 Conclusions

The procedure for simulation of the piezo-actuators with hysteresis presented in this paper allows the designer to approach the behavior of A-TCM in the mechanism synthesis stage.

The hysteresis effect may be important in function or path generating mechanisms and is not to be neglected.

The continuous Preisach model for hysteresis is useful for stable input voltage signals oscillating stably between minimal and maximal values.

For variable input signals, the discrete Preisach model may provide a simulation tool able to predict the mechanism's behavior in the synthesis stage of the development procedure.

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