Modeling and Compensation of Complex Nonlinearities with Memory in Systems with Active Materials

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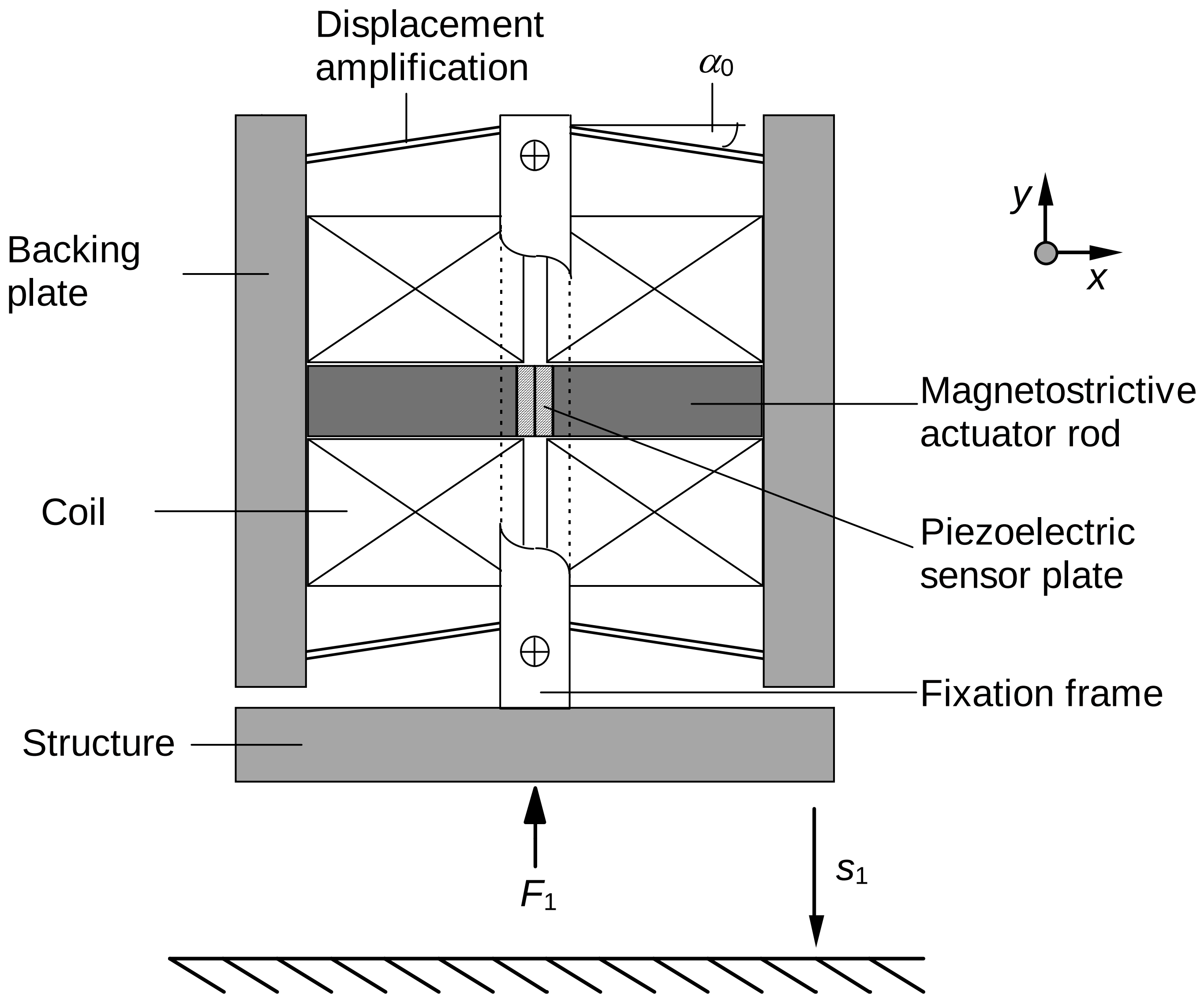
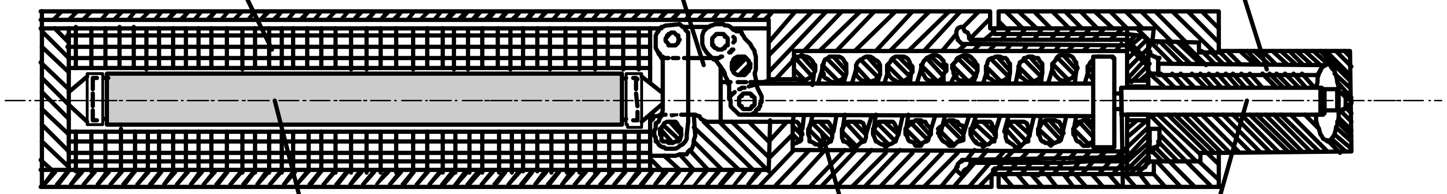
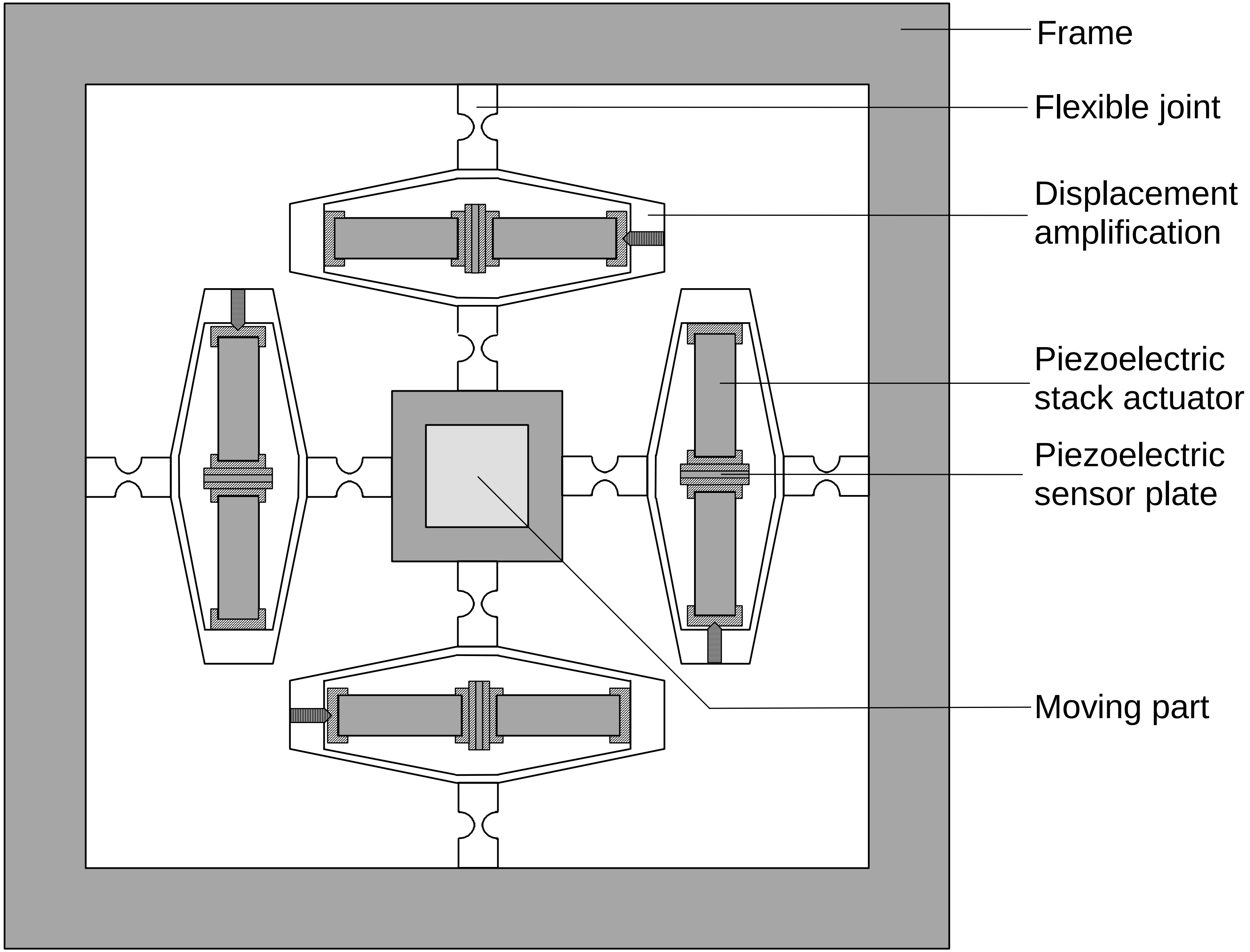
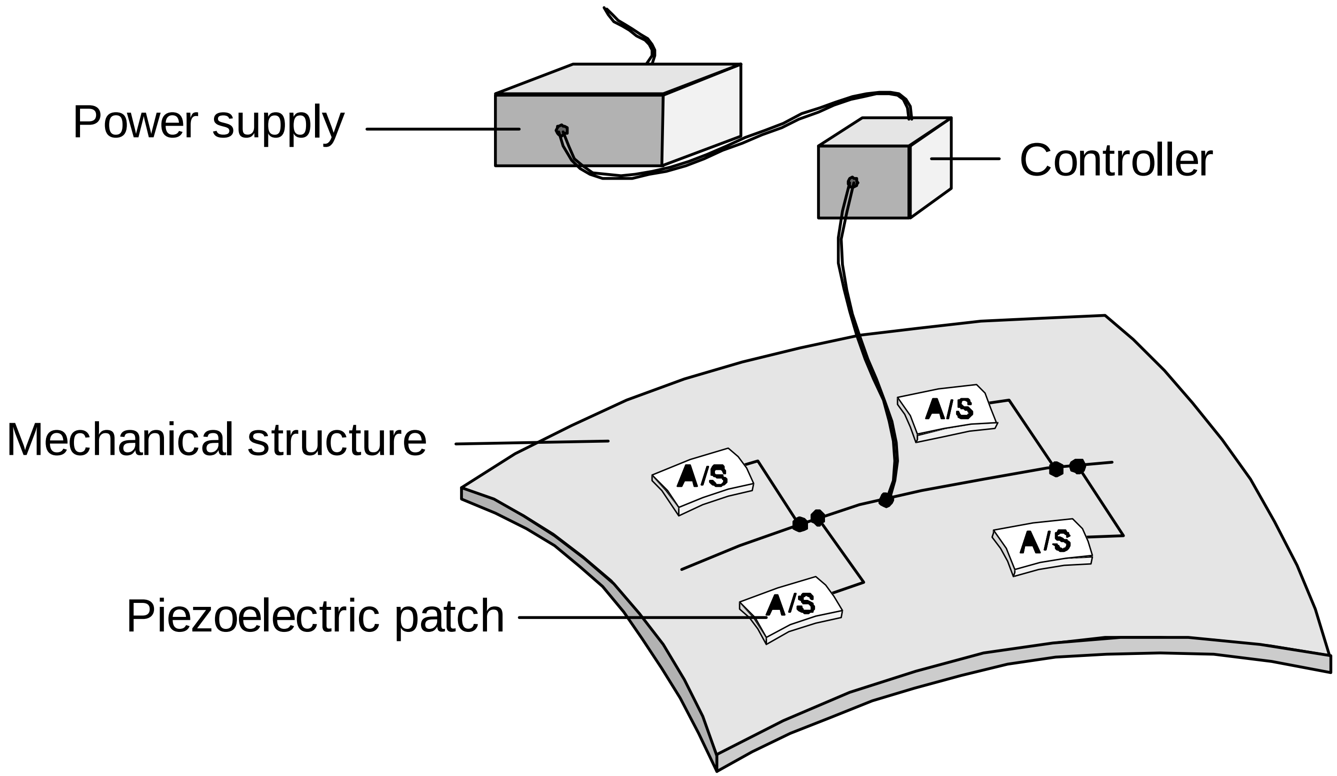
Johann Radon Institute for Computational and Applied Mathematics (RICAM)

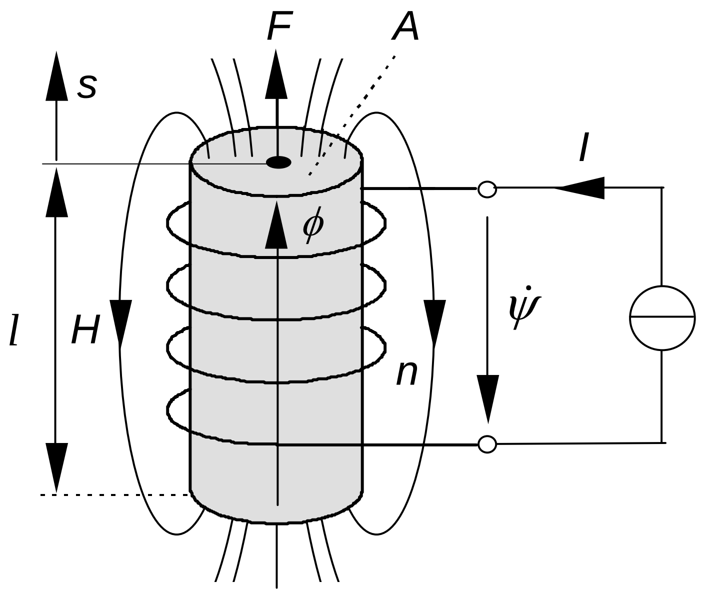
1. Systems with Active Materials
2. Solid-State Actuators
3. Experimental Structure Analysis of Material Properties
4. Modeling of Memory Nonlinearities in Solid-State Actuators
5. Compensator Design
6. Applications: Self-sensing Solid-state Actuator
7. Conclusions and Prospects


Displacement amplification
α_0
Backing plate
Coil
Magnetostrictive actuator rod
Piezoelectric sensor plate
Fixation frame
Structure
y
x
F_1
s_1


Coil
Displacement amplification
Injection canal
Magnetostrictive rod
Spring
Needle


Frame
Flexible joint
Displacement amplification
Piezoelectric stack actuator
Piezoelectric sensor plate
Moving part

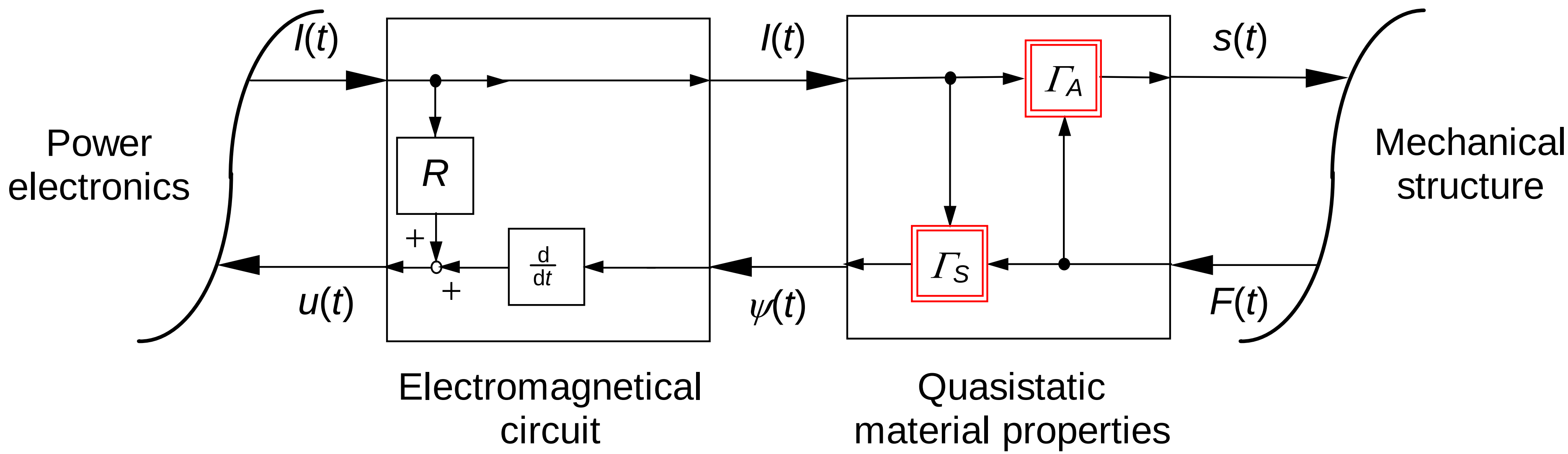

Power supply
Controller
Mechanical structure
Piezoelectric patch
A/S
A/S
A/S
A/S

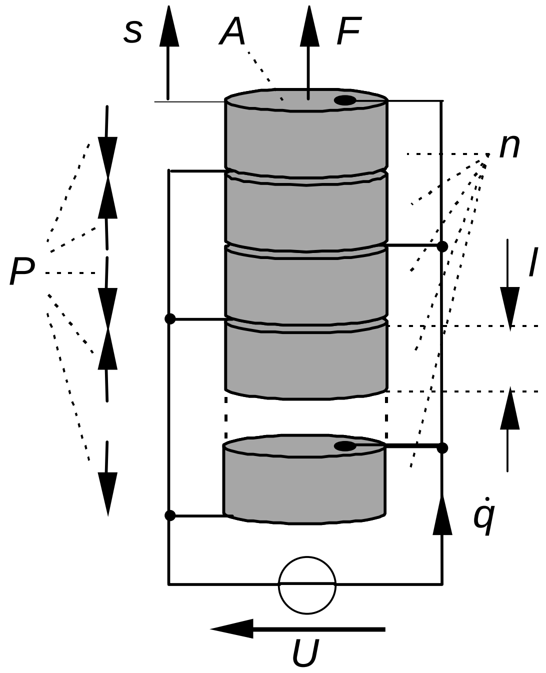


Induction law: $u(t) = \dot{\psi}(t) + RI(t)$

Sensor equation: $\psi(t) = \Gamma_S[I,F](t)$

Actuator equation: $s(t) = \Gamma_A[I,F](t)$

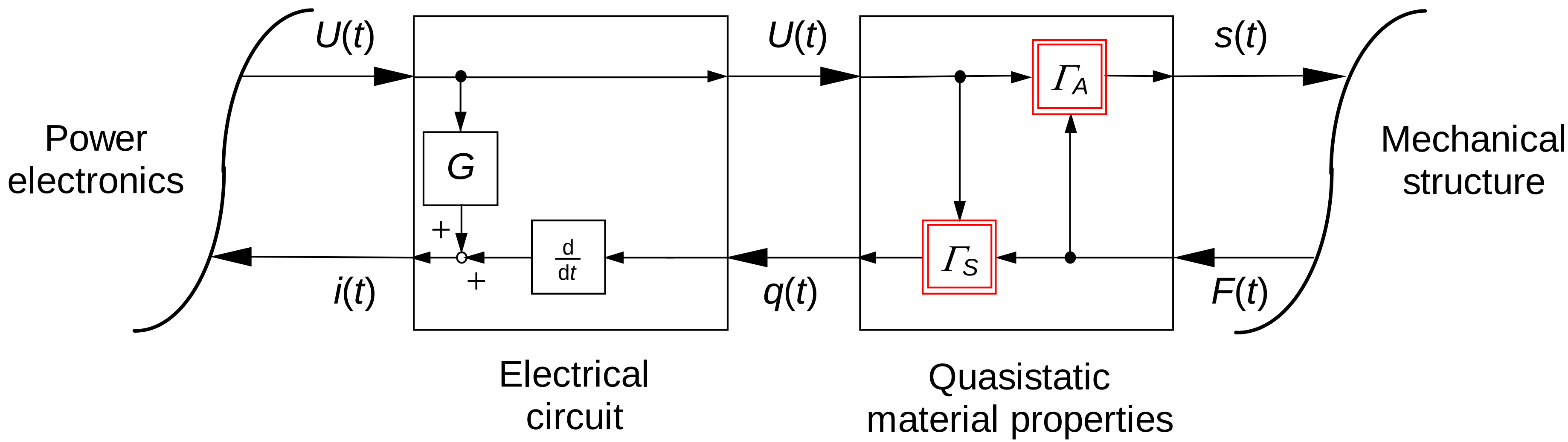




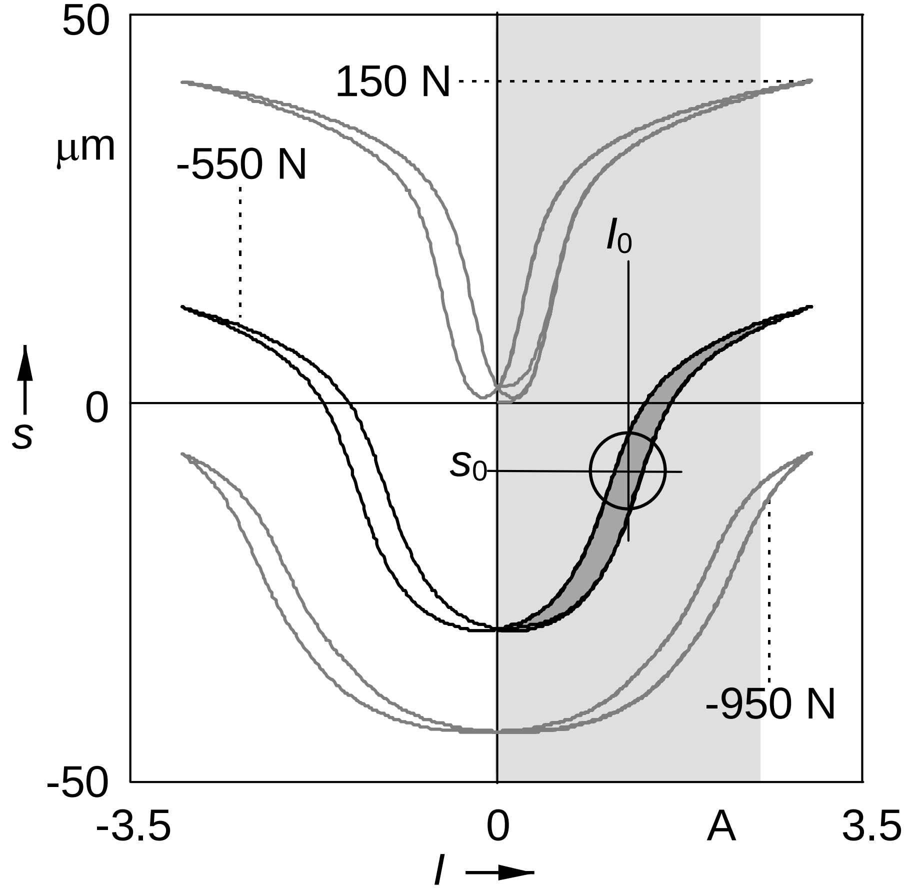
Isolation properties: $i(t) = \dot{q}(t) + GU(t)$

Sensor equation: $q(t) = \Gamma_S[U,F](t)$

Actuator equation: $s(t) = \Gamma_A[U,F](t)$

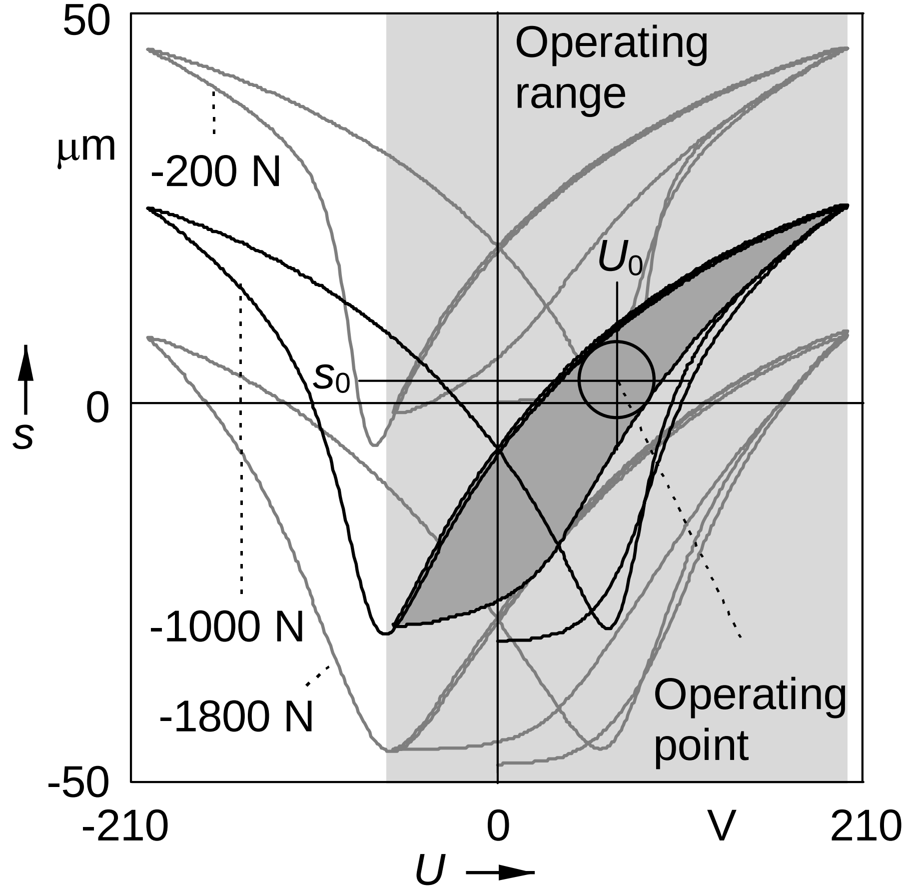


Magnetostrictive actuator



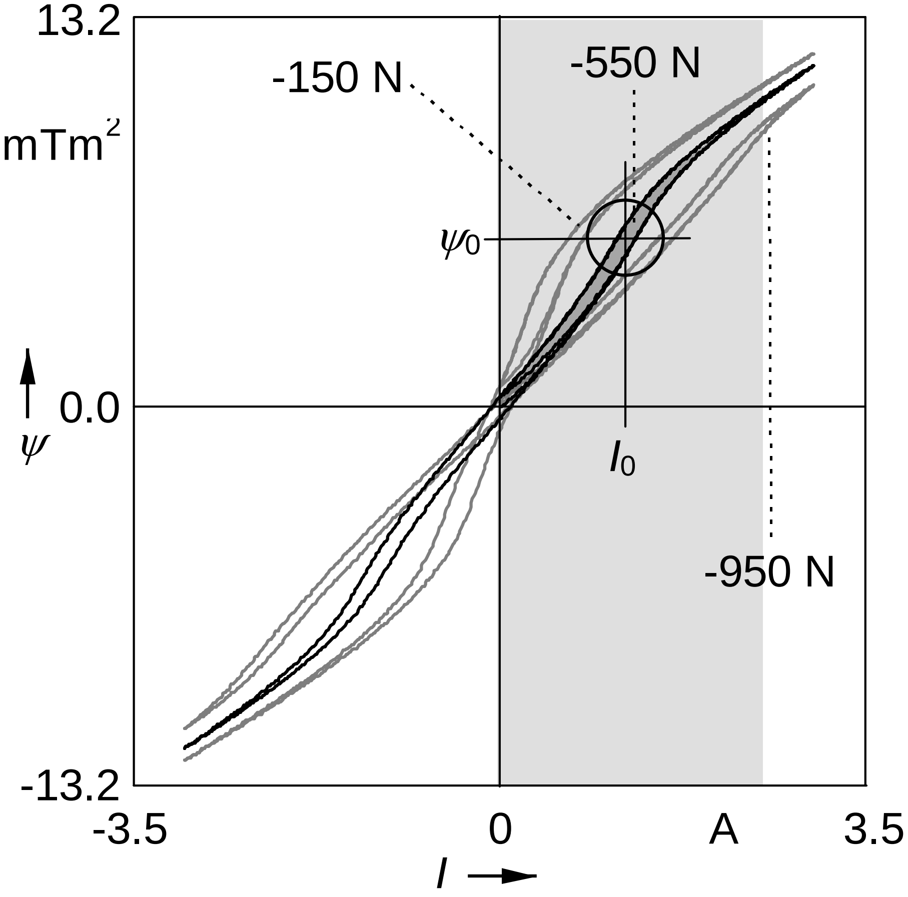
$$s(t) = \Gamma_A[I,F](t)$$

Piezoelectric actuator



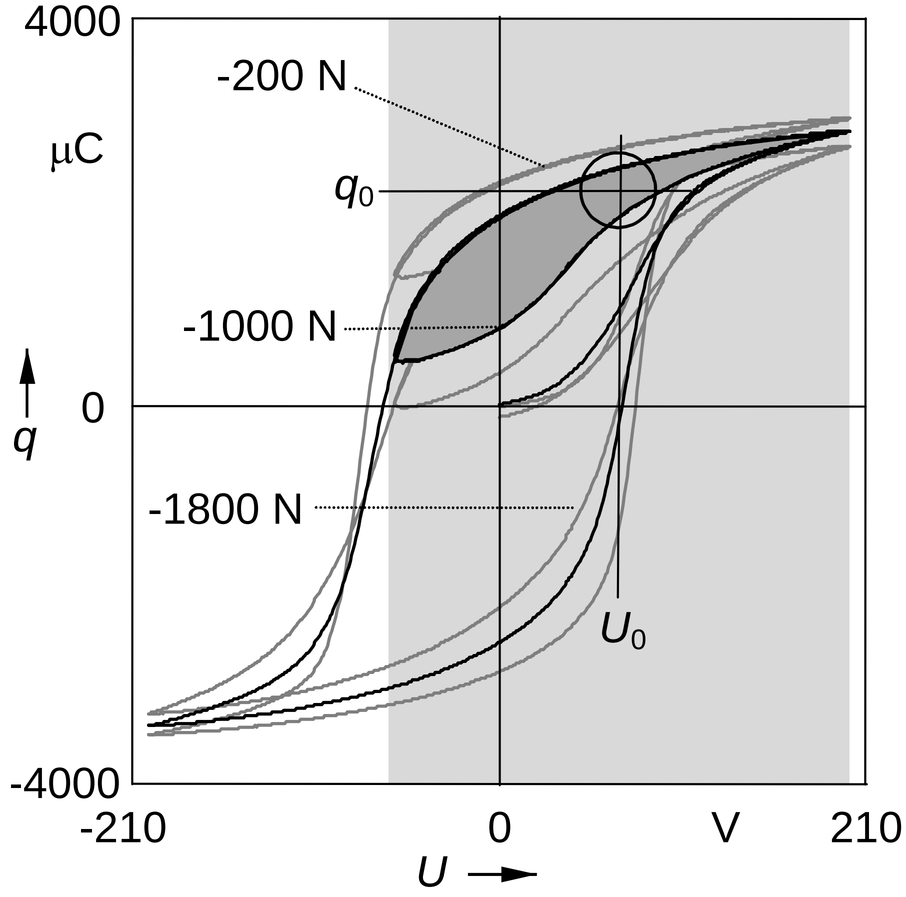
$$s(t) = \Gamma_A[U,F](t)$$

Magnetostrictive actuator



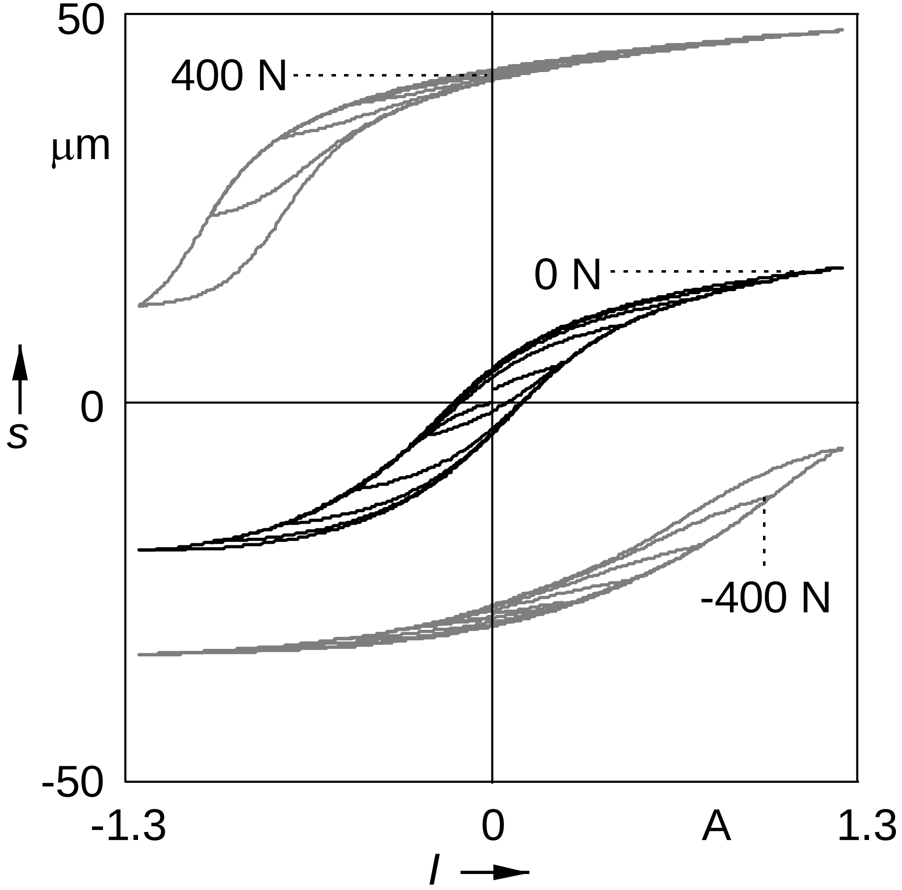
$$\psi(t) = \Gamma_S[I,F](t)$$

Piezoelectric actuator

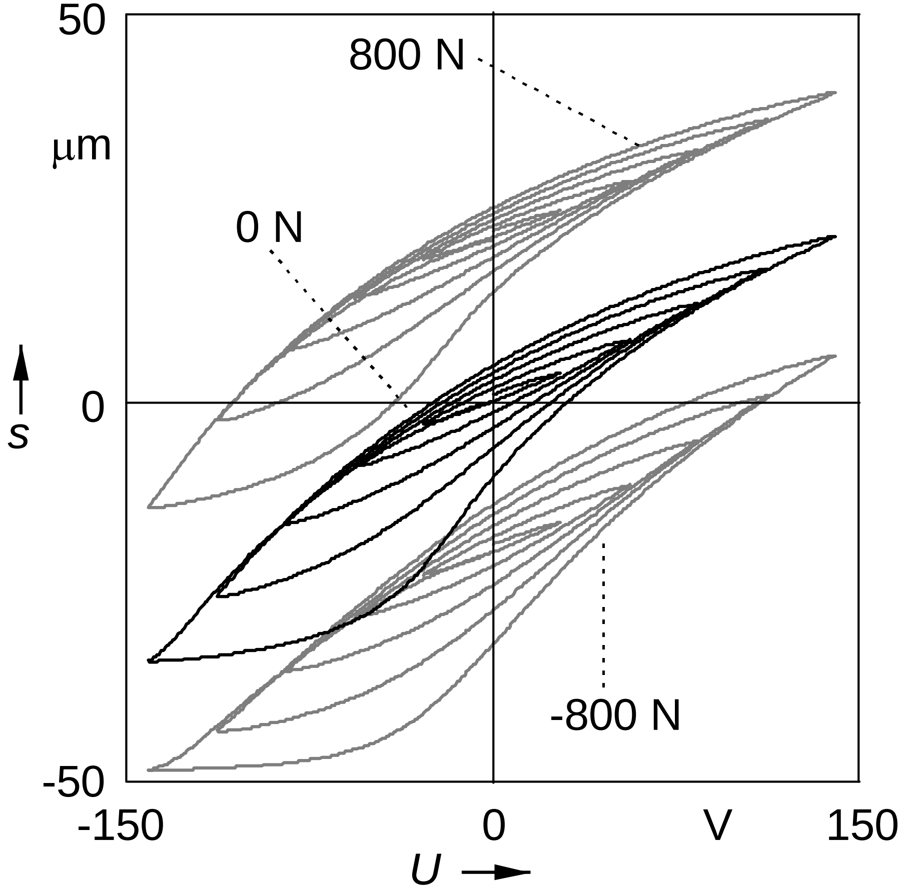


$$q(t) = \Gamma_S[U,F](t)$$

Magnetostrictive actuator

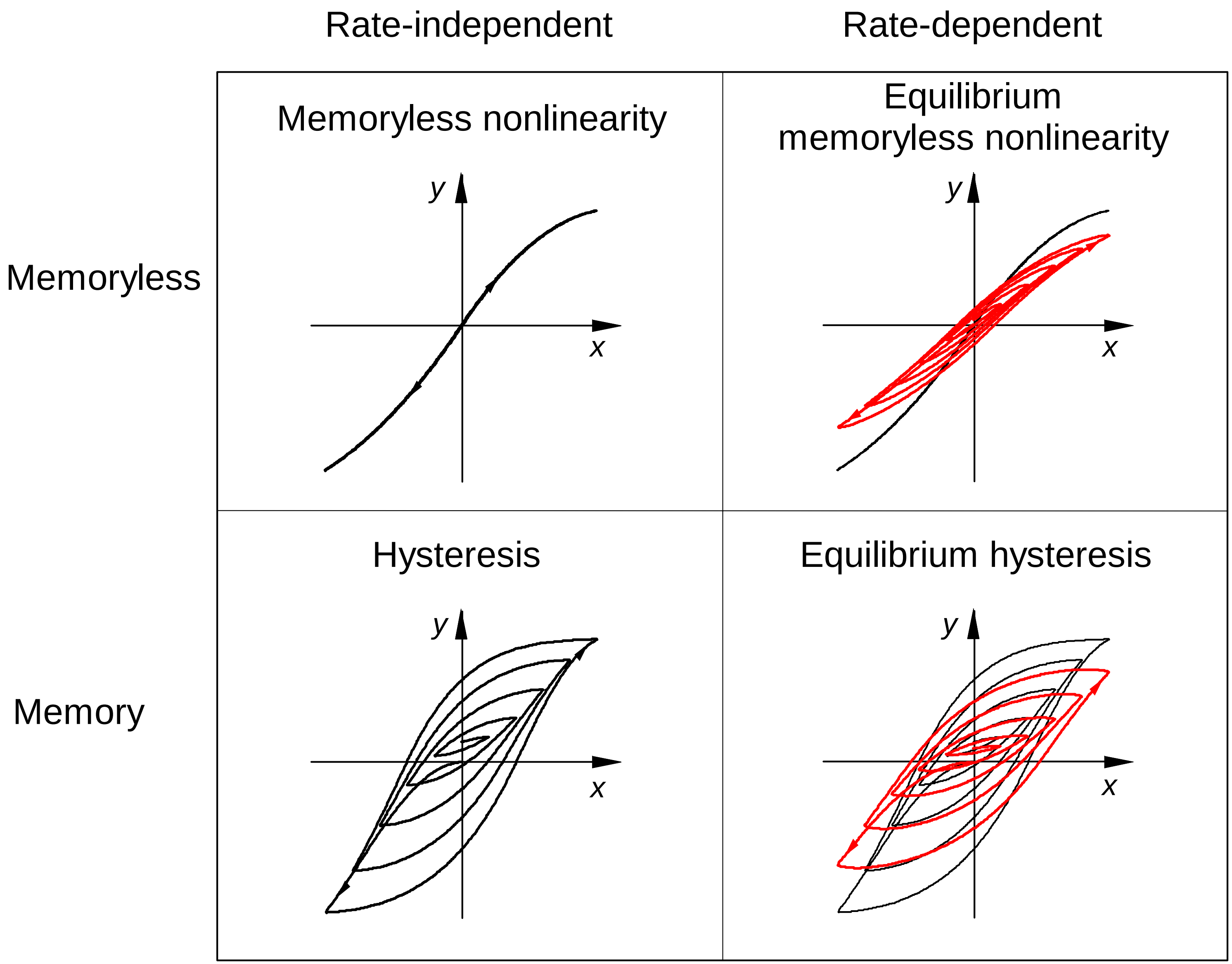


Piezoelectric actuator

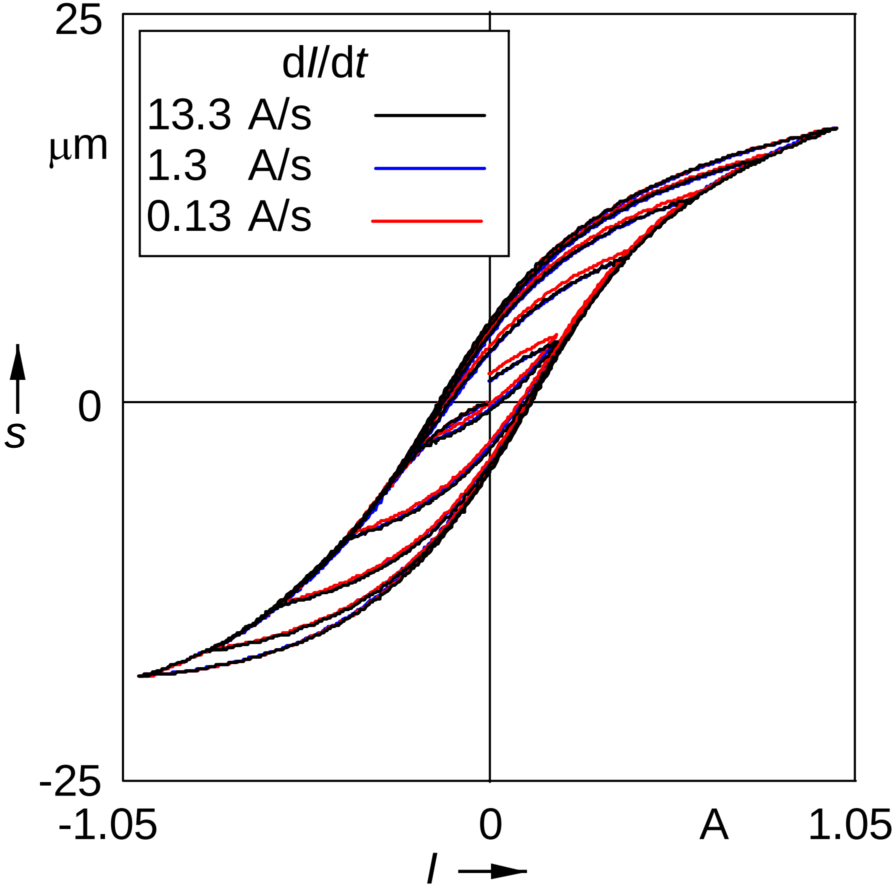


Sensor equation: $\psi(t) = \Gamma_{\mathrm{S}}[I](F,t)$ $\quad q(t) = \Gamma_{\mathrm{E}}[U](t) + \Gamma_{\mathrm{S}}[F](t)$

Actuator equation: $s(t) = \Gamma_{\mathrm{A}}[I](F,t)$ $\quad s(t) = \Gamma_{\mathrm{A}}[U](t) + \Gamma_{\mathrm{M}}[F](t)$

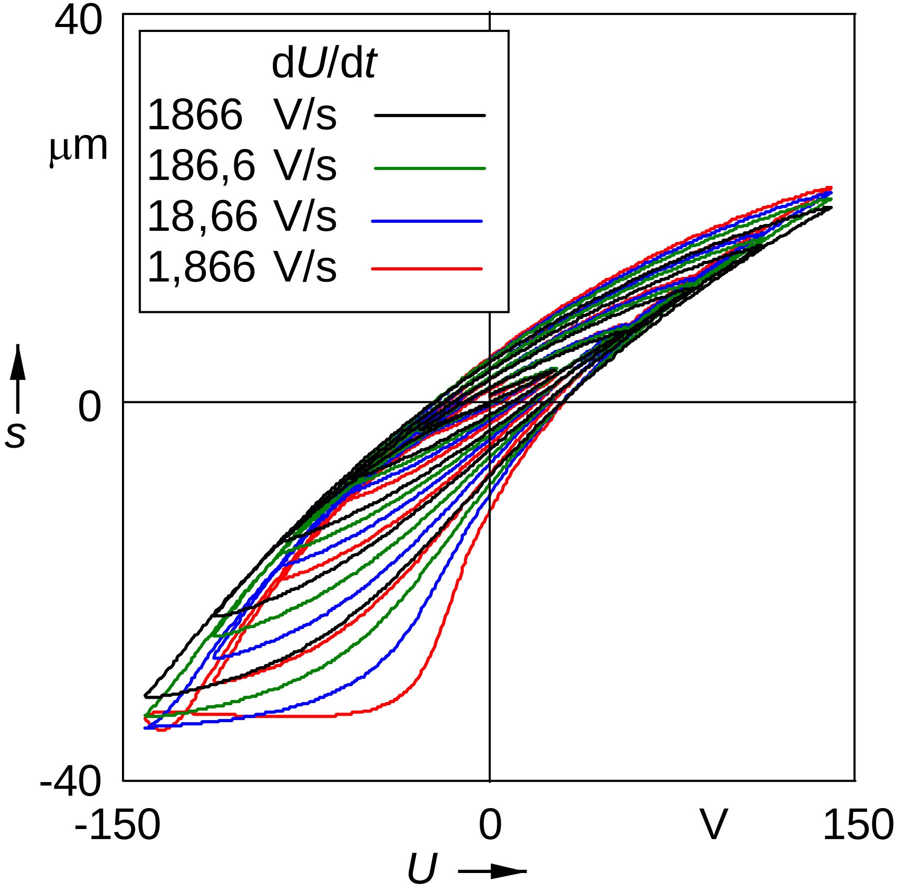

Rate-independent
Rate-dependent
Memoryless
Memory
Memoryless nonlinearity
Equilibrium memoryless nonlinearity
Hysteresis
Equilibrium hysteresis
y
x
y
x
y
x
y
x

Magnetostrictive actuator

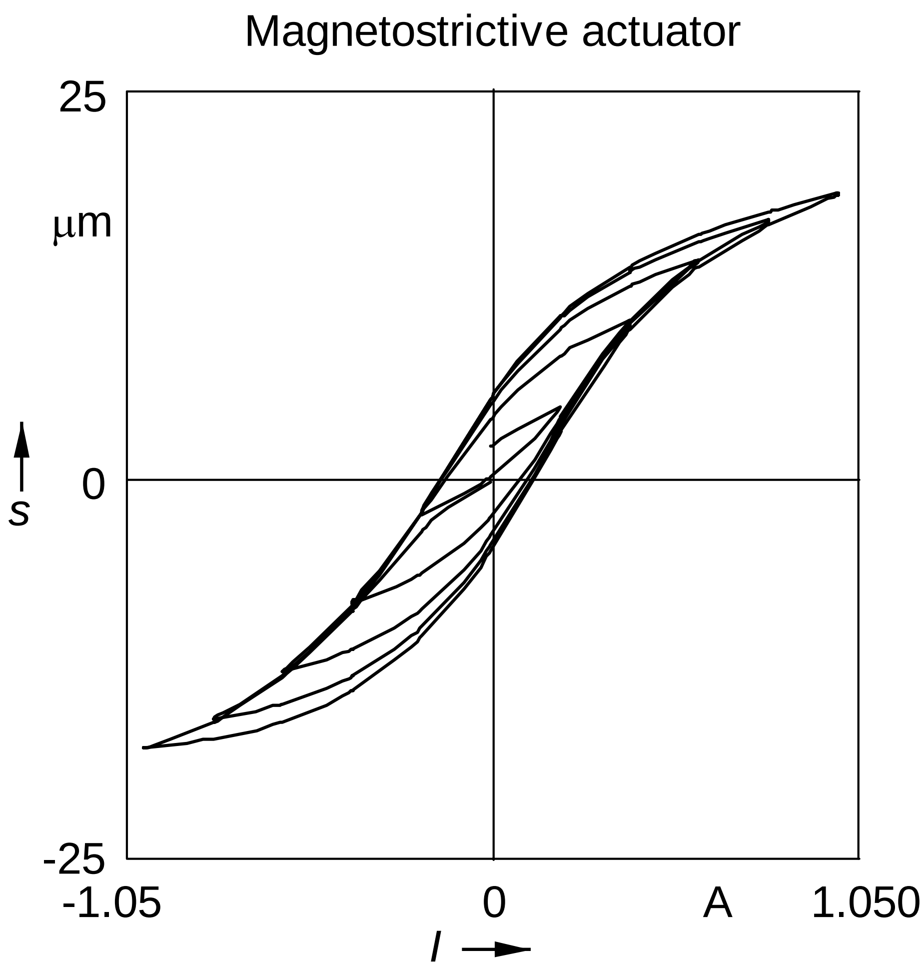


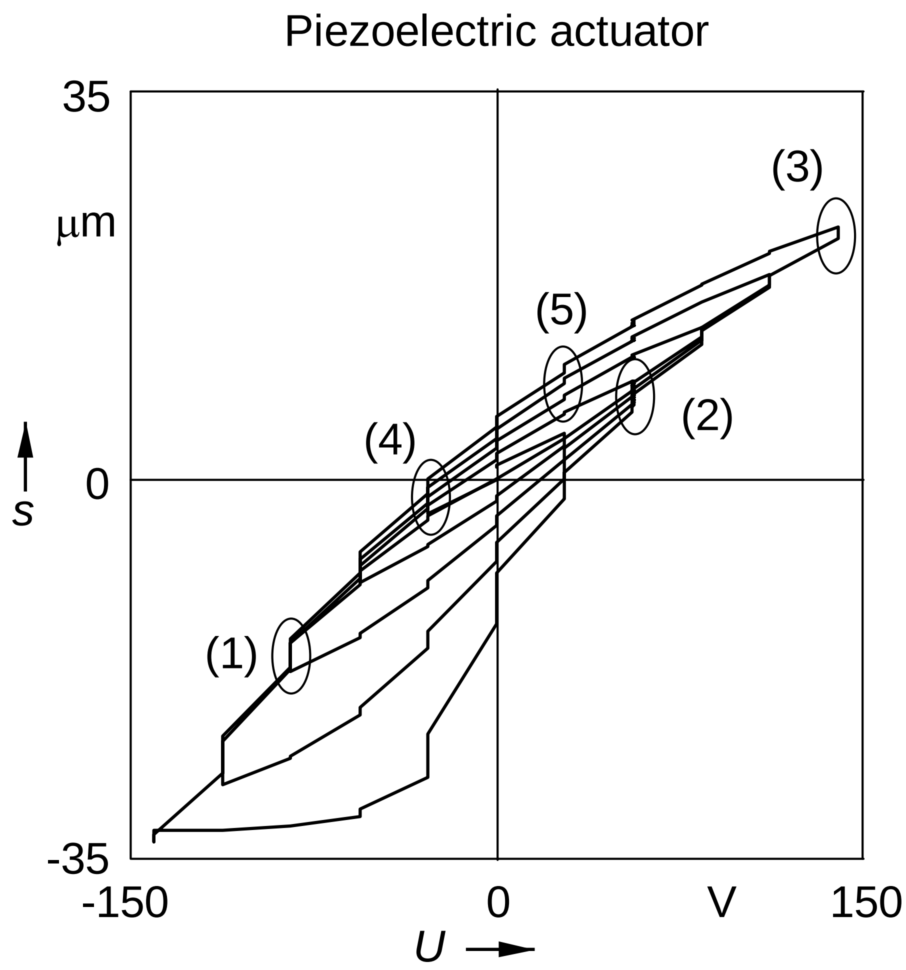
Rate-independent

Piezoelectric actuator



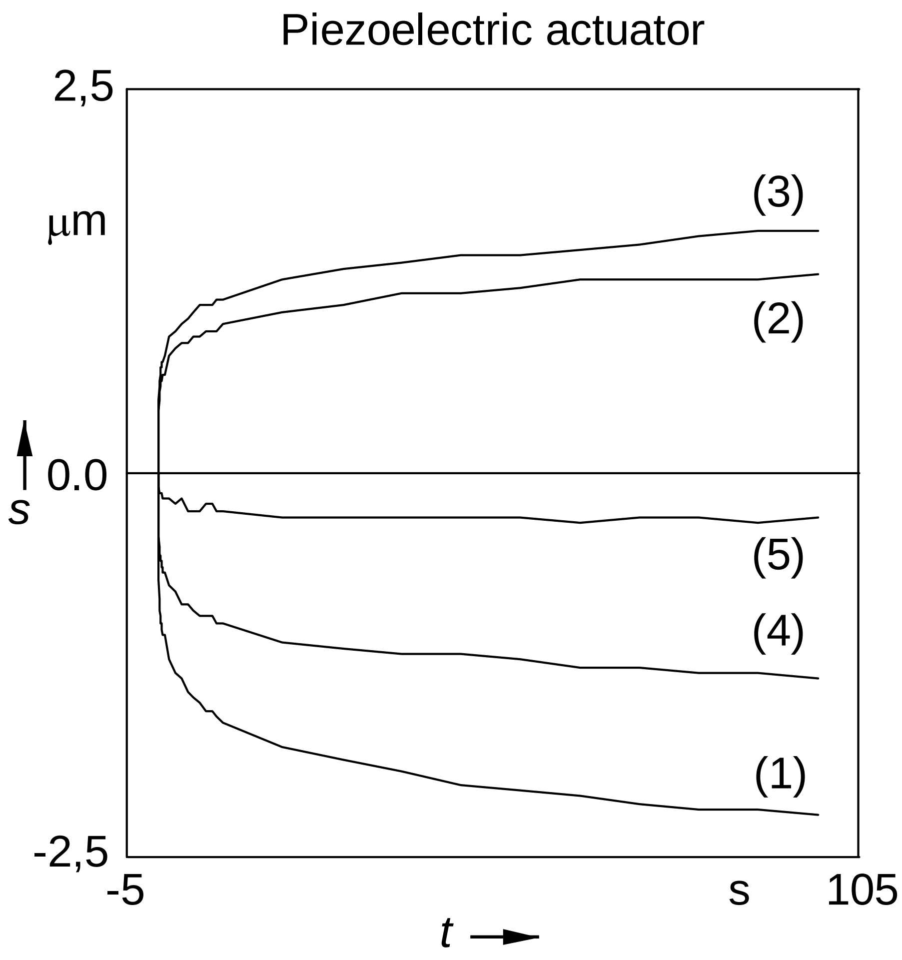
Rate-dependent

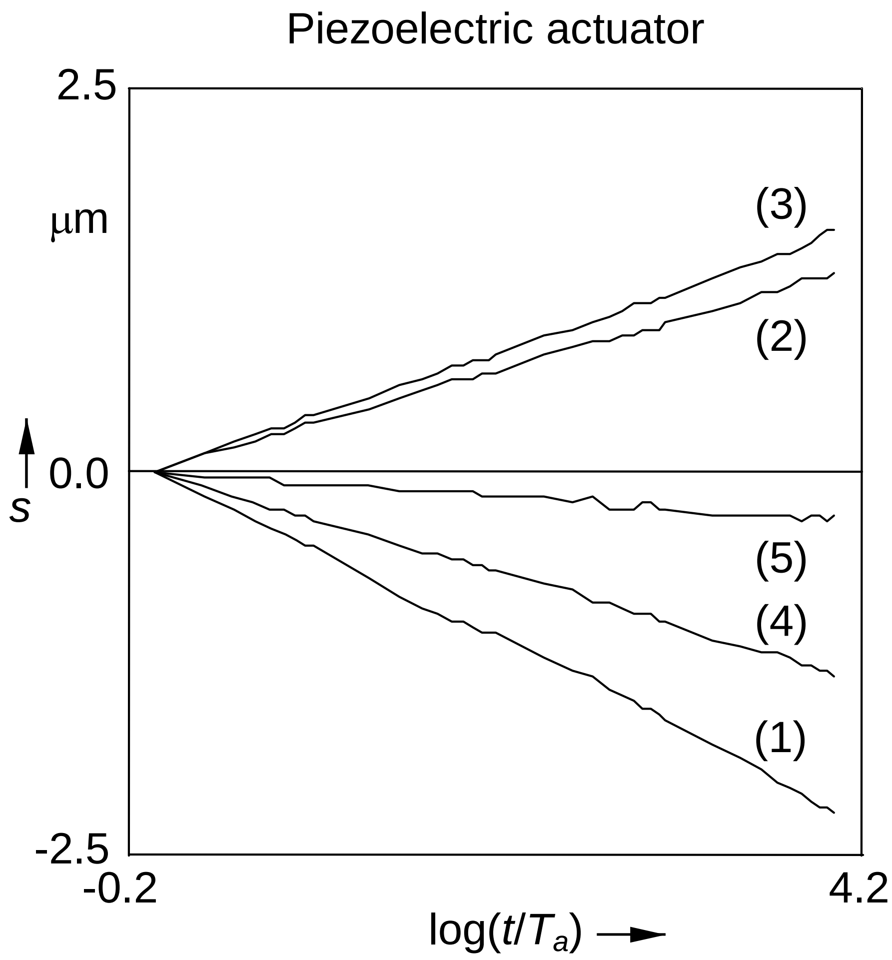




⇒ Negligible creep effects

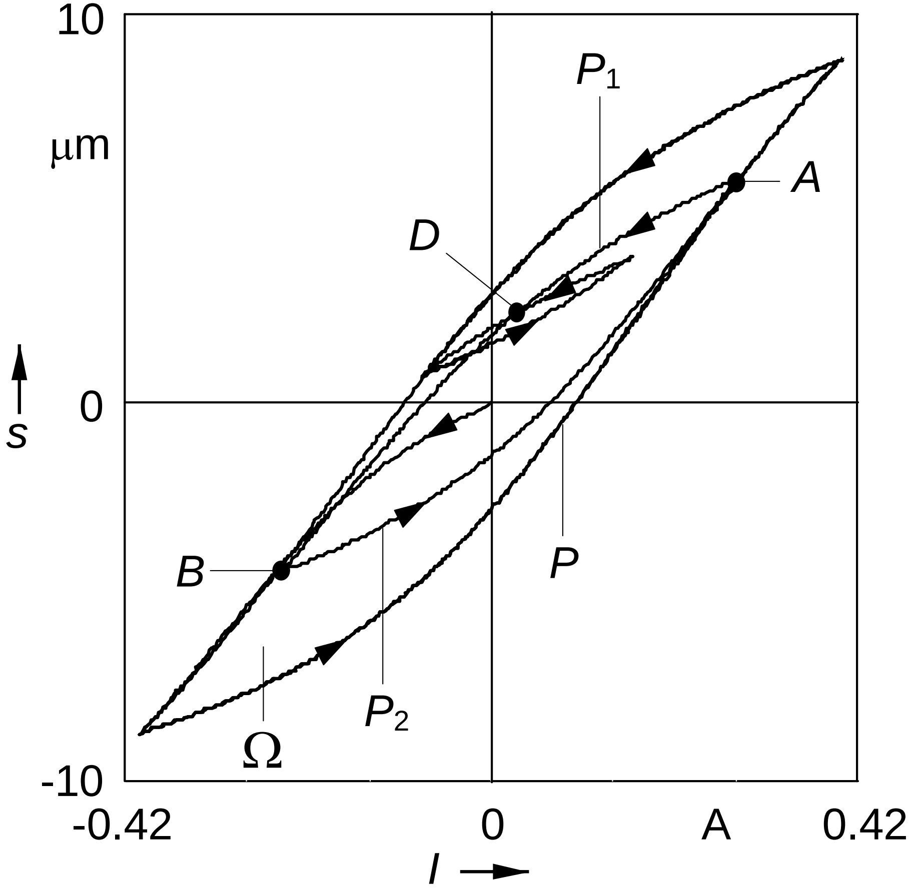
⇒ Strong creep effects





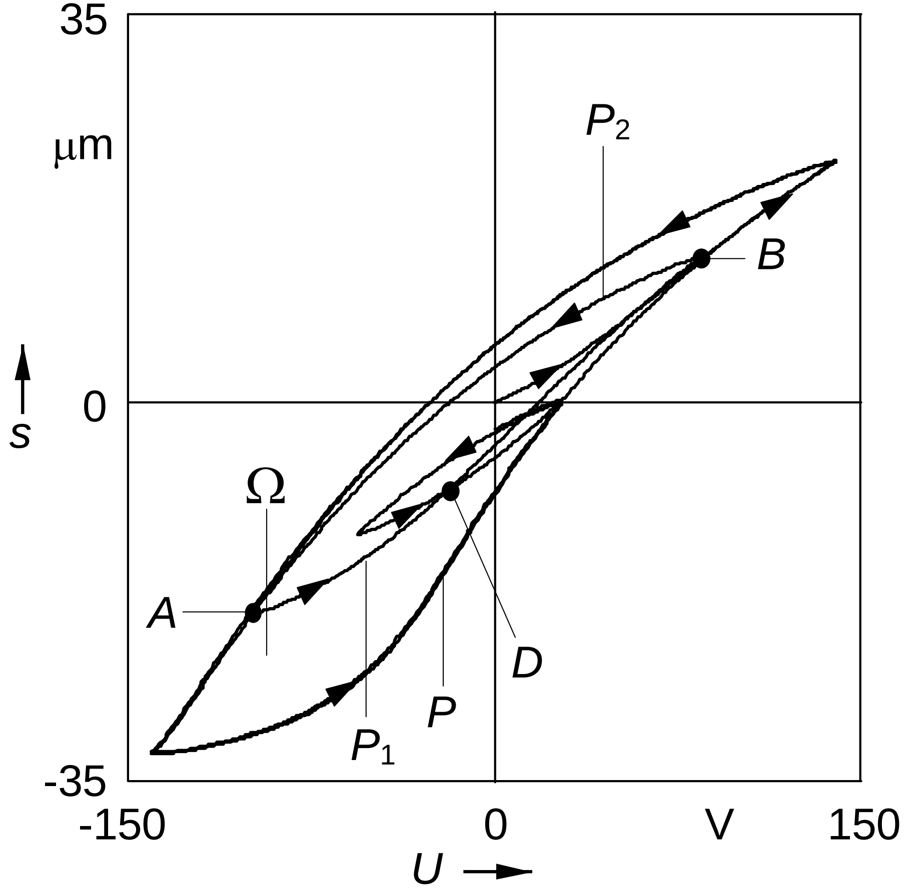
⇒ Log(t)-type creep dynamics

Magnetostrictive actuator

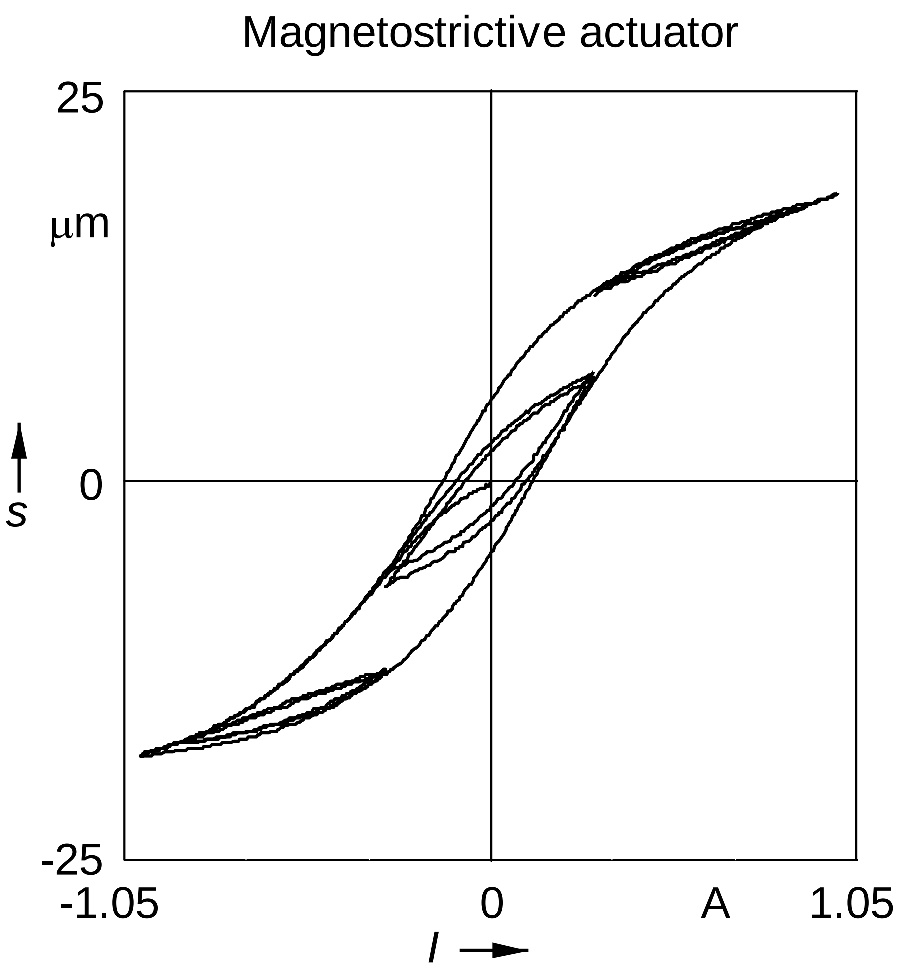


Complex hysteresis

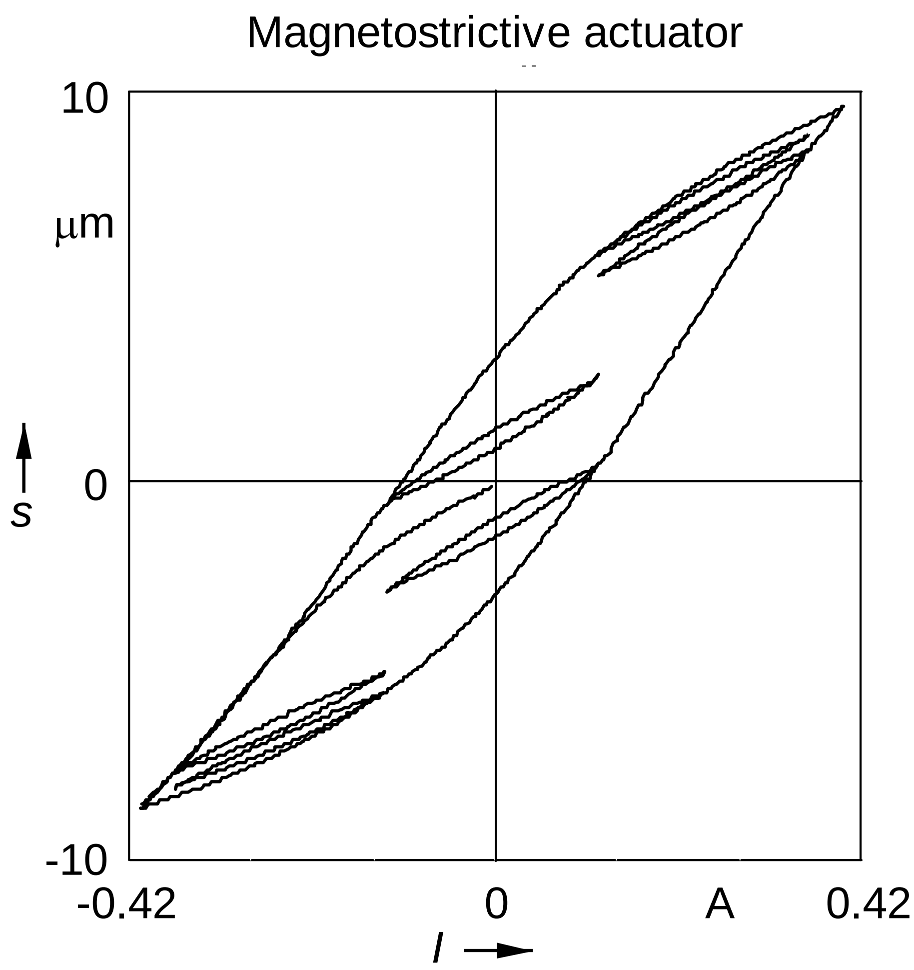
Piezoelectric actuator



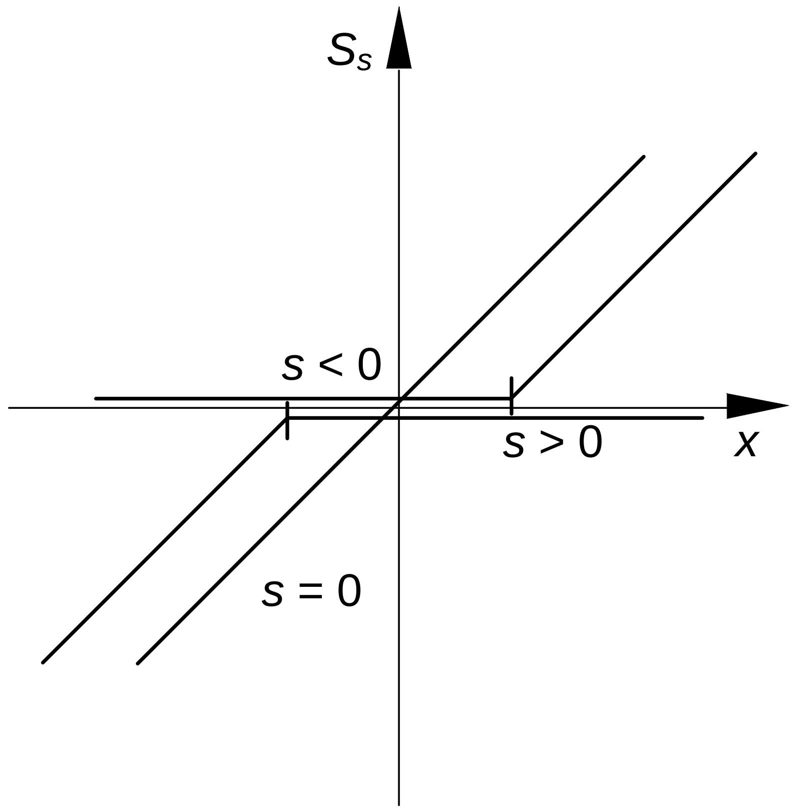
Complex equilibrium hysteresis



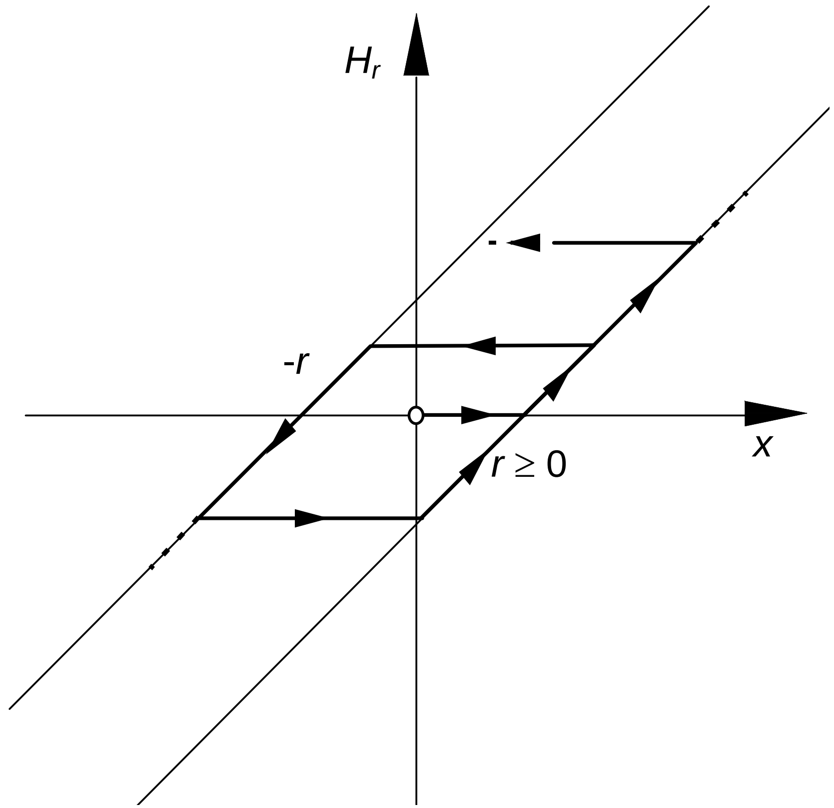
Congruence property



Masing property



$$S_s(x(t)) := \begin{cases} \max\{x(t) - s, 0\} & ; \quad s > 0 \\ x(t) & ; \quad s = 0 \\ \min\{x(t) - s, 0\} & ; \quad s < 0 \end{cases}$$

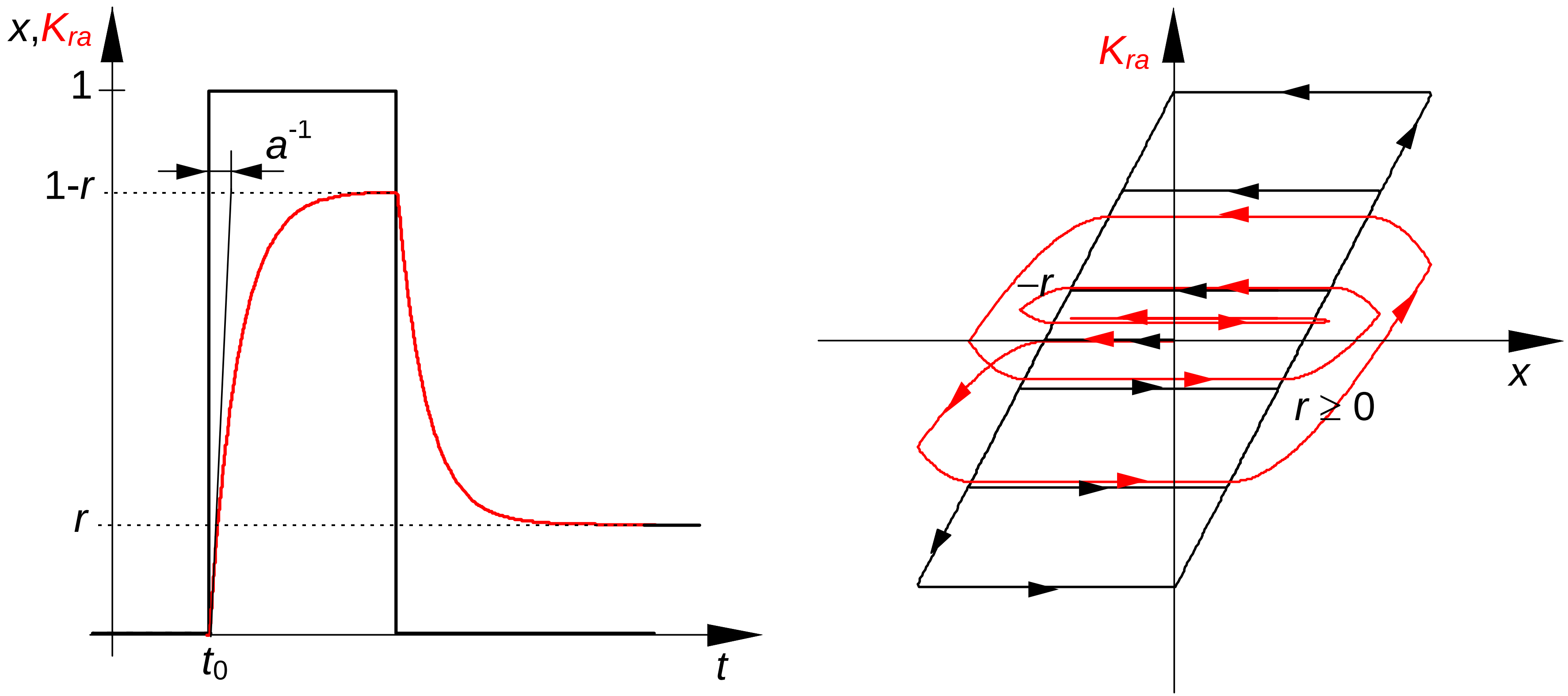


$$H_r[x, z_{H0}](t)$$

$$\Updownarrow$$

$$z_H(t) = \max\{x(t) - r, \min\{x(t) + r, z_H(t_i)\}\} \ , \ t_i < t \leq t_{i+1} \ , \ i = 0 \,..\, N$$

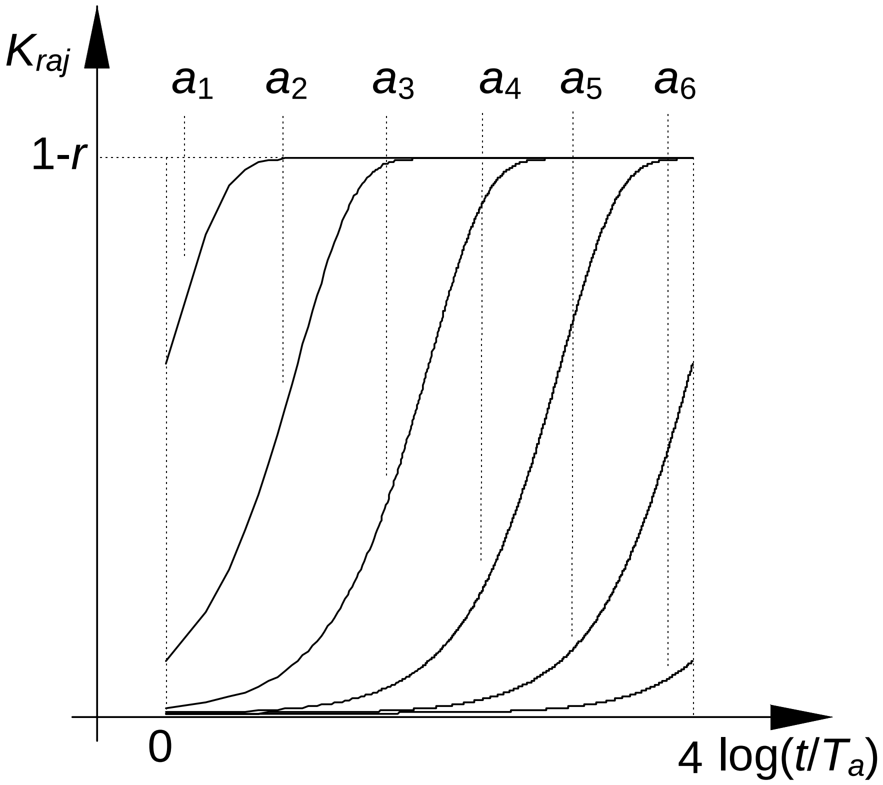
$$z_H(t_0) = \max\{x(t_0) - r, \min\{x(t_0) + r, z_{H0}\}\}$$

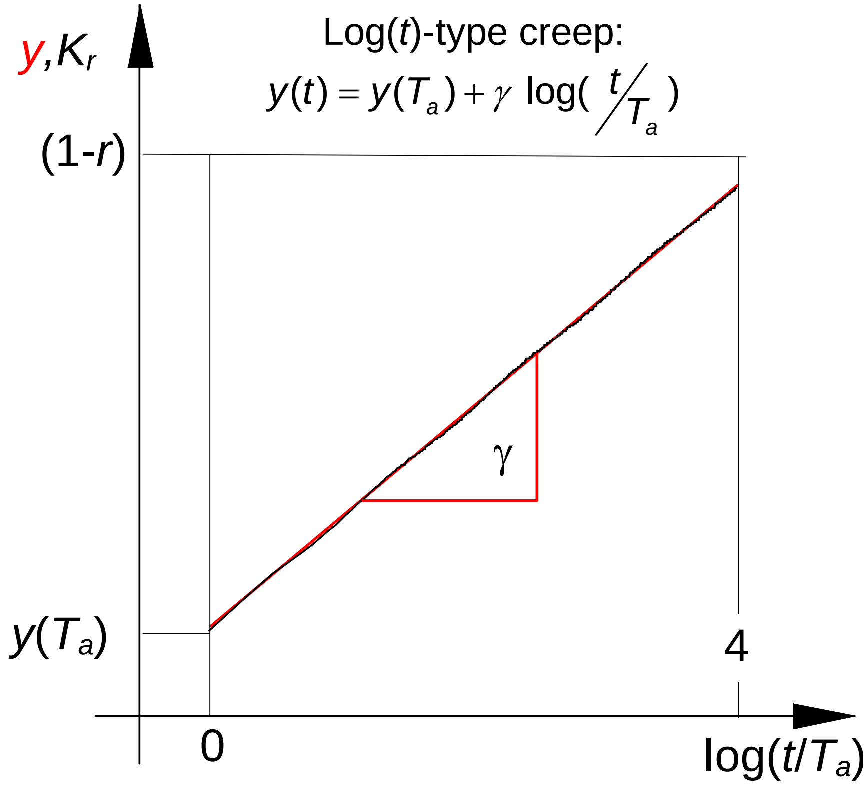


$$K_{ra}[x,z_{K0}](t) \Leftrightarrow \dot{z}_K(t) - a\max\{x(t)-z_K(t)-r,\min\{x(t)-z_K(t)+r,0\}\} = 0 \quad , \quad z_K(t_0) = z_{K0}$$

$$\lim_{a\to\infty} K_{ra}[x,z_{K0}](t) = H_r[x,z_{H0}](t) \Rightarrow \lim_{\dot{x}(t)\to 0} K_{ra}[x,z_{K0}](t) = H_r[x,z_{H0}](t)$$

$$\lim_{r\to 0} K_{ra}[x,z_{K0}](t) = L_a[x,z_{L0}](t)$$



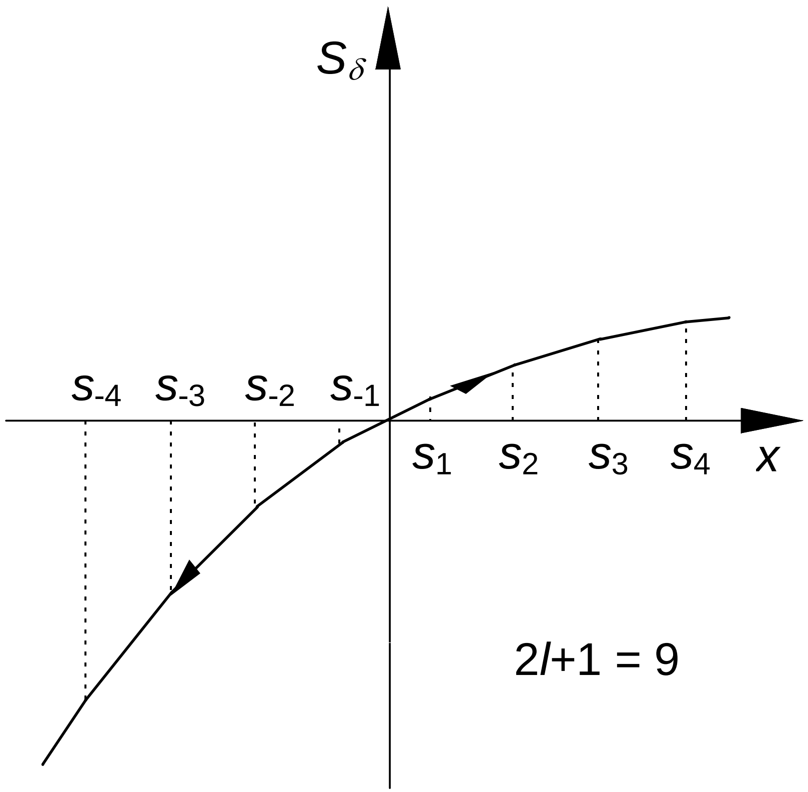


$$K_r[x, \mathbf{z}_{K0}](t) = \frac{1}{m}\sum_{j=1}^{m} K_{ra_j}[x, z_{K0j}](t) \quad , \quad a_j = \frac{1}{10^{j-1}T_a} \quad , \quad j = 1 \,.\,.\, m$$

$$\lim_{\dot{x}(t)\to 0} K_r[x, \mathbf{z}_{K0}](t) = H_r[x, \mathbf{z}_{H0}](t)$$

$$\lim_{r\to 0} K_r[x, \mathbf{z}_{K0}](t) = L[x, \mathbf{z}_{L0}](t)$$

$$S(x(t)) := w_{s0}x(t) + \int_{-\infty}^{\infty} w_s(r) S_s(x(t))\,\mathrm{d}r$$



Threshold-discrete approximation

$$S_\delta(x(t)) = \begin{pmatrix} w_{s-l} & \cdots & w_{s0} & \cdots & w_{s+l} \end{pmatrix} \cdot \begin{pmatrix} S_{s_{-l}}(x(t)) \\ \vdots \\ x(t) \\ \vdots \\ S_{s_{+l}}(x(t)) \end{pmatrix}$$

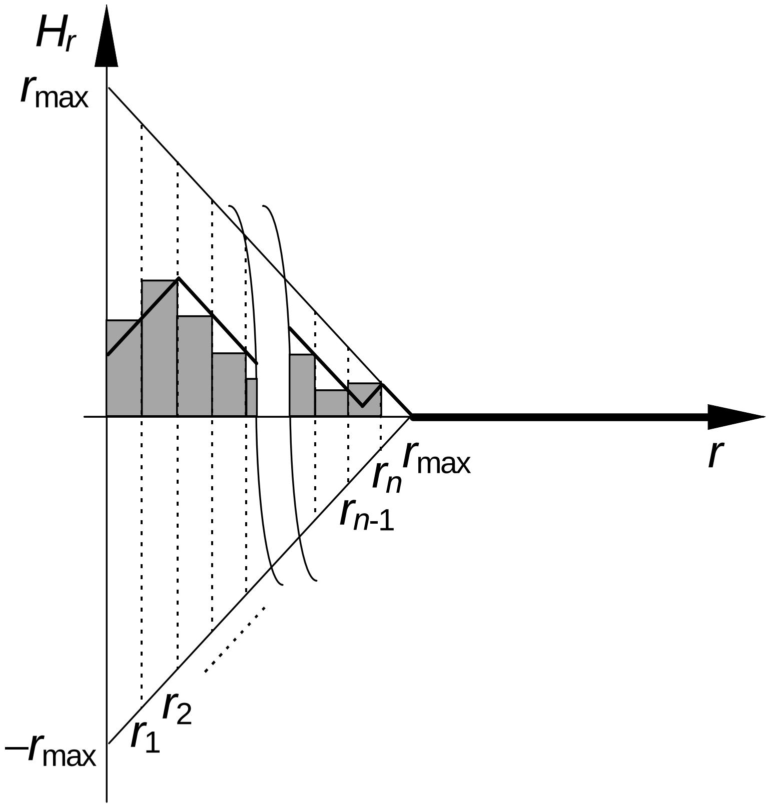
$$= \mathbf{w}_s^T \cdot \mathbf{S}_s(x(t))$$

Conditions for strong monotonicity

$$\begin{pmatrix} 1 & \cdots & 1 & \cdots & 0 \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ 0 & \cdots & 1 & \cdots & 0 \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ 0 & \cdots & 1 & \cdots & 1 \end{pmatrix} \cdot \begin{pmatrix} w_{s-l} \\ \vdots \\ w_{s0} \\ \vdots \\ w_{s+l} \end{pmatrix} - \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon \\ \vdots \\ \varepsilon \end{pmatrix} \geq \begin{pmatrix} 0 \\ \vdots \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

$$\mathbf{U}_s \cdot \mathbf{w}_s - \mathbf{u}_s \geq \mathbf{o}$$

$$H[x, z_{H0}(r)](t) := w_{H0} x(t) + \int_0^{\infty} w_H(r) H_r[x, z_{H0}(r)](t) \mathrm{d}r$$



Threshold-discrete approximation

$$H_\delta[x, \boldsymbol{z}_{H0}](t) = \begin{pmatrix} w_{H0} & w_{H1} & \cdots & w_{Hn} \end{pmatrix} \cdot \begin{pmatrix} x(t) \\ H_{r_1}[x, z_{H01}](t) \\ \vdots \\ H_{r_n}[x, z_{H0n}](t) \end{pmatrix}$$

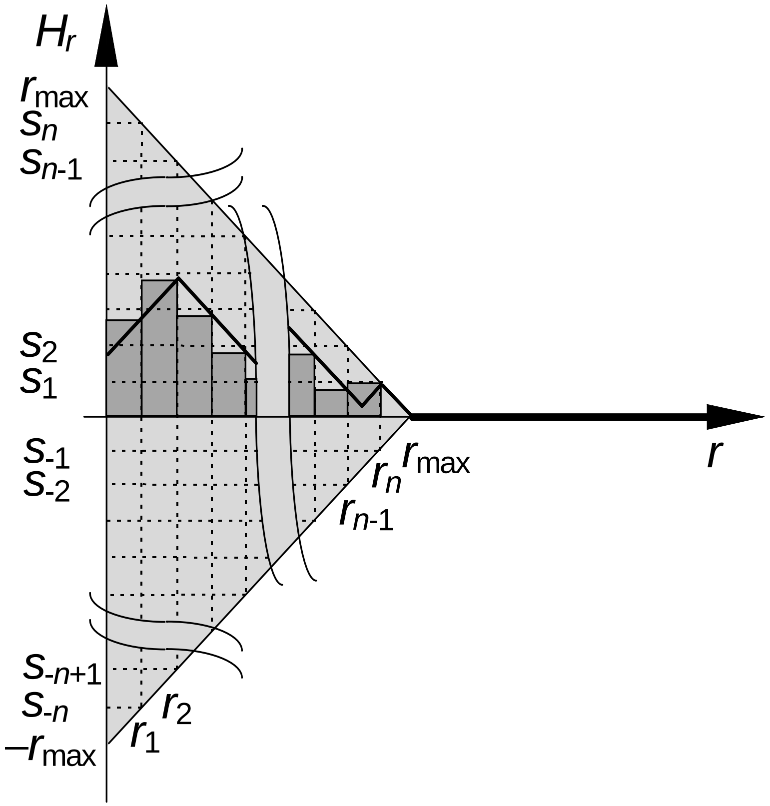
$$= \boldsymbol{w}_H^T \cdot \boldsymbol{H}_{\boldsymbol{r}}[x, \boldsymbol{z}_{H0}](t)$$

Conditions for inversion and dissipation

$$\begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{pmatrix} \cdot \begin{pmatrix} w_{H0} \\ w_{H1} \\ \vdots \\ w_{Hn} \end{pmatrix} - \begin{pmatrix} \varepsilon \\ 0 \\ \vdots \\ 0 \end{pmatrix} \geq \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

$$\boldsymbol{U}_H \cdot \boldsymbol{w}_H - \boldsymbol{u}_H \geq \boldsymbol{o}$$

$$R[x,z_{H0}(r)](t) := w_{H0}(x(t)) + \int_0^{\infty} w_H(H_r[x,z_{H0}(r)](t),r)\,\mathrm{d}r + w_{off}$$



Threshold-discrete approximation

$$R_\delta[x,\boldsymbol{z}_{H0}](t) = \sum_{i=0}^{n} w_{Hi}(H_{r_i}[x,z_{H0i}](t)) + w_{off}$$

$$R_{\delta\delta}[x,\boldsymbol{z}_{H0}](t) = \sum_{i=0}^{n} \sum_{j=-n+i}^{+n-i} w_{Sij} S_{s_j}(H_{r_i}[x,z_{H0i}](t)) + w_{off}$$

$$= \boldsymbol{w}_R^T \cdot \boldsymbol{R}_{\boldsymbol{rs}}[x,\boldsymbol{z}_{H0}](t)$$

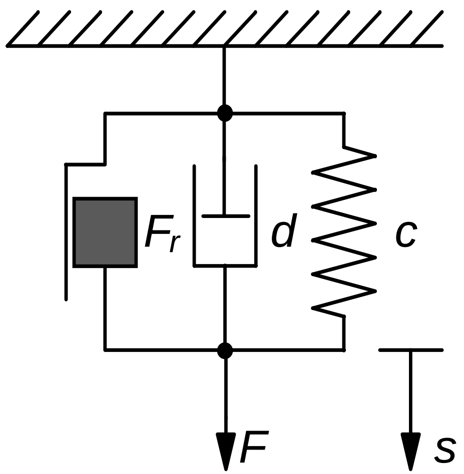
Conditions for inversion and dissipation

$$\begin{pmatrix} \boldsymbol{U}_{S0} & \boldsymbol{O} & \cdots & \boldsymbol{O} & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{U}_{S1} & \cdots & \boldsymbol{O} & \boldsymbol{O} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \boldsymbol{O} & \boldsymbol{O} & \cdots & \boldsymbol{U}_{Sn} & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{O} & \cdots & \boldsymbol{O} & 1 \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{w}_{S0} \\ \boldsymbol{w}_{S1} \\ \vdots \\ \boldsymbol{w}_{Sn} \\ w_{off} \end{pmatrix} - \begin{pmatrix} \varepsilon \\ \boldsymbol{o} \\ \vdots \\ \boldsymbol{o} \\ -\infty \end{pmatrix} \geq \begin{pmatrix} \boldsymbol{o} \\ \boldsymbol{o} \\ \vdots \\ \boldsymbol{o} \\ 0 \end{pmatrix}$$

$$\boldsymbol{U}_R \cdot \boldsymbol{w}_R - \boldsymbol{u}_R \geq \boldsymbol{o}$$

$$K[x,\mathbf{z}_{K0}(r)](t) := w_{K0}L[x,\mathbf{z}_{L0}](t) + \int_{0}^{+\infty} w_K(r)K_r[x,\mathbf{z}_{K0}(r)](t)\mathrm{d}r$$

$$\lim_{\dot{x}(t)\to 0} K[x,\mathbf{z}_{K0}(r)](t) = H[x,z_{H0}(r)](t)$$



$$s(t) = c^{-1}K_{F_r\, c/d}[F,s_0](t)$$

$$\updownarrow$$

$$y(t) = w_K K_{ra}[x,y_0](t)$$

Threshold-discrete approximation

$$K_\delta[x,\mathbf{Z}_{K0}](t) = \begin{pmatrix} w_{K0} & w_{K1} & \cdots & w_{Kn} \end{pmatrix} \cdot \begin{pmatrix} L[x,\mathbf{z}_{L0}](t) \\ K_{r_1}[x,\mathbf{z}_{K01}](t) \\ \vdots \\ K_{r_n}[x,\mathbf{z}_{K0n}](t) \end{pmatrix}$$

$$= \mathbf{w}_K^T \cdot \mathbf{K}_{\mathbf{r}}[x,\mathbf{Z}_{K0}](t)$$

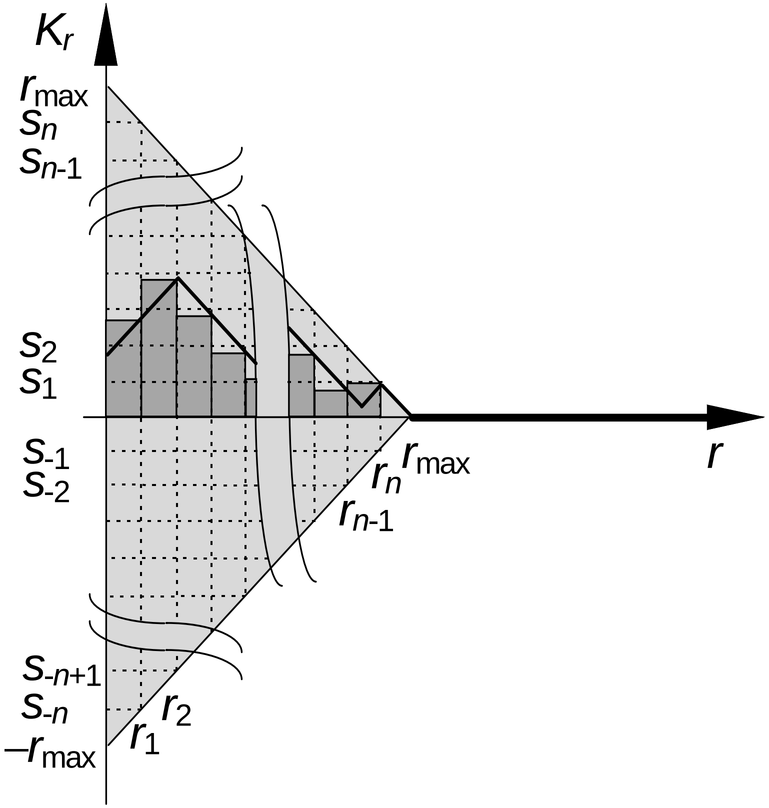
Conditions for dissipation

$$\begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{pmatrix} \cdot \begin{pmatrix} w_{K0} \\ w_{K1} \\ \vdots \\ w_{Kn} \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix} \geq \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

$$\mathbf{U}_K \cdot \mathbf{w}_K - \mathbf{u}_K \geq \mathbf{o}$$

$$C[x,\boldsymbol{z}_{K0}(r)](t) := w_{K0}(L[x,\boldsymbol{z}_{L0}](t)) + \int_{0}^{+\infty} w_K(K_r[x,\boldsymbol{z}_{K0}(r)](t),r)\,\mathrm{d}r$$

$$\lim_{\dot{x}(t)\to 0} C[x,\boldsymbol{z}_{K0}(r)](t) = R[x,z_{H0}(r)](t)$$



Threshold-discrete approximation

$$C_{\delta}[x,\boldsymbol{Z}_{K0}](t) = \sum_{i=0}^{n} w_{Ki}(K_{r_i}[x,\boldsymbol{z}_{K0i}](t))$$

$$C_{\delta\delta}[x,\boldsymbol{Z}_{K0}](t) = \sum_{i=0}^{n}\sum_{j=-n+i}^{+n-i} w_{Sij} S_{s_j}(K_{r_i}[x,\boldsymbol{z}_{K0i}](t)) = \boldsymbol{w}_C^T \cdot \boldsymbol{C}_{\boldsymbol{rs}}[x,\boldsymbol{Z}_{K0}](t)$$

Conditions for inversion and dissipation

$$\begin{pmatrix} \boldsymbol{U}_{S0} & \boldsymbol{O} & \cdots & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{U}_{S1} & \cdots & \boldsymbol{O} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{O} & \boldsymbol{O} & \cdots & \boldsymbol{U}_{Sn} \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{w}_{S0} \\ \boldsymbol{w}_{S1} \\ \vdots \\ \boldsymbol{w}_{Sn} \end{pmatrix} - \begin{pmatrix} \boldsymbol{o} \\ \boldsymbol{o} \\ \vdots \\ \boldsymbol{o} \end{pmatrix} \geq \begin{pmatrix} \boldsymbol{o} \\ \boldsymbol{o} \\ \vdots \\ \boldsymbol{o} \end{pmatrix}$$

$$\boldsymbol{U}_C \cdot \boldsymbol{w}_C - \boldsymbol{u}_C \geq \boldsymbol{o}$$

Prandtl-Ishlinskii creep extension

$$H_{K\delta}[x,\boldsymbol{z}_{H0},\boldsymbol{Z}_{K0}](t) := H_{\delta}[x,\boldsymbol{z}_{H0}](t) + K_{\delta}[x,\boldsymbol{Z}_{K0}](t) = \begin{pmatrix} \boldsymbol{w}_H^T & \boldsymbol{w}_K^T \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{H}_{\boldsymbol{r}}[x,\boldsymbol{z}_{H0}](t) \\ \boldsymbol{K}_{\boldsymbol{r}}[x,\boldsymbol{Z}_{K0}](t) \end{pmatrix}$$

$$= \boldsymbol{w}_{HK}^T \cdot \boldsymbol{H}_{K\boldsymbol{r}}[x,\boldsymbol{z}_{H0},\boldsymbol{Z}_{K0}](t)$$

$$\begin{pmatrix} \boldsymbol{U}_H & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{U}_K \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{w}_H \\ \boldsymbol{w}_K \end{pmatrix} - \begin{pmatrix} \boldsymbol{u}_H \\ \boldsymbol{u}_K \end{pmatrix} \geq \begin{pmatrix} \boldsymbol{o} \\ \boldsymbol{o} \end{pmatrix} \Rightarrow \boldsymbol{U}_{HK} \cdot \boldsymbol{w}_{HK} - \boldsymbol{u}_{HK} \geq \boldsymbol{o}$$

Preisach creep extension

$$R_{C\delta\delta}[x,\boldsymbol{z}_{H0},\boldsymbol{Z}_{K0}](t) := R_{\delta\delta}[x,\boldsymbol{z}_{H0}](t) + C_{\delta\delta}[x,\boldsymbol{Z}_{K0}](t) = \begin{pmatrix} \boldsymbol{w}_R^T & \boldsymbol{w}_C^T \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{R}_{\boldsymbol{rs}}[x,\boldsymbol{z}_{H0}](t) \\ \boldsymbol{C}_{\boldsymbol{rs}}[x,\boldsymbol{Z}_{K0}](t) \end{pmatrix}$$

$$= \boldsymbol{w}_{RC}^T \cdot \boldsymbol{R}_{C\boldsymbol{rs}}[x,\boldsymbol{z}_{H0},\boldsymbol{Z}_{K0}](t)$$

$$\begin{pmatrix} \boldsymbol{U}_R & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{U}_C \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{w}_R \\ \boldsymbol{w}_C \end{pmatrix} - \begin{pmatrix} \boldsymbol{u}_R \\ \boldsymbol{u}_C \end{pmatrix} \geq \begin{pmatrix} \boldsymbol{o} \\ \boldsymbol{o} \end{pmatrix} \Rightarrow \boldsymbol{U}_{RC} \cdot \boldsymbol{w}_{RC} - \boldsymbol{u}_{RC} \geq \boldsymbol{o}$$

$$H_\delta[x, \boldsymbol{z}_{H0}](t) = \boldsymbol{w}_H^T \cdot \boldsymbol{H}_{\boldsymbol{r}}[x, \boldsymbol{z}_{H0}](t)$$

$$\boldsymbol{U}_H \cdot \boldsymbol{w}_H - \boldsymbol{u}_H \geq \boldsymbol{o}$$

	↓	↑
Weight mapping:	$\boldsymbol{w}'_H = \Phi_H(\boldsymbol{w}_H)$	$\boldsymbol{w}_H = \Phi_H(\boldsymbol{w}'_H)$
Threshold mapping:	$\boldsymbol{r}' = \Psi_H(\boldsymbol{w}_H, \boldsymbol{r})$	$\boldsymbol{r} = \Psi_H(\boldsymbol{w}'_H, \boldsymbol{r}')$
Initial state mapping:	$\boldsymbol{z}'_{H0} = \Theta_H(\boldsymbol{w}_H, \boldsymbol{z}_{H0})$	$\boldsymbol{z}_{H0} = \Theta_H(\boldsymbol{w}'_H, \boldsymbol{z}'_{H0})$

$$H_\delta^{-1}[y, \boldsymbol{z}'_{H0}](t) = \boldsymbol{w}'^T_H \cdot \boldsymbol{H}_{\boldsymbol{r}'}[y, \boldsymbol{z}'_{H0}](t)$$

$$H_{K\delta}[x,\boldsymbol{z}_{H0},\boldsymbol{Z}_{K0}](t) := H_{\delta}[x,\boldsymbol{z}_{H0}](t) + K_{\delta}[x,\boldsymbol{Z}_{K0}](t) = \boldsymbol{w}_{HK}{}^{T}\cdot \boldsymbol{H}_{K\boldsymbol{r}}[x,\boldsymbol{z}_{H0},\boldsymbol{Z}_{K0}](t)$$

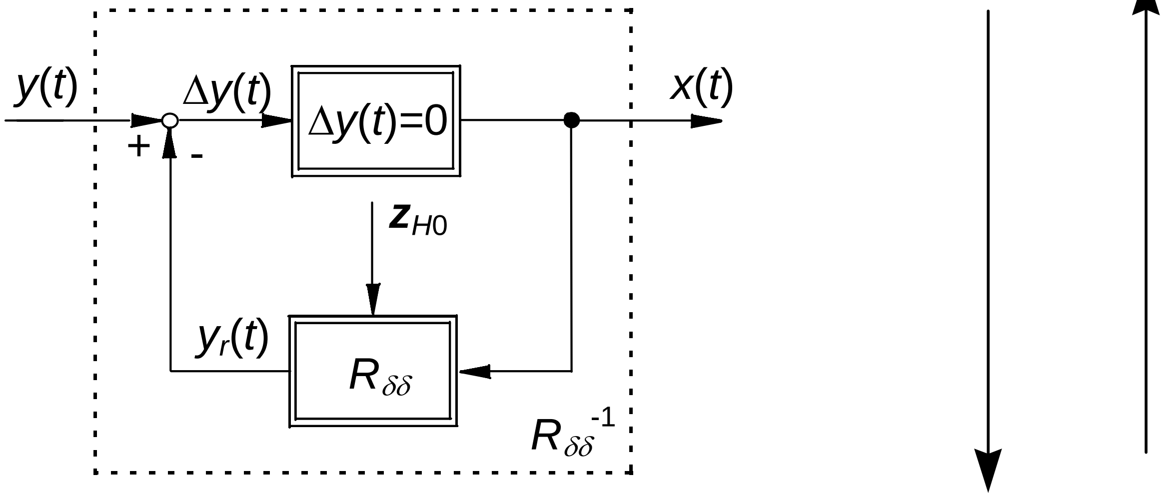
$$\boldsymbol{U}_{HK}\cdot \boldsymbol{w}_{HK} - \boldsymbol{u}_{HK} \geq \boldsymbol{o}$$

Weight mapping:	$\boldsymbol{w}'_{H} = \Phi_{H}(\boldsymbol{w}_{H})$	↓ ↑	$\boldsymbol{w}_{H} = \Phi_{H}(\boldsymbol{w}'_{H})$
Threshold mapping:	$\boldsymbol{r}' = \Psi_{H}(\boldsymbol{w}_{H},\boldsymbol{r})$		$\boldsymbol{r} = \Psi_{H}(\boldsymbol{w}'_{H},\boldsymbol{r}')$
Initial state mapping:	$\boldsymbol{z}'_{H0} = \Theta_{H}(\boldsymbol{w}_{H},\boldsymbol{z}_{H0})$		$\boldsymbol{z}_{H0} = \Theta_{H}(\boldsymbol{w}'_{H},\boldsymbol{z}'_{H0})$

$$H_{K\delta}^{-1}[y,\boldsymbol{z}'_{H0},\boldsymbol{Z}'_{K0}](t) \Leftrightarrow x(t) = H_{\delta}^{-1}[y - K_{\delta}[x,\boldsymbol{Z}_{K0}],\boldsymbol{z}'_{H0}](t) = \boldsymbol{w}'_{H}{}^{T}\cdot \boldsymbol{H}_{\boldsymbol{r}'}[y - \boldsymbol{w}_{K}^{T}\cdot \boldsymbol{K}_{\boldsymbol{r}}[x,\boldsymbol{Z}_{K0}],\boldsymbol{z}'_{H0}](t)$$

$$R_{\delta\delta}[x,\boldsymbol{z}_{H0}](t) = \boldsymbol{w}_R^T \cdot \boldsymbol{R_{rs}}[x,\boldsymbol{z}_{H0}](t)$$

$$\boldsymbol{U}_R \cdot \boldsymbol{w}_R - \boldsymbol{u}_R \geq \boldsymbol{o}$$



$$R_{\delta\delta}^{-1}[y,\boldsymbol{z}'_{H0}](t)$$

$$\Updownarrow$$

$$y(t) - \boldsymbol{w}_R{}^T \cdot \boldsymbol{R_{rs}}[x,\boldsymbol{z}_{H0}](t) = 0$$

$$R_{C\delta\delta}[x,\boldsymbol{z}_{H0},\boldsymbol{Z}_{K0}](t) := R_{\delta\delta}[x,\boldsymbol{z}_{H0}](t) + C_{\delta\delta}[x,\boldsymbol{Z}_{K0}](t) = \boldsymbol{w}_{RC}{}^{T} \cdot \boldsymbol{R}_{C\boldsymbol{rs}}[x,\boldsymbol{z}_{H0},\boldsymbol{Z}_{K0}](t)$$

$$\boldsymbol{U}_{RC} \cdot \boldsymbol{w}_{RC} - \boldsymbol{u}_{RC} \geq \boldsymbol{o}$$

$$R_{C\delta\delta}^{-1}[y,\boldsymbol{z}'_{H0},\boldsymbol{Z}'_{K0}](t) \Leftrightarrow x(t) = R_{\delta\delta}^{-1}[y - C_{\delta\delta}[x,\boldsymbol{Z}_{K0}],\boldsymbol{z}'_{H0}](t)$$

$$\Updownarrow$$

$$x(t) = R_{\delta\delta}^{-1}[y - \boldsymbol{w}_{C}{}^{T} \cdot \boldsymbol{C}_{\boldsymbol{rs}}[x,\boldsymbol{Z}_{K0}],\boldsymbol{z}'_{H0}](t)$$

Error model: $E[x](t,y(t),\boldsymbol{w}_R) := R_{\delta\delta}[x,\boldsymbol{z}_{H0}](t) - y(t) = \boldsymbol{w}_R{}^T \cdot \boldsymbol{R_{rs}}[x,\boldsymbol{z}_{H0}](t) - y(t)$

Cost function: $V(\boldsymbol{w}_R) = \frac{1}{2}\int_{t_0}^{t_E} E^2[x](t,y(t),\boldsymbol{w}_R)\mathrm{d}t = \frac{1}{2}\boldsymbol{w}_R^T \cdot \boldsymbol{A}_R \cdot \boldsymbol{w}_R + \boldsymbol{b}_R^T \cdot \boldsymbol{w}_R + c_R$

$$\boldsymbol{A}_R = +\int_{t_0}^{t_E} \boldsymbol{R_{rs}}[x,\boldsymbol{z}_{H0}](t)\boldsymbol{R_{rs}}^T[x,\boldsymbol{z}_{H0}](t)\mathrm{d}t \qquad \boldsymbol{b}_R = -\int_{t_0}^{t_E} y(t)\boldsymbol{R_{rs}}[x,\boldsymbol{z}_{H0}](t)\mathrm{d}t \qquad c_R = +\frac{1}{2}\int_{t_0}^{t_E} y^2(t)\mathrm{d}t$$

1. Step

$$r_i = \frac{i}{n+1}\max_{t_0 \le t \le t_E}\{|x(t)|\}$$
$$s_i = \frac{i}{n+1}\max_{t_0 \le t \le t_E}\{|x(t)|\}$$
$$z_{H0i} = 0$$

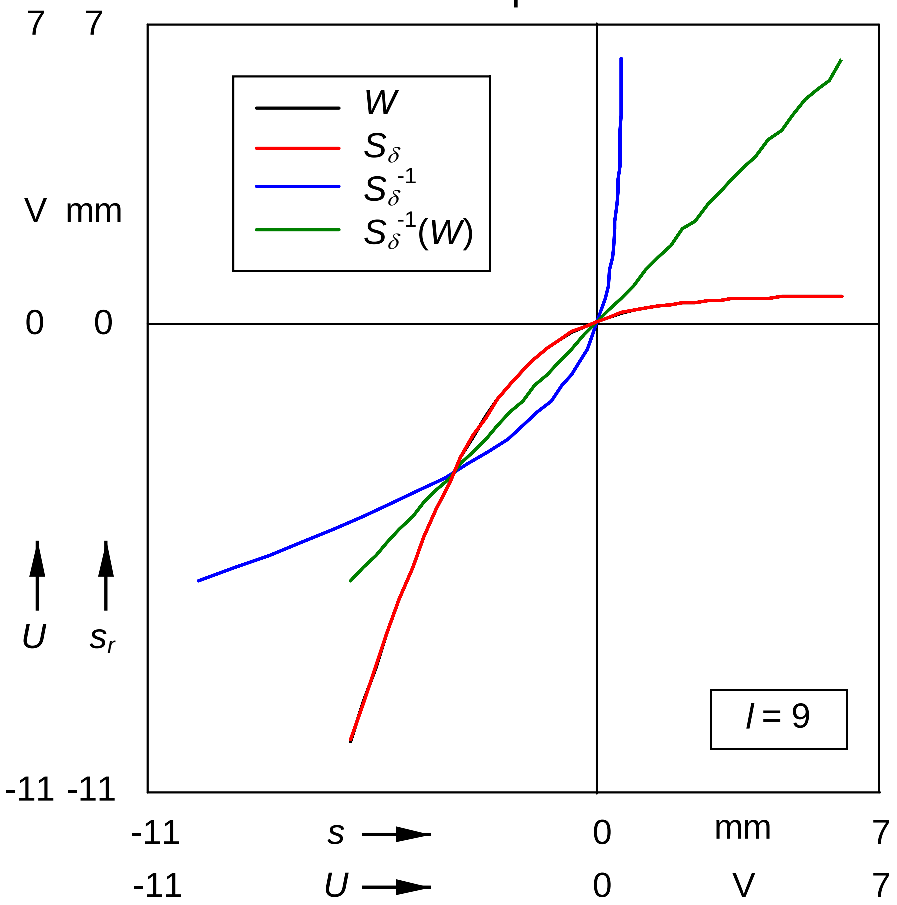
2. Step

$$\arg\min\{V(\boldsymbol{w}_R)\}$$
u.B.v.
$$\boldsymbol{U}_R \cdot \boldsymbol{w}_R - \boldsymbol{u}_R \ge \boldsymbol{o}$$

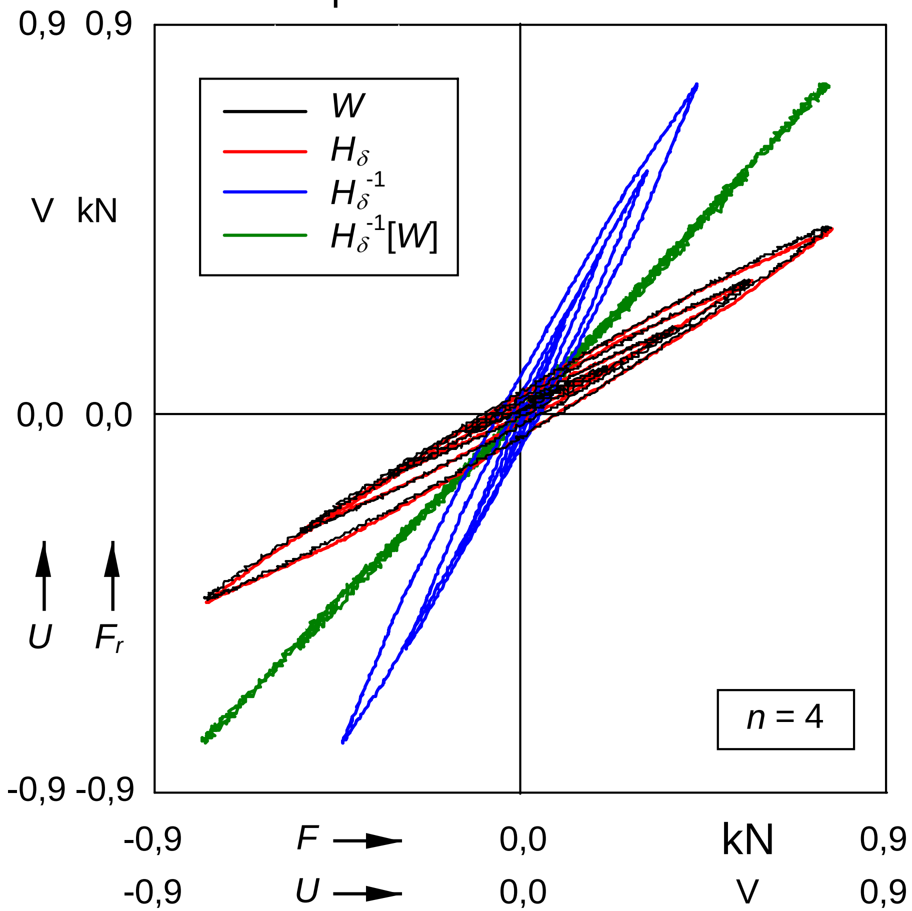
3. Step

Numerical inversion

Memoryless nonlinearity
of an inductive position sensor



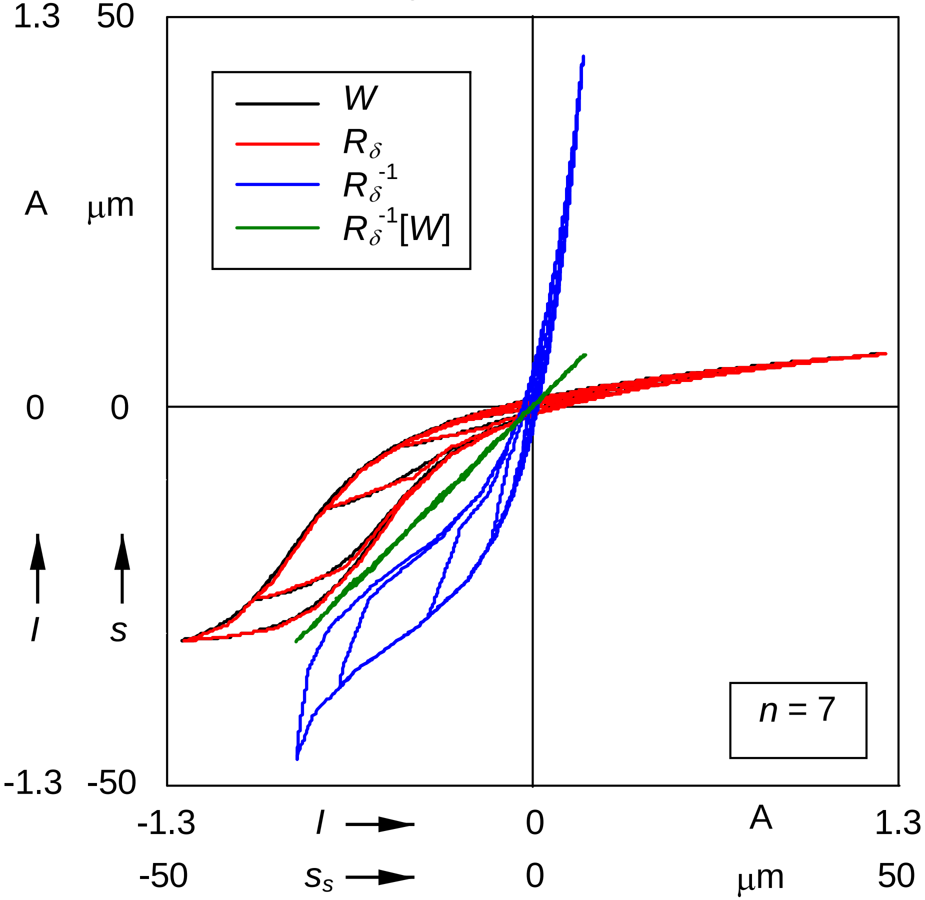
Prandtl-Ishlinskii-type hysteretic nonlinearity
of a piezoelectric force sensor



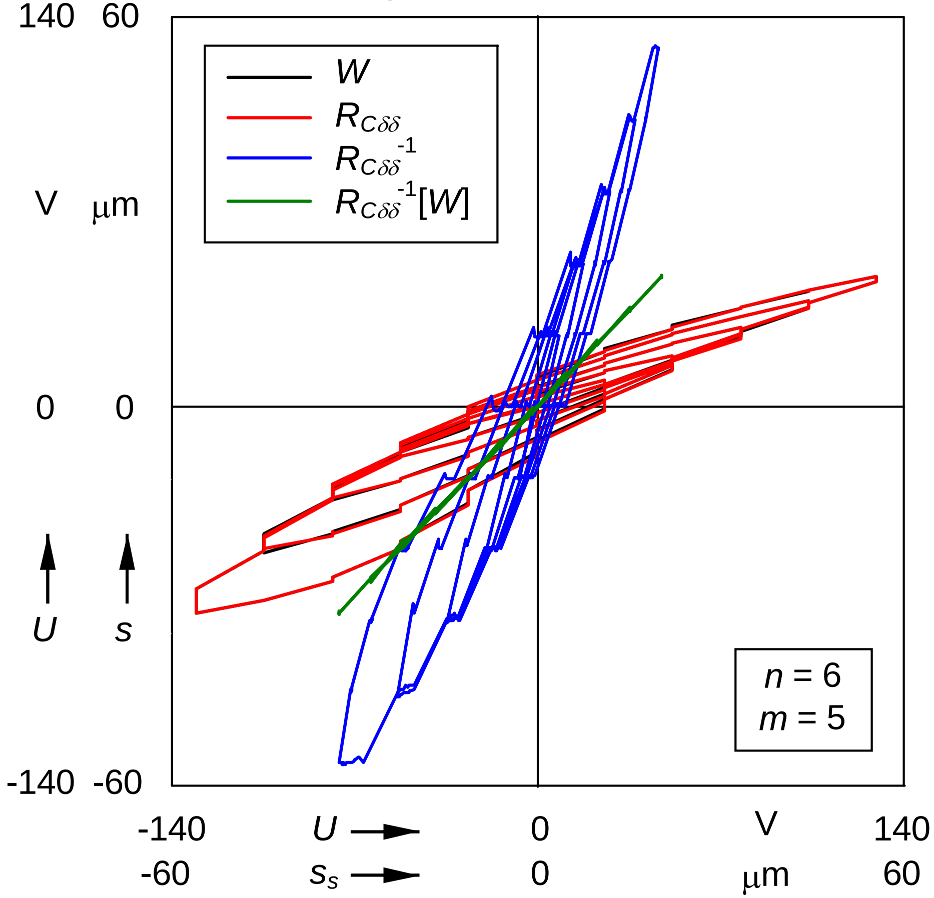
$$e_{S_\delta} = \frac{\|S_\delta(s) - U\|_\infty}{\|S_\delta(s)\|_\infty} = 0{,}3\%(57\%)$$

$$e_{H_\delta} = \frac{\|H_\delta[F,\mathbf{z}_{H0}] - U\|_\infty}{\|H_\delta[F,\mathbf{z}_{H0}]\|_\infty} = 5{,}1\%(12{,}8\%)$$

Preisach-type hysteretic nonlinearity of a magnetostrictive actuator

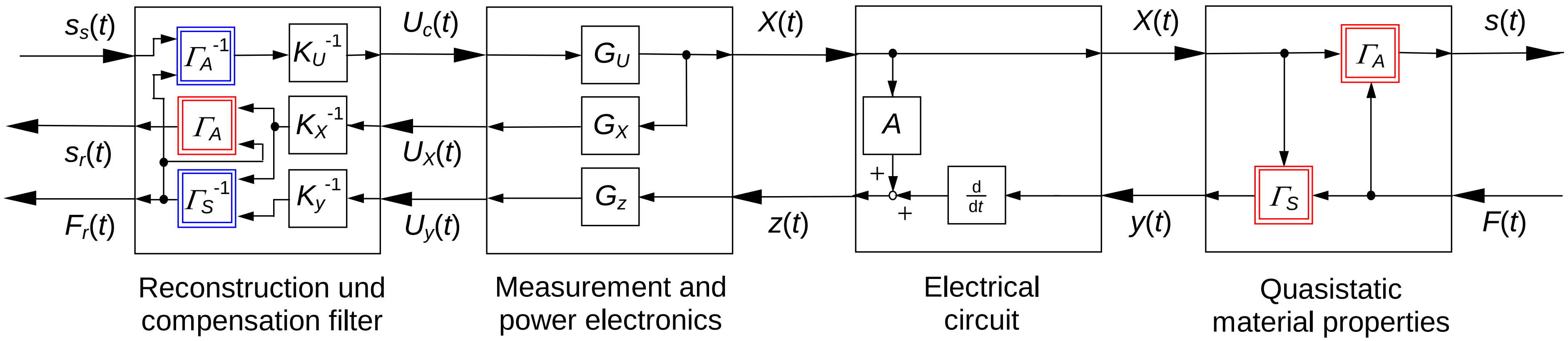


Preisach-type memory nonlinearity of a piezoelectric actuator



$$e_{R_\delta} = \frac{\left\|R_\delta[I,\mathbf{z}_{H0}]-s\right\|_\infty}{\left\|R_\delta[I,\mathbf{z}_{H0}]\right\|_\infty} = 2{,}2\%(78{,}9\%)$$

$$e_{R_{C\delta\delta}} = \frac{\left\|R_{C\delta\delta}[U,\mathbf{z}_{H0},\mathbf{Z}_{K0}]-s\right\|_\infty}{\left\|R_{C\delta\delta}[U,\mathbf{z}_{H0},\mathbf{Z}_{K0}]\right\|_\infty} = 1{,}7\%(39{,}6\%)$$



$$F_r(t) = \Gamma_S^{-1}[K_X^{-1}U_X, K_y^{-1}U_y](t) \qquad U_X(t) = G_X[X](t) \qquad U(t), I(t) \Rightarrow X(t) \qquad z(t) = \dot{y}(t) + AX(t)$$

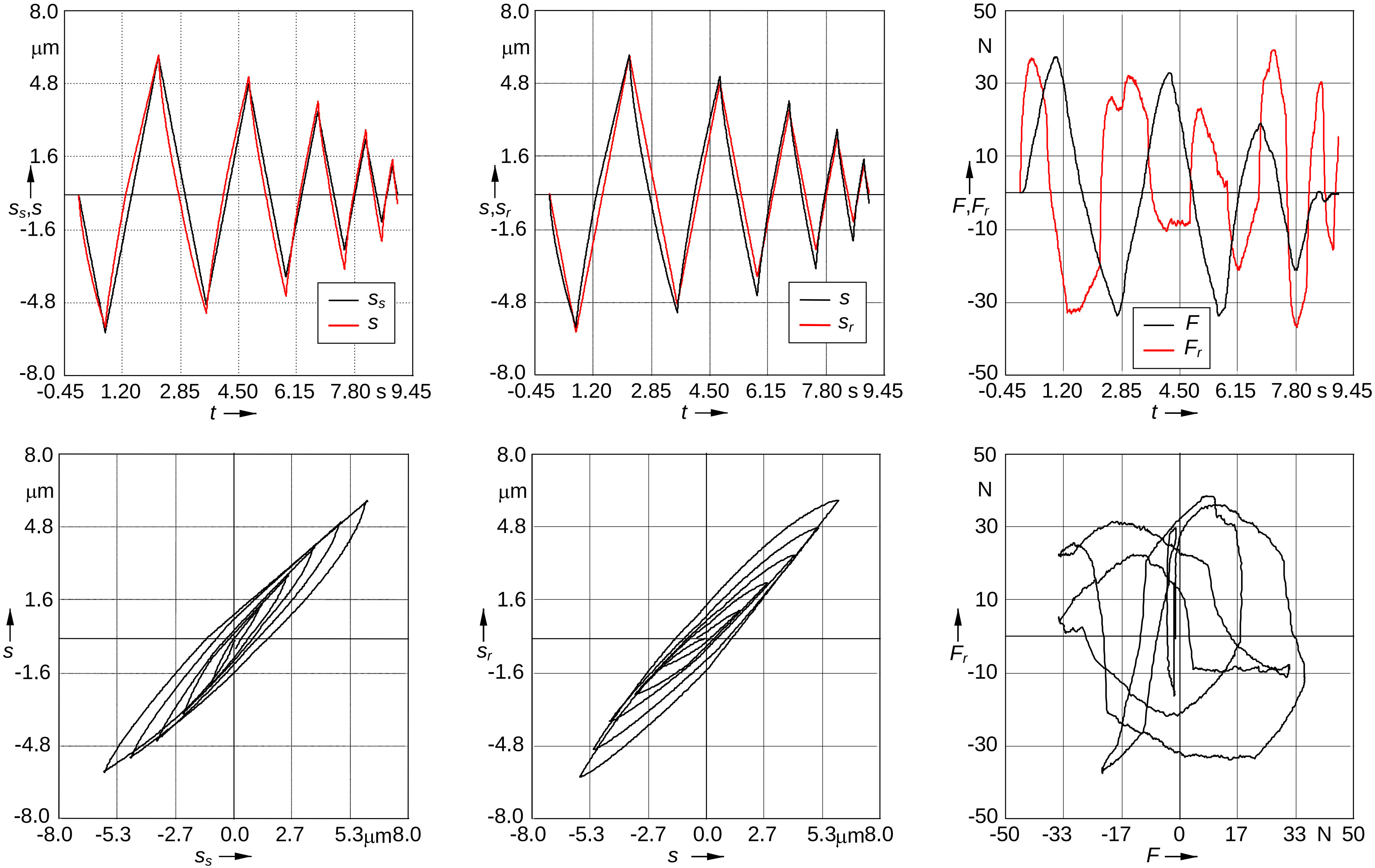
$$s_r(t) = \Gamma_A[K_X^{-1}U_X, F_r](t) \qquad U_y(t) = G_z[z](t) \qquad q(t), \psi(t) \Rightarrow y(t) \qquad y(t) = \Gamma_S[X,F](t)$$

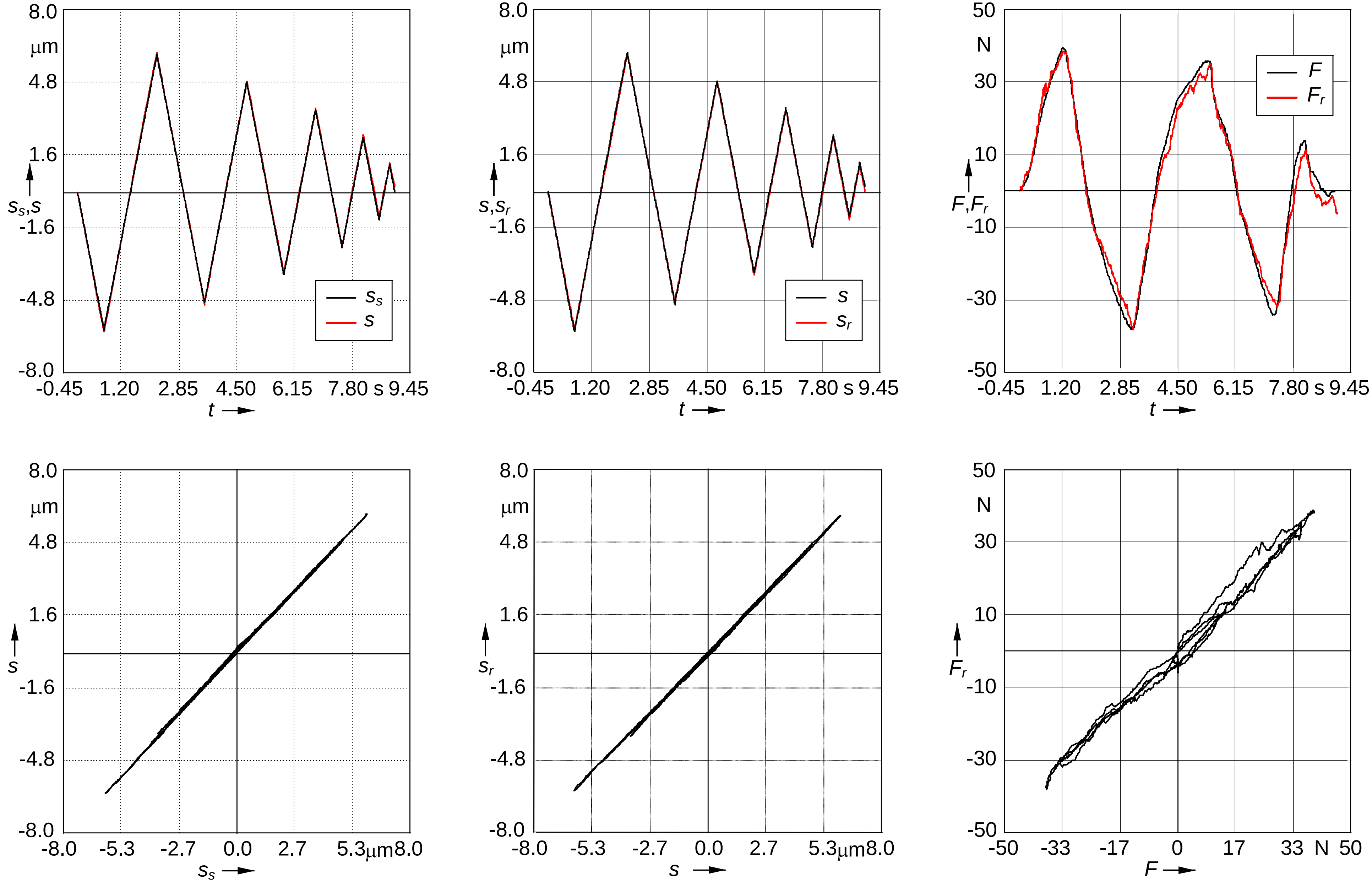
$$U_C(t) = K_U^{-1}\Gamma_A^{-1}[s_s, F_r](t) \qquad X(t) = G_U[U_C](t) \qquad i(t), u(t) \Rightarrow z(t) \qquad s(t) = \Gamma_A[X,F](t)$$

$$G, R \Rightarrow A$$

$$\Downarrow$$

$$\begin{pmatrix} F_r(t) \\ s_r(t) \\ s(t) \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} F(t) \\ s(t) \\ s_s(t) \end{pmatrix}$$


8.0
μm
4.8
1.6
s_s,s
-1.6
-4.8
-8.0
-0.45 1.20 2.85 4.50 6.15 7.80 s 9.45
t
s_s
s
s,s_r
s_r
50
N
30
10
F,F_r
-10
-30
-50
F
F_r
-8.0 -5.3 -2.7 0.0 2.7 5.3 μm 8.0
-50 -33 -17 0 17 33 N 50


8.0
μm
4.8
1.6
-1.6
-4.8
-8.0
s_s, s
t
-0.45 1.20 2.85 4.50 6.15 7.80 s 9.45
s_s
s
s, s_r
s
s_r
50
N
30
10
-10
-30
-50
F, F_r
F
F_r
-8.0 -5.3 -2.7 0.0 2.7 5.3 μm 8.0
s_r
-50 -33 -17 0 17 33 N 50

1. Self-learning and Adaptive Compensators for Complex Memory Nonlinearities

2. Realisation of Compensators with FPGA’s for high-speed Applications

3. Integration into high-performance control strategies for mechatronic components

Thank you for your attention

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