Experimental model inverse-based hysteresis compensation on a piezoelectric actuator

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   - Prandtl-Ishlinskii model.
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   - Multiplicative inverse structure of Preisach model.
   - Inverse Prandtl-Ishlinskii model.
   - Inverse Modified Prandtl-Ishlinskii model.
5. Experimental results.
6. Conclusion.

Introduction

- Piezoelectric actuators are used at micro-/nanoscale (see Binning & Rohrer 1986).
- Hysteresis nonlinearity degrades piezoactuators performance (see Abramovitch 2007).
- Preisach model of hysteresis (see Preisach 1935) is the most used approach.
- Several alternatives to Preisach model (see Bobbio 1993).
- Comparison of Preisach model with its alternative models :
  - classical Prandtl-Ishlinskii model.
  - Modified Prandtl-Ishlinskii model (see Kuhnen 2001).

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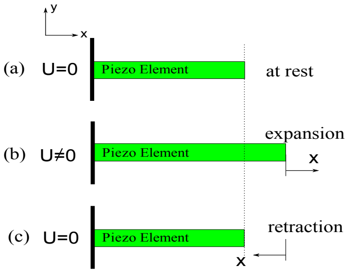
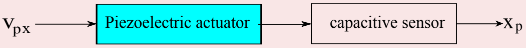


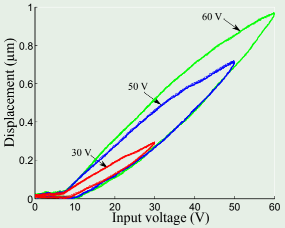
Operating principle of piezoelectric actuators.

Hysteresis nonlinearity in PE actuators

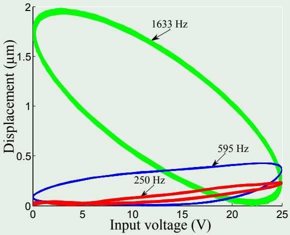


Piezoelectric actuator in open-loop.

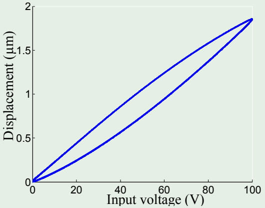
x_p is the piezoactuator displacement.
v_{px} is the control input voltage.



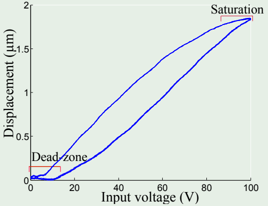
Static hysteresis.



Dynamic or rate-dependent hysteresis.



Symmetric hysteresis.

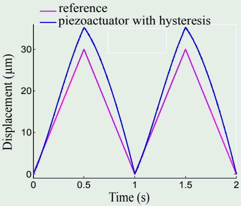


Asymmetric hysteresis.

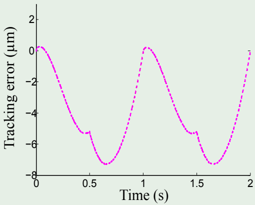
Context : Accurate micropositioning with piezoelectric actuators.

Problem statement :

- Hysteresis generates positioning errors.



Triangle waveform tracking.

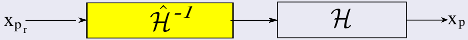


Tracking error.

- Choose a precise and an easily implementable compensation approach.

Introduction

Aims of work



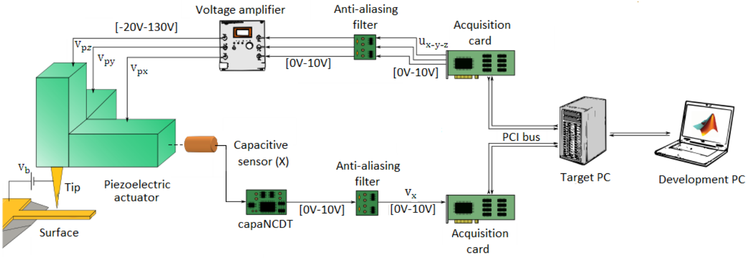
Open-loop compensation of hysteresis.

$\mathscr{H}$ is the hysteresis.

$\hat{\mathscr{H}}^{-1}$ is the inverse hysteresis model ↗ Mathematical inverse. ↘ Multiplicative inverse structure.

- Modeling hysteresis for compensation.
  - ☐ Classical Preisach model.
  - ☐ Classical Prandtl-Ishlinskii (PI) model
  - ☐ Modified Prandtl-Ishlinskii (MPI) model
- Experimental comparison :
  - ☐ Multiplicative inverse structure of Preisach model,
  - ☐ Inverse PI model, and Inverse MPI model.

System description and experimental setup



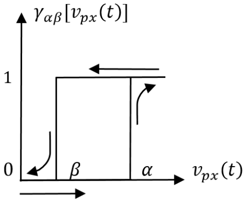
Experimental setup of micro-/nanopositioning platform, GIPSA-lab

The horizontal direction (X)

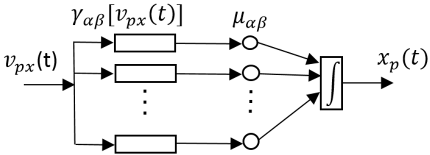
- Piezoelectric actuator Tritor T-402-00.
- Capacitive sensor.
- Development PC.

Hysteresis modeling

Classical Preisach model



Preisach operator.



Block diagram of the Preisach model.

$$x_p(t) = H(v_{px}(t)) = \iint_{\alpha \geq \beta} \mu(\alpha, \beta)\gamma[v_{px}(t)]\mathrm{d}\alpha\mathrm{d}\beta \qquad (1)$$

$\mu(\alpha, \beta)$ is the Preisach weighting function,
$\gamma[v_{px}(t)]$ is the Preisach operator having an output of $+1$ or 0,
α, β are the upper and lower switching values of the input $v_{px}(t)$.

Hysteresis modeling

Classical Preisach model

$$\dot{v}_{px}(t) > 0$$
$$x_p(t) = \sum_{k=1}^{N} [X_p(\alpha_k, \beta_{k-1}) - X_p(\alpha_k, \beta_k)] + X_p(v_{px}(t), \beta_N) \quad (2)$$

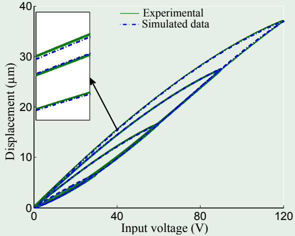
$$\dot{v}_{px}(t) < 0$$
$$x_p(t) = \sum_{k=1}^{N-1} [X_p(\alpha_k, \beta_{k-1}) - X_p(\alpha_k, \beta_k)] + X_p(\alpha_N, \beta_{N-1}) - X_p(\alpha_N, v_{px}(t)) \quad (3)$$

$$X_p(\alpha, \beta) = x_{p_\alpha} - x_{p_{\alpha\beta}} \quad (4)$$

x_{p_α} is the displacement when the input voltage increases from 0 to α.
$x_{p_{\alpha\beta}}$ is the displacement when the input voltage decreases from α to β.

Approximation of $X_p(\alpha,\beta)$

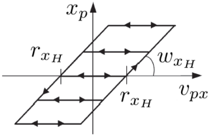
$$X_p(\alpha,\beta) = \theta_0\beta + \theta_1\alpha + \theta_2\beta^2 + \theta_3\beta\alpha + \theta_4\alpha^2 + \theta_5\beta^3 + \theta_6\beta^2\alpha + \theta_7\beta\alpha^2 + \theta_8\alpha^3 \quad (5)$$



Experimental and identified Preisach model.

+ Capture asymmetric hysteresis.

− Its inverse is numerical.



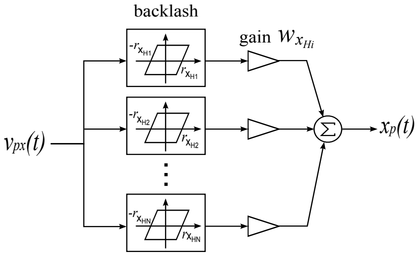
Weighted backlash operator.

$$x_p(t) = H_{x_{r_H}}[v_{px}, x_{p0}](t) = \max\{v_{px}(t) - r_{x_H}, min\{v_{px}(t) + r_{x_H}, x_p(t - T_s)\}\}, \quad (6)$$

$\boldsymbol{H}_{\boldsymbol{r}_{x_H}}$ is the backlash operator,
$\boldsymbol{x}_{p0}$ the initial state of the backlash,
$\boldsymbol{r}_{x_H}$ is the threshold,
T_s is the sampling time.

Hysteresis model

Classical Prandtl Ishlinskii Model



Superposition of backlash operators

$$x_p(t) = H_x[v_{px}](t) = \boldsymbol{w}_{x_H}{}^T \boldsymbol{H}_{\boldsymbol{r}_{x_H}}[v_{px}, \boldsymbol{x}_{p0}](t), \tag{7}$$

$\boldsymbol{w}_{x_H}$ is the vector of weights.

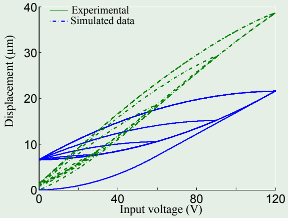
- **Thresholds and initial states initialization :**

$$r_{x_{Hi}} = \frac{i}{n+1} max\{v_{px}\}, \quad i = 0, ..., n, \quad x_{p0_i} = 0, \quad i = 0, ..., n. \tag{8}$$

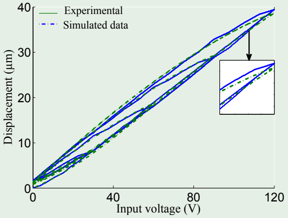
- **Weights identification**

$$E_x[v_{px}, \tilde{x}_p](t) = H_x[v_{px}](t) - \tilde{x}_p(t) \qquad (9)$$

$\tilde{x}_p(t)$ is the measured output displacement.



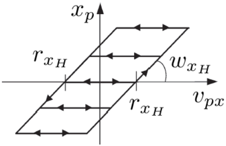
Before identification (PI).

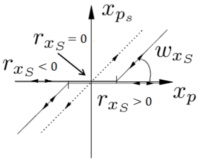


After identification (PI).

+ Its inverse is analytic.

− Can not Capture asymmetric hysteresis.

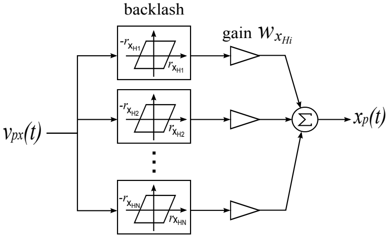




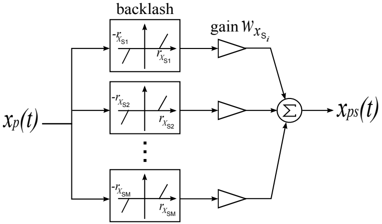
Weighted backlash operator. Weighted dead-zone operator.

$$x_{p_s}(t) = S_{r_{xs}}[x_p](t) = \begin{cases} \max\{x_p(t) - r_{xs}, 0\}, & r_{xs} > 0 \\ x_p(t), & r_{xs} = 0 \end{cases} \quad (10)$$

$\boldsymbol{S_{r_{xs}}}$ is the dead-zone,
$\boldsymbol{r_{xs}}$ is threshold of dead-zone.



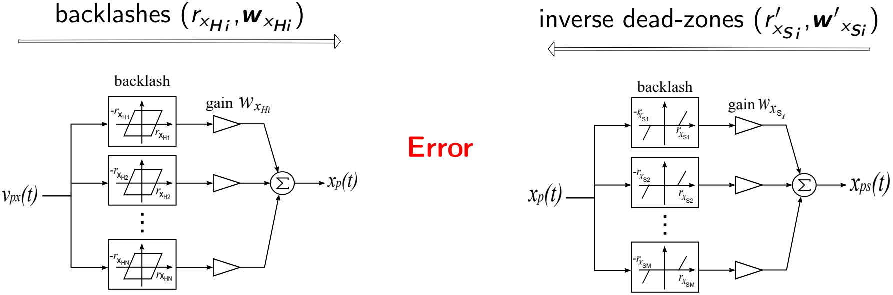
Superposition of backlash operators.



Superposition of dead-zone operators.

$$\begin{aligned} x_{p_s}(t) &= S_x[H_x[v_{px}]](t) \\ &= \boldsymbol{w}_{x_S}{}^T \boldsymbol{S}_{r_{x_S}}[\boldsymbol{w}_{x_H}{}^T \boldsymbol{H}_{r_{x_H}}[v_{px}, \boldsymbol{x}_{p0}]](t) \end{aligned} \quad (11)$$

$\boldsymbol{w}_{x_S}$ is the vector of dead-zones weights.



Superposition of backlash operators.

Superposition of dead-zone operators.

- **Weights identification**

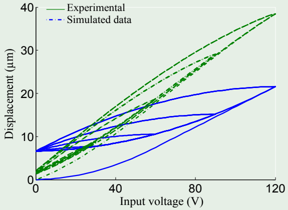
$$\begin{aligned} E_x[v_{px}, \tilde{x}_p](t) &= H_x[v_{px}](t) - S_x^{-1}[\tilde{x}_p](t) \\ &= \boldsymbol{w}_{xH}^T \boldsymbol{H}_{r_{xH}}[v_{px}, \boldsymbol{x}_{p0}](t) - \boldsymbol{w}'^T_{xS} \boldsymbol{S}_{r'_{xS}}[\tilde{x}_p](t) \end{aligned} \quad (12)$$

$\boldsymbol{w}'^T_{xS}$ are the weights of inverse dead-zones, $\boldsymbol{S}_{r'_{xS}}$ are the inverse dead-zones.

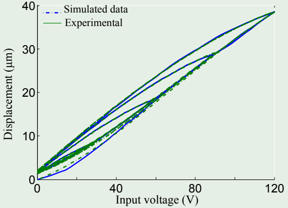
- **Inverse dead-zones thresholds initialization :**

$$r'_{xs_i} = \frac{i}{m+1} max\{x_p\}, \quad i = 0, ..., m, \tag{13}$$

r'_{xs_i} is the inverse dead-zones thresholds.

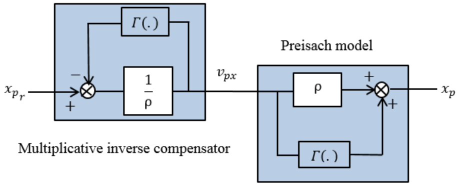


Before identification (MPI).



After identification (MPI).

+ Can Capture asymmetric hysteresis.
+ Its inverse is analytic.



Multiplicative inverse structure of Preisach model.

$$x_p(t) = H(v_{px}(t)) = \rho(v_{px}(t)) + \Gamma(v_{px}(t)) \tag{14}$$

$$v_{px}(t) = \rho^{-1}(v_{px}(t))[x_{p_r}(t) - \Gamma(v_{px}(t))] \tag{15}$$

- **Approximated multiplicative inverse structure**

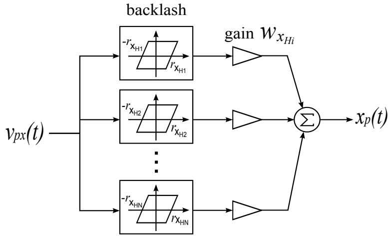
$$v_{px}(t) = \rho^{-1}(v_{px}(t - T_s))[x_{p_r}(t) - \gamma(v_{px}(t - T_s))] \tag{16}$$

T_s is the sampling time.

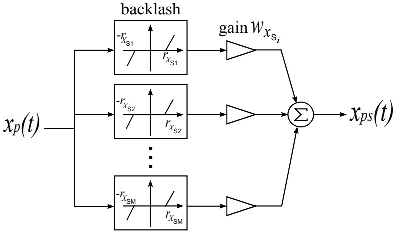
Open-loop hysteresis compensation

Inverse Classical and Modified Prandtl-Ishlinskii models

inverse backlashes $(r'_{xH\,i}\,?, \mathbf{w}'_{xHi}\,?)$



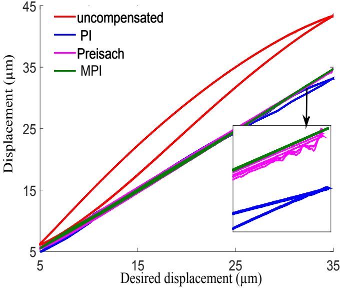
inverse dead-zones $(r'_{xS\,i}\,✓, \mathbf{w}'_{xSi}\,✓)$



$$r'_{xH\,i} = \sum_{j=0}^{i} w_{xHj}(r_{xH\,i} - r_{xHj}), \quad i = 0, \ldots, n, \tag{17}$$

$$w'_{xHi} = -\frac{w_{xHi}}{\left(w_{xH0} + \sum_{j=1}^{i} w_{xHj}\right)\left(w_{xH0} + \sum_{j=1}^{i-1} w_{xHj}\right)}, w'_{xH0} \quad = \quad \frac{1}{w_{xH0}}, i = 1, \ldots, n \tag{18}$$

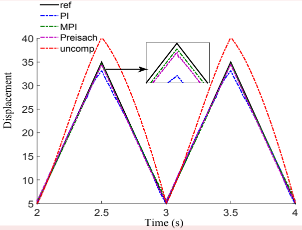
Experimental results



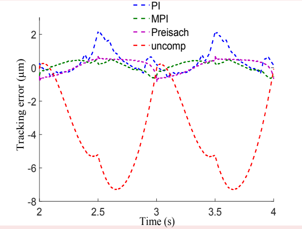
Experimental hysteresis compensation for 1 Hz triangle input signal.

- **In the saturated zone**
  - Uncompensated system : 10 %.
  - Compensated system with inverse PI : 3.3 %.
  - Compensated system with multiplicative inverse of Preisach : 1.2 %.
  - Compensated system with inverse MPI : 0.5 %.

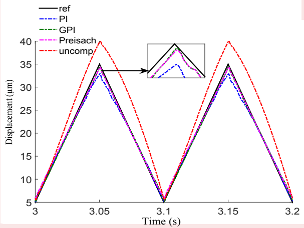
Experimental results



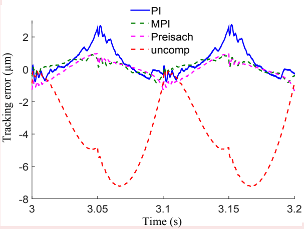
Triangular waveform tracking (1 Hz).



Tracking error (1 Hz).

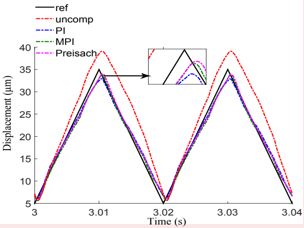


Tracking waveform tracking (10 Hz).

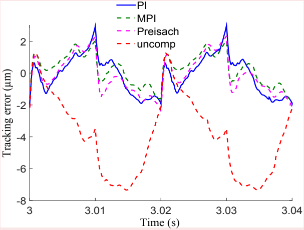


Tracking error (10 Hz).

Experimental results



Triangular waveform tracking (50 Hz).



Tracking error (50 Hz).

Table: RMS and maximal tracking error - numerical values

		uncomp	Preisach	PI	MPI
1 Hz	rms (μm)	4.6996	0.4182	0.7975	0.3133
	max (μm)	7.3042	0.8807	2.1765	0.6841
10 Hz	rms (μm)	4.6659	0.5522	0.9998	0.4436
	max (μm)	7.2417	1.3547	2.7494	0.9556
50 Hz	rms (μm)	4.660	1.1560	1.1797	0.9688
	max (μm)	7.4270	2.4660	3.0836	2.1547

Conclusion

- Experimental validation on the horizontal (X) axis.
- Inverse multiplicative structure of Preisach model,
  - \+ analytic,
  - \+ compensates for asymmetric hysteresis.
  - − computationally intensive.
- Inverse Prandtl-Ishlinskii (PI) model,
  - \+ analytic,
  - \+ less time consuming.
  - − does not Compensate for asymmetric hysteresis.
- Modified inverse Prandtl-Ishlinskii (MPI) model,
  - \+ analytic,
  - \+ less time consuming,
  - \+ compensate for asymmetric hysteresis.

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THANK YOU FOR YOUR ATTENTION

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Questions ?