A Critical Review of Materials Available for Health Monitoring and Control of Offshore Structures

M. Riley, F. Taheri, R. Islam
Department of Civil Engineering
Dalhousie University

Overview of Presentation

- Introduction to classification for smart materials and structures
- The different materials available
  - Functionality of smart materials
  - Uses of smart materials
  - Advantages and disadvantages of the different materials
- Conclusion of preferred applications

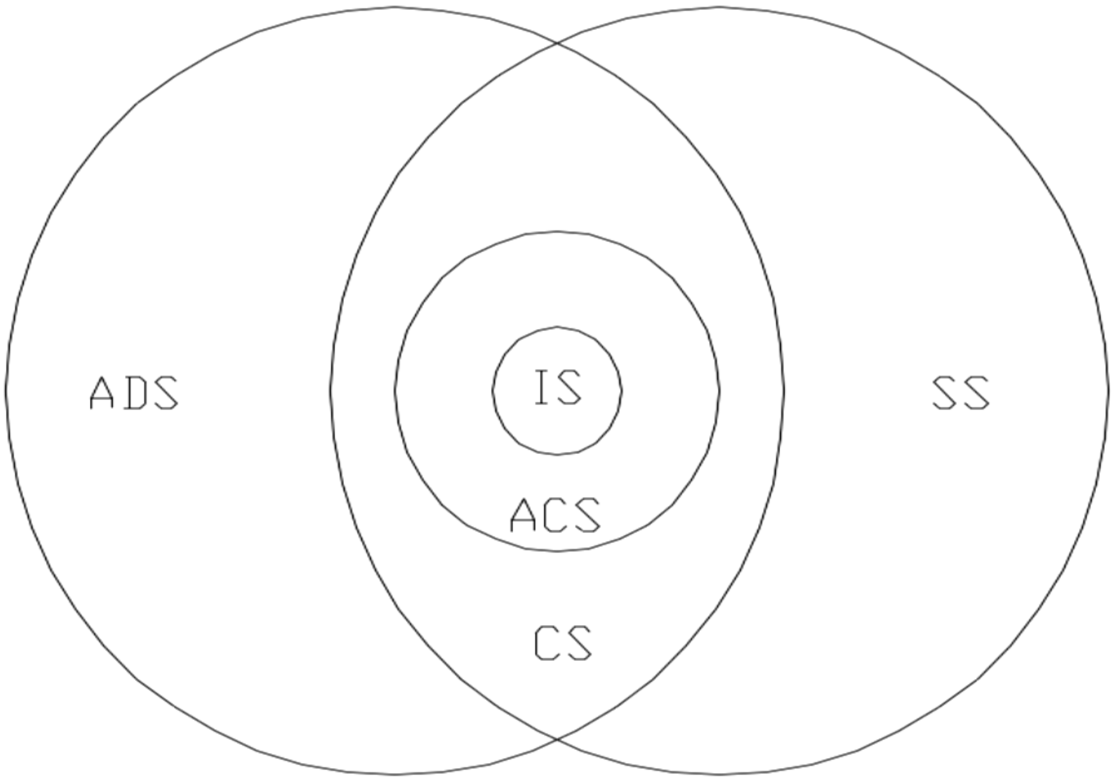
Smart Materials

- Materials that function as sensing and/or actuating materials
- Passively smart materials posses self-repairing or stand-by characteristics
- Actively smart materials utilize feedback
- Smart materials reproduce biological functions in load bearing systems

Smart Structures

- Three criteria in characterizing smart structures
  - A definite purpose
  - Means to achieve that purpose
  - Posses a biological pattern of functionality

Terminologies Used in Field of Smart Structures



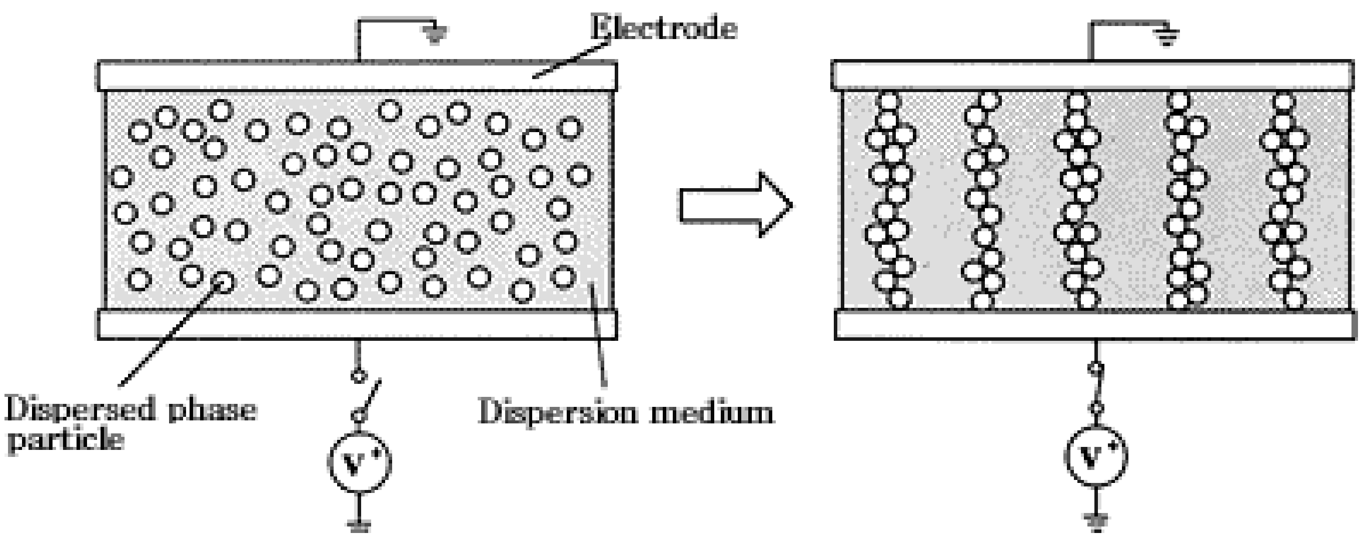
- ADS = Adaptive Structure, SS = Sensory Structure, CS = Controlled Structure, ACS = Active Structure, IS = Intelligent Structure

Smart Materials Available

- Actuating Materials
  - Electrorheological Fluids (ER Fluids)
  - Shape Memory Alloys (SMA)
- Sensing Materials
  - Fiber Optic (F.O.) sensors
- Dual-Purpose Materials (Actuating & Sensing)
  - Magnetostrictive Materials
  - Piezoelectric Materials

Electrorheological Fluids

- Consist of dielectric particles submersed in an oily fluid
- Respond to an electric field by the aligning of dielectric particles



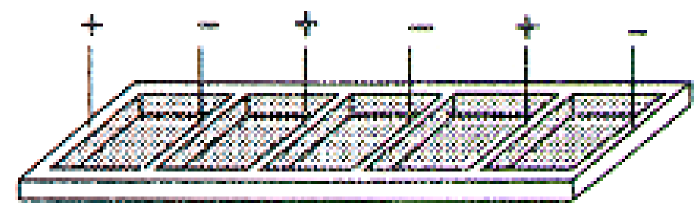
Functionality of ER Fluids

- Generally used in laminated composite sandwich beam structures
  - Ease of manufacturing
  - Makes addition of ER fluid simple

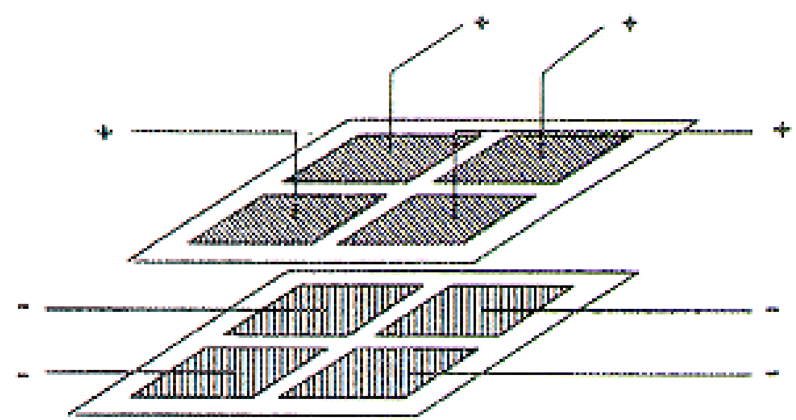
Common ER Fluid Sandwich Beam Configurations

- Simple sandwich beam
  - Increased shear properties

- Compartmentalization
  - Extensional properties



  - Mode shape control



ER Fluid Advantages

- Quick response (msec)
- Fairly good structural durability
- Can operate with both AC and DC voltages
- Induced shear stress is large

ER Fluid Disadvantages

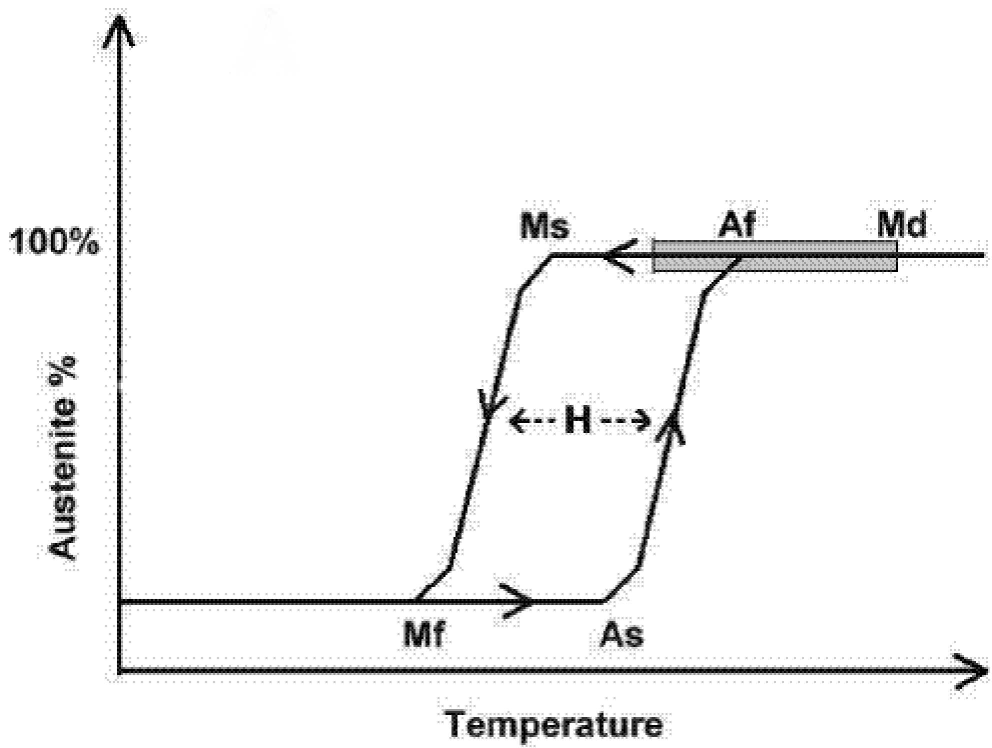
- Behavior is not well known
- Poor reproducibility
  - Due to settlement of dielectric particles
- Produce small forces
  - Requires large amount of material
- Creep is an issue
- Strength is relatively low
- Require large amounts of power

Shape Memory Alloys

- Respond to an applied electric current by returning to their manufactured shape (Resistive heating)
- Contain two distinct solid forms
  - Martensite: Low temperature form
  - Austenite: High temperature form
- Most commonly implemented SMA is Nitinol (Nickel-Titanium Alloy)
  - Due to superior properties compared to other SMA's

Characterization of SMA Behavior

- SMA's follow a hysteresis loop as follows

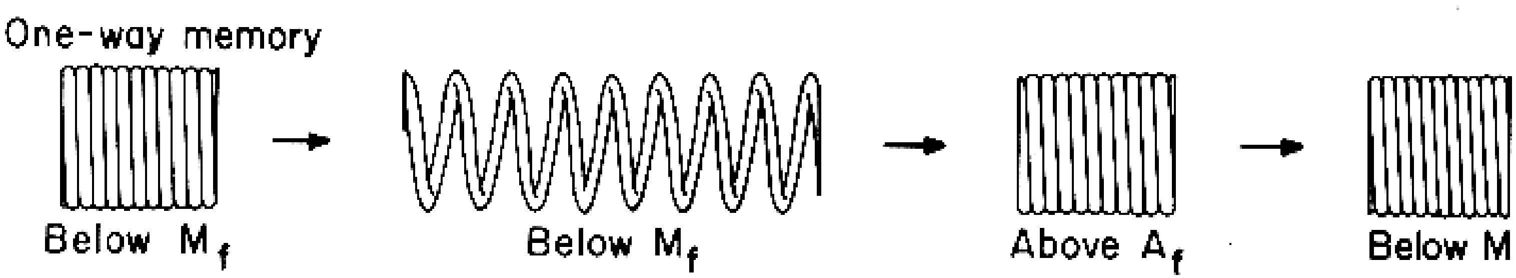


Properties of Nitinol Martensite and Austenite

	NiTi	
	Austenite	Martensite
Ultimate Tensile Strength (MPa)	800-1500	103-1100
Tensile Yield Strength (MPa)	100-800	50-300
Modulus of Elasticity (GPa)	70-110	21-69
Elongation at Failure (%)	1-20	Up to 60

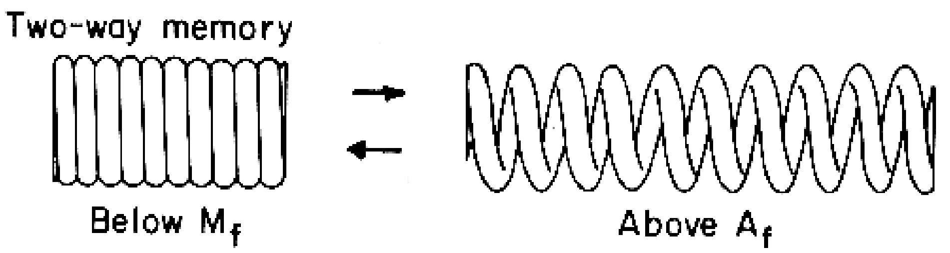
Functionality of SMA

- Functionality depends on manufacturing process and operation temperature
  - Three functional methods
- One-way Shape Memory

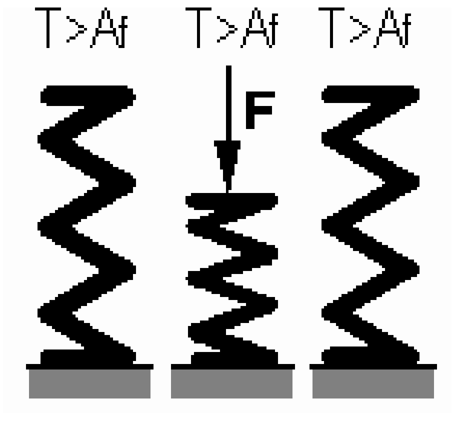


Functionality of SMA

- Two-Way Shape Memory



- Superelastic Effect



SMA Transformation Strain Capabilities

Number of Cycles	Transformation Strain
Up to 1	Up to 8%
1-100	Up to 5%
100-10,000	Up to 3%
10,000-100,000	Max 2%

SMA Advantages

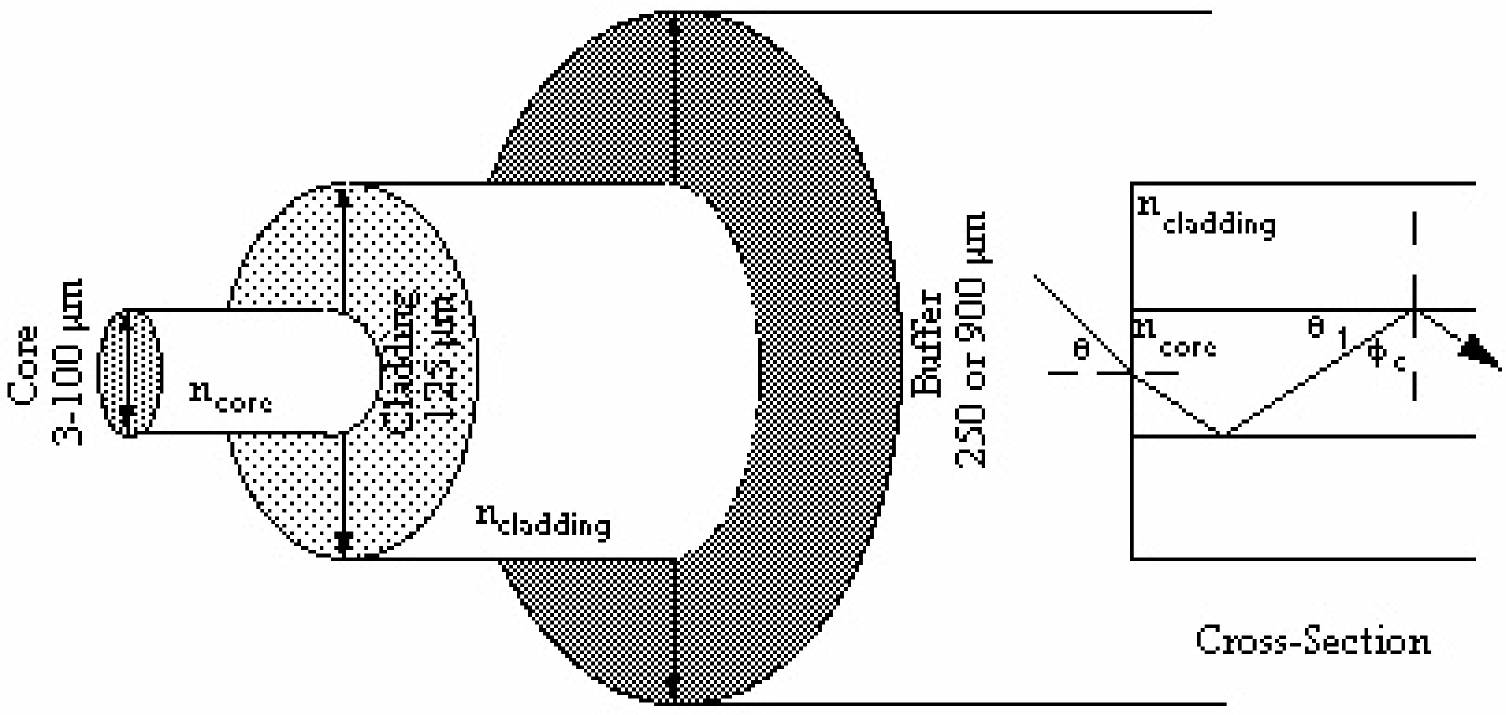
- Produce very large recovery stresses
- Easily machined into different shapes and sizes
- Manufactured to desired properties
  - Mechanical and transition temperatures
- Material is ductile
- Very effective for low frequency vibrations
  - (< 5 Hz.)
- Heating is easily done with resistive heating
- Easily embedded into laminated composites

SMA Disadvantages

- Slow reaction time
  - Ineffective at higher frequency ranges
- Low energy efficiency conversion
- May not be able to operate in conditions with large temperature ranges
- Unweldable and expensive for large scale projects
- Non-linear thermomechanical behavior can limit the accuracy

Fiber Optic Sensors

- Typical fiber optic is constructed as follows



Classification of Fiber Optic Sensors

- Four methods of classification
  - Type of media transmitted
  - Mode of the fiber
  - Measured parameter
  - Location of sensing element

Fiber Optic Media Measurement Methods

- Light Intensity
  - Intensiometric sensor
- Phase Change
  - Interferometric sensor
- Frequency Change
  - Polarimetric sensor
- Polarization
  - Modalmetric sensor

Fiber Optic Modes of Measurement

- Single Mode Fibers
  - Light is transmitted directly down the fiber without refraction between core and cladding
- Multimode Fibers
  - Light is refracted between core and cladding

Sensing Parameter of Sensor

- Physical Sensor
  - Stress, temperature etc.
- Chemical Sensor
  - pH, gas composition, etc.
- Bio-medical Sensor
  - Blood flow, glucose content, etc.

Location of Sensing Element

- Extrinsic
  - Sensing is done outside fiber optic cable
  - Fiber only acts as a data conduit
- Intrinsic
  - Physical properties of the fiber are changed

Fiber Optic Advantages

- Small size and light weight
- High sensitivity
- Corrosion resistant
- Wide frequency bandwidth
- Simultaneous sensing of numerous parameters
- High tensile strength and fatigue life
- Quick response
- Immune to electromagnetic interference

Fiber Optic Disadvantages

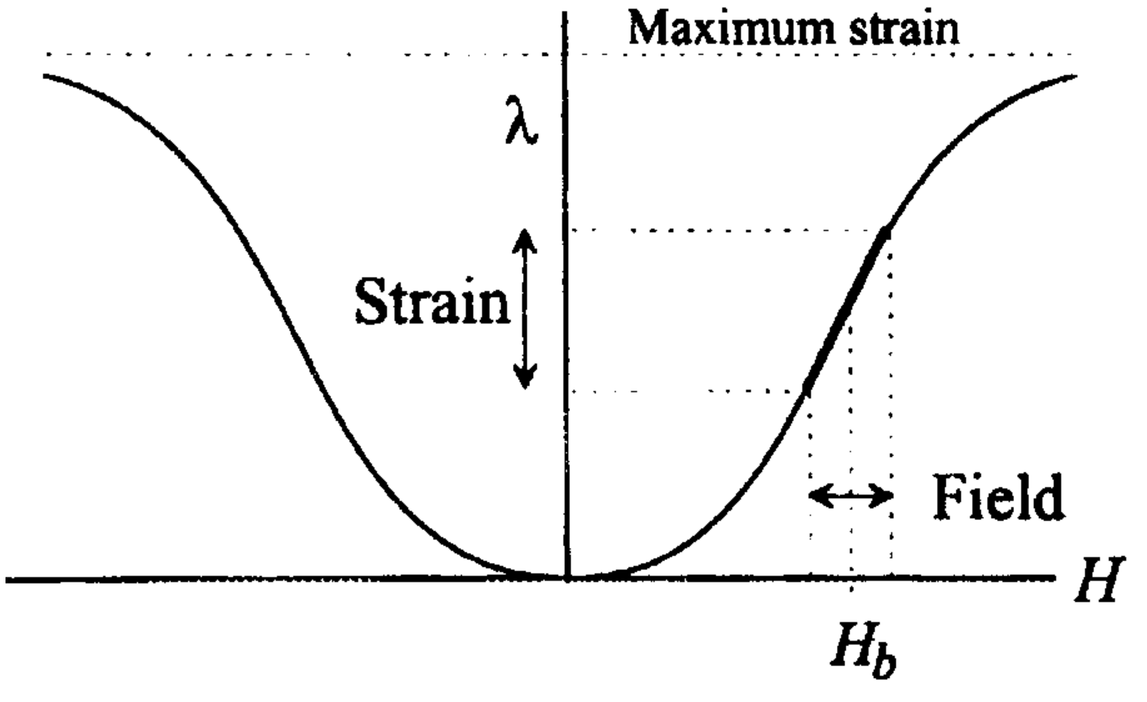
- May need to isolate from unwanted parameters
- Availability of optical sources
- Cost and availability of instrumentation
- Long term stability is relatively unknown
- Low awareness of fiber optic sensor technology

Magnetostrictives

- Implemented as an actuator with an applied magnetic field
  - Magnetic field is generally created by running a current through wire loop
- Used as a sensor by producing a magnetic field when strained

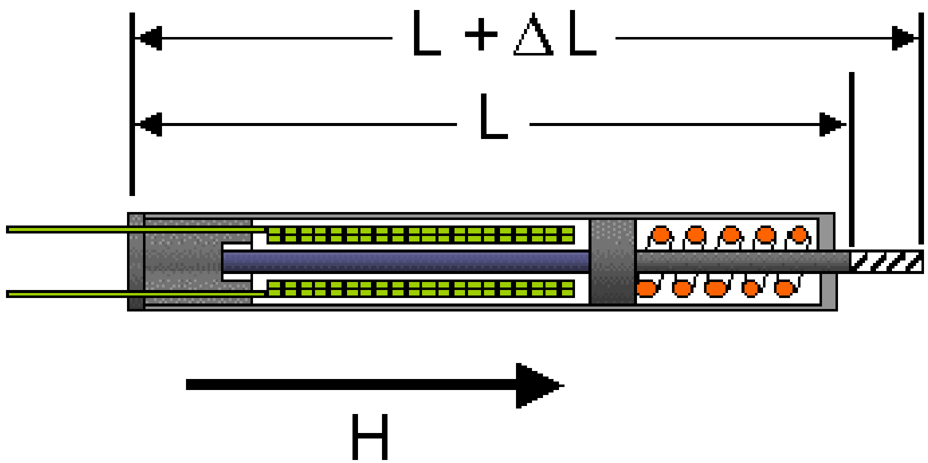
Magnetostrictive Behavior

- Behavior follows the following curve



Magnetostrictive Functionality

- Generally implemented as a linear actuator



- Displacement is independent of the applied field direction
  - Depends on material

Magnetostrictive Advantages

- Fast response time (μsec)
- High Curie temperature
- Relatively high strain and force capabilities compared to piezoelectrics
- No aging effects
- Operate over large temperature range
- Low voltage operation

Magnetostrictive Disadvantages

- Low tensile strengths
- Brittle
- Costly due to rare earth metals involved
- Large magnetic field required
- Equipment intensive
  - In order to produce magnetic field

Piezoelectric Materials

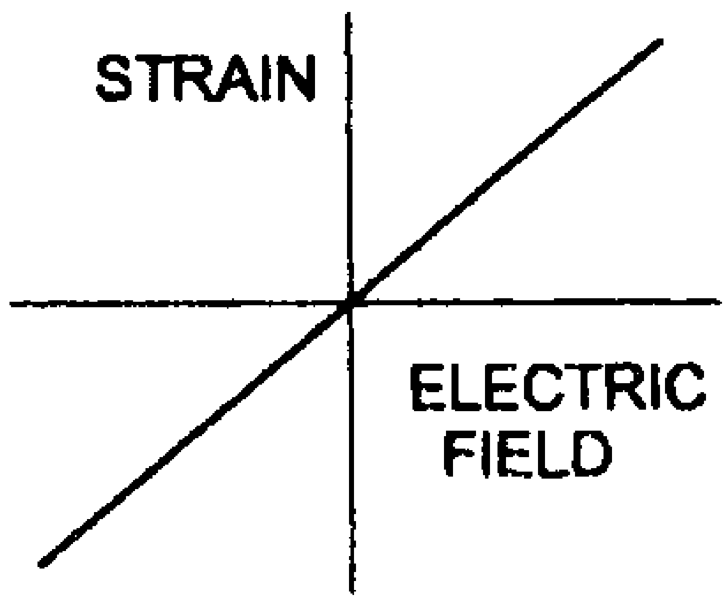
- Operate as actuator with an electric field applied causing displacements
- Operate as sensor by producing an electric field when strained
- Classified based on polarized direction and resulting displacement directions

Piezoelectric Classification

- Three directions are generally considered
  - 33-Mode: Polarized through thickness and displaces in the thickness direction
  - 31-Mode: Polarized through thickness and displaces in the longitudinal direction
  - 15-Mode: Polarized in longitudinal direction and displaces in shear

Piezoelectric Behavior

- Behave in a linear fashion
  - Resulting strain is directly proportional to applied field

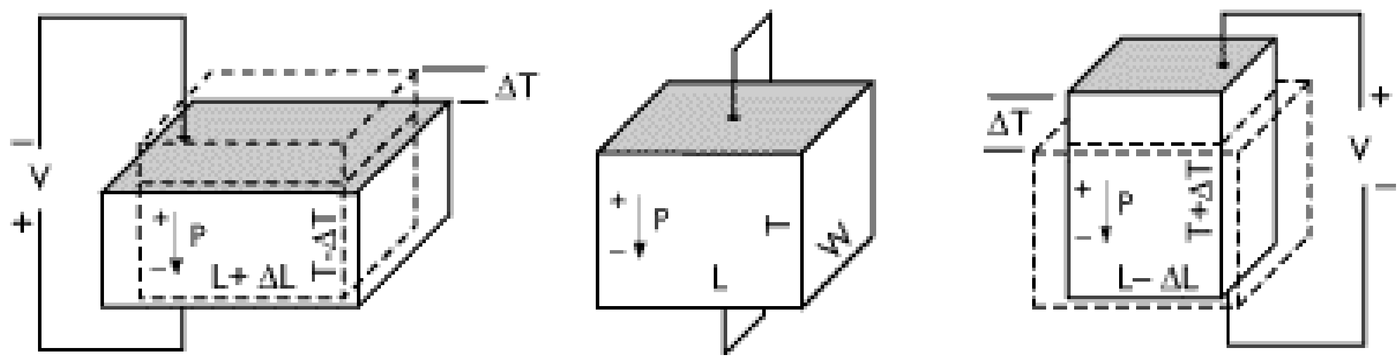


Piezoelectric Functionality

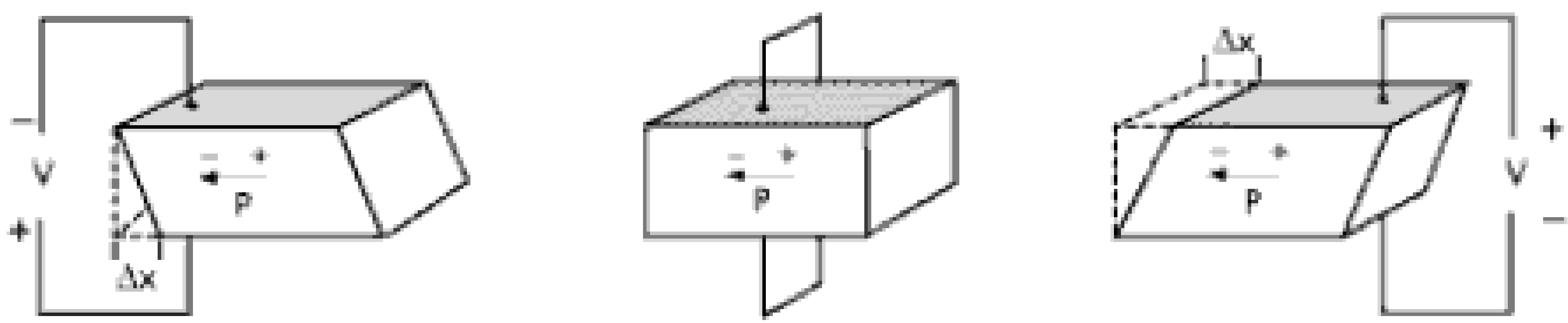
- Three typical actuator modes
  - Expansion/Contraction
    - Utilizes 33-mode and 31-mode properties
  - Shear
    - Utilizes 15-mode properties
  - Bending
    - Utilizes 31-mode properties

Piezoelectric Functionality

- Expansion/Contraction Actuator

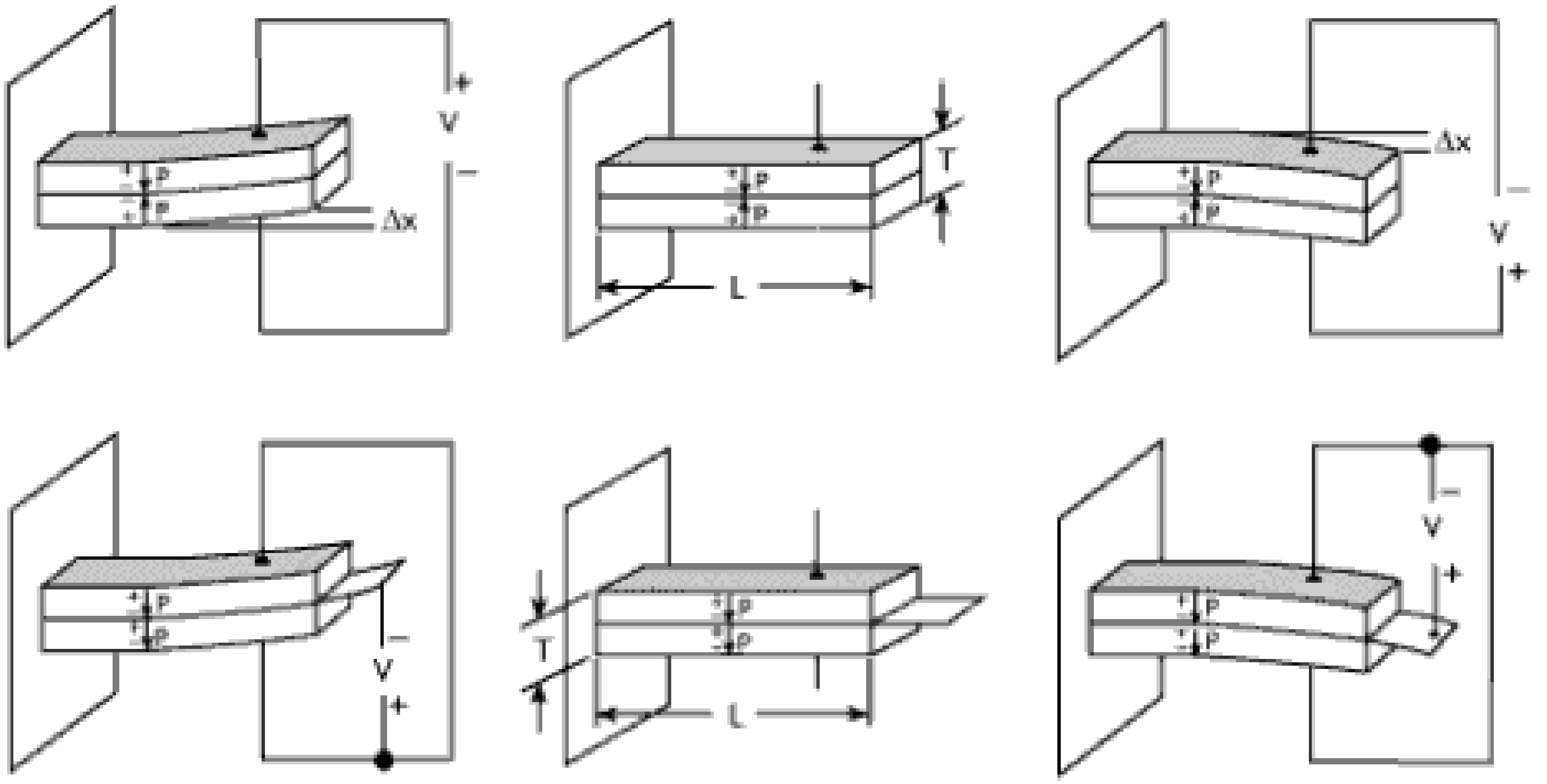


- Shear Actuator



Piezoelectric Functionality

- Bending Actuator: Series or parallel connection



Piezoelectric Advantages

- Compact and light weight
- Displacement proportional to applied voltage
- Operate over large temperature range
- Fast response to applied voltage (msec)
- Repeatable sub-nanometer steps at high frequency
- No moving parts
  - No wear an tear on the element
- Function at high frequencies
- Excellent stability
- Easily embedded into laminated composites

Piezoelectric Disadvantages

- Brittle due to crystalline structure
- Produce small strains compared to SMA and magnetostrictives
- Cannot withstand high shear and tension
- Material does age
- Uses active control
  - Can lead to instability
- Can become depolarized
  - High voltages, high temperatures, large stresses

Conclusion

- Piezoelectrics and magnetostrictives are most effective for high frequency control applications
  - Piezoelectrics for applications were size of the element is of concern
  - Magnetostrictives are good when size is of no concern
- Shape memory alloys are very effective for low frequency vibration or shape control
- Electrorheological fluids are still being explored
  - Sandwich beams are generally the only structural application
- Fiber optic sensors are very effective in all applications

Questions