Design of Piezoelectric Active Structures

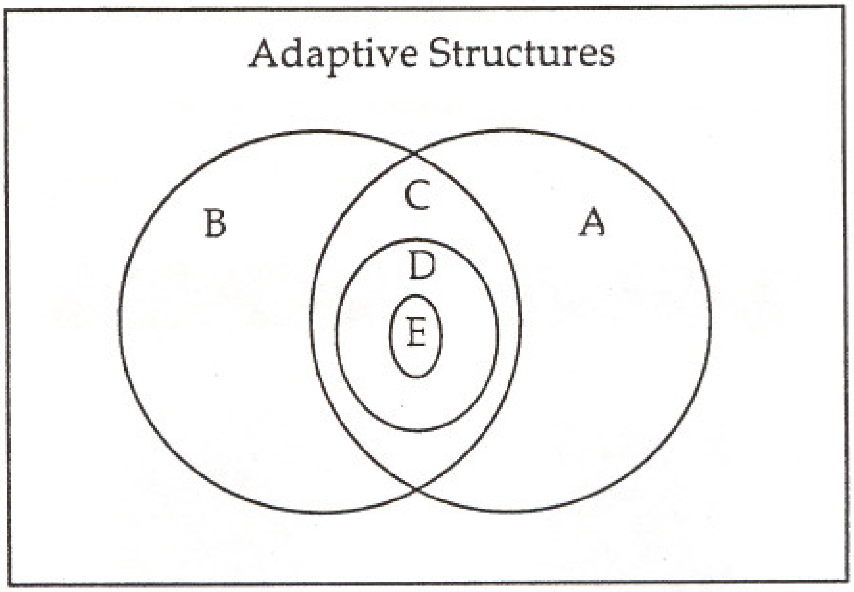
Lecture 1:

Introduction to Active Materials and Structures

Adaptive Structures

- An Adaptive Structure is one whose characteristics can be beneficially changed in response to environmental stimuli.
- Characteristics :
  - shape, stiffness
  - vibration response
  - acoustic reflectivity
  - radar signature, etc.
- Stimuli :
  - external force disturbances
  - pressure fields,
  - thermal loading
  - applied voltages and control signals
- Controllable Response allows new functionality to meet mission requirements such as precision pointing, stealth, etc.
- The goal of the technology is to develop adaptation mechanisms, sensing mechanisms, and processing hardware and algorithms which can enhance the performance of an aerospace structure and vehicle.

Classifications



A **Actuated Structures** posses actuation/adaptation mechanisms

B **Sensory Structures** posses capability to sense environment

C **Controlled Structures** couple actuation and sensing with processing

D **Active Structures** have integrated actuators and sensors

E **Intelligent Structures** have integrated/distributed processing.

Applications for Active Structures

- Vibration Suppression
  - Precision Pointing of Optical Systems
  - Precision Machining
- Active Noise Control
  - Structural Acoustics
  - Modification of Acoustic Reflection and Transmission
- Optics
  - Static Optical Positioning and Surface Correction
  - Adaptive Optics - Dynamic Wavefront Correction
- Flow-Structure Interactions
  - Static Aeroelastic Control
  - Gust Load Alleviation
  - Flutter Suppression
  - Boundary Layer Control
- Structural Health Monitoring
- Solid State Motors and Articulating Devices

Survey of Adaptation Mechanisms

- Adaptation properties are usually associated with a given active material which is incorporated into the structure.

- Controllable Size (Induced Strain Actuation)

Electrically:	Piezoelectric Ceramics Piezoelectric Polymers Electrostrictive Materials Shape Memory Ceramics
Thermally :	Shape Memory Alloys Thermoelastic Materials
Magnetically:	Magnetostrictive
Optically:	Photoelastic Materials
Chemically	

- Controllable Stiffness

Thermally:	Shape Memory Alloys Viscoelastics
Electrically:	Electrostrictives
Magnetically:	Magnetostrictives

- Controllable Viscosity

Thermally:	Water
Electrically	Electrorheological Fluids
Magnetically	Magneto rheological Fluids

- Electrical Conductivity, Resistivity, Transmission

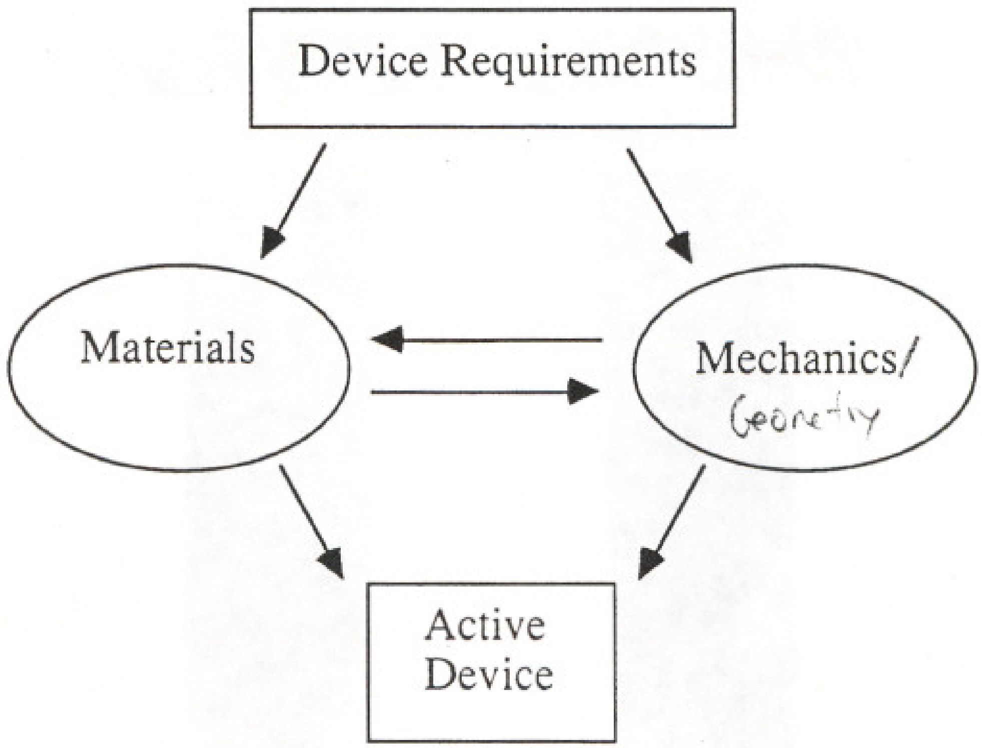
Electrically:	Transistors
Mechanically:	Strain Gauges
Optically:	Photochromatic Glasses

- Some materials operate as transducers and can therefore be used as sensors. e.g.. Piezoelectrics

- Solid State Actuators · Sensors

Design of Active Structures/Devices

- Design of active devices requires coordinated selection of mechanical, electrical parameters as well as selection of material and operating environment. - based on requirements.



- The 2 fundamental design problems:

  1) The active material is an integral part of the structure, and therefore the actuation or sensing is entirely dependent on host/actuation elastic interaction. - elastic actuators and sensors

  2) The active element usually couples electric, magnetic and mechanical fields in the material.
  - material physics

Active Material Selection Criteria

- Broad range of materials: Piezoelectrics, electrostrictors available as ceramics, piezoelectrics also in polymer form, magnetostrictors and shape memory alloys available as metal alloys.

- Within each type there are many variants. eg. PZT-4 (Navy Type I), PZT-5A (Navy Type II), PZT-5H (Type VI) etc.

- Large variation in:

  modulus, anisotropy,
  mechanical strength, fracture toughness
  dielectric strength,
  maximum actuation strain,
  maximum inducable stress,
  sensitivity to input fields,
  temperature ranges for operation,
  property stability over time
  frequency response, hysteresis
  linearity,
  availability, cost.

- Need coherent modeling and design capability to establish relative material performance for a given application.

Actuation Figures of Merit

- Stroke Actuation (induced strain)

  Max stroke (free strain) at highest field allowable

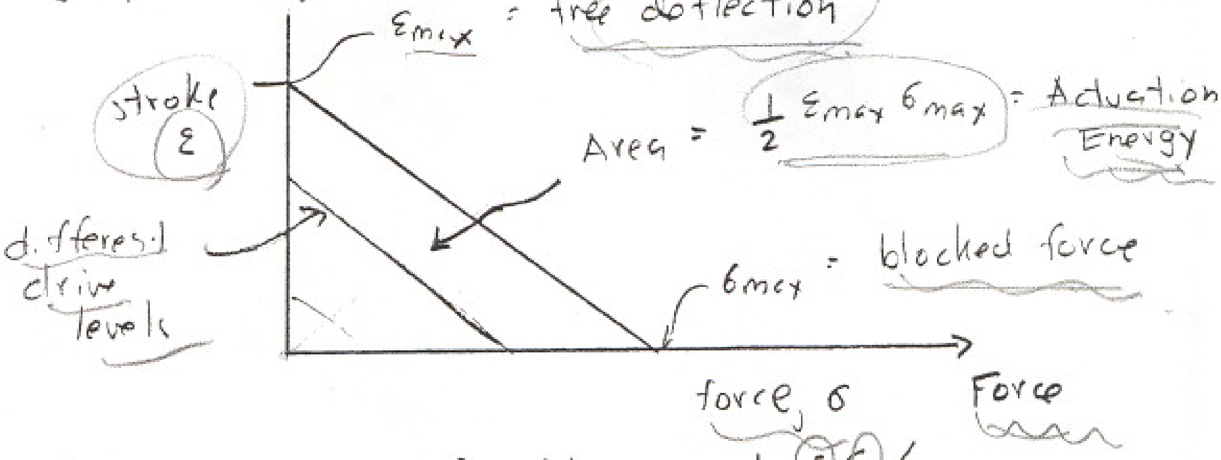
  Strain/field if field is limited

- Force Actuation (induced stress)

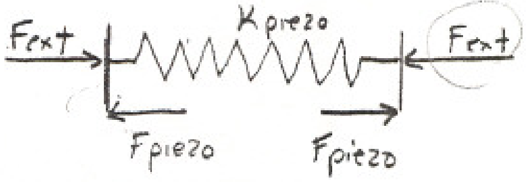
  Max Force (clamped stress) at highest field allowable

  Stress/field if field is limited

- Same types with applied charge rather than electric field.
- More complicated in distributed problems since it is no longer uniaxial.
- graphically

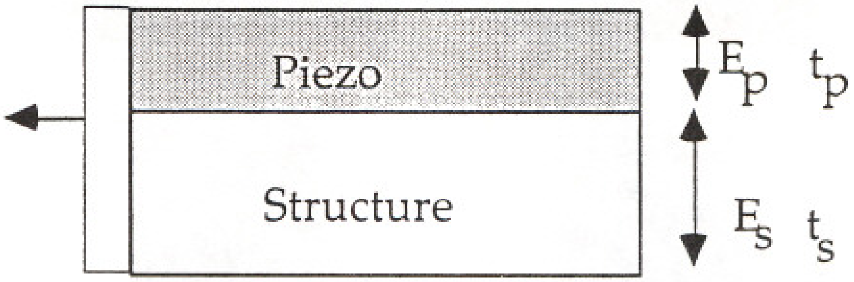


- Actuation Energy Density = $\frac{1}{2}\varepsilon\sigma/\rho$
- Simple 1-D model



Elastic Actuation - I

- Must really consider the coupled active material/substructure system
- Simple Bar Example:



- Possible figure of merit for coupled system: maximum strain induced in a bar with surface bonded actuation strain material.

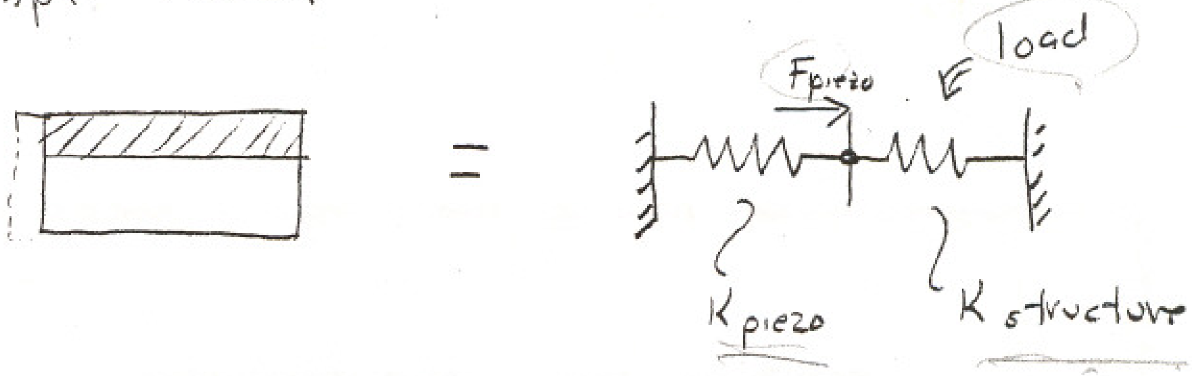
$$\varepsilon_{tot} = \varepsilon_{p_{\max}}\left(\frac{1}{1+\Psi}\right)$$

$$\Psi = \frac{E_s t_s}{E_p t_p} = \frac{K_s}{K_p}$$

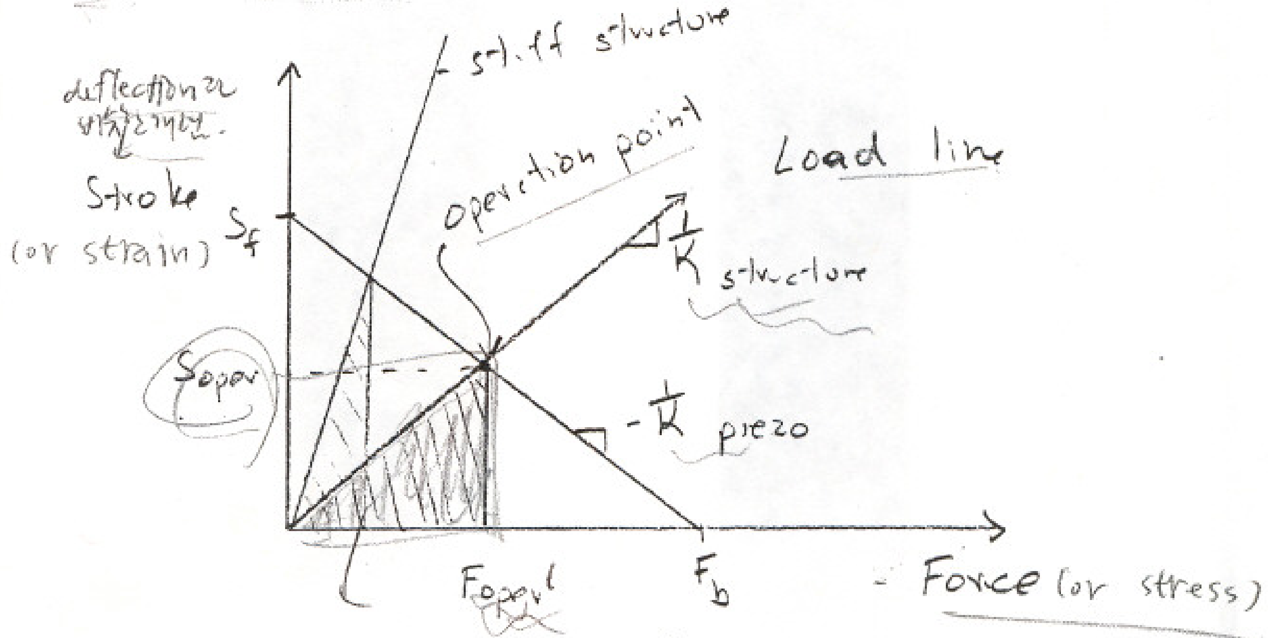
- Actuation strain and material stress depend on *relative* values of active material and structure.

Elastic Actuation - II

- Simple Model



- Graphical Representation

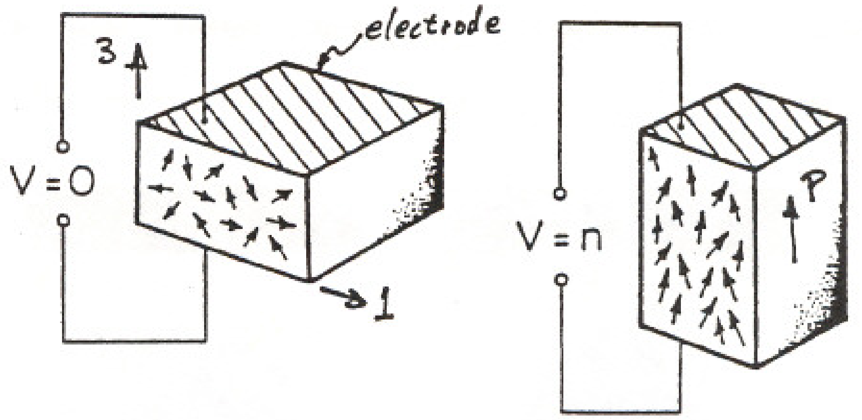


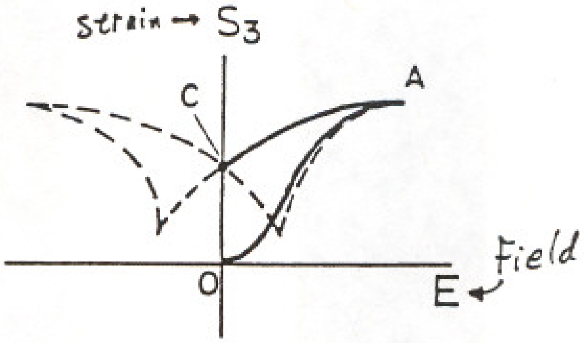
area: energy transfered to the system.
linear

- Max work delivered to load is $\frac{1}{4}\frac{F_b S_f}{2}$

  when Kstructure = Kpiezo
  (Impedance matching)

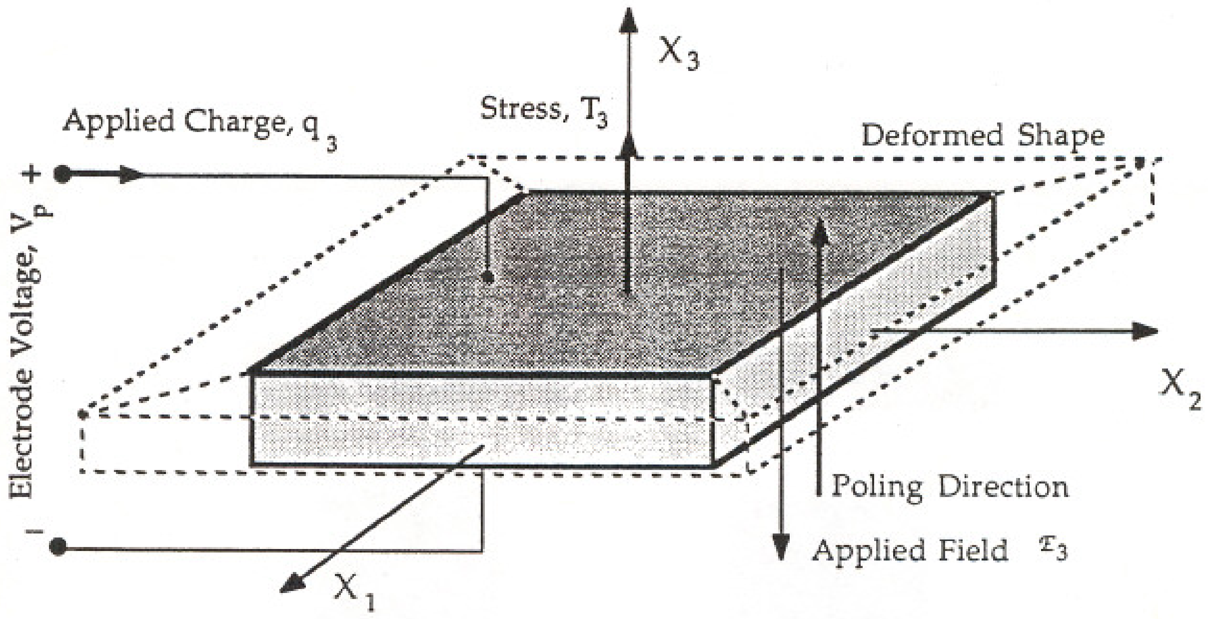
Piezoelectric Action





- Poling, or application of a large coercive field on the order of 50 Volts/mil, aligns crystalline subdomains in the ceramic.
- Poling causes the ceramic to grow in the field direction and to shrink laterally, roughly according to Poisson's ratio.
- Subsequent application of field in the poling direction also causes the ceramic to grow in that direction.
- Application of reverse field causes the ceramic to shrink until a negative coercive field level is reached. Poling action then switches and the ceramic grows again. Hence the "butterfly" curve.

What is Piezoelectricity?



- Piezoelectric causes deformation when voltage is applied (or vice-versa).
- Piezoelectric actuation strain enters equations in a manner analogous to thermal strain but is field dependent.
- High bandwidth, well into structural acoustic range.

Piezoelectric Materials in Structures

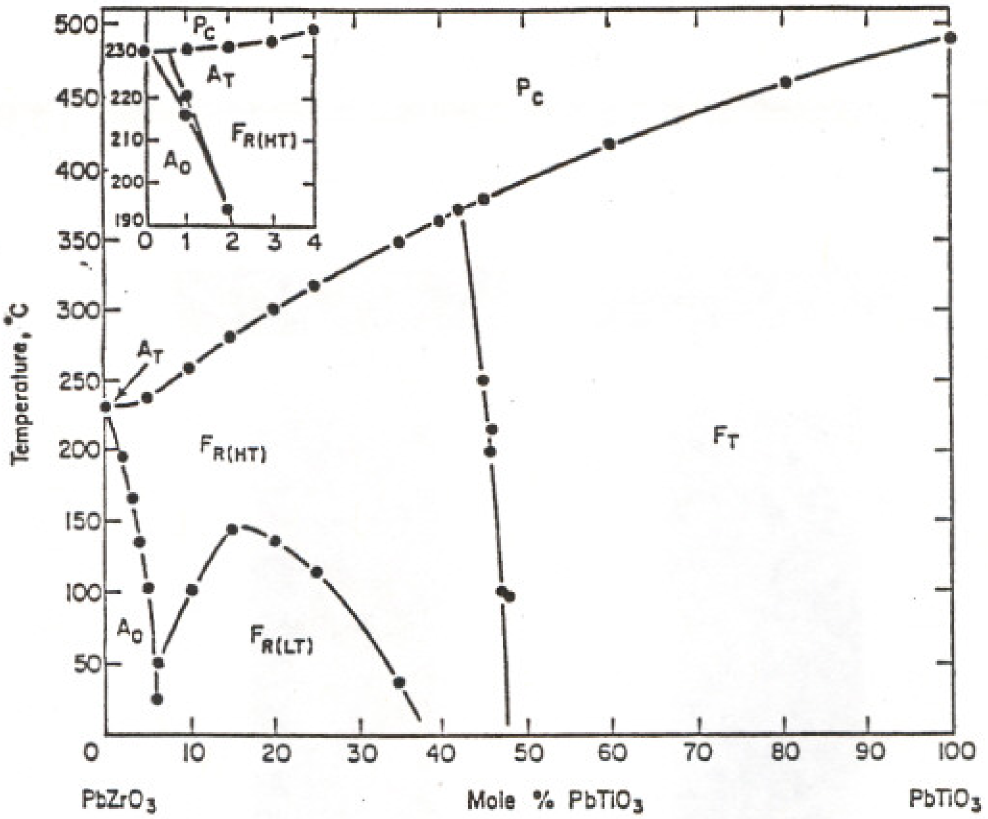
- Piezoelectric materials have been modelled in surface bonded and embedded configurations in beams, plates, and tubes.

- Intelligent structures have been manufactured with piezoelectric materials embedded in glass/epoxy and graphite /epoxy laminates.

- Piezoelectric materials have been used in passive damping applications as a replacement for viscoelastic materials.

- Piezoelectric materials have been used as actuators in active structural control applications such as structural vibration, aeroelastic, and acoustic control.

PZT Phase Boundaries



- PZT is a solid solution of lead zirconate ($PbZrO_3$) and lead titanate ($PbTiO_3$). The ratio ot these two molecules and addition of other trace compounds determines the phase transition boundaries, and hence the properties.
- PZT and Barium Titanate are Perovskite ceramics. PZT has somewhat better piezoelectric and dielectric properties.
- These Perovskites have very high dielectric constants (capacitance) relative to free space of D'~1700. This is due to offsets in the charged ions in the crystal lattice. The previous highest known material had D'~30.
- The electric offsets in the crystal lattice also cause very high mechanical strains when subjected to a field, and conversely.

PZT Actuators

- Principle: Bond or embed piezoelectric wafer on surface.

  Apply voltage V across electrodes generating field $\Phi = V / t$.

  Actuate in lateral mode (note $d_{33} \sim 2.5 \times d_{31}$)

  Max Free Strain: $\varepsilon_{max} = \Phi_{max} d_{31} \sim 120$ µ-strains (Type II)

  Max Blocked Stress: $\sigma_{max} = E\, \Phi_{max} d_{31} \sim 1{,}100$ psi

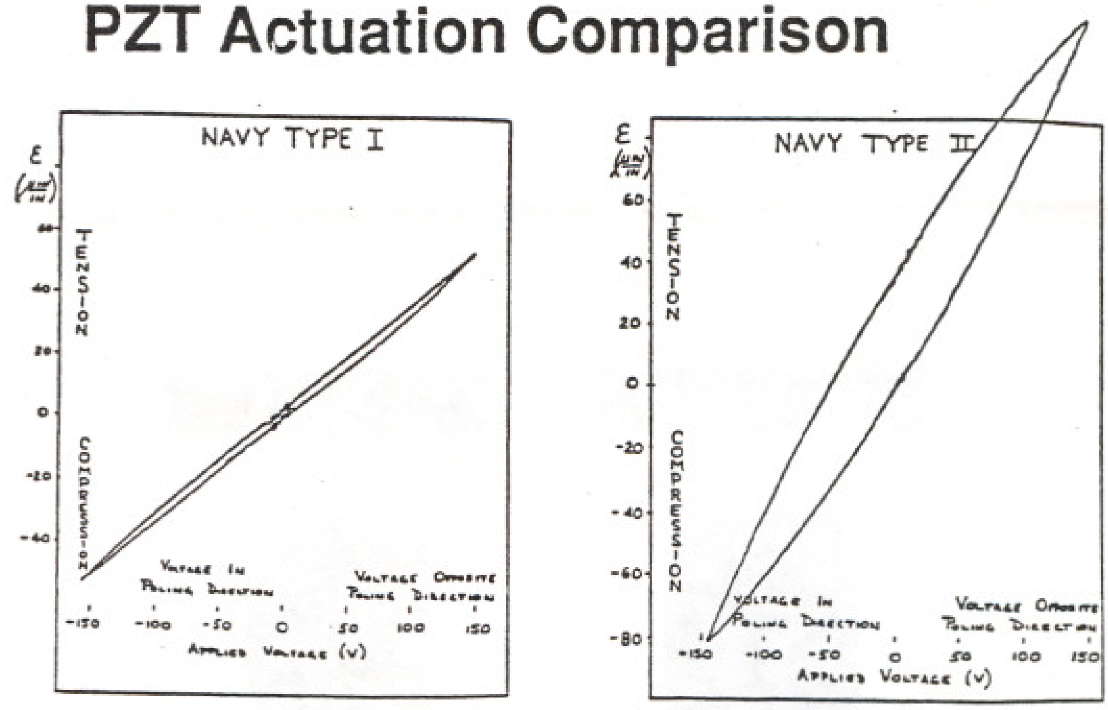
  Max Line Force for 7.5 mil wafer: $N_{max} = \sigma_{max} t \sim 8$ lb/inch
  (requires 150 Volts DC)

- Attaching PZT to structure drops strain levels by stiffness ratio: $E_p t_p / (E_p t_p + E_s t_s)$

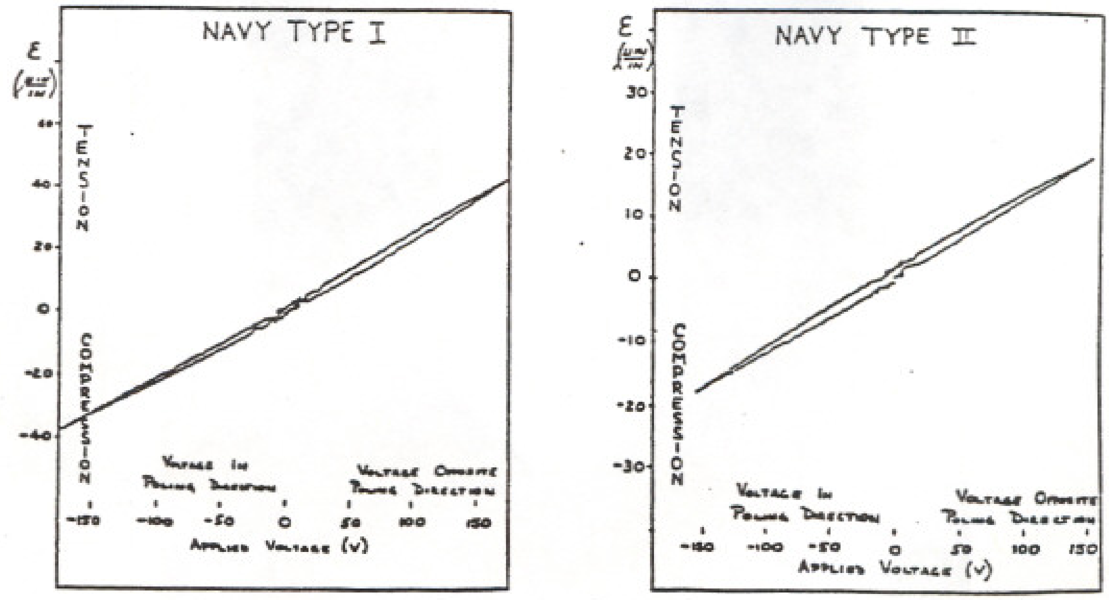
- <u>To Push on a Stiff Structure You Need a Hard Ceramic!</u>

			Material			
Quantity	Description	Units	Type I	Type II	PZWT	PVF_2
d_{31}	Lateral Strain Coeff.	m/V or C/N	1.23e-10	1.66e-10	2.8e-10	0.23e-10
ϵ_{AC}	Max AC Field	V/m	1.6e6	.71e6	1.6e6	30.e6
ϵ_R	Max Reverse Field	V/m	1.6e6	.71e6	.39e6	7.9e6
$d_{31}V_R$	Max Reverse Strain	m/m	2.0e-4	1.2e-4	1.1e-4	1.8e-4
E	Young's Modulus	N/m^2 (Pa)	9.9e10	6.9e10	4.8e10	2e9
Ed_{31}	Stress per Field	$(N/m^2)/(V/m)$	12.2	11.5	13.4	.046
$Ed_{31}\epsilon_R$	Max Reverse Stress	N/m^2	19.5e6	8.2e6	5.2e6	0.36e6
D	Permittivity	Farad/m	1.3e-8	1.5e-8	2.9e-8	1.06e-10
Ed_{31}/D	Stress per Charge	$(N/m^2)/(C/m^2)$	9.4e8	7.7e8	4.6e8	4.3e8

PZT Actuation Comparison



Free PZTs

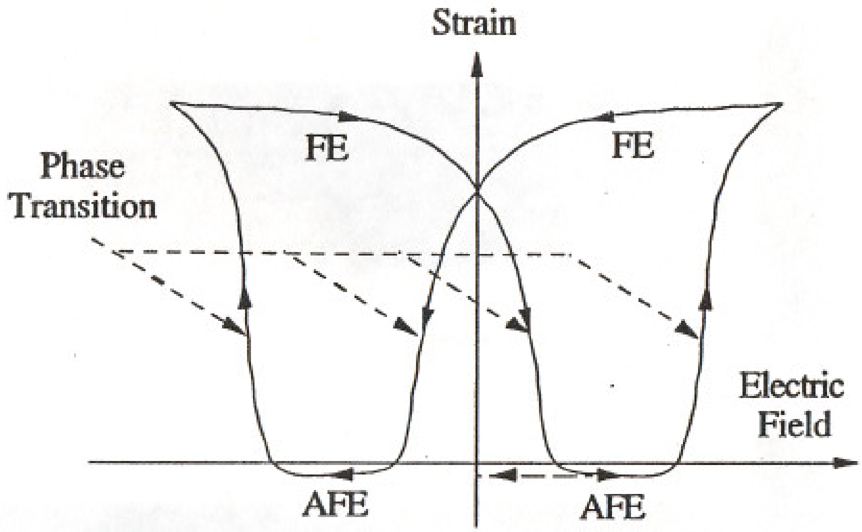


PZTs Embedded in Graphite/Epoxy

Type I has lower intrinsic hysteresis & better stiffness match to graphite.
Type II has higher free strain. Embedding decreases hysteresis.

Shape Memory Ceramics

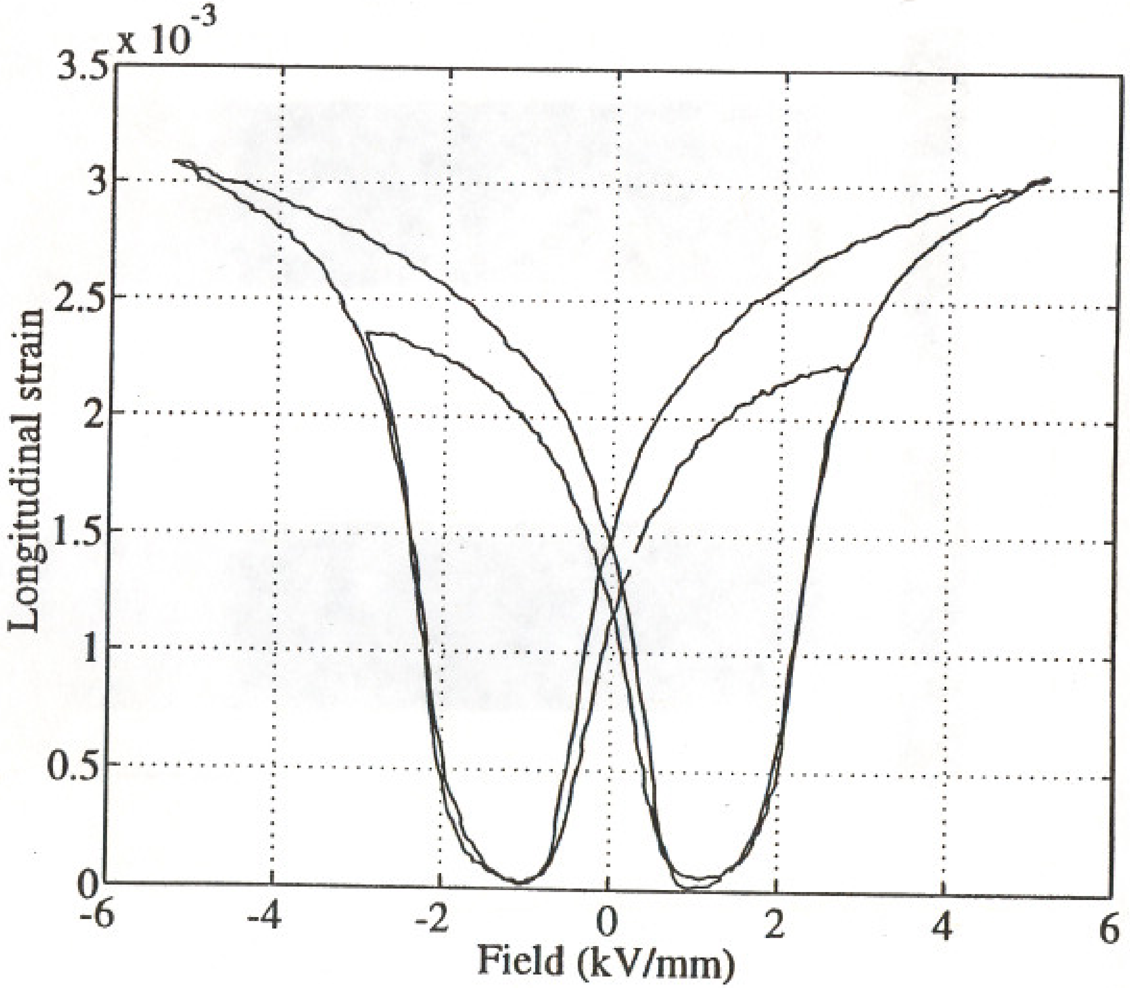
- Concept: Electric field induces phase transition between Ferroelectric (FE) and anti-ferroelectric (AFE) phases:



- Large isotropic strains (0.5%) accompany transition between phases
    - Material exhibits shape memory and requires electric field or stress to return to original state
- High switching rates permit high bandwidth applications: Adaptive Mirrors and Optics (JPL), Antennas

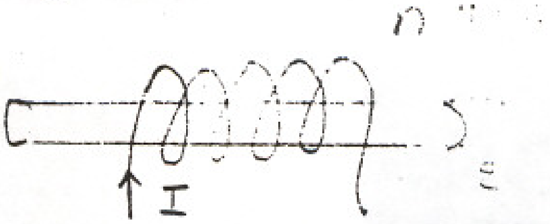
High Field Experimental Data for PLZST (A3)

$Pb_{0.97}La_{0.02}(Zr_{0.66}Ti_{0.105}Sn_{0.235})O_3$



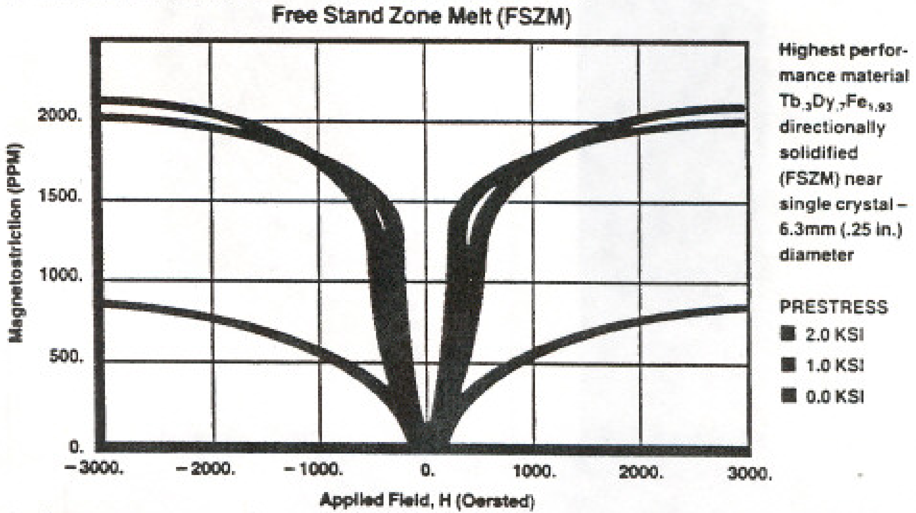
Magnetostrictive Materials

- Discovered by James Joule, 1840 in Nickel
- Terfenol-D is an alloy of Iron, Terbium, and Dyspropsium developed in late 70's by the Navel Ordinance Lab.
- Typical Configuration:



$$H = nI = \text{coercive field (A/m)}$$

- Coercive Field - Strain Curve



Highest performance material $Tb_{.3}Dy_{.7}Fe_{1.93}$ directionally solidified (FSZM) near single crystal – 6.3mm (.25 in.) diameter

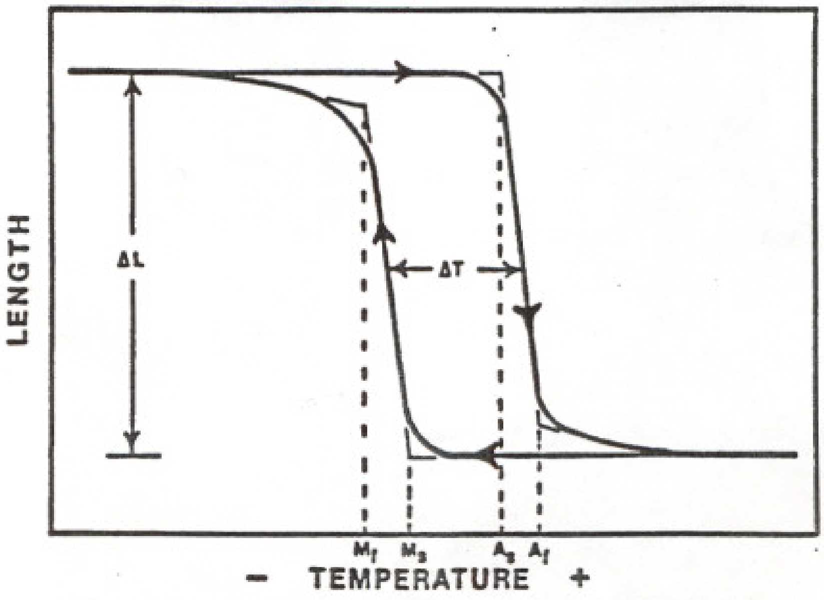
Material is typically biased magnetically h = 500-1000 Oersteads (=1000/4π A/m) to produce linear properties

Shape Memory Metals

- Nitinol is the most widely used SMM. It is a NIckel-TItanium alloy developed at the Naval Ordnance Laboratory.
- The high temperature phase is Austenitic.
- The low temperature phase is Martensitic.
- Transition Temperature (TTR) can be adjusted by varying alloy. TTR is stress dependent.
- Nitinol working stress = 25,000 psi

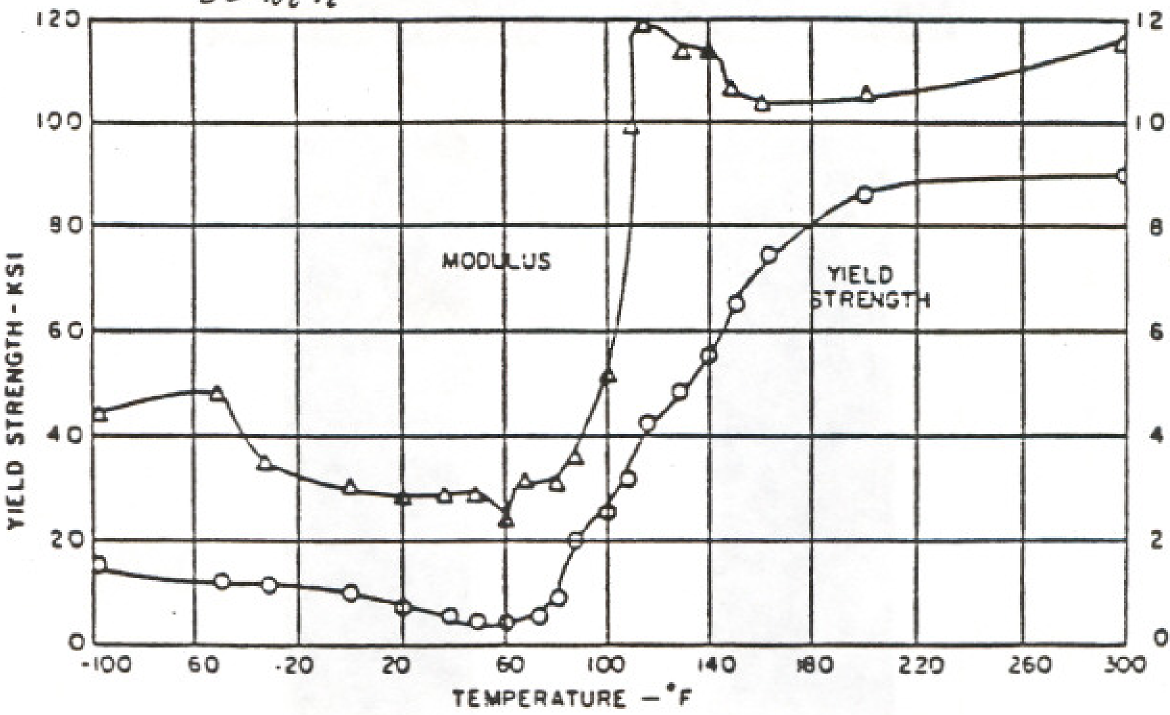
  working strain = 3.5%.
- To pull one must heat SMM wire with electric current

  To push one must cool by convection, conduction and/or radiation.
- Vibration damping frequency is limited by maximum cooling rate and hysteresis. Control demonstrated to 3 Hz.
- Difficult to control temperature accurately.
- CTE mismatch makes attachment to structure difficult.



Nitinol Properties Vs. Temperature

55 Ni Ti



Comparison of Commercially Available and Potential Actuation Materials

	PZT-5H	PVDF	PMN	TERF-DZ	NITINOL	PLZST
Actuation Mechanism	piezo-ceramic	piezo film	electro-strictor	magneto-strictor	shape memory alloy	shape memory ceramic
ε_{max} (strain)	0.13%	0.07%	0.1%	0.2%	2%-8%	0.3%-0.9%
E (Msi)	16 (D)	0.3	17	7	4 (m), 13 (a)	12 (FE)
σ_{max} (kpsi)	20.8	0.21	17	14	26 - 104	36-108
Density (kg/m3)	7500	1780	7800	9250	7100	7500
Actuation Energy Density (J/kg)	13.5	0.285	7.51	10.4	252-4032	49.6-446
Hysteresis	10%	>10%	<1%	2%	High	High
Temp Range	-20C to 200C	Low	0C to 40C	High	-	0C to 40C
Bandwidth	100kHz	100kHz	100kHz	<10kHz	<5Hz	<100Hz

(m) = martensite (a) = austenit (FE) ferroelectric (D) = open circuit

Actuation Energy Density= $1/2\ \varepsilon_{max}\sigma_{max}/\rho$

Sensing Figures of Merit

- Consider sensing of mechanical fields (stress or strain). Sensing duals are:

Electrical:	Voltage	Charge
Magnetic:	Current	Voltage

- Volt per stress or strain
- Charge per stress or strain
- In the sensing case you usually look at the normalized figures of merit since you rarely exceed material capability - exception is high stress of piezoceramic.

PZT Sensor Example

Material Properties for Navy Type II PZT & PVF_2 Film

Quantity	Description	Units	Material	
			Ceramic	Film
d_{31}	Lateral Strain Coefficient	m/V or Coul/N	1.8e-10	23e-12
d_{33}	Axial Strain Coefficient	"	3.6e-10	33e-12
d_{15}	Shear Strain Coefficient	"	5.4e-10	n.a.
E	Young's Modulus	N/m^2 or Pascal	6.30e10	2e9
G	Shear Modulus	"	2.34e10	n.a.
ν	Poisson's Ratio	–	0.35	n.a.
Ed_{31}	Actuation & Sensing	N/m/V or $Coul/m^2$	11.34	.046
D_0	Free Space Permittivity	Farad/m or N/V^2	8.85e-12	=
D'	Relative Permittivity	–	1700	12
D	Absolute Permittiviy	"	1.5e-8	1.06e-10
ρ	Resistivity	Ω-m or V^2-sec/N	1e10	1e13
α	CTE	μ-strain/°K	5	~ 30-40
p	Pyroelectric Coefficient	Coul/(m^2 °K)	4e-4	2.5e-5
k	Boltzmann's Constant	Joules/°K	1.38e-23	=

- Lateral Mode PZT Sensor: 1" x 1" x .0075"
  Q = 7.1e-9 Coulomb / μ-strain
  C = .05 μ-Farads : V = Q/C = .14 Volts / μ-strain
- Lateral Mode PVF_2 Sensor: 1" x 1" x .002"
  Q = 2.9e-11 Coulomb / μ-strain
  C = .0013 μ-Farads : V = Q/C = .022 Volts / μ-strain
- PZT sensors have 200X higher charge sensitivity, and thus give less noise for a charge amplifier. They are universally employed in accelerometers.
- PVF_2 Sensors have reasonable voltage sensitivity. They are easy to apply and inexpensive.

Strain Gages

- Principle: A metal strip is attached to a surface. Strain causes a cross-sectional area change in the conductor, changing its resistivity. The gage is placed in a bridge with balanced nominal resistances such that zero strain gives zero differential voltage. Voltage changes for a constant current source produce an indication of resistance and hence strain.

- Sensitivity is defined by Gage Factor:

$$GF = \frac{(\Delta R/R)}{(\Delta L/L)}$$

- For most metal foil strain gages GF ~ 2 - 4.

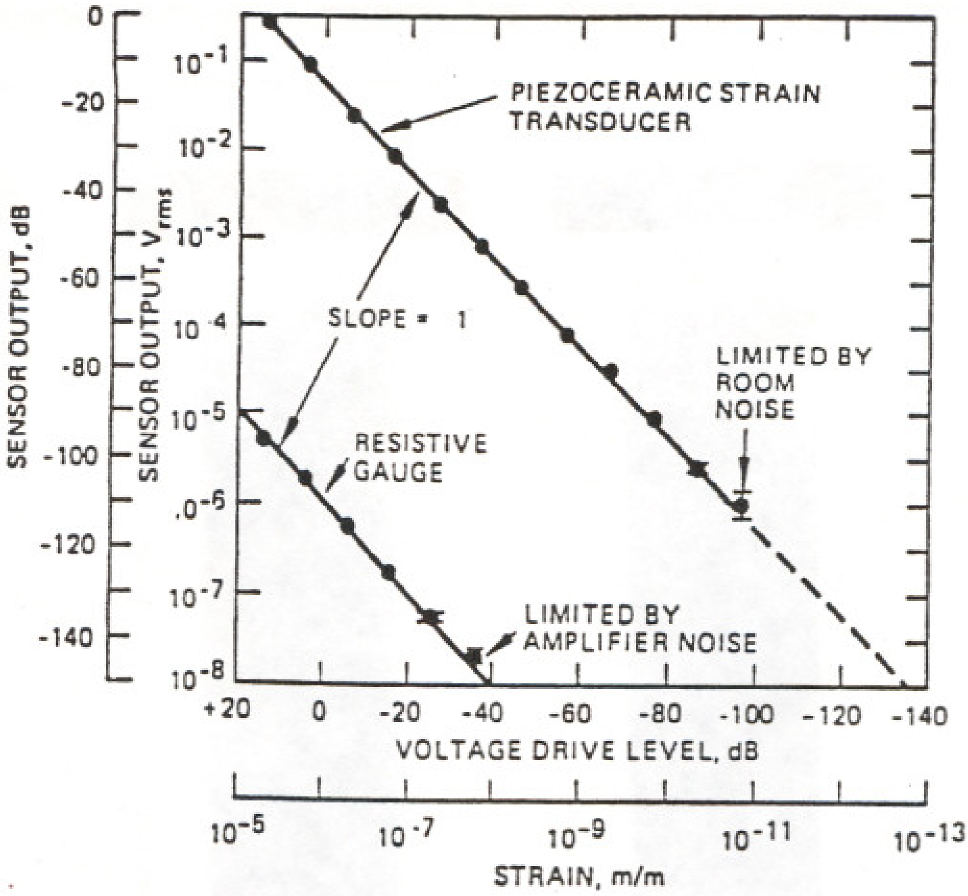
  Thus sensitivity is ~2 μ- Volts / μ-strain.

  A factor of 100,000 lower sensitivity than a PZT sensor.

- Shape memory metal gage factor is around 100X higher.

  However, GF is extremely temperature sensitive.

PZT Sensor vs. Strain Gage



- This experiment was published by Bob Forward of Hughes Research Labs in 1980.
- Forward used PZTs in an attempt to measure gravitational waves.
- The limit of measurable strain in a PZT is 1e-13 strains.
- Op amp noise is the limiting factor.

Summary

- There are numerous applications for integral sensors and actuators in active structures and devices.
- To determine the systems behaviour must consider 2 couplings: material/structure and mechanical/electrical.