Lecture Outline

- Actuator Technologies
- Shape Memory Alloys
- Magnetostrictive Materials
- Piezoelectric & Electrostrictive Materials
- Electrorheological Fluids
- Fibre-optics
- Selection of Actuator Materials
- Selection of Sensor Materials

Actuator Technologies

PROPERTY	ACTUATORS	DRIVING ENERGY	DEVICES
Shape Memory	Nitinol	T, S	Strip, Spring, Tube
Magnetostriction	Terfenol-D	H	Rod, Stack, Wire
Piezoelectric Electrostrictive	BT, PZT PMN	E, S	Disc, Plate, Stack, Tube, Cylinder
Electrorheological		E	Plate, Cylinder

T: Thermal energy   S: Mechanical strain   H: Magnetic Field   E: Electric Field

Shape Memory Effect

- The term 'shape-memory' is used to describe the ability of a material to regain its original shape when heated to a higher temperature, after being deformed at a lower temperature.
- The shape-memory effect occurs in a number of alloys, which undergo a special type of phase transformation called the 'thermoelastic martensite transformation'.

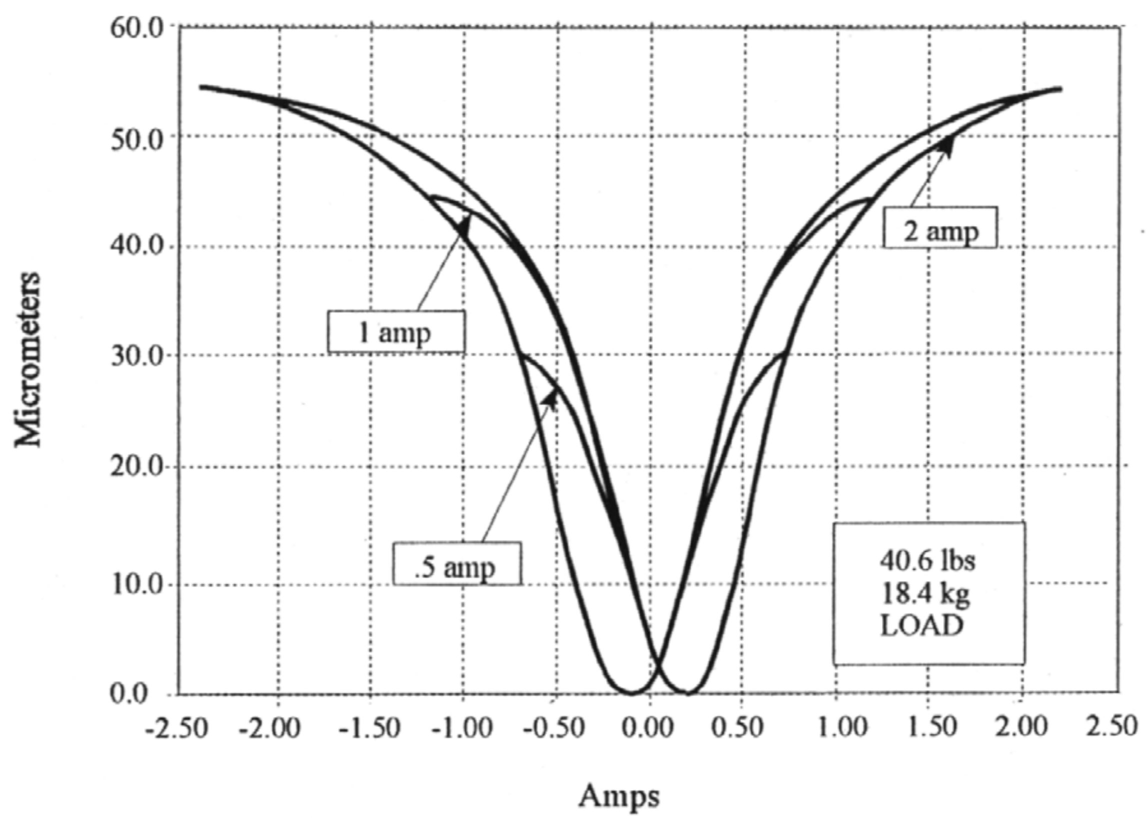
Shape-Memory Alloy Applications

Automobile Transmissions	Control of automatic transmissions in cold weather due to change in oil viscosity (Mercedes, 1989).
Shock Absorbers	Improve low temperature properties of shock absorbers by controlling their pressure valves.
Small Pumps	Laser controlled shape-memory alloy actuators drive a cantilever beam that operates a pump.
Window Openers	Cu-Zn-Al shape-memory alloys are used in greenhouse window openers. When the temperature rises, the windows are automatically opened.

Magnetostrictive Effect

- Magnetostriction is a transduction process in which electrical energy is converted to mechanical energy.
- Magnetostrictive materials exhibit a change in dimension when placed in a magnetic field. This is a result of a re-orientation of the magnetic domains, which produces internal strains in the material.

Magnetostrictive Effect



Properties of Terfenol-D

Properties	Terfenol-D*
Force Generation Strain Bandwidth	50 MPa 0.6% < 1 kHz
Hysteresis Coupling Factor Density	~ 10% 0.7 – 0.75 9,250 kG/m^3
Young's Modulus Tensile Strength Compressive Strength Curie Temperature	2.5 – 3.5 x 10^{10} N/m^3 28 MPa 700 Mpa 380^{0}C

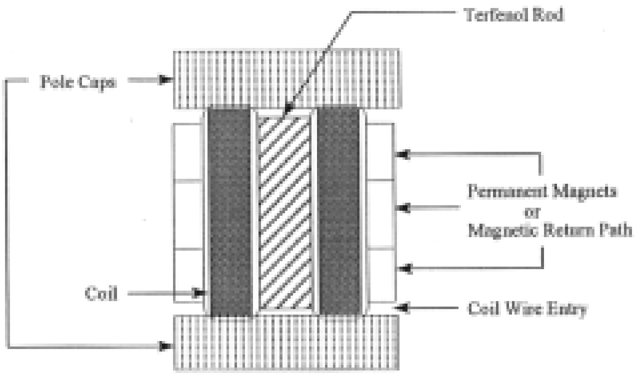
*Reference – Edge Technologies.

Magnetostrictive Materials Applications

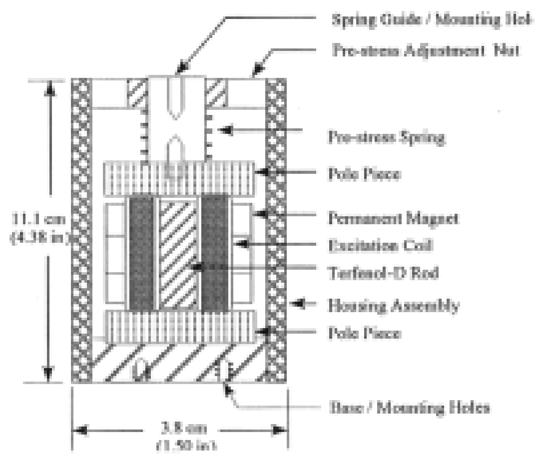
Sonar Transducers	Very high-power transducers at frequencies of 1kHz and lower. Of interest to Navy for long-range transmission, towed arrays, and communications.
Hydraulic Valves	High-speed valves, operating at frequencies of 1kHz, displace 3mm at 300Hz. Can generate pressure changes of 100psi at 2,000psi operating pressures.
Inchworm Motors	Motors can generate 12Nm of torque directly off its shaft at 0.5rpm. Applications in low-frequency acoustic transducers, pumps, and mechanical systems.
Helicopter Rotors	Potential application in active control of vibration in trailing edge flaps by modifying their shape.

J.R. Oswin, R.J. Edenborough and K. Pitman, Aerospace Dynamics, 24, 9-10 (1988)
F. Claeyssen and D. Boucher, Undersea Defence Technologies, paris, 10-59-1065 (1991)

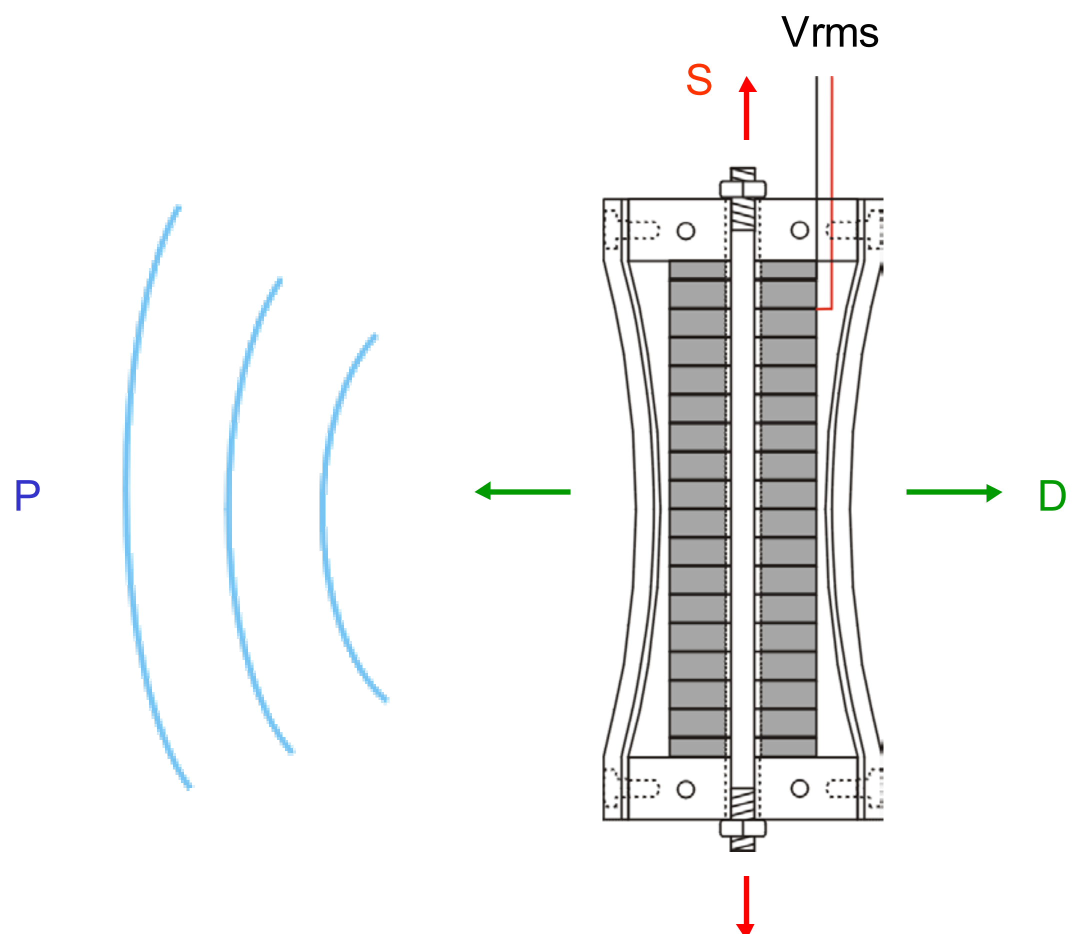
Magnetostrictive Applications



Actuator cross section drawing



Magnetostrictive Applications - Flextensional Transducers



Piezoelectric Effect

- Piezoelectric behaviour can be manifested in two distinct ways.
  - ‘direct’ piezoelectric effect
  - ‘converse’ piezoelectric effect.

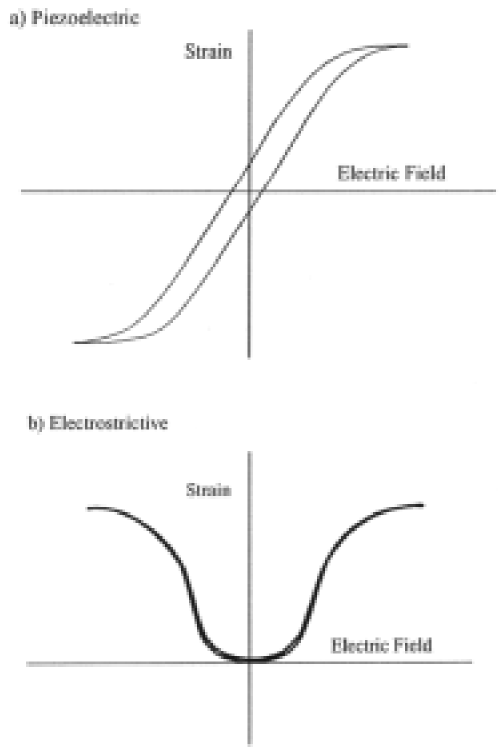
Direct Piezoelectric Effect

- ‘Direct’ piezoelectric effect occurs when a piezoelectric material becomes electrically charged when subjected to a mechanical stress.
- These devices can be used to detect strain, movement, force, pressure or vibration by developing appropriate electrical responses, as in the case of force and acoustic or ultrasonic sensors.

Converse Piezoelectric Effect

- 'Converse' piezoelectric effect occurs when the piezoelectric material becomes strained when placed in an electric field.
- This property can be used to generate strain, movement, force, pressure, or vibration through the application of suitable electric field.

Piezoelectric and Electrostrictive Effect



Piezoelectric and Electrostrictive Strain
versus Applied Electric Field

Piezoelectric Materials

Type	Materials
Single Crystals	Quartz Lead Magnesium Niobate (PMN-PT and PZN-PT)
Ceramics	Lead Zirconate Titanate (PZT) Lead Metaniobate (LMN) Lead Titanate (LT) Lead Magnesium Niobate (PMN)
Polymers	Polyvinylenedifluoride (PVDF)
Composites	Ceramic-polymer Ceramic-glass

Piezoelectric Material Applications

Sonar Transducers	Underwater communication and imaging systems. Use both direct and converse piezoelectric effects.
Ultrasonic Cleaners	Piezoelectric material (using converse piezoelectric effect) transmits sound energy into a liquid bath. A process called cavitation provides the cleaning action.
Printer Head	Ink jet printers use a piezoelectric stack actuator (using converse piezoelectric effect) to provide fast operation of nozzles. Can provide rates of up to 500 pages per minute.
Scanning Tunneling Microscope (STM)	Produces three-dimensional images of electronic structure of materials. Can also be used in MEMS manufacturing and lithography.

Electrorheological Effect

- Rheology is the science of the flow and deformation of matter, i.e., the response of the matter to a force or stress.
- The viscous properties or a fluid's resistance to flow can be altered or modified in an electrorheological (ER) fluid through the application of an electric field.

Electrorheological Effect

- ER materials exist in a wide variety of colloidal suspensions of dielectric solids in non-conducting liquids.
- In the absence of electric field, the colloidal suspension is composed of fine particles (0.1 - 1.0μm) which are uniformly distributed throughout the field.

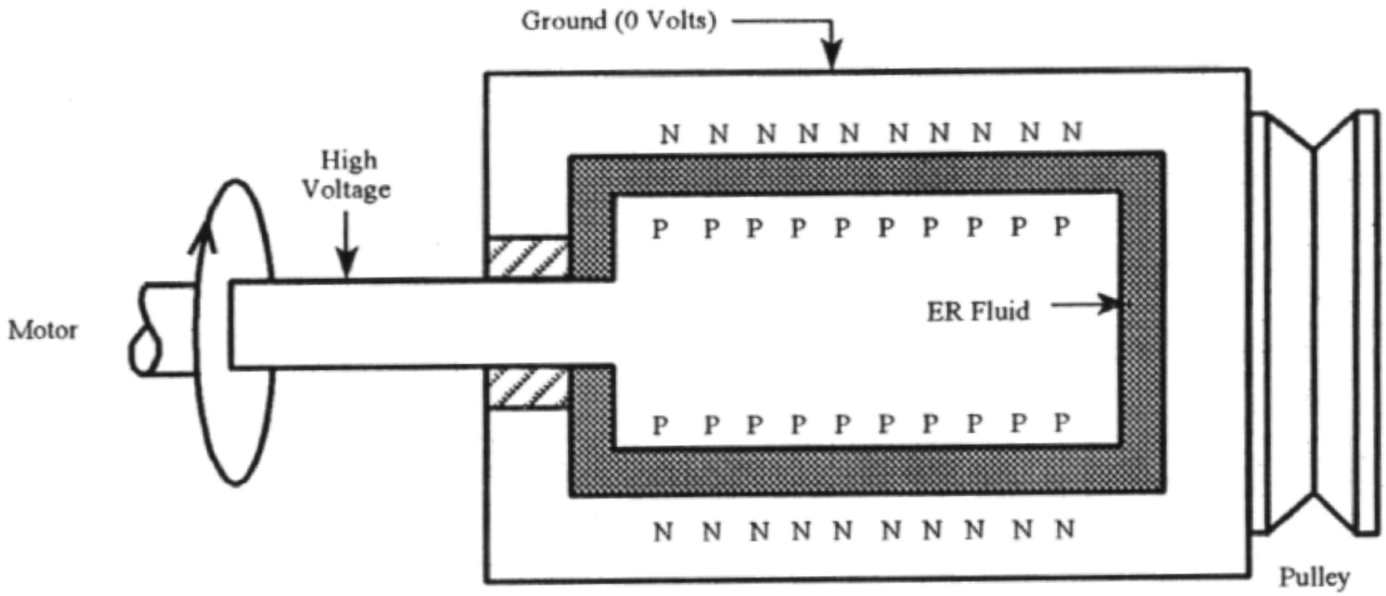
Electrorheological Effect

- When an electric field is applied, the dielectric properties of the particles causes them to align with the electric field and causes them to adhere to adjacent particles which join to form fibrils.
- The presence of these fibrils considerably modifies the viscosity of the fluid (by as much as a factor of 50).
- The alignment disappears when the electric field is removed, thus creating the desired property of complete cyclic reproducibility.

ER Material Applications

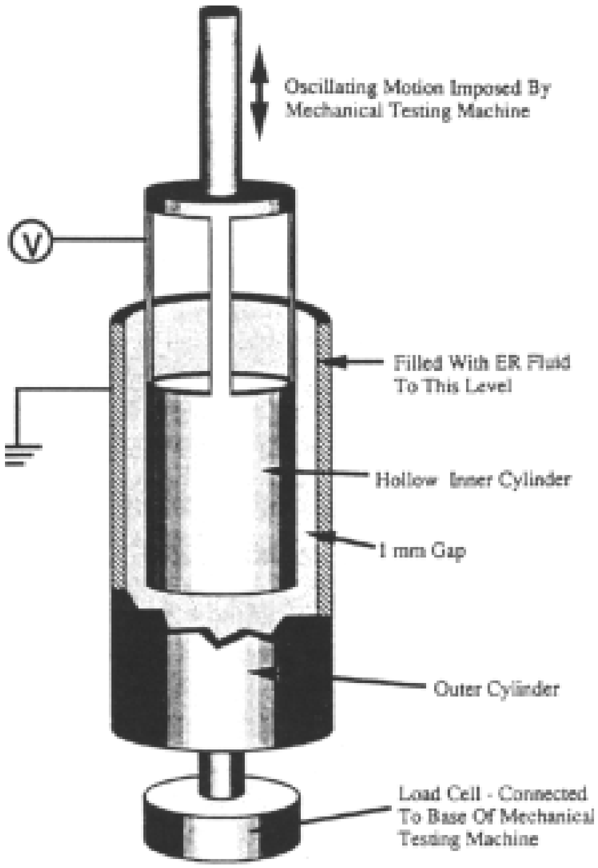
Static Mode	Release mechanisms
Shear Mode	Clutch Devices. ER fluid mechanically couples two surfaces by increasing or decreasing its viscosity with the application or removal of an electric field.
Damping Devices	Shock Absorbers. ER fluid usually operates in either the shear or extensional configuration. Shear configuration is used when the fluid undergoes strain, and extensional configuration used for compression stress.
Variable Flow Controls	Adjusting the viscosity of a fluid as it flows through a porous electrode separating two chambers can control the volume of the flow.

ER Clutch



Ground (0 Volts)
High Voltage
Motor
N N N N N N N N N N
P P P P P P P P P P
ER Fluid
P P P P P P P P P P
N N N N N N N N N N
Pulley

ER Pump



Schematic of annular pumping apparatus.

K.D. Weiss and J.D. Carlson, 'Material aspects of electrorheological systems',
Advances in Electrorheological Fluids, pp30-52, 1994,
Technomic Publishing Company.

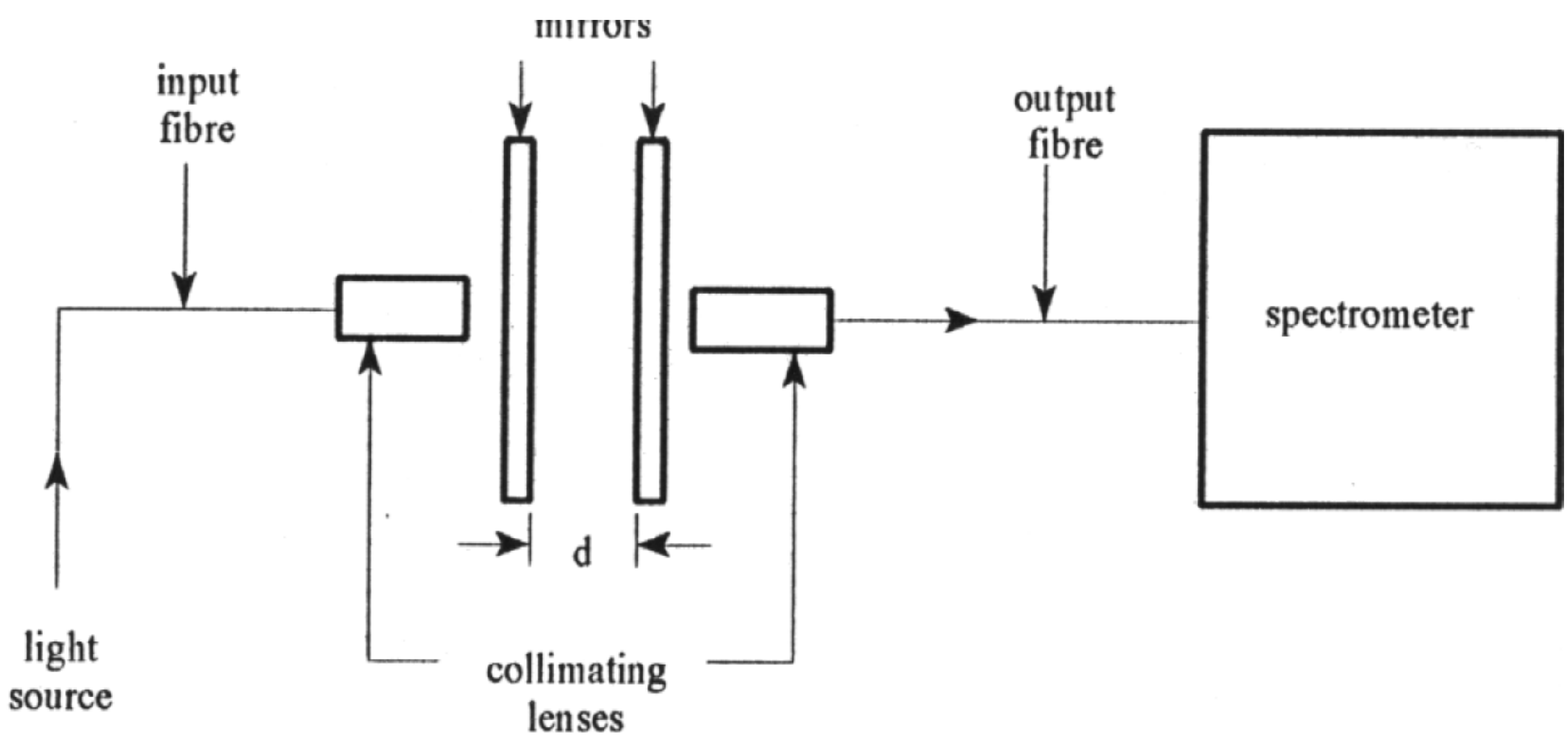
Fibre-Optics

- Fibre-optic sensors can be used to detect heat or stress. Two types of fibre-optic sensors are used, intrinic and extrinsic types.
- In the extrinsic type, fibre acts as a medium of transmission. The light exits and interacts with the environment to be analyzed and then re-enters the fibre. This is a low cost method and can use photodiodes for the operation.

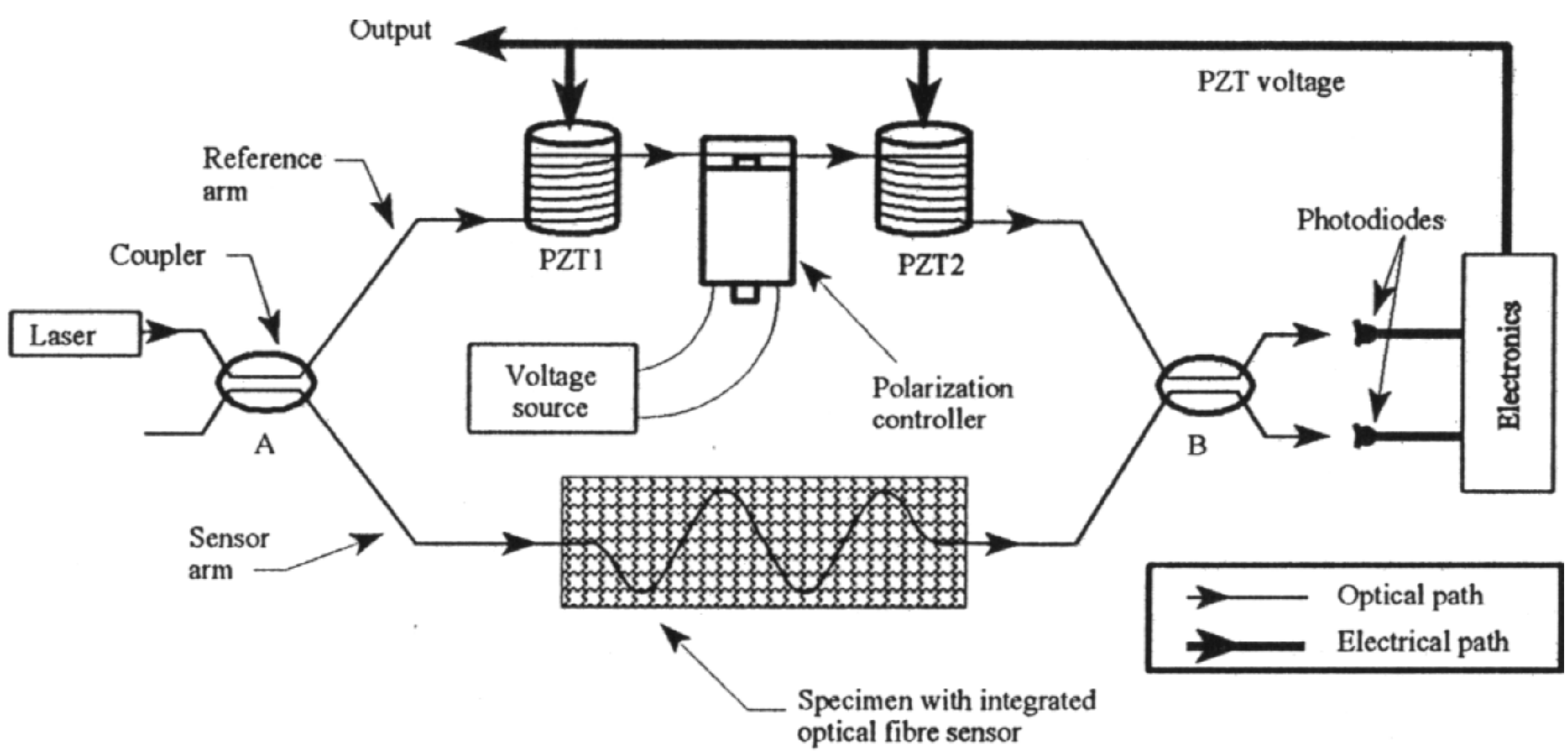
Fibre-Optics

- In the intrinsic type, one or more field parameters become modulated with the field which propagates in the fibre to allow the measurement of environmental effects. Generally these techniques involve interferometric techniques and can detect both strain and temperature fluctuations.

Fibre-Optics : Fabry-Perot Resonator



Fibre-Optics: Mach-Zender Interferometer



Selection of Actuator Technology

Performance Parameter	Nitinol	Terfenol-D	PZT
Linear Displacement	High	Moderate	Moderate
Linear Force	Low	Moderate	High
Weight	Moderate	High	Moderate
Volume	Moderate	High	Moderate
Cost	Moderate	High	High

Selection of Actuator Technology

Performance Parameter	Nitinol	Terfenol-D	PZT
Bending Displacement	High	Moderate	High
Bending Force	Low	Low	Moderate
Weight	Low	High	Low
Volume	Low	High	Low
Cost	Moderate	High	Low

Selection of Actuator Technology

Actuator Technology	Strain	Strength (Mpa)		Operating Temperature Range
		Tensile	Compressive	
Shape memory (Nitinol)	5% (two-way)	900-1500	-	Up to 400^{0}C (thermal actuation)
Magnetostrictive (Terfenol-D)	200 με (1 kA/m)	28	700	Up to 300^{0}C (Tc=380^{0}C)
Electrostrictive (PMN)	1500 με (1 MV/cm)	11.7	300	0? -30^{0}C (T_C)
Piezoelectric (BM500)	1000 με (1 MV/cm)	75.8 (static) 27.6 (dynamic)	> 500	-20^0-250^{0}C (T_C=365)

Selection of Actuator Technology

Actuator Technology	Typical Displacement	Force	Hysteresis	Frequency Range
Shape memory (Nitinol)	500 µm (L=5 cm)	500 N	10-30%	<5 Hz
Magnetostrictive (Terfenol-D)	100 µm	1.1 kN	~10%	<4 kHz
Electrostrictive (PMN)	65 µm	9 kN	1-4%	<1 kHz
Piezoelectric (BM500)	100 µm (L=5cm)	20 kN	8-15%	<30 kHz

Sensor technology Limited (Product Information) ; Edge Technologies Inc (Product Information)
C.D. Near, W.J. Dawson, S.L. Swartz and J. Issartel, SPIE Vol 1916, pp396-404(1993).

Sensor Technologies

PARAMETER	ACTUATORS	PRINCIPLE
Displacement	Potentiometers LVDT Eddy Current Capacitance	Change of resistance Electromagnetic induction Electromagnetic induction Variation of capacitance
Strain	Strain Gauges Fiber Optics Piezoelectric	Change of resistance Fabry-Perot resonator Mach-Zender interferometer Generation of voltage

Sensor Technologies

PARAMETER	ACTUATORS	PRINCIPLE
Force and Acceleration	Load Cells Piezoelectric	Change of resistance Generation of voltage
Temperature	Thermistors Thermocouples Fibre Optics	Change of resistance Generation of voltage Resonator or Interferometer

Selection of Strain Sensors

Performance Parameter	Strain Gauge	Fibre Optics	Piezoelectric
Sensitivity	High	Moderate	Moderate
Gage Length	As desired	Moderate	High
Bandwidth	Moderate	High	Moderate
Resolution	Moderate	High	Moderate
Temperature Range	Moderate	High	High

Selection of Temperature Sensors

Performance Parameter	Thermocouple		RTD		Thermistor	
	J-type	K-type				
Sensitivity	61 mV/^{0}C	40 mV/^{0}C	n.a.	n.a.	±0.2^{0}C	±0.1^{0}C
Response Time	<5 s	<5 s	.1 s	13.5 s	Fast	Fast
Bandwidth	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Resolution	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Temperature Range	-210^0 to 1200^{0}C	-270^0 to 1372^{0}C	-70^0 to 600^{0}C	-50^0 to 150^{0}C	-80^0 to 120^{0}C	-80^0 to 75^{0}C

Selection of Acceleration Sensors

Performance Parameter	Load Cell		Accelerometer 1		Accelerometer 2	
Sensitivity	n.a.	n.a.	n.a.	n.a.	1000 mV/g	100 mV/g
Range	50 g	50 Klb	±80 g	±1000 g	±4 g	±50 g
Bandwidth	n.a.	n.a.	3 Hz to 5 kHz	2 Hz to 10 kHz	1 Hz to 2 kHz	0.3 Hz to 7 kHz
Resolution	0.2 fsd	0.2 fsd	n.a.	n.a.	0.001 g pk	0.0001 g pk
Temperature Range	15° to 71°C	-54° to 121°C	-18° to 82°C	-55° to 120°C	n.a.	-54° to 125°C
Linearity	±0.15% fs	0.4% fs	±1%	±2%	<1%	±1%
Mass	<15 g	n.a.	50 g	1.5 g	5.2 g	160 g

Selection of Displacement Sensors

Performance Parameter	Potentiometer		LVDT	
Sensitivity	n.a.	n.a.	110 mV/mm	1.12 V/mm
Stroke Range	25 mm	155 mm	0.125mm	1.25 mm
Bandwidth	n.a.	n.a.	<2 kHz	<2 kHz
Resolution	0.1 mm	0.1 mm	n.a.	n.a.
Temperature Range	n.a.	n.a.	-55° to 150°C	-55° to 150°C

Conclusions

- The current 'state-of-the-art' with respect to smart material technologies has been established.
- Selection criteria for these material technologies has also been presented.