A UNIFIED MODEL FOR HYSTERESIS IN FERROIC MATERIALS

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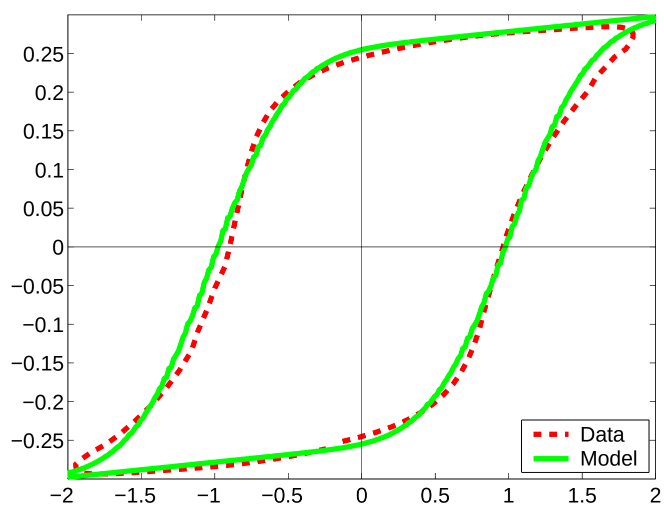

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TALK OVERVIEW

I. Smart Material Applications

- Piezoelectrics – Tunable lenses, nanopositioning
- Shape Memory Alloys – Shape modification
- Magnetostrictives – High force transduction

II. Modeling Hierarchies

- Develop energy relations at lattice level for single crystal, homogeneous compounds.
- Incorporate polycrystallinity and material nonhomogeneities through stochastic homogenization to obtain macroscopic constitutive relations.

III. Experimental Validation

- PZT5A – Major and biased minor loops
- Terfenol-D – Major and biased minor loops
- SMA – Thin film

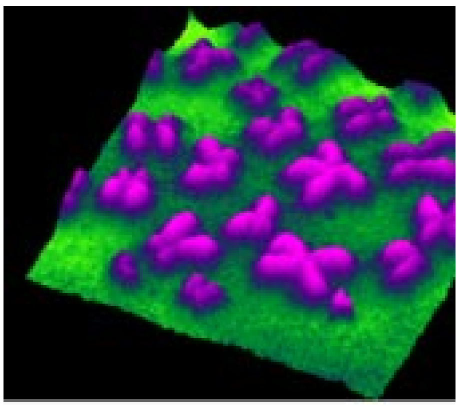
Goal:

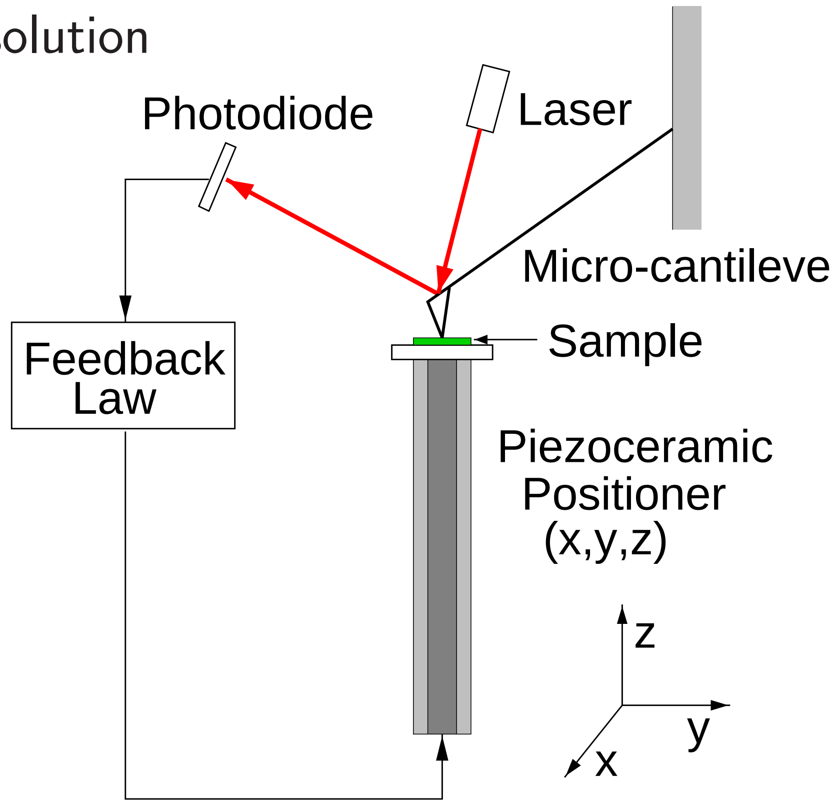
- Develop a unified framework for model and control design for ferroic (ferromagnetic, ferroelectric and ferroelastic) materials.

I. PIEZOCERAMICS – NANOPOSITIONING

Atomic Force Microscope:

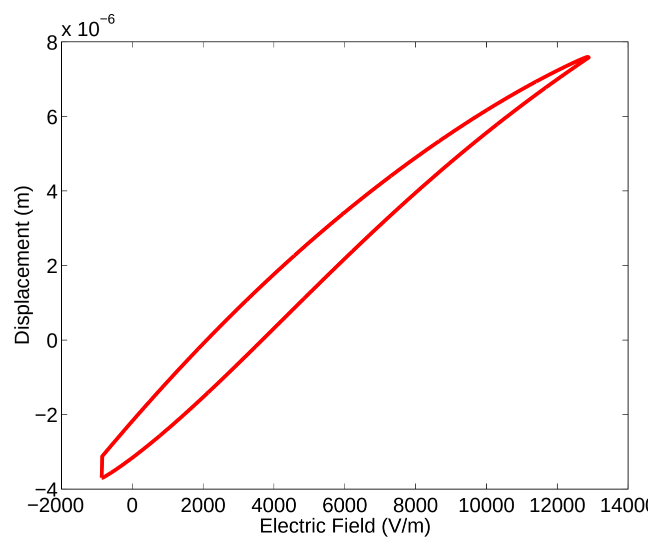
- Can provide atomic resolution
- Human chromosomes





Model Development:

- Must be able to attain Angstrom-level resolution
- Must be implemented in real time



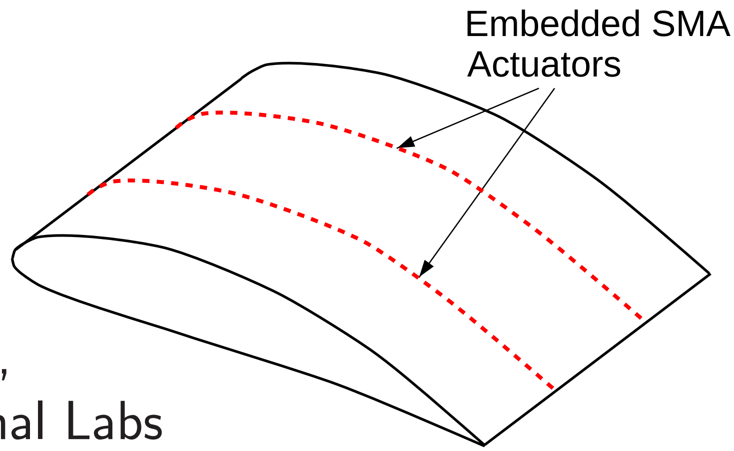
Future Capabilities:

- Nanopositioning at the atomic level
- Electron spin detection: requires angstrom-level tracking

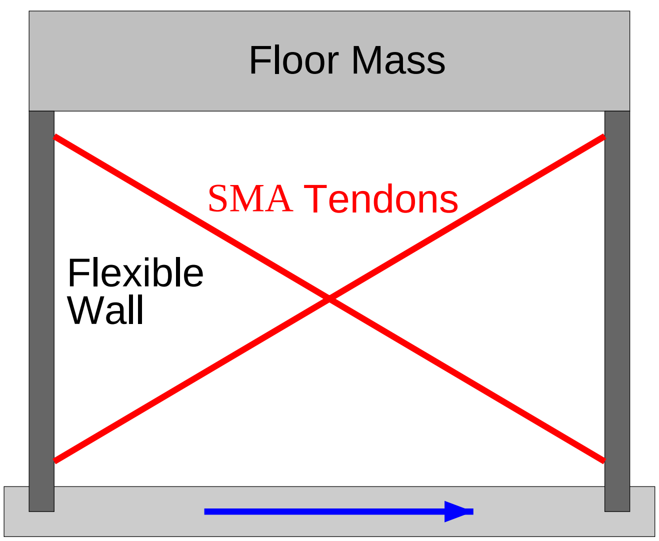
SHAPE MEMORY ALLOYS

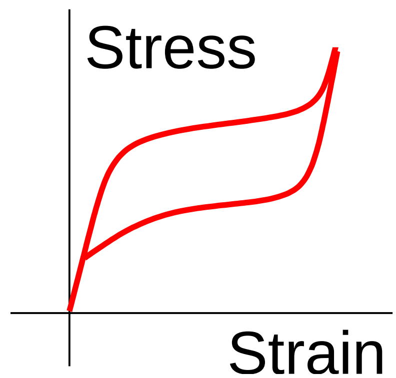
Aerospace and Aeronautic Applications:

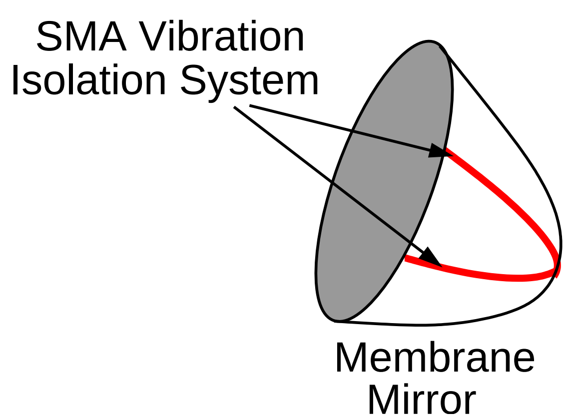
- Shape modification of airfoils
- Construction of modular mirrors and antennas
- Future Directions: MEM's, thin films – Sandia National Labs



Vibration Attenuation:







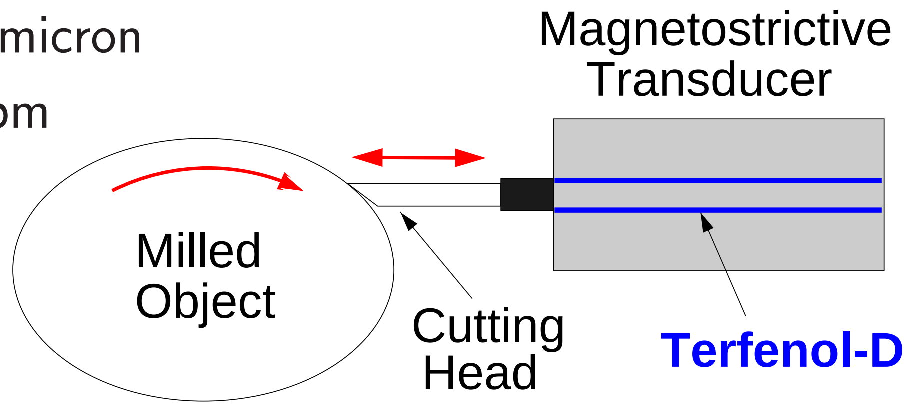
Strategy:

- Vibration attenuation in aerospace structures (e.g., mirrors)
- Operate in hysteretic regime to optimize damping

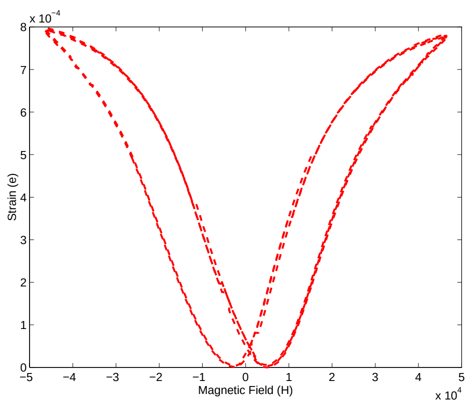
MAGNETOSTRICTIVE MATERIALS

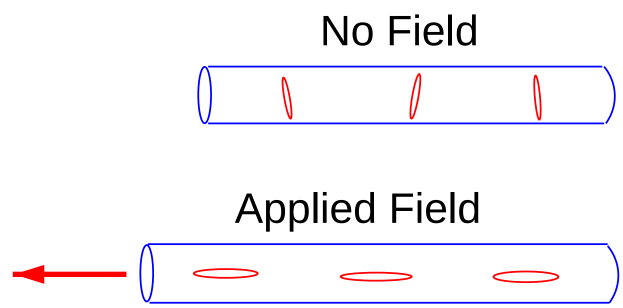
Automotive Application: e.g., High speed milling

- Accuracy: ± 1 micron
- Speed: 3000 rpm



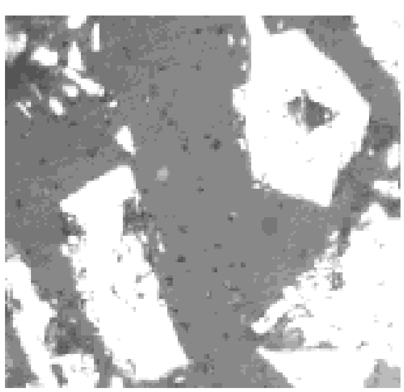
Field-Strain Relation

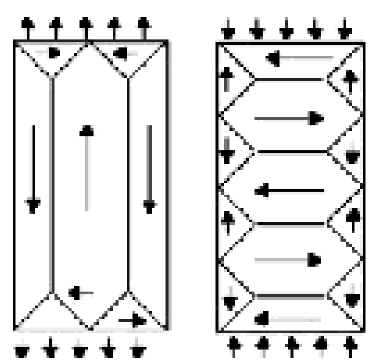




Aerospace Applications:

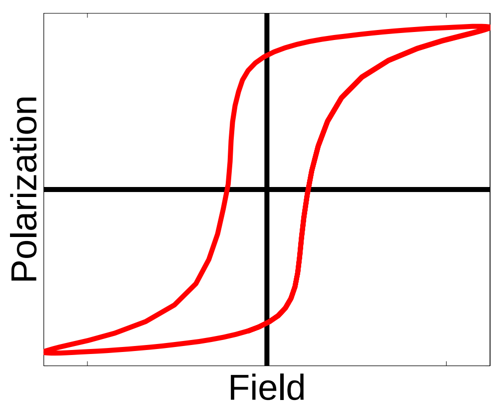
- Magnetostrictive composites for active structural damping

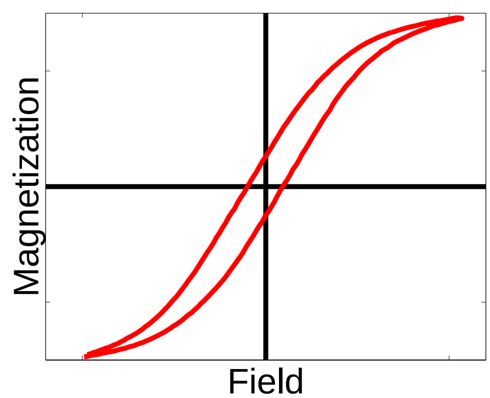


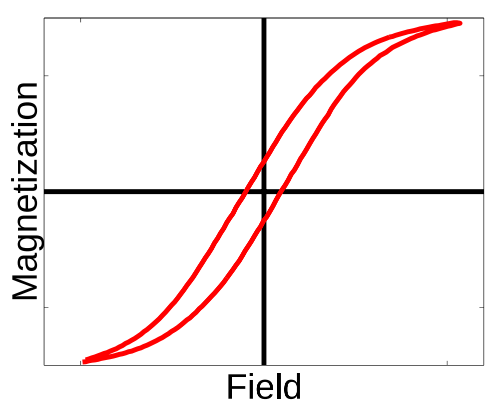


MATERIAL ANALOGIES

Ferroelectric	Ferromagnetic	Ferroelastic
Polarization	Magnetization	Strain
Electric field	Magnetic field	Stress
Paraelectric phase	Paramagnetic phase	Austenite phase
Ferroelectric phase	Ferromagnetic phase	Martensite phase
Ferroelectric domain walls	Bloch or Neel walls	Boundaries between martensite variants
Devonshire theory	Mean field (Weiss) theory	Landau theory
	Micromagnetic theory	Ginzburg-Landau theory

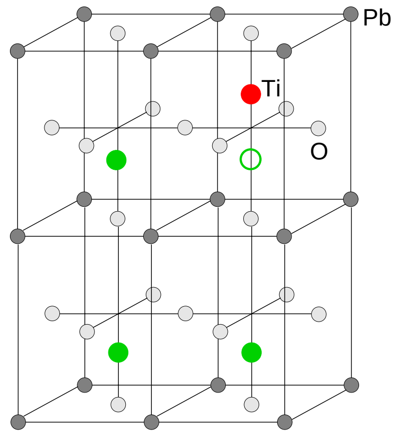


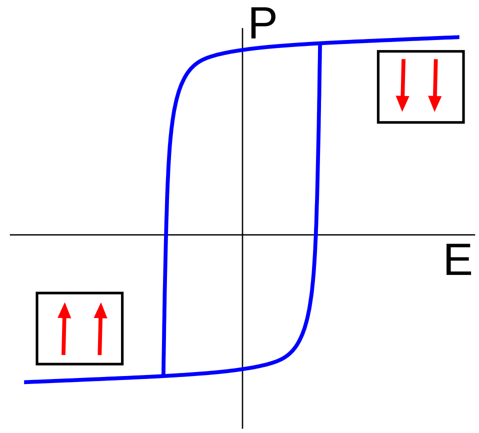




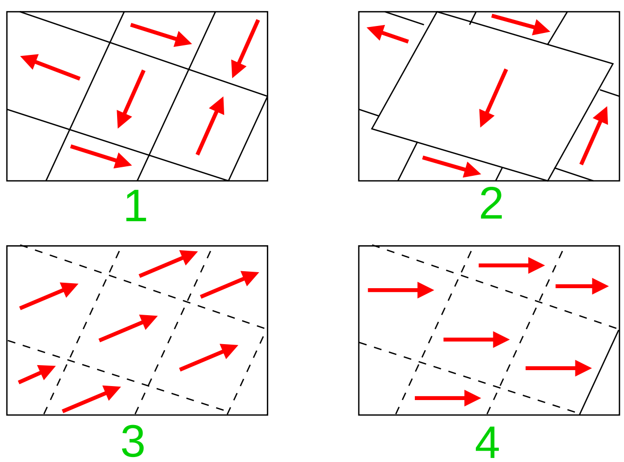
MECHANISMS WHICH PRODUCE HYSTERESIS

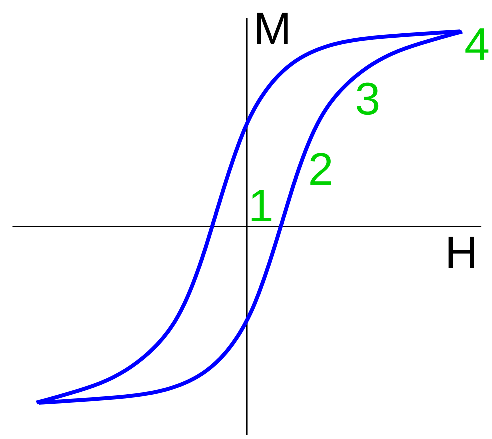
Ferroelectric: Dipole switching



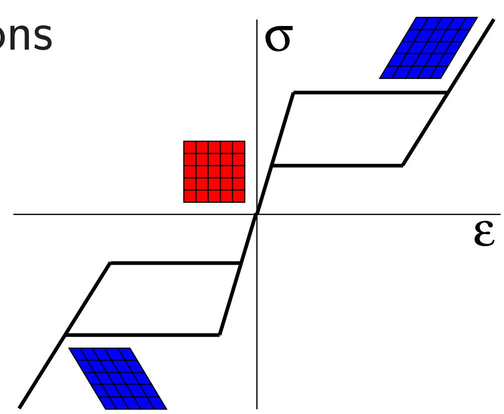


Ferromagnetic: Moment rotation, domain wall losses

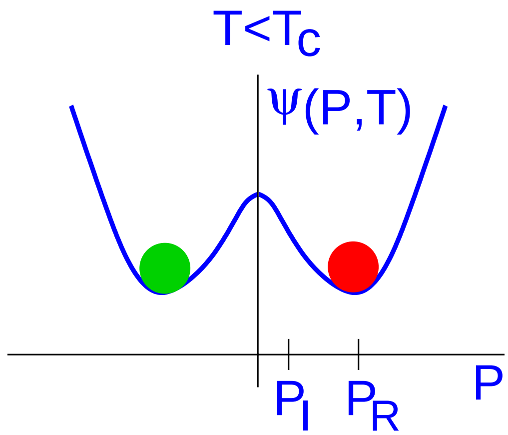


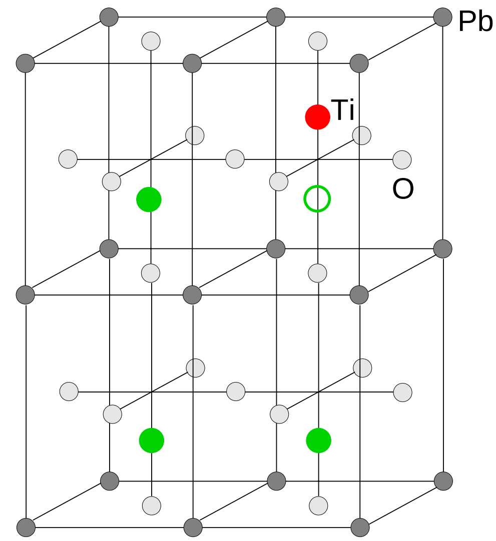


Ferroelastic: Phase transitions



MESOSCOPIC MODEL – HELMHOLTZ ENERGY





Helmholtz Energy:

$$\psi(P,T) = U - ST$$

$$= \frac{\Phi_0 N}{4V}[1-(P/P_s)^2] + \frac{TkN}{2VP_s}\left[P\ln\left(\frac{P+P_s}{P_s-P}\right) + P_s\ln(1-(P/P_s)^2)\right]$$

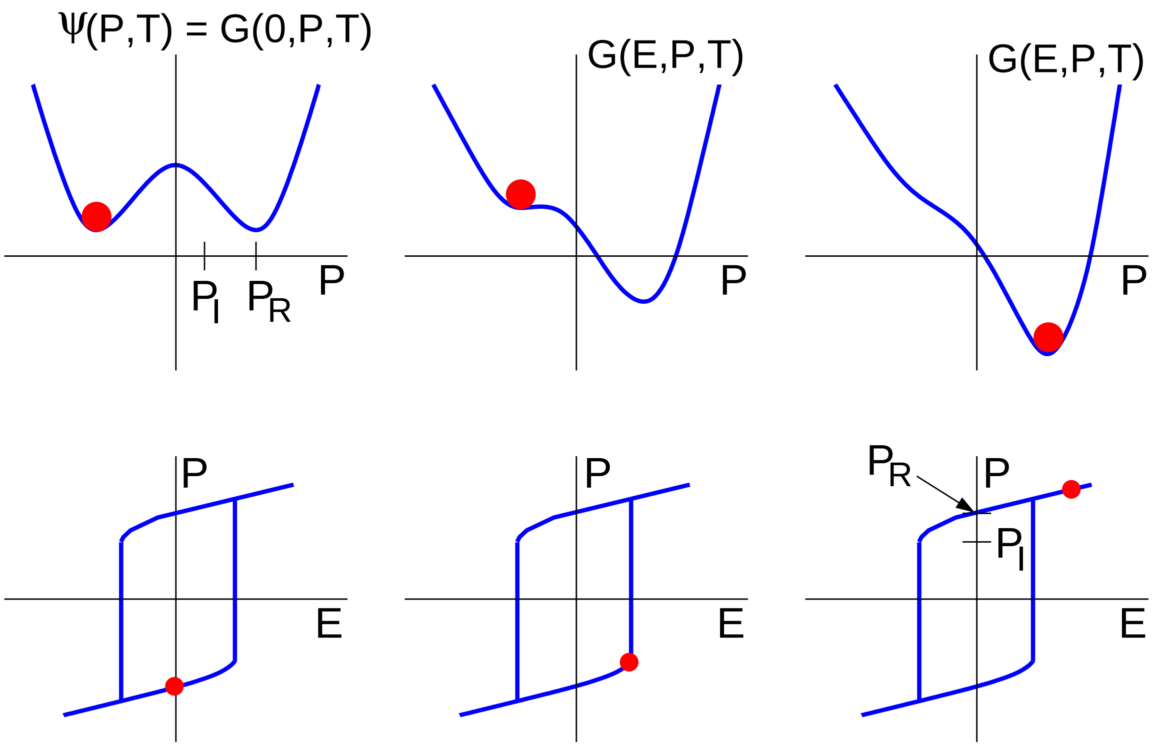
Helmholtz Energy Relations:

$$\psi(P) = \begin{cases} \frac{\eta}{2}(P \pm P_R)^2 & , \ |P| \geq P_I \\ \frac{\eta}{2}(P_I - P_R)\left[\frac{P^2}{P_I} - P_R\right] & , \ |P| < P_I \end{cases}$$

$$\psi(M) = \begin{cases} \frac{\eta}{2}(M \pm M_R)^2 & , \ |M| \geq M_I \\ \frac{\eta}{2}(M_I - M_R)\left[\frac{M^2}{M_I} - M_R\right] & , \ |M| < M_I \end{cases}$$

$$\psi(\varepsilon,T) = \begin{cases} \frac{E_M}{2}(\varepsilon \pm \varepsilon_T)^2 & , \ |\varepsilon| \geq \gamma_M(T) \\ -\frac{E_0(T)}{2}[\varepsilon \pm \varepsilon_0(T)]^2 + \psi_0(T) & , \ |\gamma_A(T)| < \varepsilon < |\gamma_M(T)| \\ \frac{E_A}{2}\varepsilon^2 + \Delta\beta(T) & , \ |\varepsilon| \leq \gamma_A(T) \end{cases}$$

MESOSCOPIC MODEL – GIBBS ENERGY



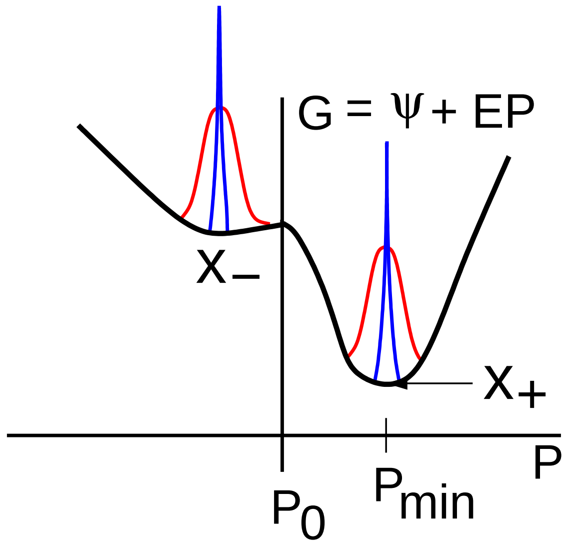
Gibbs Energy Relations:

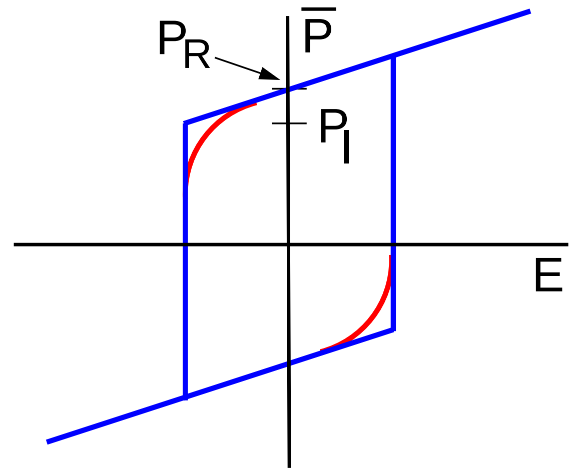
$G(E,P,T) = \psi(P,T) - EP$ (Ferroelectric)

$G(H,M,T) = \psi(M,T) - \mu_0 HM$ (Ferromagnetic)

$G(\sigma,\varepsilon,T) = \psi(\varepsilon,T) - \sigma\varepsilon$ (Ferroelastic)

MESOSCOPIC MODELS – UNIFORM LATTICE





Boltzmann Probability:

$$\mu(G) = Ce^{-GV/kT} \;\Rightarrow\; p_{+-} = \sqrt{\frac{kT}{2\pi m V^{2/3}}} \cdot \frac{e^{-G(E,P_0(T),T)V/kT}}{\int_{P_0}^{\infty} e^{-G(E,P,T)V/kT} dP}$$

Evolution Relations:

$$\frac{dx_+}{dt} = -p_{+-}x_+ + p_{-+}x_-$$

$$\frac{dx_-}{dt} = -p_{-+}x_- + p_{+-}x_+$$

Ferroelastic: Analogous

Polarization:

$$\overline{P} = x_+ \langle P_+ \rangle + x_- \langle P_- \rangle$$

where

$$\langle P_+ \rangle = \int_{P_0}^{\infty} P\mu(G)dP$$

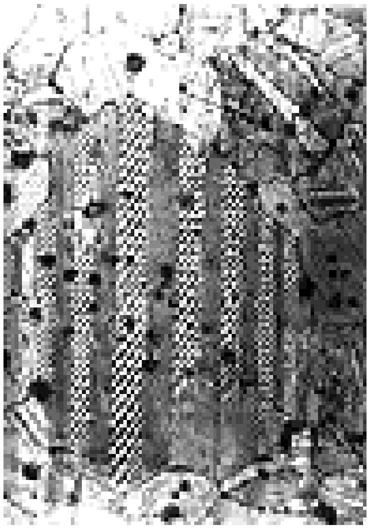
Magnetization:

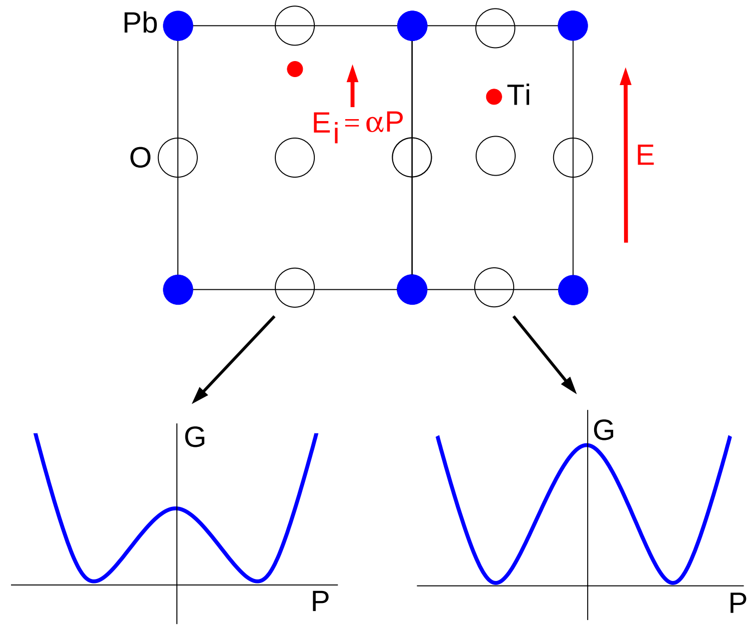
$$\overline{M} = x_+ \langle M_+ \rangle + x_- \langle M_- \rangle$$

where

$$\langle M_+ \rangle = \int_{M_0}^{\infty} M\mu(G)dM$$

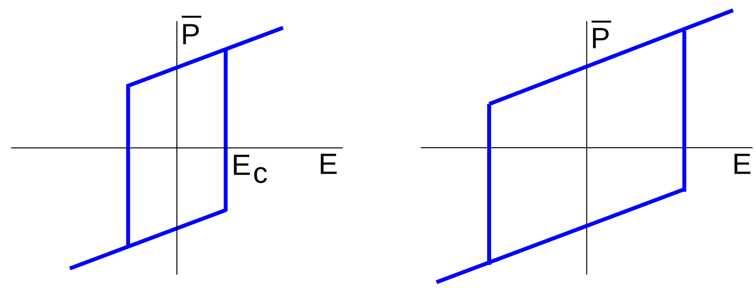
MACROSCOPIC MODELS





Nonuniform Lattice:

$$f(E_c) = C_1 e^{-[\ln(E_c/\overline{E}_c)/2b]^2}$$



Variable Effective Fields:

$$\widehat{f}(\mathcal{E}) = C_2 e^{-(\mathcal{E}-E)^2/\bar{b}}$$

Macroscopic Models:

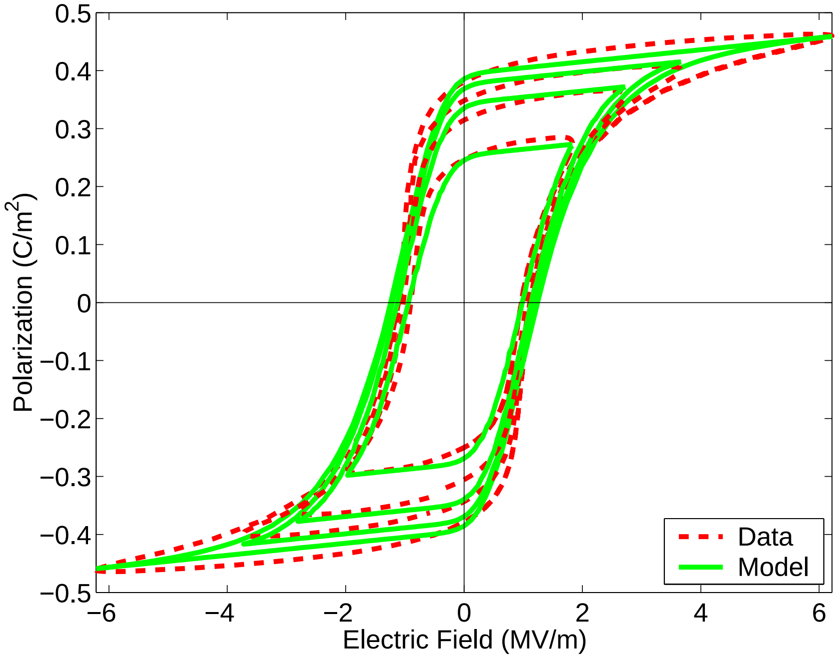
$$[P(E,T)](t) = C \int_0^\infty \int_{-\infty}^\infty f(E_c) \widehat{f}(\mathcal{E}) [\overline{P}(\mathcal{E}+E,T)](t) d\mathcal{E} dE_c$$

$$[M(H,T)](t) = C \int_0^\infty \int_{-\infty}^\infty f(H_c) \widehat{f}(\mathcal{H}) [\overline{M}(\mathcal{H}+H,T)](t) d\mathcal{H} dH_c$$

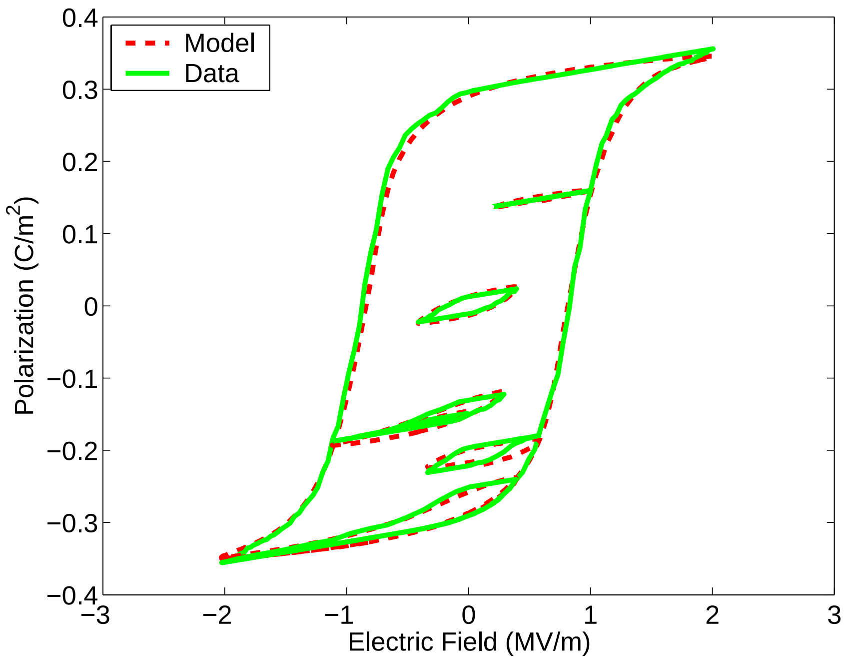
$$[\varepsilon(\sigma,T)](t) = C \int_0^\infty \int_{-\infty}^\infty f(\delta) \widehat{f}(\sigma_E) [\overline{\varepsilon}(\sigma_E+\sigma,T)](t) d\sigma_E d\delta$$

III. EXPERIMENTAL VALIDATION

PZT5A: Lognormal/normal densities

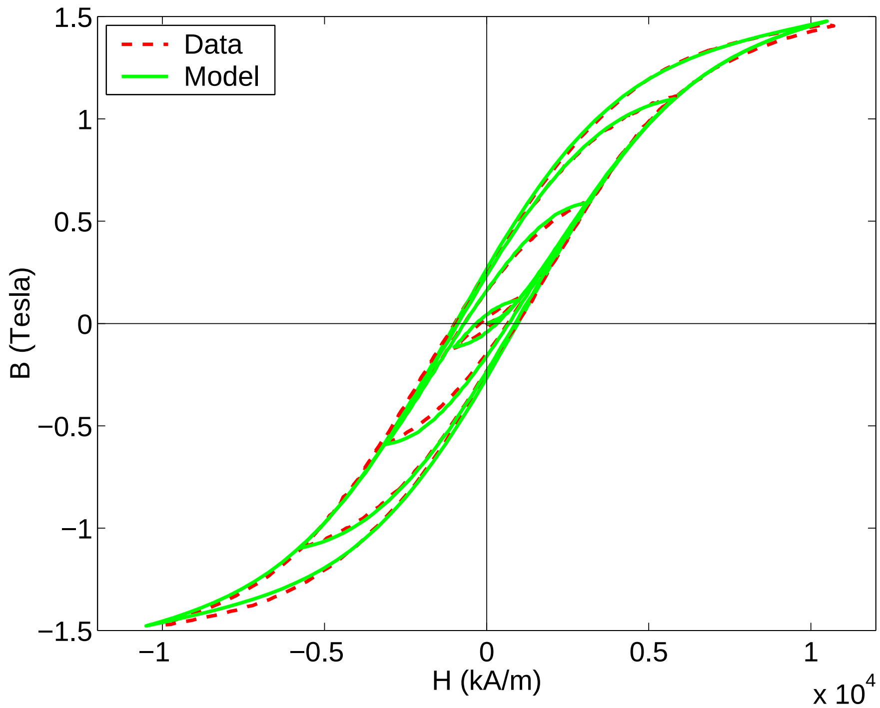


PZT5A: ID of general densities [B. Mukherjee, S-F. Liu - Data]

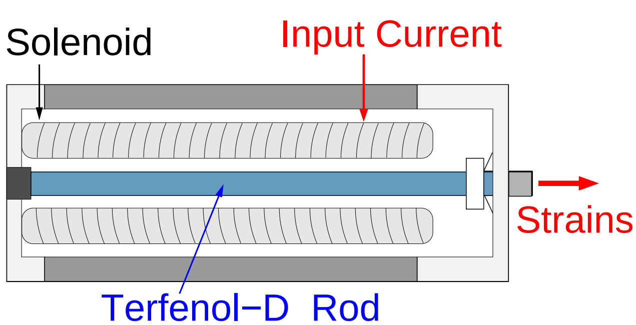


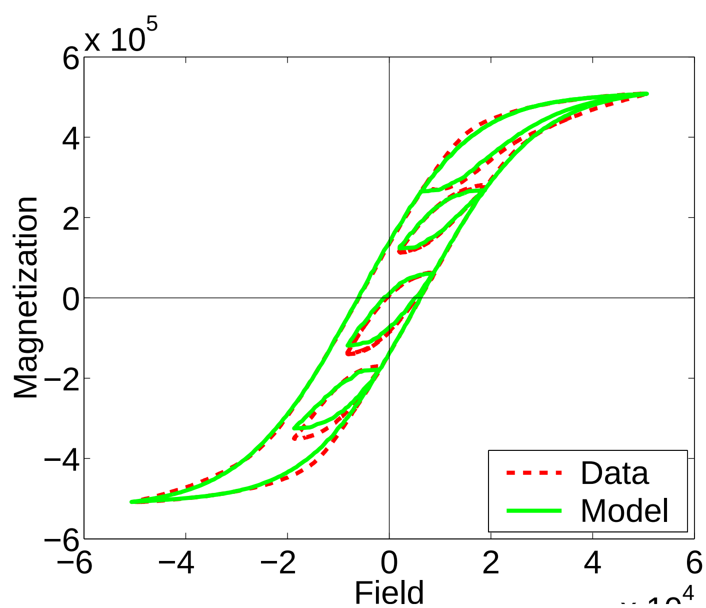
VALIDATION – FERROMAGNETIC MATERIALS

Example 1: Steel data from [Jiles and Atherton; 1984]



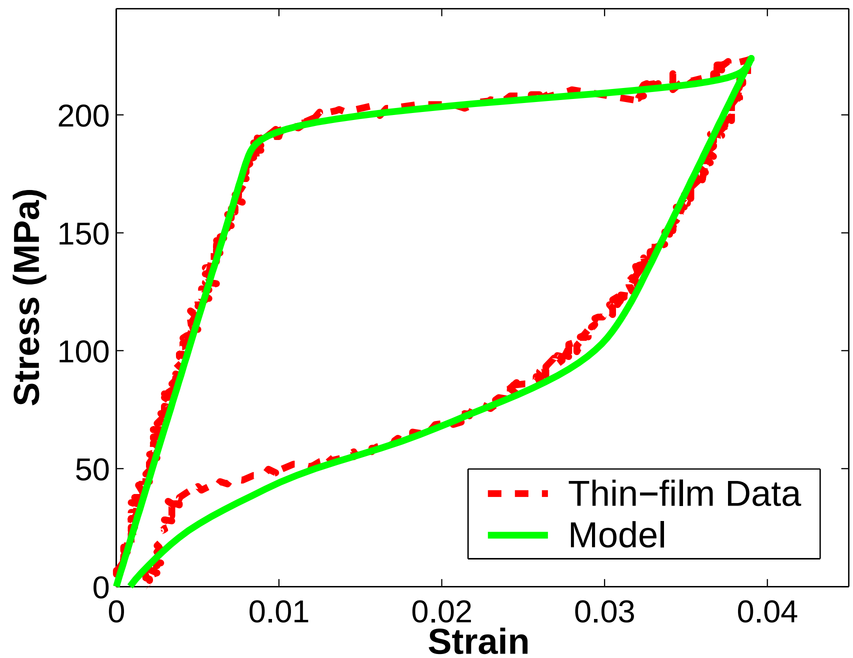
Example 2: Terfenol-D Transducer





EXPERIMENTAL VALIDATION – SMA

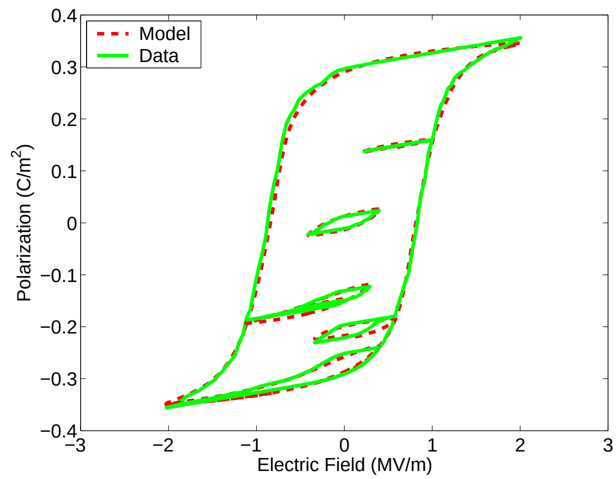
Thin Films:



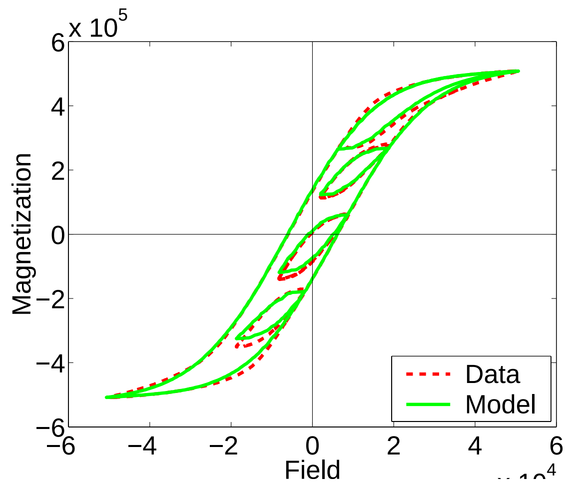
CONCLUDING REMARKS

Model Attributes:

(1) Technique provides unified framework for modeling hysteresis in ferroelectric, ferromagnetic and ferroelastic materials.

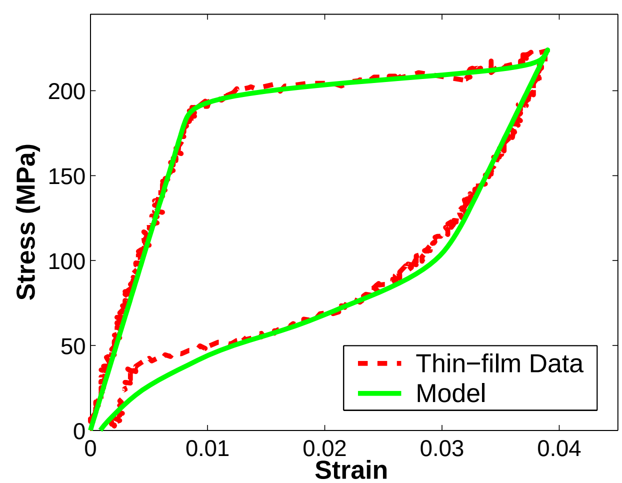


(2) Low number (5-10) and physical nature of parameters facilitates parameter estimation and control implemen mentation.



(3) Model guarantees closure of biased minor loops.

(4) Model is amenable to inversion which facilitates linear control design.



(5) Method provides energy basis for Preisach models.

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