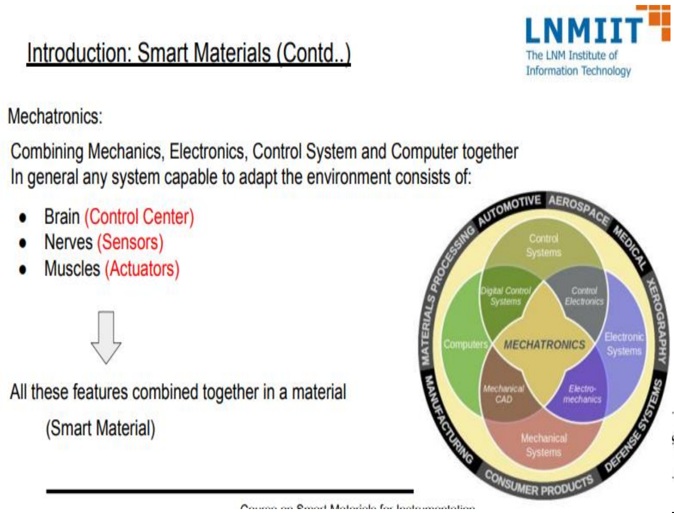
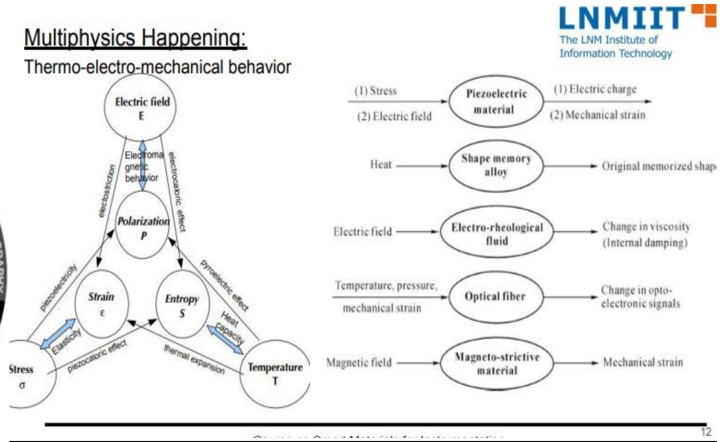




Skin ● Integrated Sensors and Actuators ● Local response to external stimuli: change of color, sweat etc. ● Self healing ● **Cell Walls** ● Change of permeability with electric fields and molecules ● Selective to the choice of molecule allowed through the wall ● **Abalone** ● Known for high toughness natural composite with hard and brittle ceramic plate embedded in protein ● Self healing Other examples: Course on Smart Materials for Instrumentation 6 ● **Thermochromic Pigments** ● Made from liquid crystal ● Changes color when heated ● **Shape Memory Alloys** ● Can be deformed and restore shape when heated ● **Pseudoelastic alloys** ● Change in elasticity when deformed and then restore back to original shape ● Respond to environment in which they are used ● Restore original state with restore of the environment (condition) "Smart Material can change their structure significantly under the influence of external stimuli" External Stimuli could be: ● Heat ● Mechanical Stress, Strain ● Electric Field ● Magnetic Field, etc. These changes result from several local phenomenon, and structural transformations

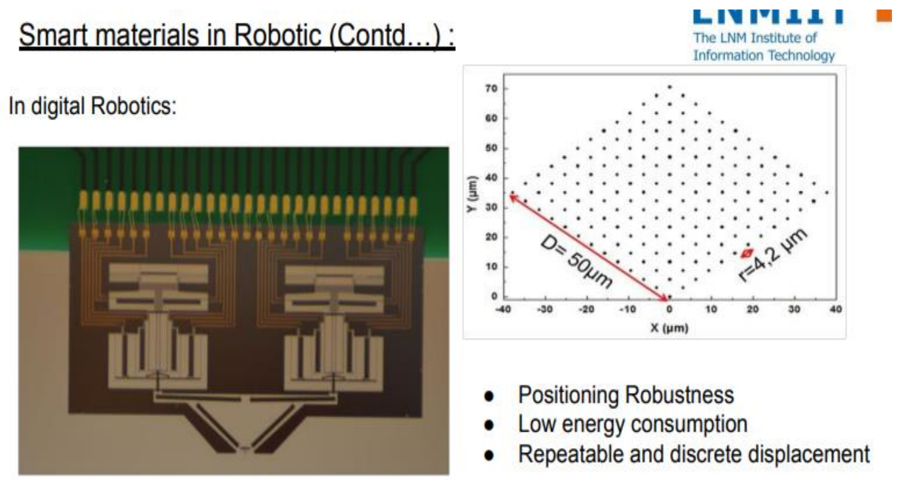
Piezoelectric : When subjected to an external stress, material will undergo potential difference development and vice versa. **Examples are**: Barium Titanate, Lithium Niobate, and Lead Zirconate Titanate (PZT) ● Typical applications are precise positioning and sensing system development.

Piezoresistive Materials: When subjected to an external stress, material will undergo change in electrical resistance. **Examples are**: Semiconductors, metals etc. ● Typical applications are stress/force sensing

Magnetostrictive Polymers Composites (MPC): Has capability to simultaneously change dimensions, elastic and/or electromagnetic properties when subjected to external magnetic field. Useful in the sensors and actuator development ● Examples are Cobalt Ferrite, Terfenol D etc.

Electroactive Polymers : Exhibits change in size and shape when subjected to electric field. Advantage of having large deformation and high force withstanding capability ● Applications are in tactile sensing, artificial muscles etc ● E.g stimuli responsive gels.

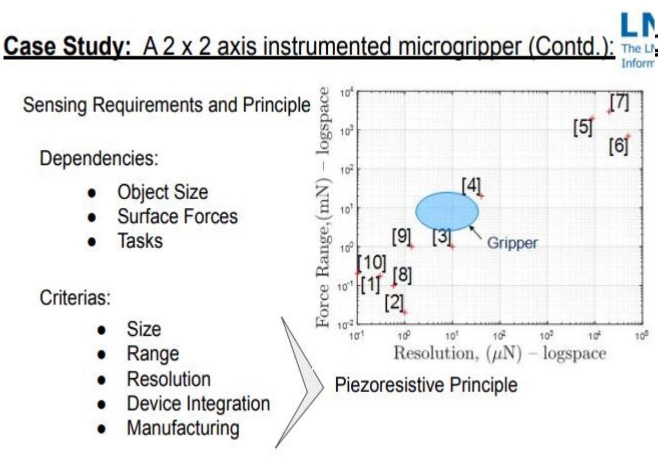
Mechanical use of Smart Materials: Actuation ● Sensing ● Energy Conservation

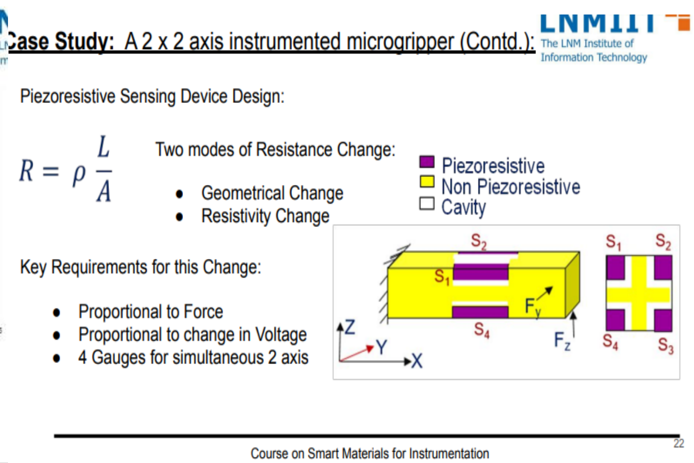


Case Study: A 2 x 2 axis instrumented microgripper: Requirements Type: ● Based on Actuation ● Based on Sensing.

Based on Actuation: ● A device with nanometric positioning resolution ● Should be able to withstand sufficient blocking force as per the task ● Should be capable to perform multi-DoF actuation ● Should be safe for the environment ● Should consume least possible energy for the operation ● Must be compatible with the sensing mechanism (to be employed).

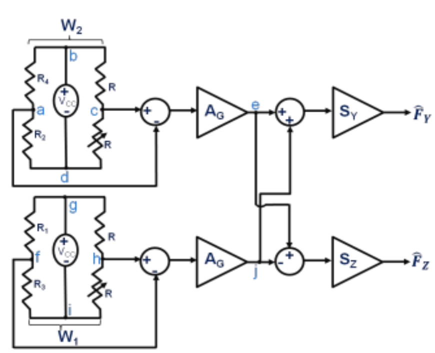
Requirements based on Sensing: Can sense typical order of force needed to grasp a micro-object (say 200 µm x 200 µm x 350 µm Si)- >to have capability to sense some µN ● To have force sensing capability up to the range so as to perform the manipulation and assembly (or aimed task)-> say some mN ● Should be capable to sense 2 DoF force simultaneously (both in gripping and out of gripping plane) ● Must not interfere with the actuation mechanism ● Should be environment friendly and easily integrable with the actuation





Piezoresistive Sensing Device Fabrication: Planar Fabrication + Assembly

Advantage of the Approach: ● Mass and Versatile Tool Production ● Minimized Fabrication Complexity

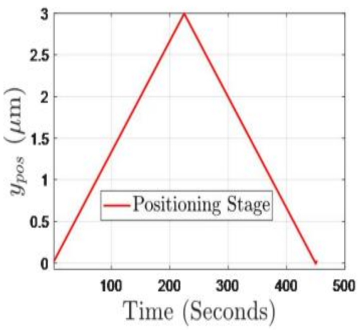


After the Device Fabrication and Integration: ●Characterization ● Calibration

Case Study: A 2 x 2 axis instrumented microgripper (Contd.):

The LNM Institute of Information Technology

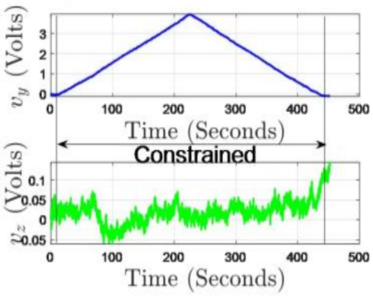
After the Device Fabrication and Integration:



Temperature, Humidity: Constant

y_{pos}: displacement positioning stage

v_y, v_z: voltage sensed along the Y and Z axis



After the Device Fabrication and Integration:

Gripping Plane — Out-of-gripping Plane

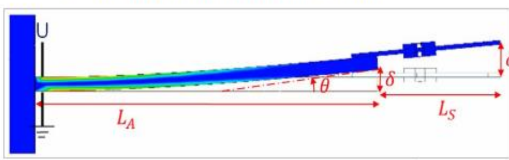
Parameters	Y	Z
Stiffness (N/m)	5130.3	2342.4
Sensitivity (μN/V)	2280	2390
Resolution (μN)	20	20
Standard deviation (μN)	28	22
Range (mN)	9	9

Case Study: A 2 x 2 axis instrumented microgripper (Contd.):

The LNM Institute of Information Technology

Gripper Tip position estimation:

- To avoid use of additional Sensors



δ: displacement of the actuator's tip

δ_S: PRT tip's displacement

k_{gs}: PRT Stiffness

F_S: force sensed by PRT

U: Input actuation voltage

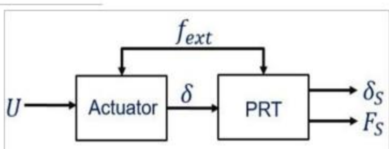
f_{ext}: External force at the PRT tip

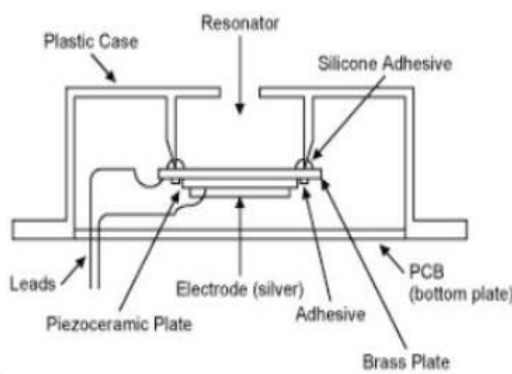
θ: Bending angle of the actuator

BW: Bouc-Wen Modeling

Assuming Circular Curvature:

$$\delta_S = \delta + L_s\theta - \frac{F_S}{k_{gs}}$$





Dielectrics without center of Symmetry:

LNMIIT The LNM Institute of Information Technology

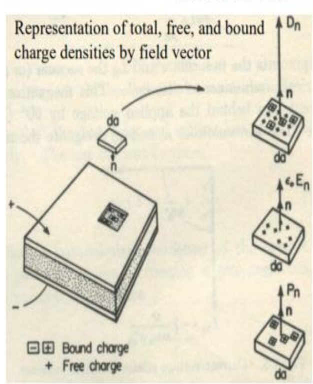
- Gauss Law for isotropic dielectric materials

$$\int_S D \cdot da = q$$

This explain why D is often called the charge density

- Electric dipoles result into polarization (P) which is equal to bound charge density

$$D = \varepsilon_o E + P$$



When applied stress results into polarization-> Direct Effect

$$P = d\,\sigma$$

When applied electric potential results into strain development-> Converse Effect

$$\varepsilon = d\,E$$

***P**- Polarization (C/m2)*

***σ**- stress (N/m2)*

***d**- Piezoelectric coefficient (C/N)*

***E**- Electric Field*

***ε**- strain*

Piezoelectric Constants ● **d** [C/N]-> charge developed per unit stress (applied) ● **g** [V-m/N]->Electric field developed per unit stress (applied) ● **h** [m/V] -> Strain developed per unit Electric field (applied) ● **e** [N/V-m]->Stress developed per unit Electric field (applied)

Electromechanical Coupling Coefficient (k) : ●Used for comparison of different piezoelectric materials ● Measure of electrical and mechanical energy interchange.

3D Expressions of Piezoelectric Effect:

- Piezoelectric Effect is orientation dependent
- P = d σ ->1 D

No electric Field

$$P_i=\sum_{k=1}^{6} d_{ik}\sigma_k \qquad \begin{bmatrix}P_1\\P_2\\P_3\end{bmatrix}=\begin{bmatrix}d_{11}&d_{12}&d_{13}&d_{14}&d_{15}&d_{16}\\d_{21}&d_{22}&d_{23}&d_{24}&d_{25}&d_{26}\\d_{31}&d_{32}&d_{33}&d_{34}&d_{35}&d_{36}\end{bmatrix}\begin{bmatrix}\sigma_1\\\sigma_2\\\sigma_3\\\sigma_4\\\sigma_5\\\sigma_6\end{bmatrix}$$

No stress

$$\begin{bmatrix}\varepsilon_1\\\varepsilon_2\\\varepsilon_3\\\varepsilon_4\\\varepsilon_5\\\varepsilon_6\end{bmatrix}=\begin{bmatrix}d_{11}&d_{21}&d_{31}\\d_{12}&d_{22}&d_{32}\\d_{13}&d_{23}&d_{33}\\d_{14}&d_{24}&d_{34}\\d_{15}&d_{25}&d_{35}\\d_{16}&d_{26}&d_{36}\end{bmatrix}\begin{bmatrix}E_1\\E_2\\E_3\end{bmatrix}$$

Polarization Stress Strain Electric Field

- i=1,2,3 axial; 4,5,6 for shear

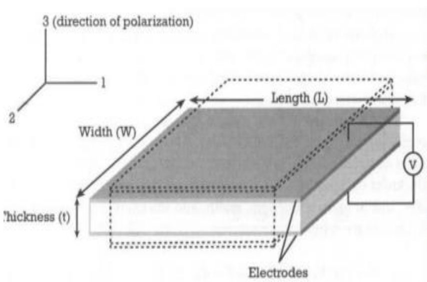
Piezoelectric Coefficient:

- Coefficient for PZT, $BaTiO_3$, $PbTiO_3$

$$P_i=\sum_{k=1}^{6} d_{ik}\sigma_k \qquad \varepsilon_k=\sum_{i=1}^{3}\tilde{d}_{ik}E_i$$

$$\begin{bmatrix}P_1\\P_2\\P_3\end{bmatrix}=\begin{bmatrix}0&0&0&0&d_{15}&0\\0&0&0&d_{15}&0&0\\d_{31}&d_{31}&d_{33}&0&0&0\end{bmatrix}\begin{bmatrix}\sigma_1\\\sigma_2\\\sigma_3\\\sigma_4\\\sigma_5\\\sigma_6\end{bmatrix} \qquad \begin{bmatrix}\varepsilon_1\\\varepsilon_2\\\varepsilon_3\\\varepsilon_4\\\varepsilon_5\\\varepsilon_6\end{bmatrix}=\begin{bmatrix}0&0&d_{31}\\0&0&d_{31}\\0&0&d_{33}\\0&d_{15}&0\\d_{15}&0&0\\0&0&0\end{bmatrix}\begin{bmatrix}E_1\\E_2\\E_3\end{bmatrix}$$

Piezoelectric Coefficient (Contd..):



With applied voltage across the plates

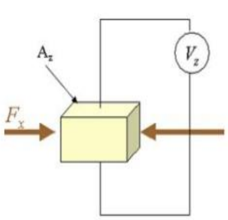
$$\Delta L=d_{31}\cdot V_3\cdot L/t,\quad \Delta w=d_{31}\cdot V_3\cdot w/t,\quad \Delta t=d_{33}\cdot V_3$$

With applied Force in length, width or thickness direction

$$V_3=d_{31}\cdot F_1/(\varepsilon_{11}\cdot L),\ V_3=d_{31}\cdot F_2/(\varepsilon_{11}\cdot w),$$
$$V_3=d_{33}\cdot F_3\cdot t/(\varepsilon_{33}\cdot L\cdot w)$$

- An applied voltage across the electrodes results into dimensional changes in all three axes.
- Conversely an applied force in any of the three directions gives rise to measurable voltage across the electrodes

---



- With external force application ; crystal gets diformed and centre of the positive and negative charges also gets displaced

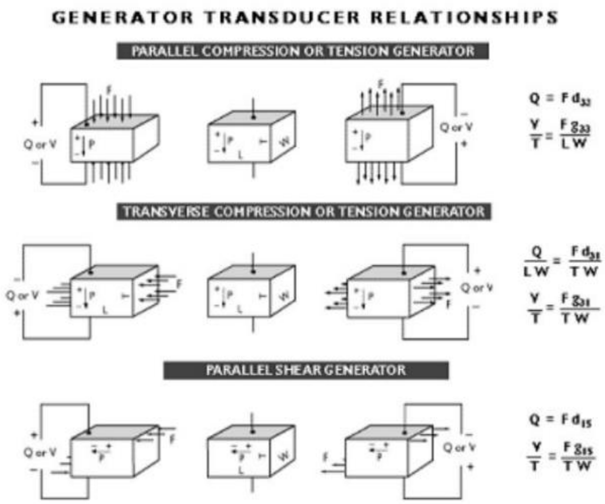
$$Q=d\,F=d\,\sigma\,A=d\,\varepsilon\,E\,A$$

d = charge sensitivity coefficient (matrix)

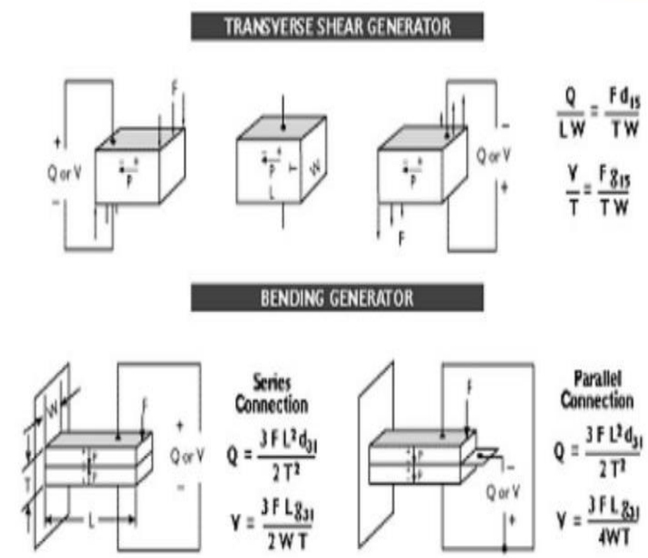
for example :

$$V_z=\frac{Q_z}{C}=\frac{d_{zx}F_x}{C}=\frac{d_{zx}F_x z}{\varepsilon_0\varepsilon_r A_z}$$

- Effect is reversible; applying a voltage will deform the crystal
- d is typically in the pC/N range



Here
T: thickness
F: applied force



- Piezoelectric Materials
    - Ceramics-> Pb(ZrTi)O3 (PZT), PbTiO3 (PT), etc.
    - Single Crystals->Quartz, LiTaO3, LiNbO3, PZN-PT,etc
    - Polymers-> PVDF and copolymers, nylon, etc.
    - Composites->PZT-polymer 0-3, 2-2, 1-3 composites, etc.
    - Thin/Thick Films-> PZT, PT, ZnO and AlN films

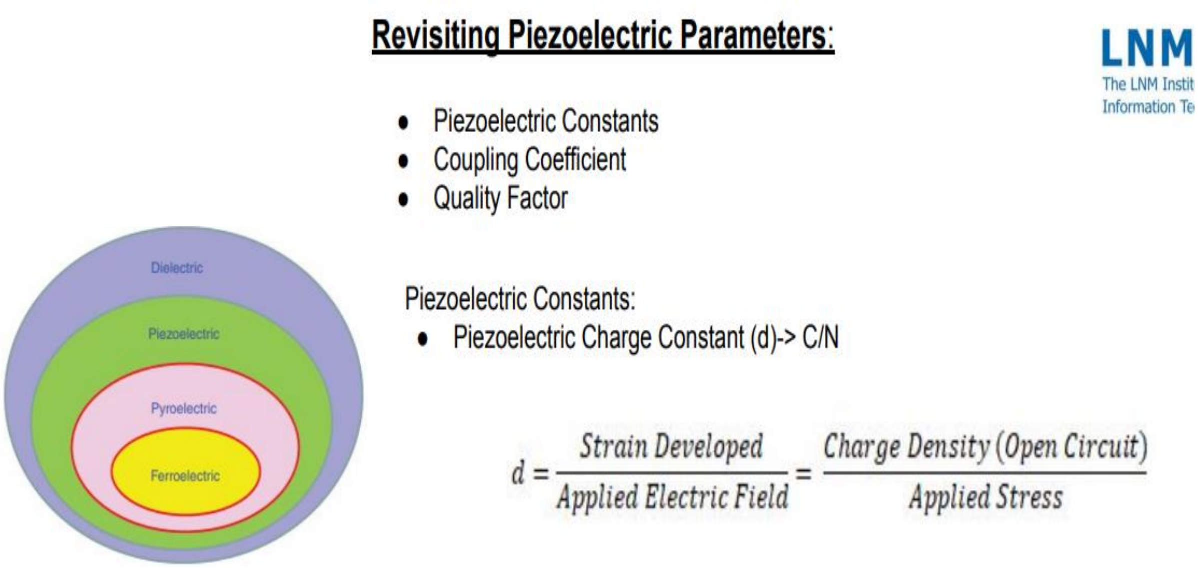
piezoelectric strain coefficient	d (m/V)
piezoelectric voltage coefficient	g(V·m/N)
electromechanical coupling	k_{33}, k_{31}, k_t
dielectric constant	K
dielectric loss tangent	$\tan\delta$
mechanical quality factor	Q
acoustic impedance	ρc

Property	Unit	PZT ceramic	PVDF	ZnO film	PZT film (4 µm on Si)
d_{33}	(10^{-12})C/N	220	-33	12	246
d_{31}	(10^{-12})C/N	-93	23	-4.7	-105
d_{15}	(10^{-12})C/N	694		-12	?
K_3	$\varepsilon_{33}/\varepsilon_o$	730	12	8.2	1400
$\tan\delta$		0.004	0.02		0.03
k_{31}		0.31	0.12		
Q		400			
ρc	(10^6)kg/m^2-sec	30	2.7		

Actuator	Force	Displacement
Longitudinal	Large	Low
Shear Mode	Medium	Medium
Bending Mode	Low	Large

What is Ferroelectricity ? = ● For electrically polarizable materiales, in most cases Polarization P is a linear function of applied Electric Field E ● In Ferroelectric materials exhibits non-linear relation between E and P ● It also demonstrates spontaneous non-zero polarization even when there is no electric field ● The key feature of this material is that spontaneous polarization can be reversed when sufficiently strong electric field is applied ● Typically material exhibits such properties below curie temperature else would be paraelectric Why we are discussing Ferroelectricity here ? Because most of the Piezoelectric material exhibits properties of ferroelectricity ● A material is said to be pyroelectric when they can generate a temporary voltage against introduction of heating or cooling ● The direction of electric dipoles cannot be changed in piezoelectric and pyroelectric material (not in ferroelectric) ● Single crystalline quartz, and ZnO are Piezoelectric but not ferroelectric. ● It can readily envisaged that a ferroelectric material once at the remnant state of polarization can be used as a piezoelectric material since it can generate charges under application of stress ● In other words, a ferroelectric material should show no piezoelectric effect when subjected to an external electric field ● In order to use ferroelectric material as a piezoelectric material, electric poling is needed

● During the poling process, applied electric field must be higher than the coercive electric field ● The poling process is accompanied with an expansion of the poled material or tensile strain, which is basically consistent with the converse piezoelectric effect ● After the poling treatment, material would have macroscopic polarization equal to remnant state ● High performance piezoelectric material must be ferroelectric in the first place



Defining 'd' constant:

LNMIIT The LNM Institute of Information Technology

It is associated with the important material properties

$$d = k\sqrt{\varepsilon_0 k^T s^E} \quad \text{(C/N)}$$

k is electromechanical coupling coefficient

k^T denotes relative dielectric constants at constant stress

s^E is elastic compliance at a constant electric field

There are two important d constant: d_{31} and d_{33}

$$d_{31} = k_{31}\sqrt{\varepsilon_0 k_3^T s_{11}^E} \qquad d_{33} = k_{33}\sqrt{\varepsilon_0 k_3^T s_{33}^E}$$

- Large d constant relates to large mechanical displacement (conversely charge collected when stress is applied)
- d_{33} applies when force is along 3 directions (parallel to polarization axis) and is impressed on the same surface from where charge is collected
- d_{31} applies when the force applied on the same surface as of charge collection, but here the applied force should be orthogonal to the polarization axis
- Commonly $d_{33} \approx -2.5\, d_{31}$

Defining 'g' constant:

LNMIIT The LNM Institute of Information Technology

Called as Piezoelectric voltage coefficient or voltage output constant (Vm/N)

$$g = \frac{\text{Strain Developed}}{\text{Applied Charge Density}} = \frac{\text{Field Developed}}{\text{Applied Stress}}$$

- g constant are calculated from piezoelectric charge constant (d) and relative permittivity (ϵ)

$$g = \frac{d}{\epsilon}$$

- Depending on the relative direction as of d, the corresponding g can be defined

Defining Piezoelectric Coupling Coefficient:

LNMIIT The LNM Institute of Information Technology

- Also known as Electromechanical Coupling Coefficient
- It is defined as ratio of mechanical energy accumulated in response to an electrical input or vice versa
- Also defined as fraction of electrical energy that can be converted to mechanical energy or vice versa

$$x = \sqrt{\frac{\text{Mechanical energy stored}}{\text{Electrical energy applied}}} = \sqrt{\frac{\text{Electrical energy stored}}{\text{Mechanical energy applied}}} \qquad k_{\text{eff}}^2 = 1 - \left(\frac{f_r}{f_a}\right)^2$$

- It can be calculated based on the measured resonance (f_r) and anti-resonance (f_a) frequencies, depending on the vibration mode it is excited
- Most used coupling factors are k_p and k_t for the vibration along radial and thickness direction in a disk
- k_{eff} is called effective coupling coefficient of an arbitrary shaped resonator either at resonance frequency or at any overtone modes

Defining Mechanical Quality Factor:

LNMIIT The LNM Institute of Information Technology

- In a Piezoelectric resonator, it is defined as ratio of reactance to the resistance in series equivalent circuit
- It is related to the sharpness of the resonance frequency

$$Q_m = \frac{f_r}{f_2 - f_1}$$

f_1 f_2 are frequencies at -3 dB of the maximum admittance

$$Q_m = \frac{1}{2\pi F_r Z_m C_0}\left(\frac{F_a^2}{F_a^2 F_r^2}\right)$$

F_r Resonance frequency (Hz)

F_a Anti-resonance frequency (Hz)

Z_m Impedance at F_r (ohm)

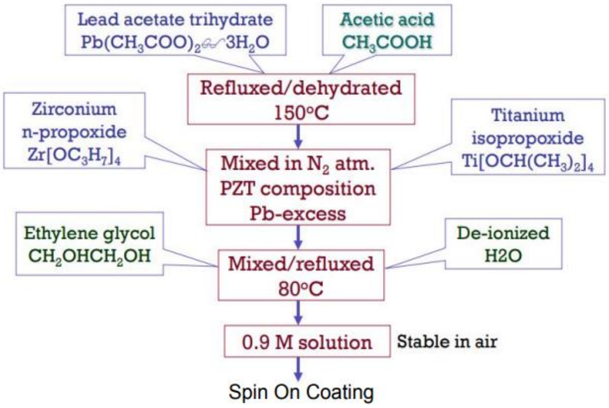
C_0 Static capacitance (Farad)

Issues for measuring Piezoelectric Properties: Berlincourt Method for Piezoelectric Coefficient: ● Don Berlincourt contributed to development of initial commercial d33 meter ● Sample size or Geometric shape taken into account strictly ● Quasi static d33 meter is used . ● Constant electric field E is the prerequisite for the measurement (large capacitor across the device under test (DUT) or virtual-ground amplifier often used) ● d33 meter must include 2 things: a force loading system and electronics for circuit control and charge measurement ● Force loading system can be further divided into 3 parts; contact probes; loading actuator; and reference sample ● Loading actuator is like a loudspeaker type coil; easily controllable and chip ● Reference should be a piezoelectric material with known coefficient ● When DUT is stimulated with an oscillating force with controlled frequency, then corresponding charge can be measured ● Charge detected gets simultaneously converted to the actual force amplitude ● Measurement then gets displayed on the screen

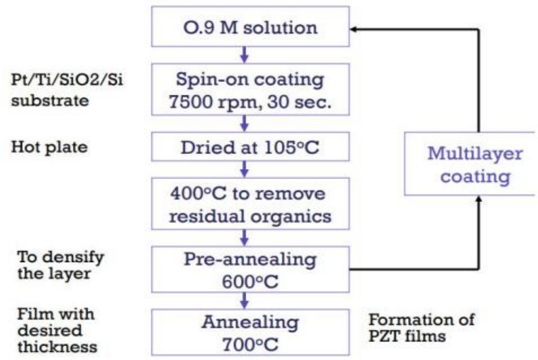
Key points of Berlincourt Method: ● Simplicity: Very easy to establish the setup ● Anyone can create the setup->lack of uniformity ● Suggested to keep the force as high as possible so that piezoelectric material is in linear region ● Typical frequencies of oscillating force: 10 kHz to 1 kHz ● Resonance frequency need to be carefully considered ● At low frequencies; for soft piezoelectric material there is pronounced downturn with increasing frequency (inhibited domains movement induced by frequency increase: Rayleigh Laws) ● For hard material it tends to increase linearly with frequency because domain wall motion is not dominant at low frequency

PZT Film Deposition: Sol-Gel Method: ● Widely Used Technique for PZT film Deposition ● Use of organometallics compounds such as metal alkoxide as precursors ● Gel with a continuous network is obtained using polymerization ● Advantages ● Homogeneity ● Low mixing temperature ● Precise control of stoichiometric

PZT Film Deposition: Solution Preparation

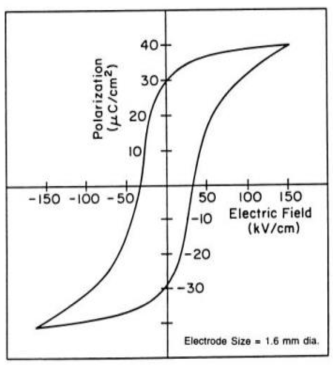


PZT Film Deposition: Thin/Thick Film Deposition

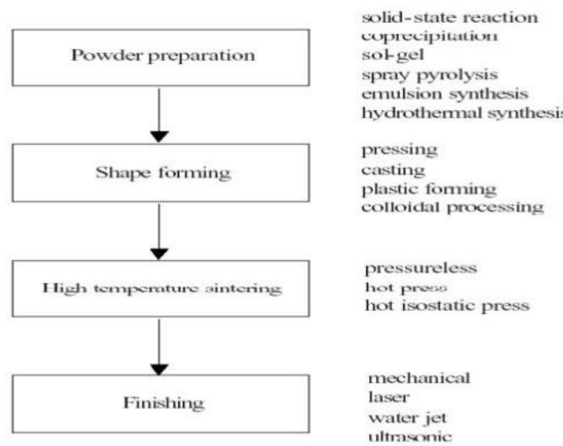


PZT Film Deposition: Hysteresis Loop

- Sol-gel PZT
- 5.0 µm
- High P

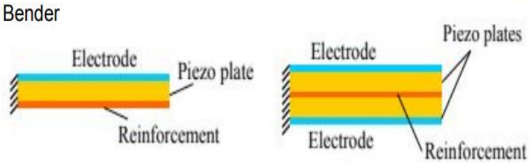


Powder Processing:



Piezoelectric Actuators and Modeling

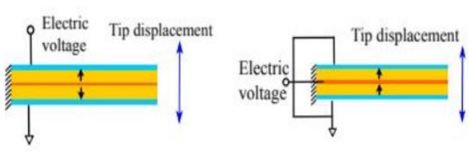
Category 1: Bender



Unimorph   Bimorph

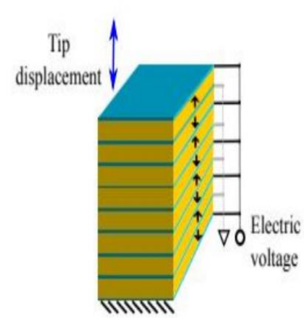
Requirements:

- Electrodes
- Piezoelectric material
- Reinforcement



(a) Series electrical configuration. (b) Parallel electrical configuration.

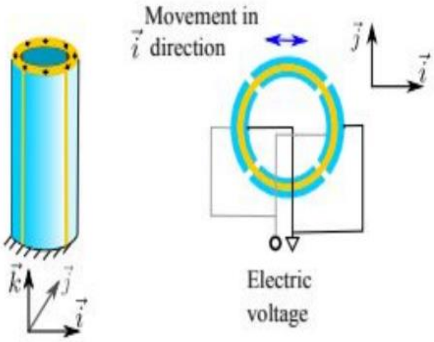
Category 2: Stack Actuators



- Made of hundreds of thin ceramic plates
- Adjacent layers have opposite poling
- Electrically connected in parallel
- All plates elongate and contract in same direction
- High Force generation

A Revisit of Piezoelectric Actuators (Contd..):

Category 3: Tube Actuators



- Made of cylindrical shape material
- Poled Radially
- Could generate motion in 3D
- Also, Rotational motion is possible

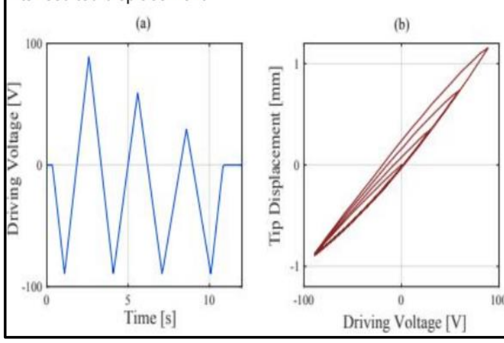
Piezoelectric actuation Modeling Challenge:

Advantage of Piezoelectric Actuators: ● Micro/Nano Positioning ● Quick Response ● Large Bandwidth ● High Stiffness

Modelling Challenges: ● Hysteresis ● Creep ● Vibration ● Temperature Change

Hysteresis in Piezoelectric Actuation:

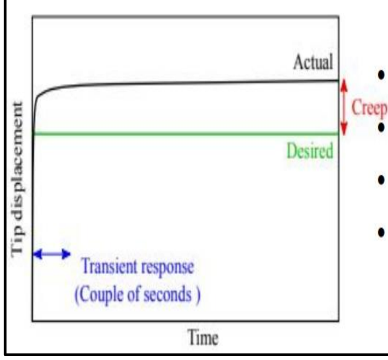
A non-linear relationship between the applied voltage to the piezoelectric actuator and its resulted displacement



- Rate dependent
- Memory effect inherent
- Dependency on previous displacement and voltage
- Originates because of interaction between the domain walls

Creep in Piezoelectric Actuation:

Creep is defined as drift in Piezoelectric Actuator position under a static voltage



- With a step voltage, actuator shows quick response
- But a slow transition happens typically in a minute span
- Happens because of slow polarization in the direction of applied voltage
- Different studies to model and compensate creap are done in literature

---

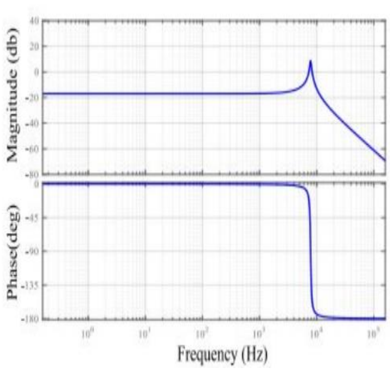
Temperature change in Piezoelectric Actuation:

- Highly sensitive to the ambient temperature
- Displacement of a tube actuator gets increased by 10 % when subjected to 25° C increase in temperature
- Effect can be explained by help of intrinsic and extrinsic responses
- At absolute zero temperature intrinsic response was* analyzed
- Extrinsic response was studied at higher temperature
- It was concluded that major influence comes from extrinsic response especially when dealing with room temperature and low electric field

* DA Hall. Review nonlinearity in piezoelectric ceramics. Journal of materials science, 36(19):4575–4601, 2001

Vibration in Piezoelectric Actuation:

Piezoelectric micro-actuators exhibits lightly damped resonance peaks in their frequency response



- Voltage inputs with high frequency components can excite the frequency resonances
- To avoid the excitation, operational frequency can be limited to 1/10 or 1/100 of their major resonance frequency
- Limits the performance of high speed devices such as AFM
- Stiffer piezoelectric have lower strokes

Modeling Piezoelectric Actuation:

$$S_i = s_{ij}^E T_j + d_{ki} E_k,$$
$$D_m = d_{mj} T_j + \epsilon_{mk}^T E_k,$$

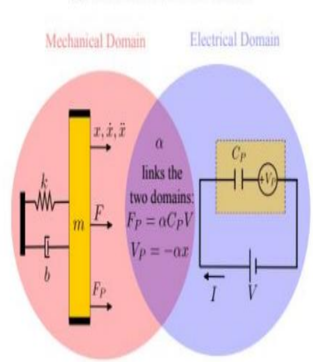
S- Strain
E- Applied Electric Field
T- Stress
D- Electric Displacement
s^E-Elastic Compliance at constant electric field
d- piezoelectric material constant
ϵ^T-Permittivity at constant stress

- Relation established in 1987 by standards committee of IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society
- Considered linear relation between Strain developed and applied electric field and stress
- Similarly, electric displacement resulted considered to have linear dependency over applied stress and electric field
- Non linearity coming from hysteresis is not explainable with this relation

Modeling Piezoelectric Actuation (Contd..):

Linear Electromechanical model* to include dynamic and non-linear behavior was introduced in 90s

(a) A linear electromechanical model



- Mechanical and Electrical domains are linked by α
- Mechanical domain modeled as mass-spring-damper system
- Electrical domain modeled as clamped capacitor in series with an internal voltage source
- Voltage source magnitude is proportional to the actuators displacement

---

- With driving voltage V, internal force F_P gets generated in the mechanical domain
- External force F, and the generated force, together acts on the actuator

$$m\ddot{x} + b\dot{x} + kx = F + \alpha C_P V,$$

$$\int I dt = q = \alpha C_P x + C_P V,$$

Employed Replacements:

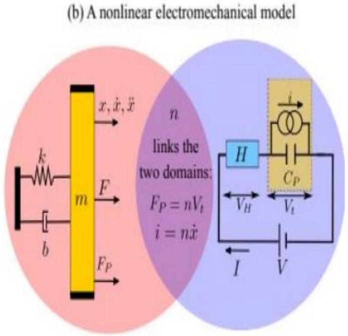
$$S_i = \frac{x}{N l_n},$$
$$T_j = \frac{F}{A_n},$$
$$D_m = \frac{q}{A_n},$$
$$E_k = \frac{V}{l_n},$$
$$s_{ij}^E = \frac{A_n}{N l_n k},$$
$$d_{ki} = d_{mj} = \frac{\alpha C_P}{k},$$
$$\epsilon_{mk}^T = \frac{l_n C_P}{N A_n} + \frac{l_n \alpha^2 C_P^2}{N A_n k}.$$

L_n and A_n are respectively nominal length and cross sectional area of the actuator

---

Non-Linear Electromechanical Model

(b) A nonlinear electromechanical model



- Electrical and Mechanical domains are linked by n
- The main difference is in Electrical Domain
- Internal Voltage is replaced by an internal current source i which is in parallel with actuators clamped capacitance C_P
- Hysteresis effect is modeled as voltage V_H across a dipole H in series with C_P
- Internal current is proportional to the actuator displacement
- Linear voltage V_T across the capacitance is proportional to internal Force

---

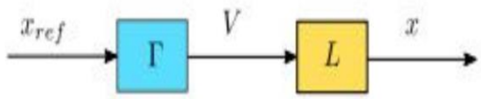
Non-Linear Electromechanical Model (Contd..)

$$m\ddot{x} + b\dot{x} + kx = F + nV_t,$$
$$q = nx + C_P V_t,$$
$$V = V_t + V_H,$$
$$V_H = H(q),$$

- Total driving voltage is sum of linear and non linear voltage
- Hysteresis voltage is function of charge q passing through the actuator
- For its use in control, Hysteresis model H is required

Control Technique for Piezoelectric Actuators : Control technique can be classified into four categories: ● Feed-forward ● Feedback ● Integrated sensors and actuators ● Self Sensing

Feed-forward control for Piezoelectric Actuators:



- Under zero external force, and quasi static condition
- Putting this in equation of q
- Combining all
- Feed-forward method applies the reference input to model to calculate the required voltage for the actuation
- For feed-forward, firstly build a model L(V) and inverse that to have the feedforward block

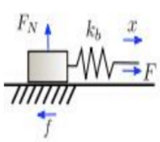
$$kx = \alpha V_P$$

$$q = (\alpha + \frac{k}{\alpha})x.$$

$$V = \frac{k}{\alpha}x + H((\alpha + \frac{k}{\alpha})x) = \Gamma(x),$$

Maxwell Hysteresis Model:

- Originally proposed for massless slider-spring system



$$F = \begin{cases} k_b(x - x_b), & k_b|x - x_b| < f, \\ f sign(\dot{x}), & else, \end{cases}$$

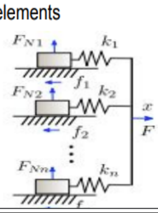
$$f = \mu F_N$$

k_b-spring stiffness
x_b-initial position of the slider
x- displacement of the slider
f-friction on the system
F_N-Normal force on the slider from the ground
μ- friction coefficient
F- External force applied on the system

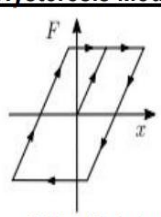
- Same model can be generalized for n number of slider-spring elements

$$F_i = \begin{cases} k_{bi}(x_i - x_{bi}), & k_{bi}|x_i - x_{bi}| < f_i, \\ f_i sign(\dot{x}_i), & else, \end{cases}$$

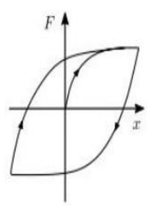
$$F = \sum_{i=1}^{n} F_i.$$



Maxwell Hysteresis Model (Contd..):



Original Relation



Modified Relation

- Behavior of slider spring system is similar to that of Hysteresis
- Each domain can be modeled as slide-spring system and domain interaction by friction
- In the relation provided by Goldfarb, F replaced by V_H and x by q
- Because of involvement of Coulomb's friction this model too is valid for rate independent Hysteresis

---

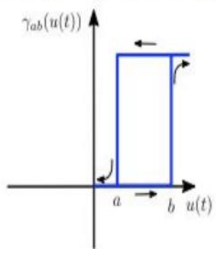
Preisach Hysteresis Model:

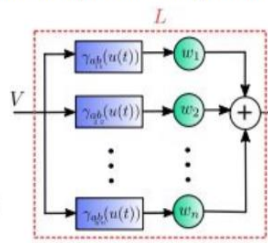
- Uses an elementary operator called Relay operator

$$\gamma_{ab}(u(t)) = \begin{cases} 1, & u(t) > a, \\ u(t-1), & b < u(t) < a, \\ 0, & u(t) < b, \end{cases}$$

u(t) is the input
a, b are the threshold of the operator

- Hysteresis Model can be developed considering n number of operators





$$x = L(V) = \sum_{j=1}^{n} w_j^t \gamma_{a_j b_j}(V).$$

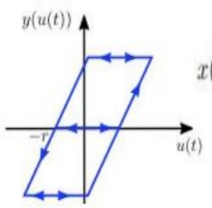
- W_j is the weight assigned
- Complicated inverse

Prandtle-Ishilinskii Hysteresis Model:

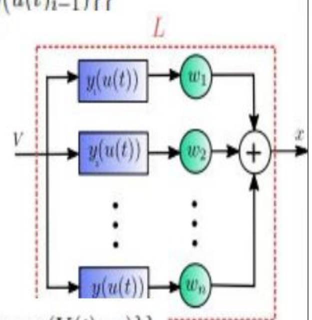
- Simplified version of Preisach model
- Doesn't requires double integration and parameters can be easily identified
- Elementary operator used is called "play operator"

$$y(u(t)_i) = max\{u(t)_i - r, min\{u(t)_i + r, y(u(t)_{i-1})\}\}$$

- r is called threshold parameter
- Initial value of $y(u(t)_0)$ is needed to build the operator



$$x(t) = L(V) = \sum_{j=1}^{n} w_j^t y_j(V(t_i))$$

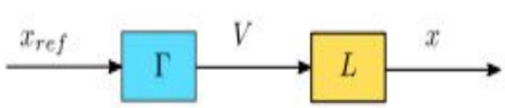


$$y_j(V(t)_i) = max\{V(t)_i - r_j, min\{V(t)_i + r_j, y_j(V(t)_{i-1})\}\}$$

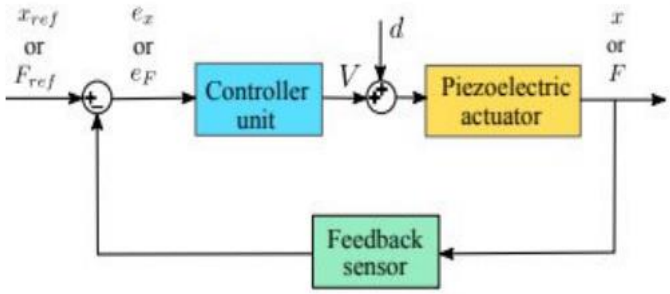
Prandtle-Ishilinskii Hysteresis Model (Contd..):

$$y_j(V(t)_i) = max\{V(t)_i - r_j, min\{V(t)_i + r_j, y_j(V(t)_{i-1})\}\}$$

- Parameter identification for optimum weight can be carried out using appropriate fitting algorithm
- Simple and effective way is to divide the voltage level into 'n' equal segments
- r is the maximum voltage level in each segment
- This model is easy to invert
- Rule for feedforward control is:
  - Identify the different parameters for L(V)=x, no external force and quasi static condition
  - Invert the model $\Gamma = L^{-1}$ and use in forward control



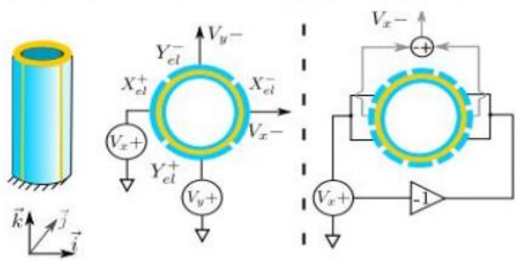
Feedback Control for Piezoelectric Actuators:



- Depending on the requirements, appropriate sensor(s) can be employed
- In many cases Hysteresis is considered as disturbance 'd' to the system
- Mostly PID control is used

Integrated Sensors and Actuators:

- Challenges from limited work space/ size
- Mounting of strain gauges may help in bringing small form factor and low cost
- Another possibility is to selectively use an actuator as actuator and as a sensor in other part
- Uses bridge circuit to measure internal voltage (linearly dependent with displacement)



- Use electrodes like "actuating electrodes" and "sensing electrodes"

Integrated Sensors and Actuators (Contd..): ● Such systems are modeled as MIMO system ● Disadvantage to have cross coupling ● Disadvantage in terms of reduction of actuation