- Lecture 1: Introduction to Smart Materials and Systems
- Lecture 2: Sensor technologies for smart systems and their evaluation criteria.
- Lecture 3: Actuator technologies for smart systems and their evaluation criteria.
- Lecture 4: Piezoelectric Materials and their Applications.
- Lecture 5: Control System Technologies.
- Lecture 6: Smart System Applications.

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Actuators for Smart System Applications

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Actuator Materials

- Shape Memory Alloys
- Magnetostrictive Materials
- Piezoelectric & Electrostrictive Materials
- Electrorheological & Magnetorheological Fluids
- Selection of Actuator Materials

Shape Memory Alloys (SMAs)

Smart Materials Demo http://www.youtube.com/watch?v=VU-dChOfkAg

Shape Memory Alloys (SMAs)

- 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 Alloys (SMAs)

- SMAs are useful for actuators as they change shape, stiffness, position, natural frequency, and other mechanical characteristics in response to temperature or electromagnetic fields. The diverse applications for these metals have made them increasingly important

Shape Memory Alloys (SMAs)

- Alloy families that exhibit shape memory effect

  copper-aluminum-nickel

  copper-zinc-aluminum

  iron- manganese-silicon

  nickel-titanium (nitinol)

- Nickel-titanium alloys have been found to be the most useful of all SMAs.

Shape Memory Alloys (SMAs)

- Transformation Strain

  for a single cycle max 8%

  for 100,000 cycles 4%

- Hysteresis 30 to 50 deg. C
- Mechanical Properties (Young's Modulus)

  austenite 83 GPa (12E6 psi)

  martensite 28 to 41 GPa (4E6 to 6E6 psi)

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Shape Memory Alloys (SMAs)-

Electrical and Magnetic Properties

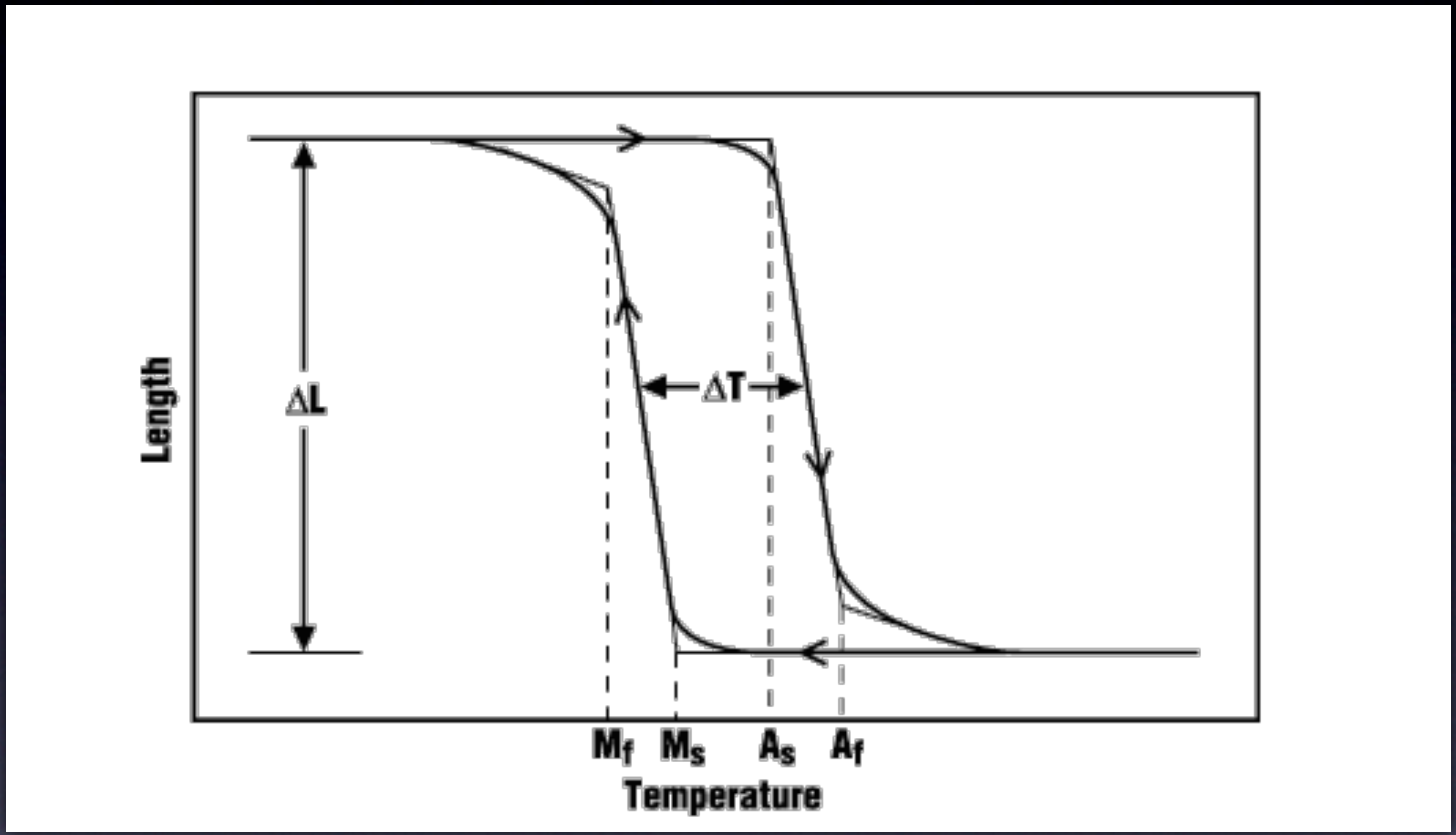
- Resistivity

  austenite   100 micro-ohms * cm

  martensite   80 micro-ohms * cm

- Magnetic Permeability < 1.002
- Magnetic Susceptibility 3.0E6 emu/g

Shape Memory Alloys (SMAs)-



10

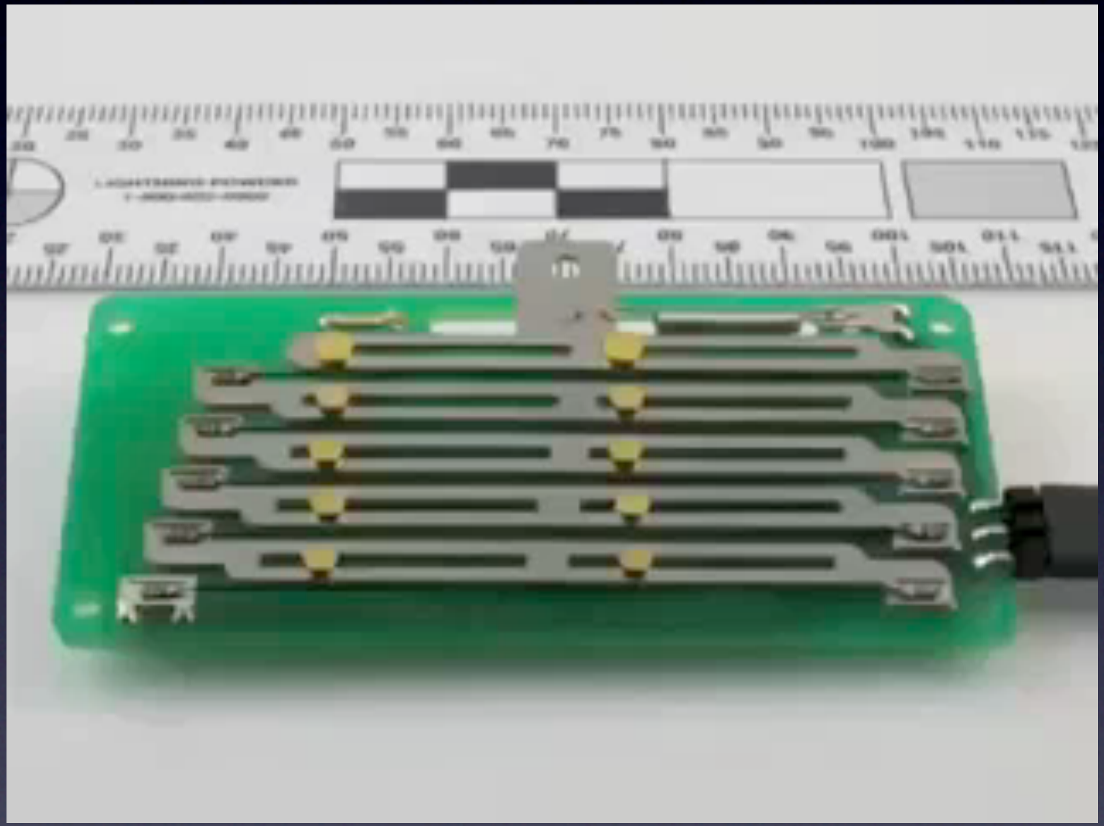
Shape Memory Alloys (SMAs)- Applications

Automobile Transmissions	Control of automatic transmissions in cold weather due to change in oil viscosity.
Shock Absorbers	Improve low temperature properties of shock absorbers.
Small Pumps	Laser controlled shape-memory alloy actuators drive a cantilever beam that operates a pump.
Window Openers	Greenhouse window openers - when the temperature rises, the window is automatically opened.

Shape Memory Alloys (SMAs)- Applications

Automotive	Bi-directional grill louver mechanism; Fuel tank door release mechanism; Trunk, glove compartment release mechanism.
Aerospace	Payload release device; Door latch release Instrument latch release, Bypass switches
Medical	Pumps and valves, Micro fluid array pumps, Latch releases
Consumer	Greenhouse window openers; Memory card ejectors, Security locks and doors.

Application of Shape Memory Alloys



SMA Actuator

Application to robotics

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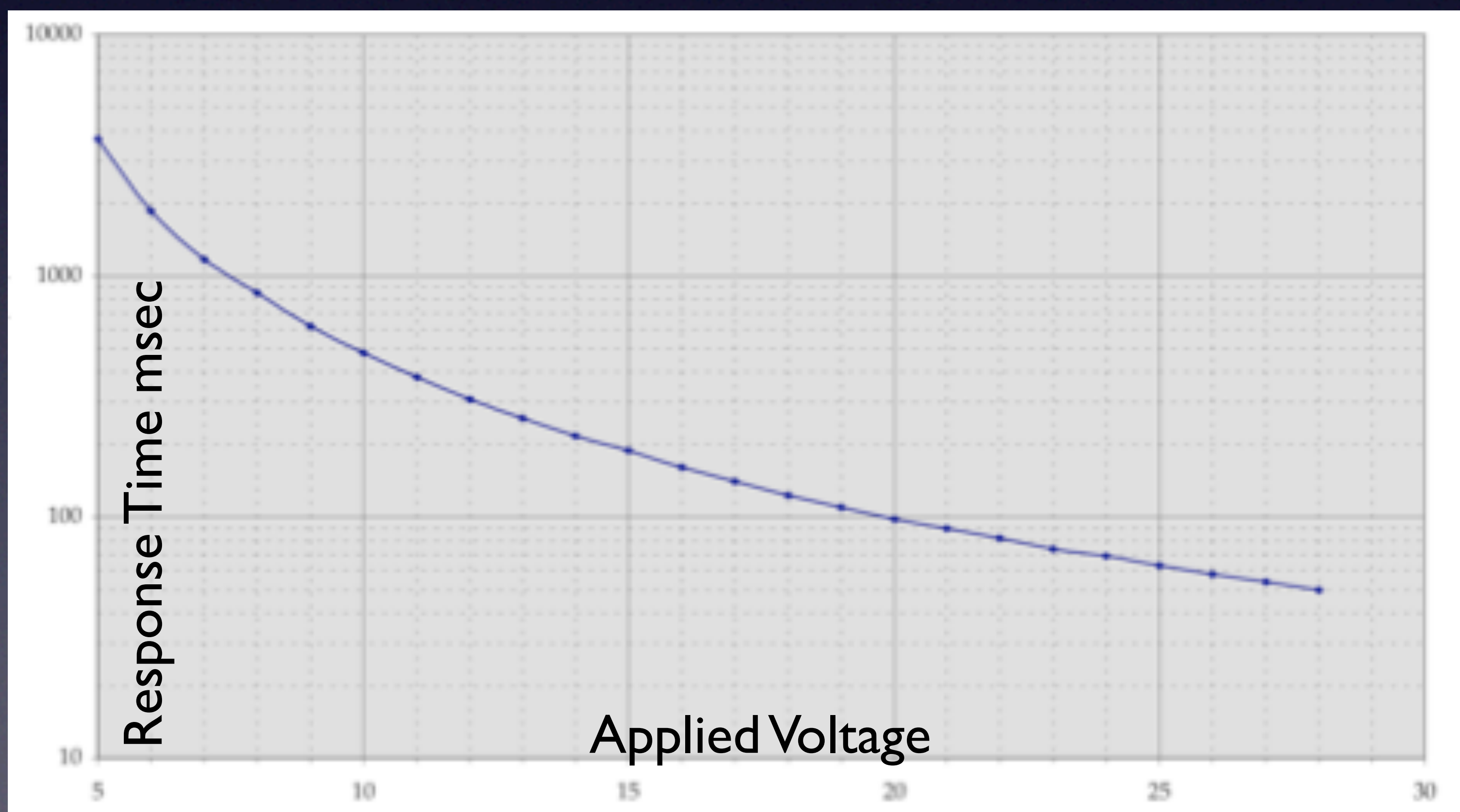
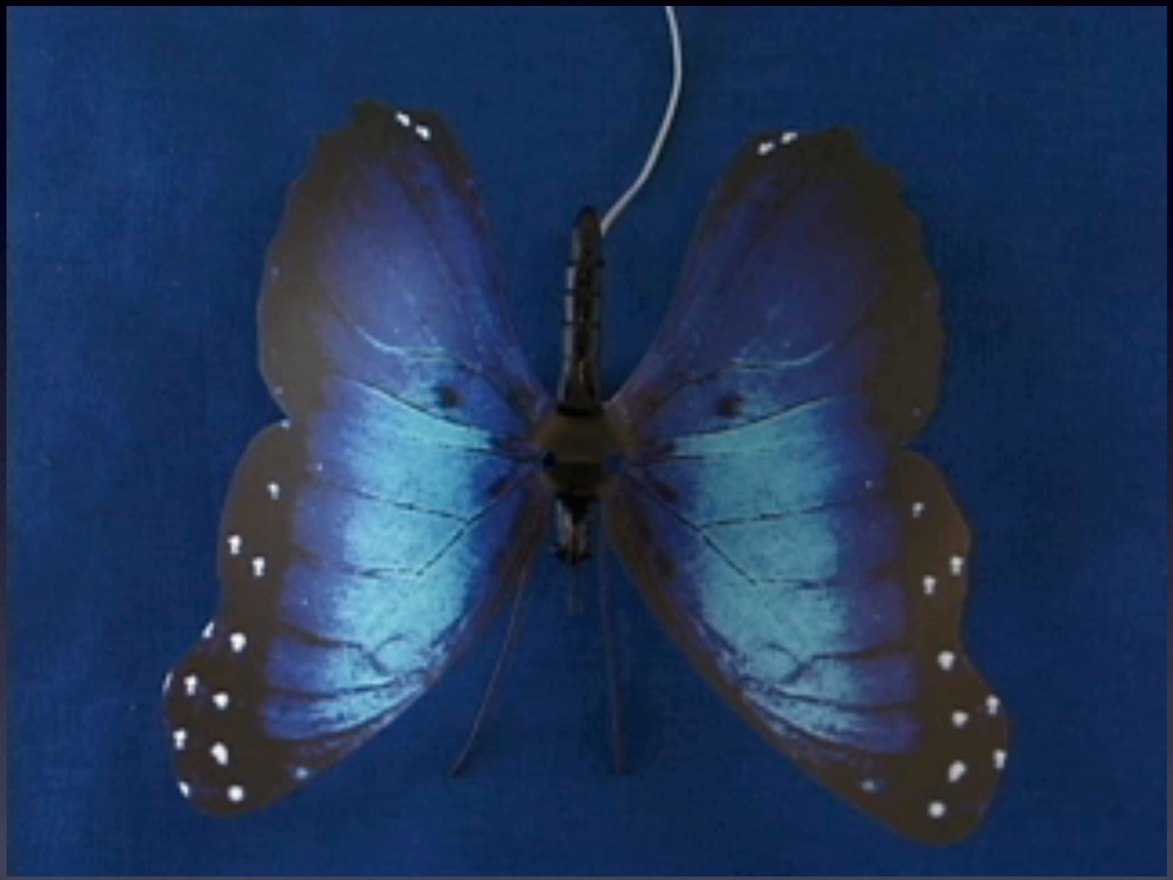
Application of Shape Memory Alloys

MigaOne Specifications

- **Stroke**: 0.375 inches (9.5mm)
- **Output Force**: constant 2.5 lb-f (11 N), peak 5.0 lb-f (22 N)
- **Actuation Time**: 50 ms to position hold (depends on input voltage or PWM)
- **Actuation Speed**: up to 200 mm/s
- **Weight** (as shown): 0.45 ounces (12.8 grams)
- **Dimensions**: 2.8" x 1.3" x 0.098" (71 x 33 x 2.5mm)
- **Mounting Holes**: 1.125" x 2.675" thru pattern for #2 SHCS
- **Vertical Height** from 0.063" FR-4 PCB Surface: 0.059" (1.5mm)
- **Operating Temperature Range**: -20˚F to 140˚F (-29˚C to 60˚C)



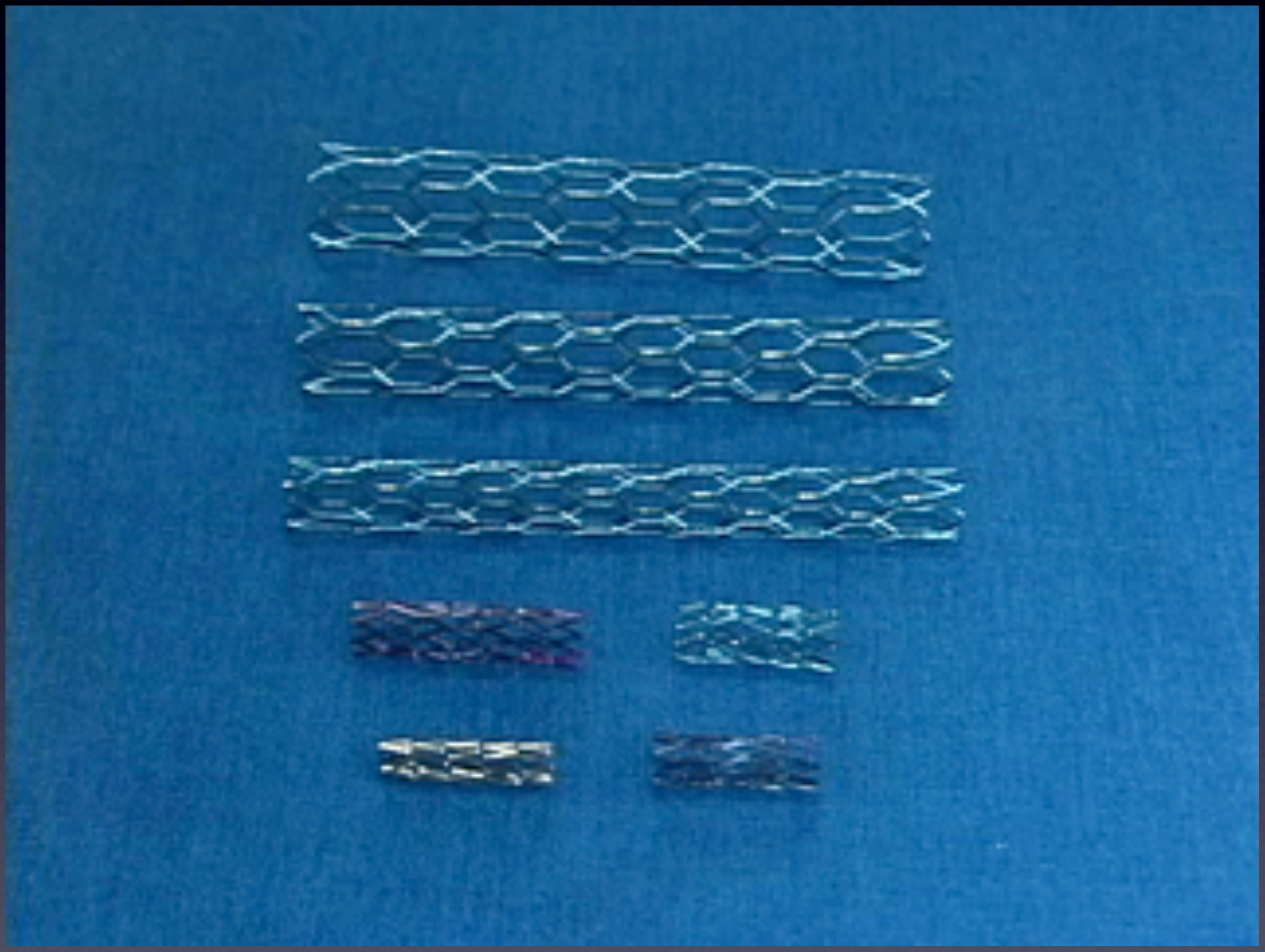
Shape Memory Alloys (SMAs)- Applications



University of Wisconsin (Materials Research Science & Engineering Centre)

This model has an electrically heated NiTi actuator. Movement of a NiTi wire causes the wings to move.

Shape Memory Alloys (SMAs)-Applications



University of Wisconsin (Materials Research Science & Engineering Centre)

NiTi is used to make medical devices such as the cardiovascular stents shown here. The superelastic "springy" property that this alloy exhibits above its transformation temperature (body temperature) is shown in the movie. These devices are very resilient even when severely compressed because of the superelastic property of NiTi.

Actuator Materials

- Shape Memory Alloys
- Magnetostrictive Materials
- Piezoelectric & Electrostrictive Materials
- Electrorheological & Magnetorheological Fluids
- Selection of Actuator Materials

Smart Magnetic Materials

- "smart" magnetic materials have high magnetostriction constants, which mean they change length when placed in a magnetic field.

- This property can be utilized in smart systems in switches or sensors.

Smart Magnetic Materials

Smart Magnetic Materials could be divided according to various criteria. One of the possible classifications distinguishes the following SMM types:

- Materials of fixed internal structure:

  solid magnetostrictive materials, including those with giant magnetostriction

  Metal, Ceramic and Polymeric Composites

  Elastomers filled with ferromagnetic material powders (e.g. carbonyl iron, GMM or their combination), polymers on the epoxy resin base containing powdered ferromagnetic materials,

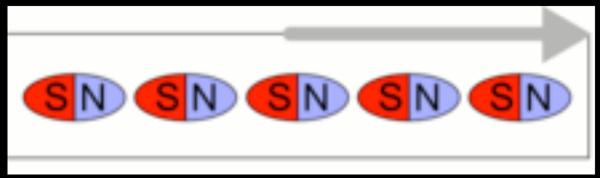
  Solid magnetocaloric materials.

Smart Magnetic Materials

Smart Magnetic Materials could be divided according to various criteria. One of the possible classifications distinguishes the following SMM types:

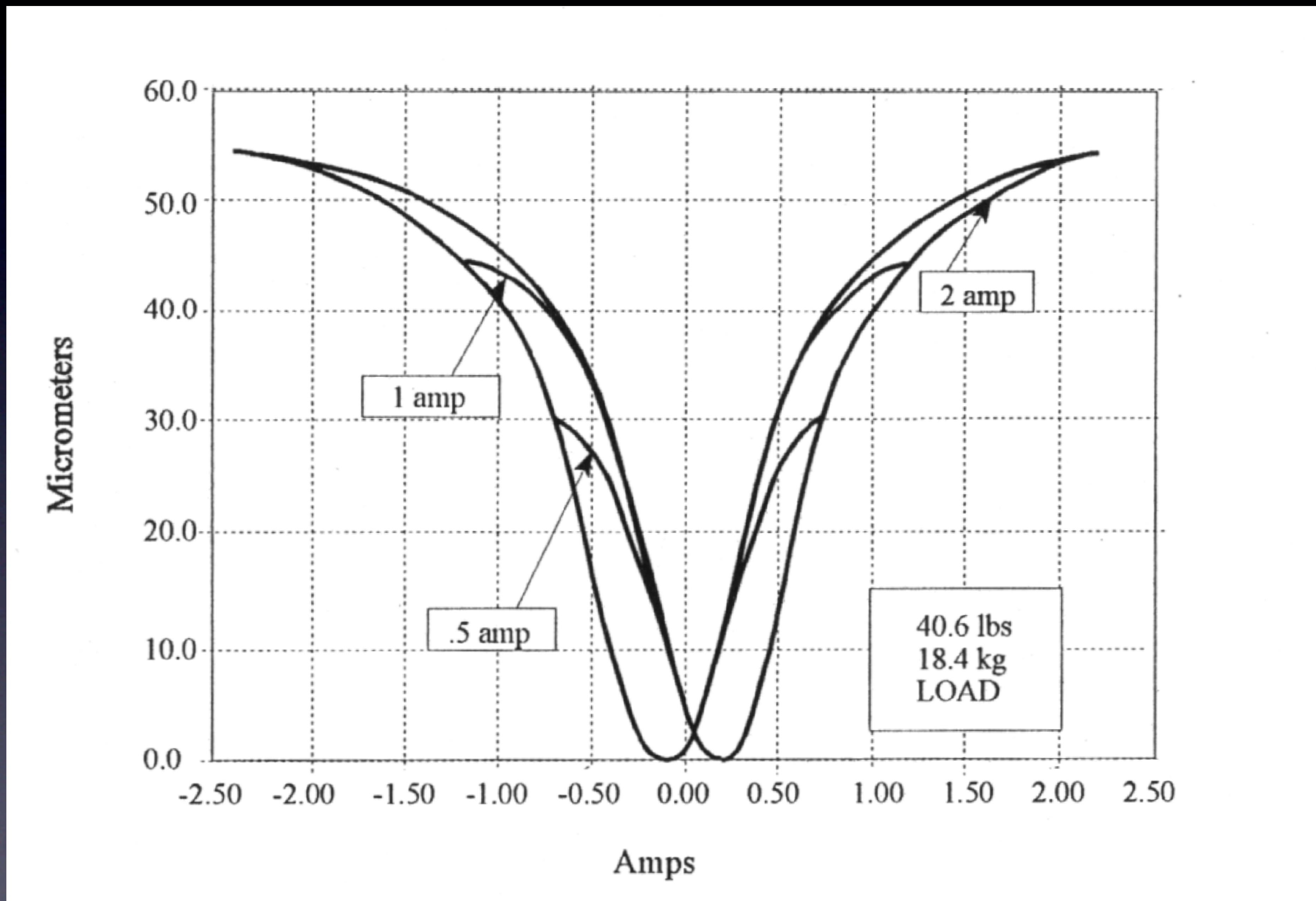
- Materials of variable internal structure
  - MagnetoRheological Fluids - MRF
  - FeRroFluids – FRF
  - Porous materials saturated with magnetorheological fluids
  - fluids with powdered magnetocaloric materials.

Magnetostrictive Actuators



- 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 Actuators



Magnetostrictive Actuators

- Giant Magnetostrictive Materials (GMM) such as Rare earth-iron feature magnetostrains two orders of magnitude larger than Nickel.
- Terfenol-D [$Tb_{0.3}Dy_{0.7}Fe_{1.9}$] is a commercially available material for use at room temperature.
- Positive magnetostrains of 1000 to 2000 ppm (0.1-0.2%) with fields of 50 to 200 kA/m are reported for Terfenol.
- Recently, the family of smart magnetic materials has also been extended with Magnetic Shape Memory Materials (MSM) such as NiMnGa alloys offering a magnetostrain of up to 6%.

Magnetostrictive Actuators - What is Terfenol-D

- Terfenol-D is an alloy of terbium, dysprosium, and iron metals and has the largest room temperature magnetostriction of any known material.

- The name Terfenol-D comes from the metallic elements; terbium (TER), iron (FE), Naval Ordnance Labs (NOL), and Dysprosium (-D). NOL (US Navy) developed the material.

- Terfenol-D is a solid-state transducer capable of converting very high energy levels from one form to another. In the case of electrical-to-mechanical conversion, the magnetostriction of the material generates strains 100 times greater than traditional magnetostrictives, and 2-5 times greater than traditional piezoceramics. The material has a high Curie temperature (380 C), which enables magnetostrictive performance greater than 1000 ppm from room temperature to 200 C.

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Magnetostrictive Materials - Terfenol-D

Physical Properties	Metric
Density	9.25 g/cc

Mechanical Properties	Metric
Tensile Strength, Ultimate	28.0 MPa
Modulus of Elasticity	25.0 - 35.0 GPa
	18.0 - 55.0 GPa
	50.0 - 90.0 GPa
Bulk Modulus	90.0 GPa

Electrical Properties	Metric
Electrical Resistivity	0.0000600 ohm-cm
Magnetic Permeability	4.50 - 10.0
Curie Temperature	357 °C

Thermal Properties	Metric
CTE, linear	12.0 µm/m-°C @Temperature 20.0 °C
Specific Heat Capacity	0.320 - 0.370 J/g-°C
Thermal Conductivity	10.5 - 10.8 W/m-K
Melting Point	1240 °C

Component Elements Properties	Metric
Dysprosium, Dy	42.3 %
Iron, Fe	40.0 %
Terbium, Tb	17.7 %

Magnetostrictive Actuators - Properties of Terfenol-D

Properties	Terfenol-D*
Force Generation	50 MPa
Strain	0.6%
Bandwidth	< 1 kHz
Hysteresis	~ 10%
Coupling Factor	0.70 to 0.75
Density	9,250 kg/m^3
Young's Modulus	2.5 -3.5 x 10^{10} N/m^3
Tensile Strength	28 MPa
Compressive Strength	700 Mpa

*** Etrema Products**

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Magnetostrictive Actuators

- Forces: Magnetostrictive actuators can offer large forces and are available as rods with large section (more than 50mm in diameter).
- Stroke: Stroke is governed by the expansion of the active rod and by its length (up to 200mm). Stroke can also be further amplified using mechanical shells.
- Voltage: The excitation voltage can be adjusted using the number of turns on the coil. With high current and large section wires, the required magnetic field can be produced with a low voltage (less than 12V if needed).

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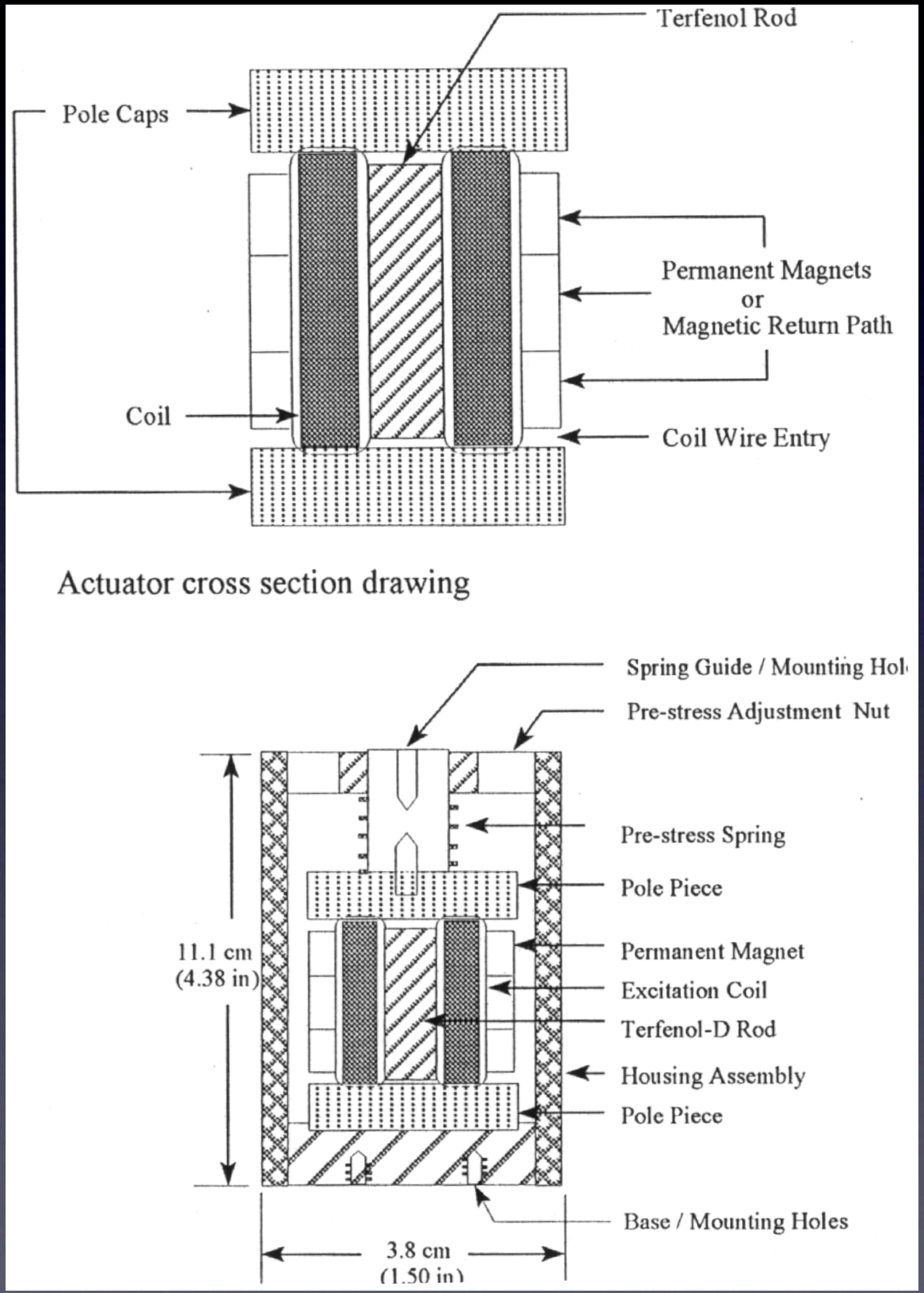
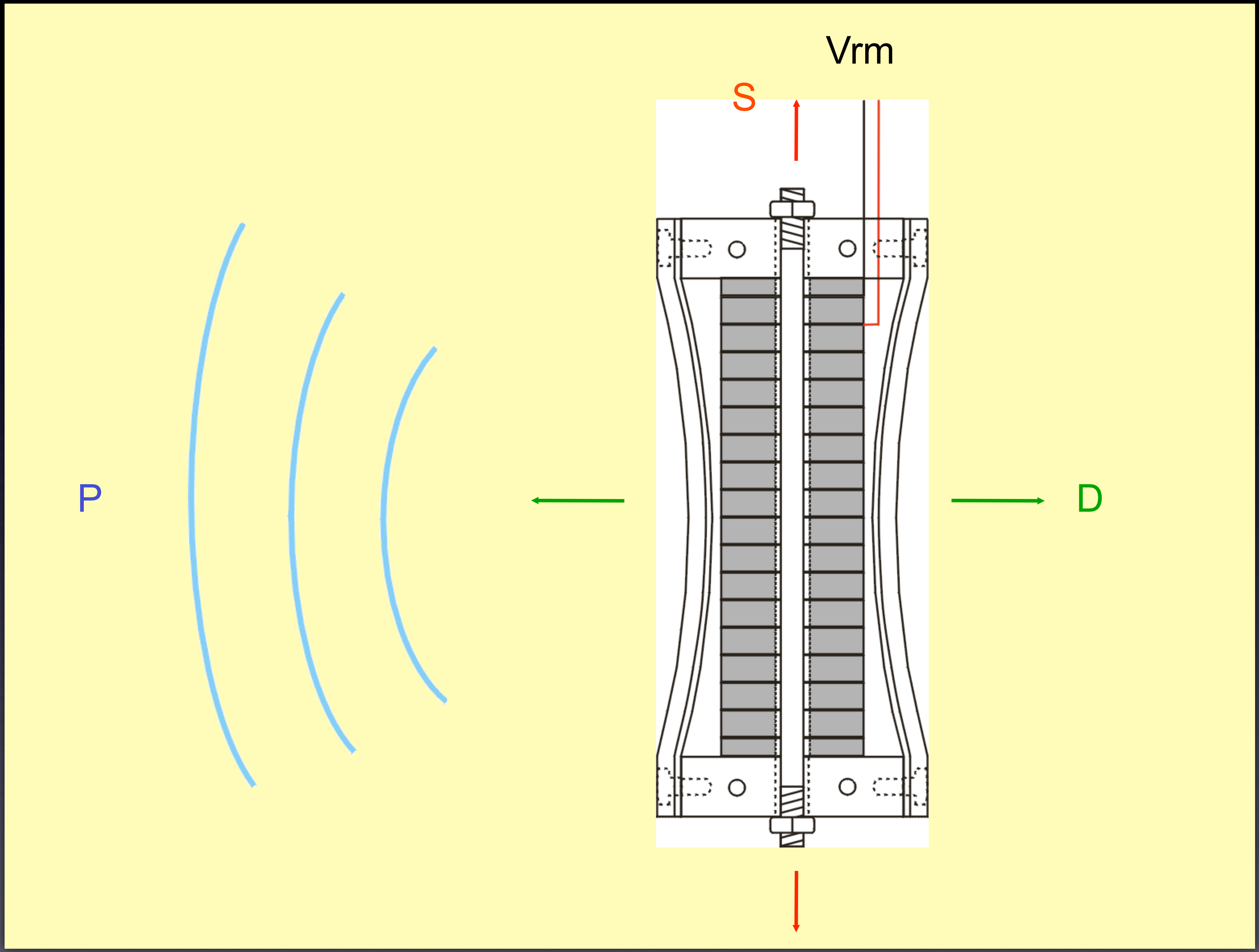
Magnetostrictive Actuators



Magnetostrictive Actuators



Magnetostrictive Actuators - Applications

- Petroleum /Oil & Gas
- Active noise and vibration cancellation
- Sonar
- Fuel injection
- Medical
- Nozzle anti-clogging system (Paper)
- Screening Applications
- Metals Casting Industry
- Fast tool servo (Machining)

Magnetostrictive Actuators - Applications

Sonar Transducers	Very high power transducers at frequencies of 1 kHz and lower. Of interest to navy for long-range transmission and communication applications.
Hydraulic Valves	High speed valves, operating at frequencies of 1 kHz, displacement of 3 mm at 300 Hz. Can generate pressure changes of 100 psi at 2,000 psi operating pressures.
Inchworm Motors	Motors can generate 12 Nm of torque directly at 0.5 rpm. 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, 1988; F. Claeyssen, and D. Boucher, Undersea Defence Technologies, 1991.

Magnetostrictive Actuators - Applications

FeONIC TECHNOLOGY

whispering | window™

Audio in the retail industry
Internal/external audio through windows

When coupled to a glass or rigid surface FeONIC™ technology turns the surface into a loudspeaker. The quality of the audio output is determined by the size and mass of the panel, it's mounting and the size of the FeONIC sounder. Recent applications of whispering window include football stadiums, restaurants, art galleries and retail locations as well as train carriages where audio and PA is delivered through the carriage windows. The device shown to the right is a standard design, devices can be completely discrete and integrated into the structure of the window they are sounding. Current FeONIC sounders are capable of driving windows of up to 200kgs in weight.

Whispering Window

Valcom TD230 dual 30W amplifier & Valcom TD230A dual 30W amplifier with AGC:

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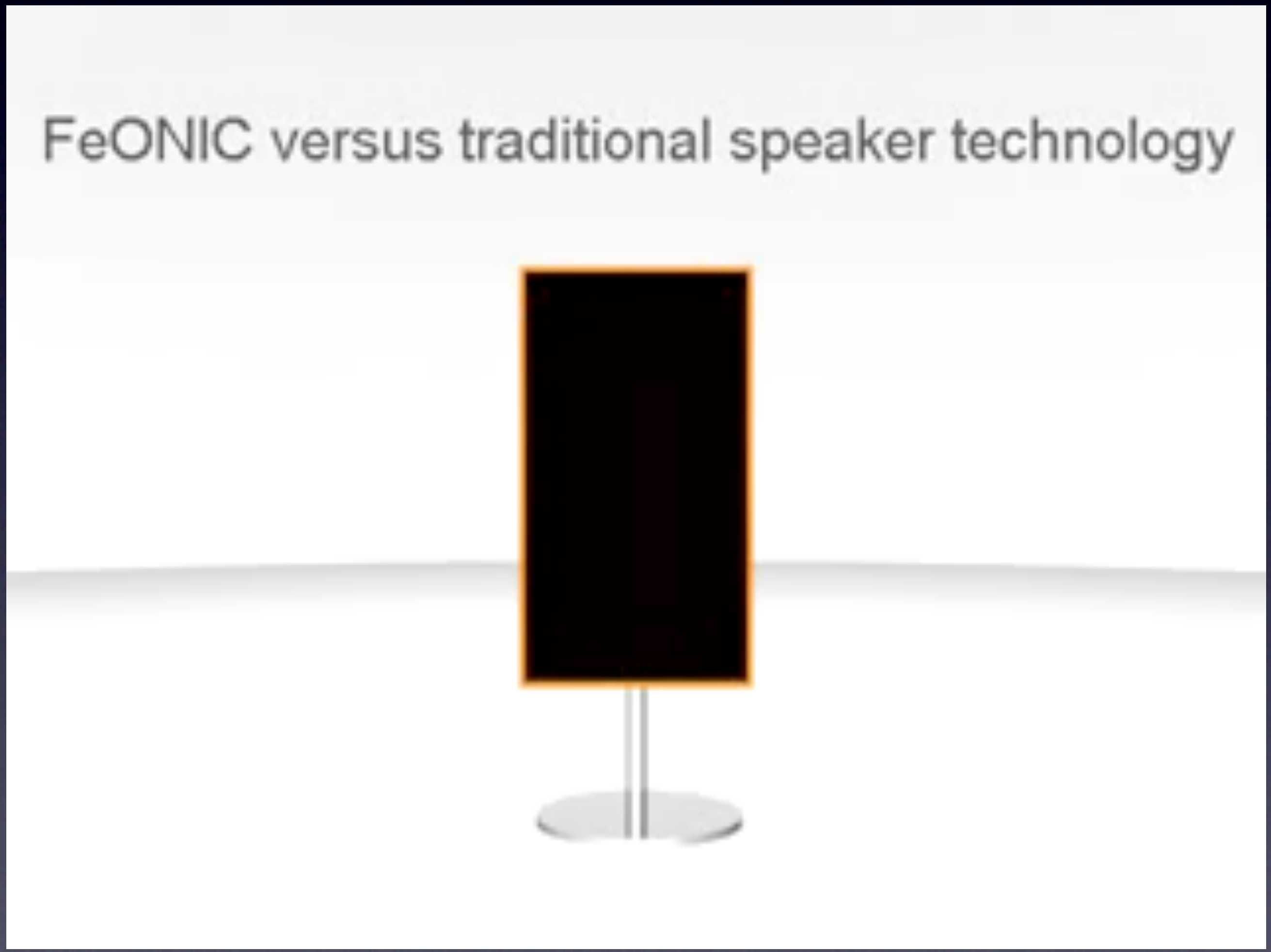
Magnetostrictive Actuators - Applications



Magnetostrictive Actuators - Applications

Feonic Technology

Actuator Materials

- **Shape Memory Alloys**
- **Magnetostrictive Materials**
- **Piezoelectric & Electrostrictive Materials**
- **Electrorheological & Magnetorheological Fluids**
- **Selection of Actuator Materials**

Electrorheological Actuators

- 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.

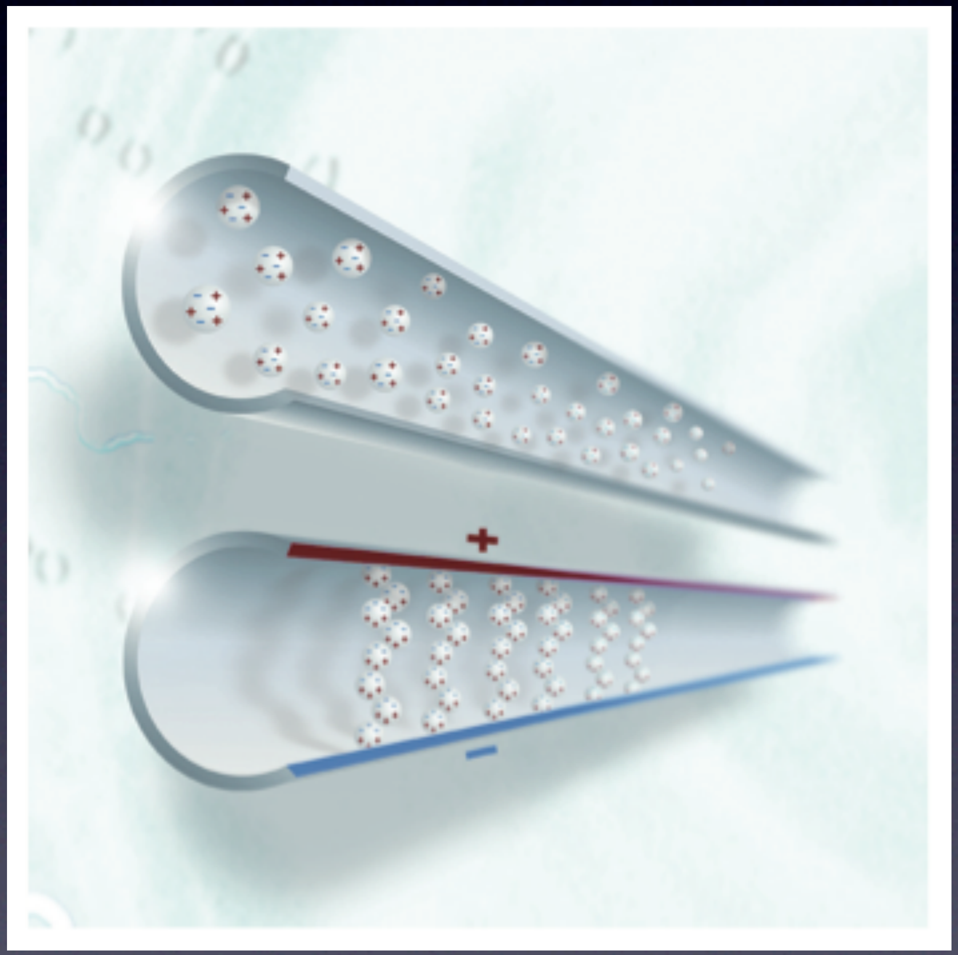
Electrorheological Actuators

- 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 Actuators

- 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.

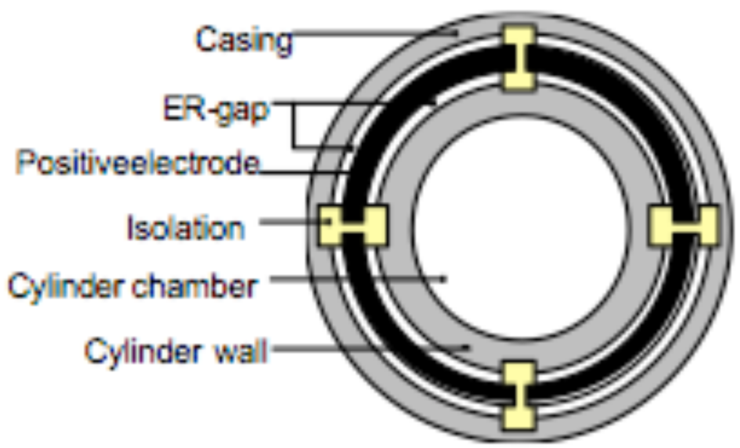
Electrorheological Fluids

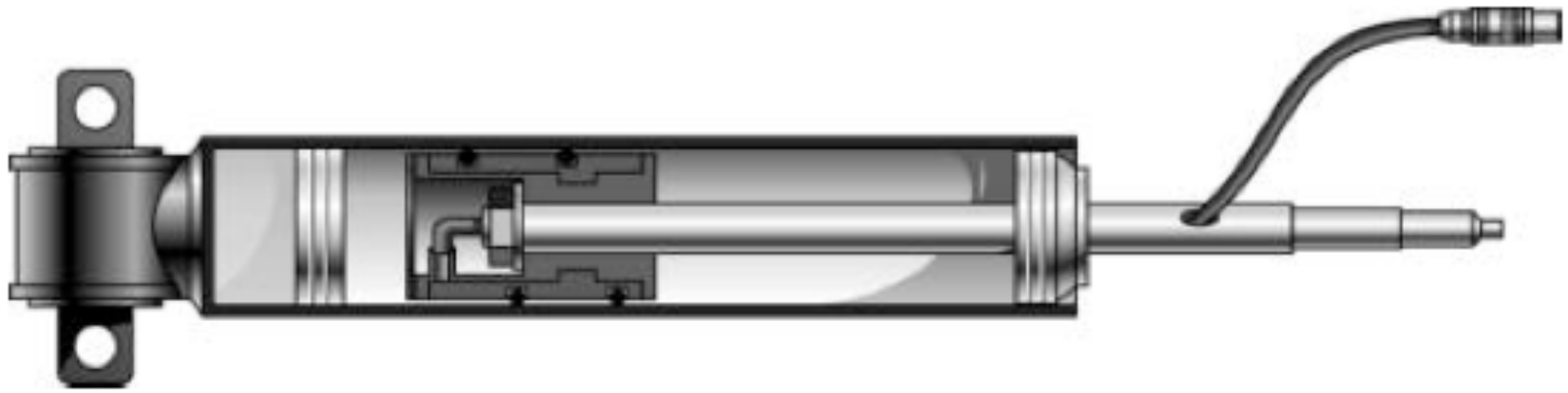


Fluidicon

ER fluids are able to change their properties through the application of an electric field. Response time is typically a millisecond.

Electrorheological Actuators

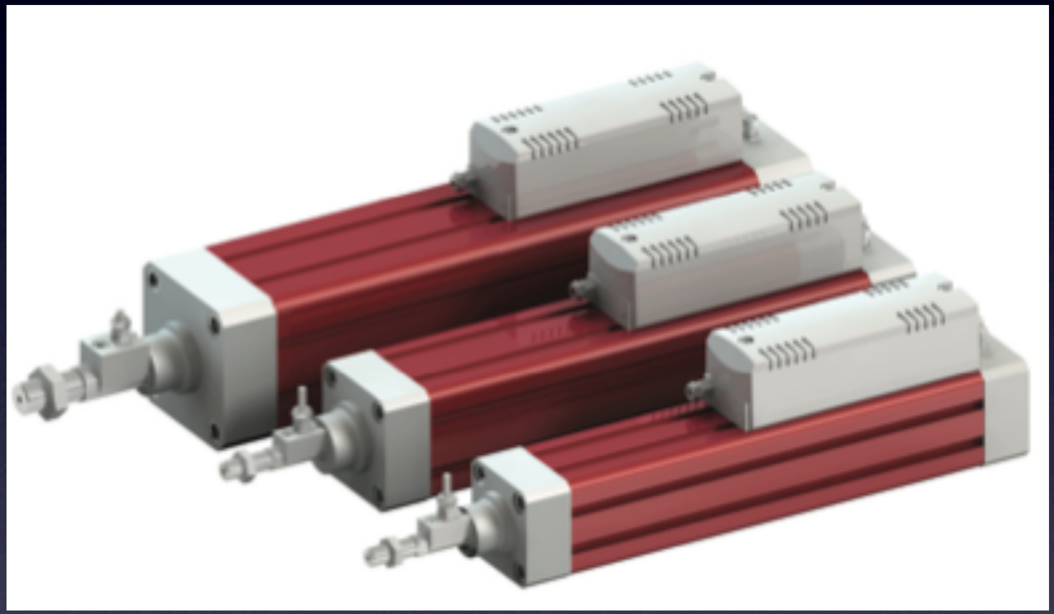




Fluidicon

ER valve and shock absorber concepts

Electrorheological Actuators Applications



Fluidicon

Tuneable shock absorbers and their use in sports equipment.

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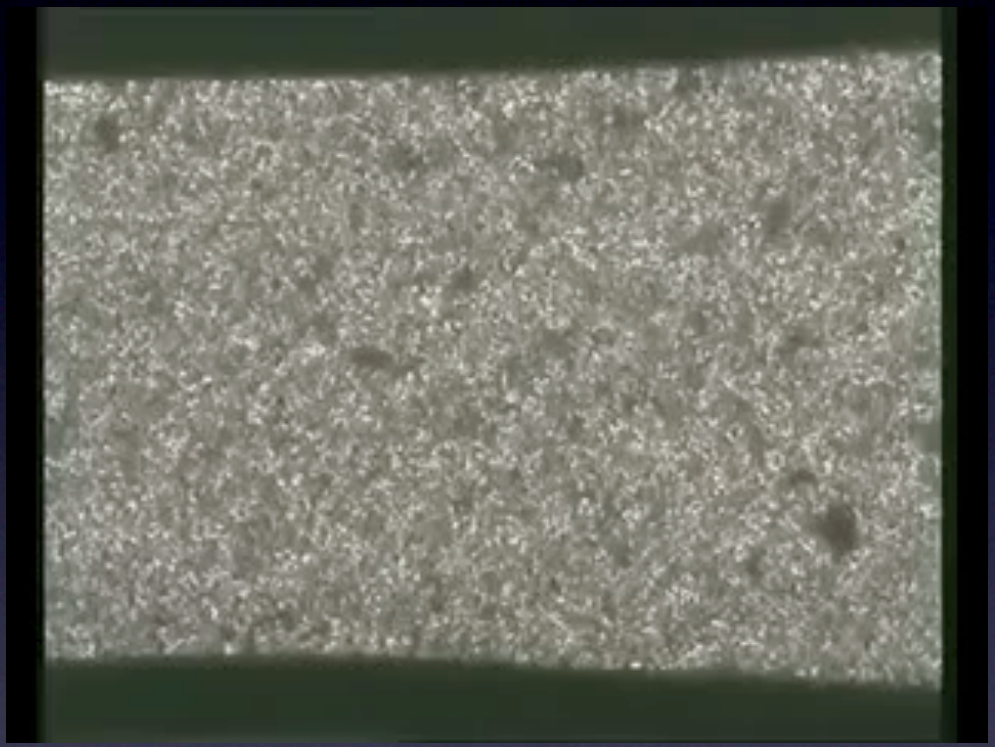
Electrorheological Actuators

Demonstration of electrorheological effect.

http://www.youtube.com/watch?v=44430l_VkGs



Alignment of particles under an electric field.

http://www.youtube.com/watch?v=F7-i6GuIA6I

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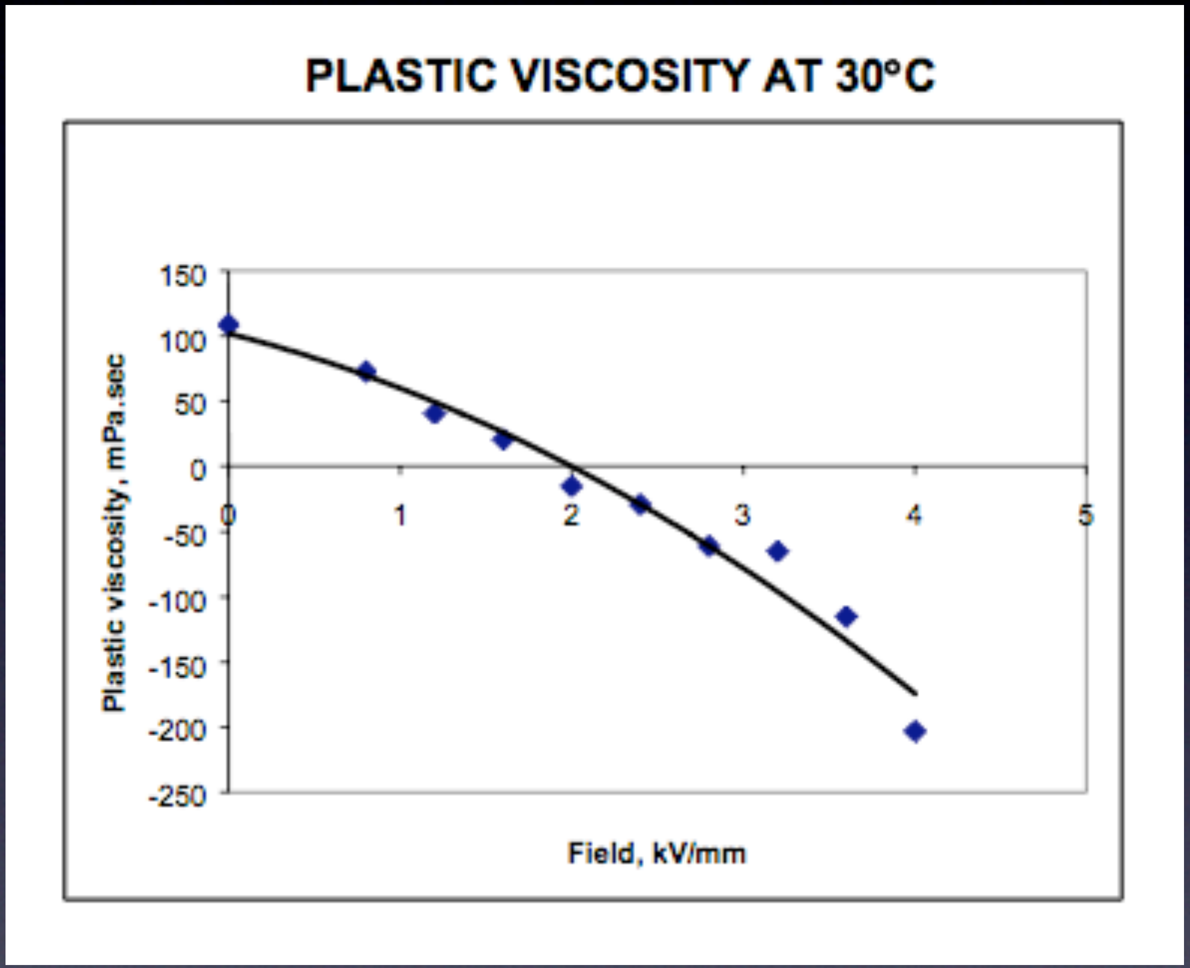
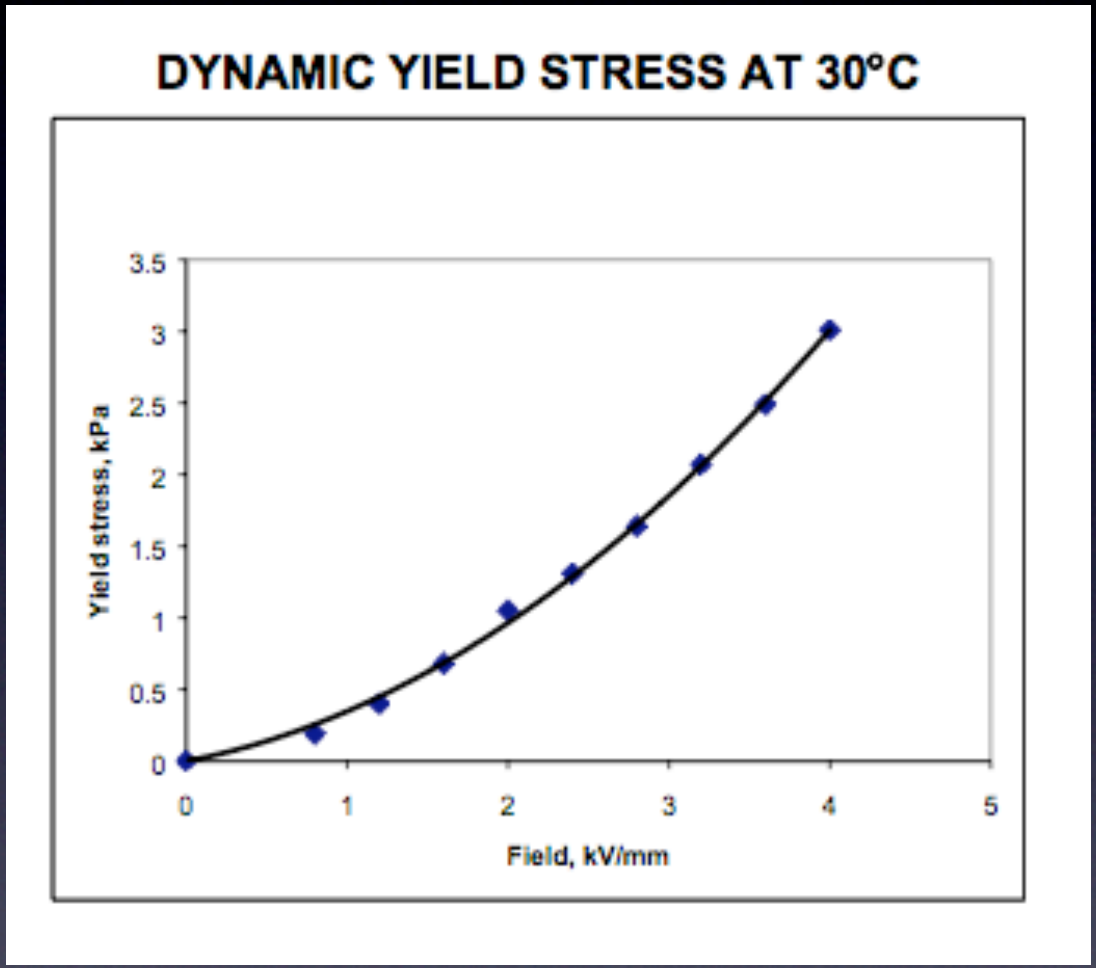
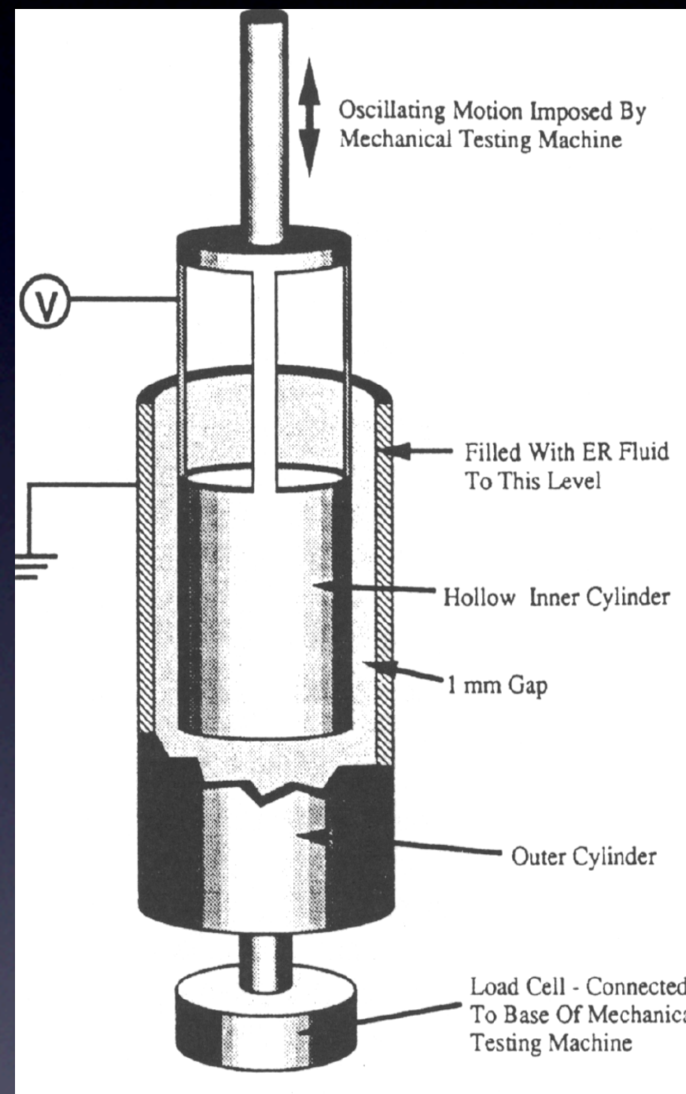
Electrorheological Actuators





LID3354s– Technical Information Sheet,Smart Technology Ltd

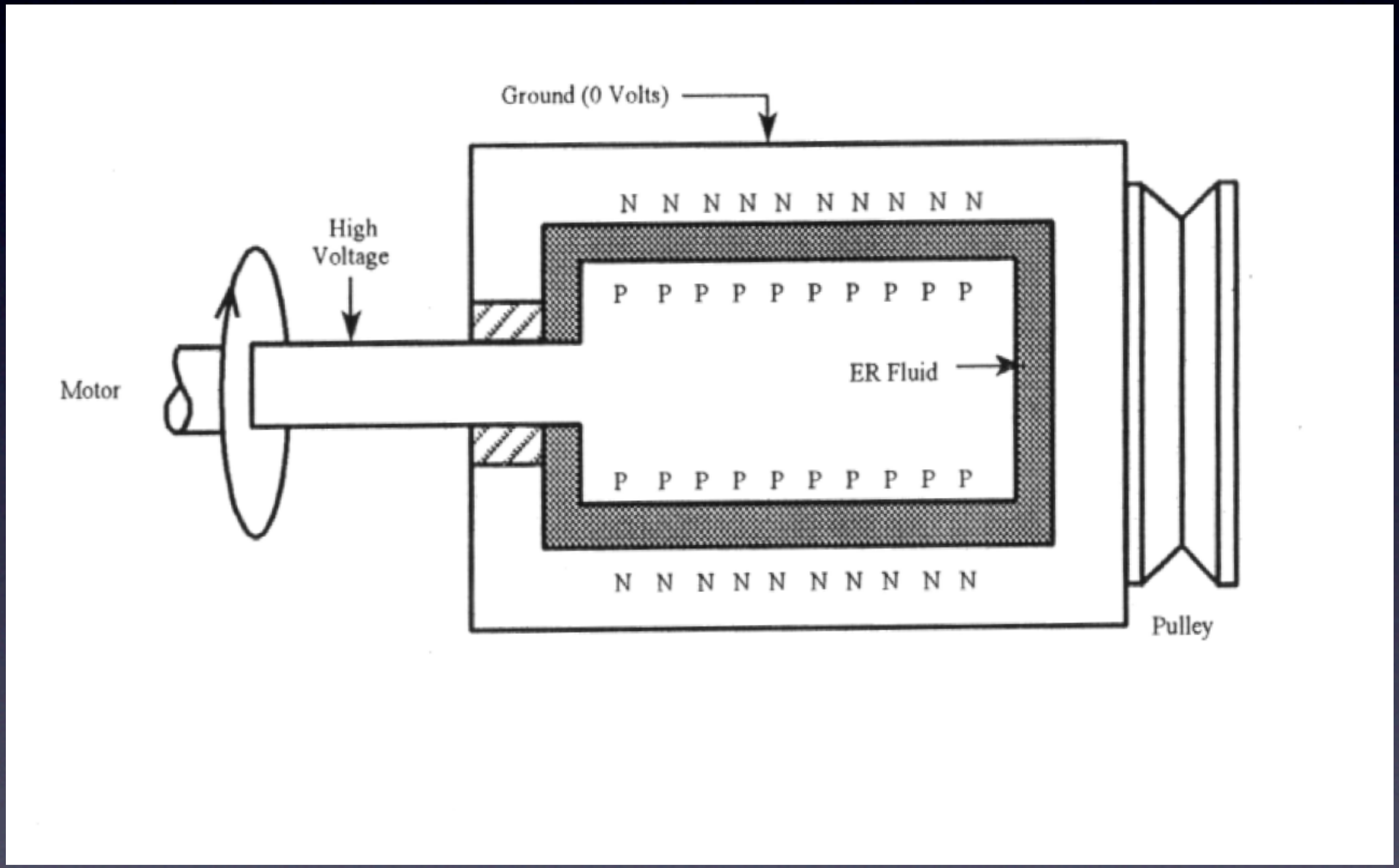
Electrorheological Actuators - Shock Absorber



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.

Electrorheological Actuators - Clutch



Electrorheological Actuators

Device Mode	Release mechanisms
Shear Mode	Clutches - 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 operates in shear (fluid under strain) or extensional configuration (fluid under compressional stress).
Variable Flow	Flow is controlled by adjusting the viscosity of fluid as it moves through a porous electrode separating the two chambers

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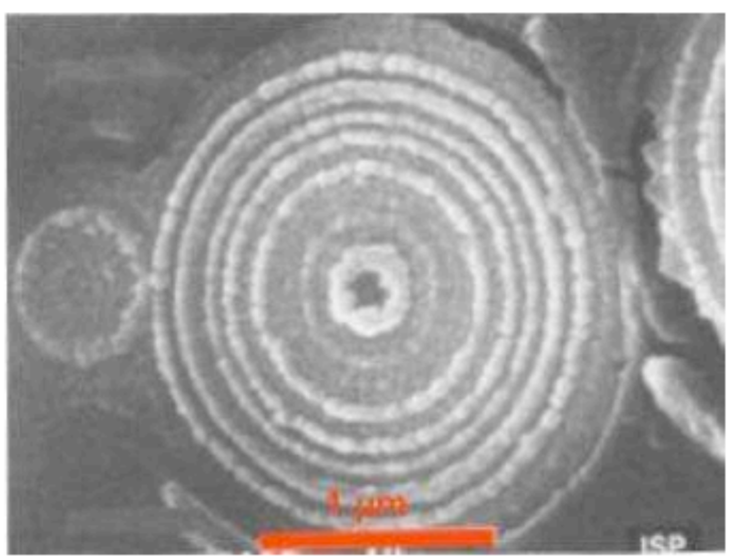
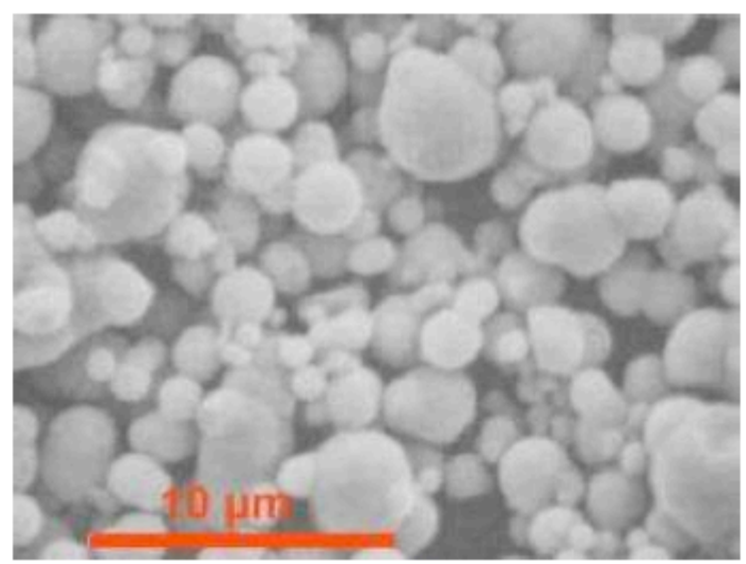
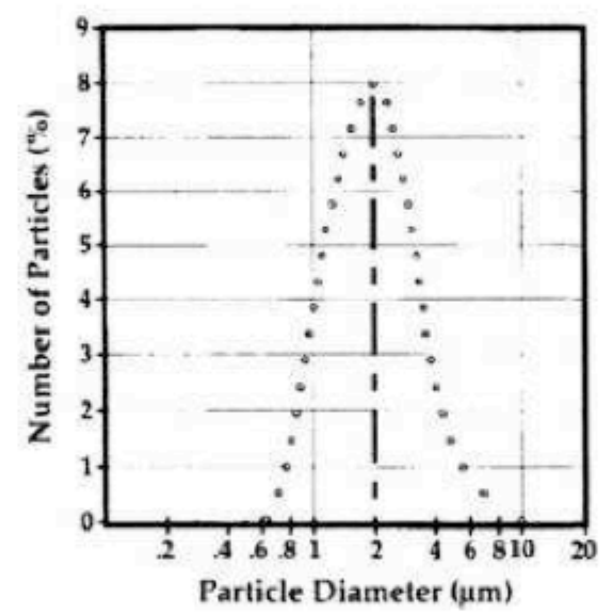
Magnetorheological Actuators

- "MR" = "magneto-rheological" or "magnetically responsive"
- Magneto-rheological fluids consist of micron-sized, magnetic particles and formulation additives in a liquid carrier
- MR fluid in the "off" state behaves like a Newtonian fluid (shear stress = viscosity x shear rate)







This part of the presentation has been adapted from Lord Corporation Presentation Magnetorheological Technology and its Applications, 2007.

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Magnetorheological Actuators

MR Technology Features

Provides variable, resistive control of force in real time

- Infinitely variable force resistance within a wide control range
- Almost instantaneous response
- Mechanical simplicity
- Broad operating temperature range
- No appreciable abrasion or sedimentation
- Low power requirements
- Failure safety in passive damping mode

Magnetorheological Fluid Components

- Liquid carrier
  - Mineral oil, synthetic hydrocarbon oil, silicone oil, water, glycols,…
- Magnetic particle
  - Carbonyl iron, iron/cobalt alloys, nickel alloys
  - 20-40% by volume
  - Typical size: 1-10 micron

- Other additives
  - Suspending agents, thixotropes, anti-wear and anti-corrosion additives, friction modifiers

Magnetorheological Actuators - Advantages

- infinitely variable force (up to 100 kPa strength)
- real time control of energy dissipation
- wide control range
- very short response times (millisecond)
- Consistent performance across wide temperature range (-40℃ to 130℃)
- long lived ($>10^7$ Joules/cm^3)
- haptic feedback

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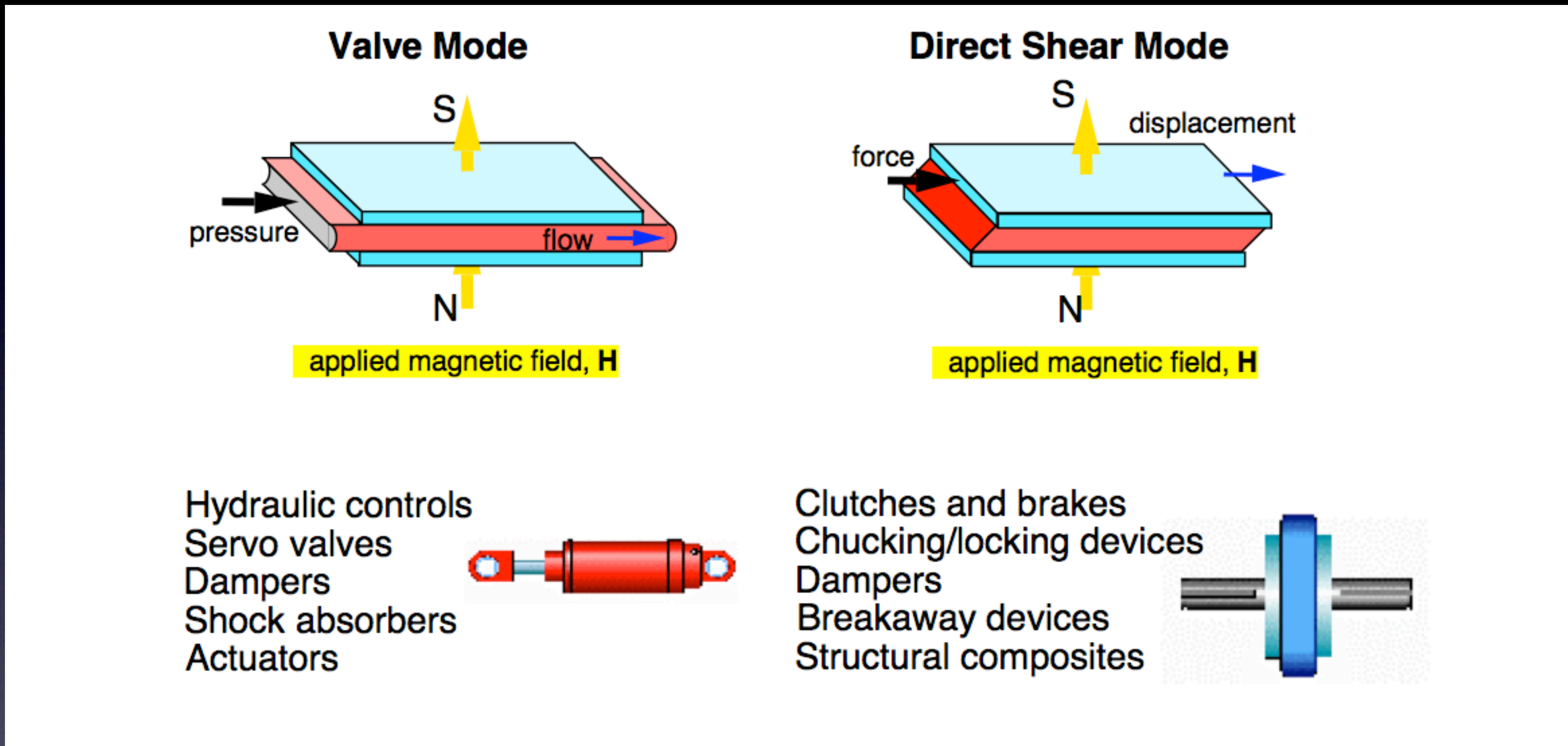
Magnetorheological Actuators



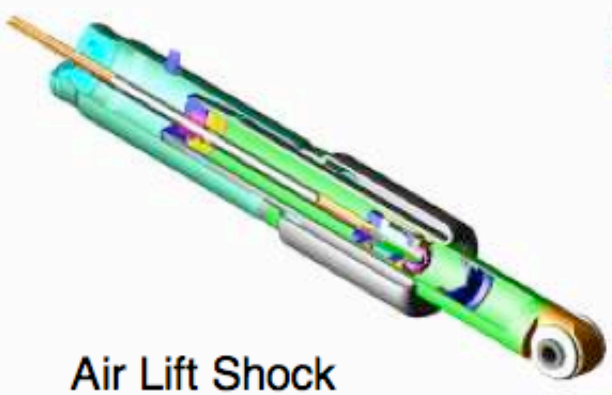
Magnetorheological Actuators

Delphi MagneRide™

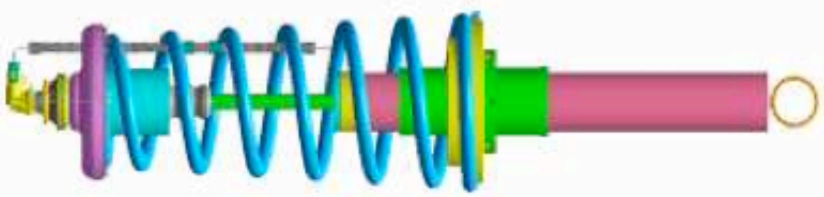
Delphi developed MR suspensions using LORD MR fluid technology.

Design advantages given by using MR fluids :

- **No moving parts**
- **Design for assembly**
- **High reliability**
- **100k+ mile durability**



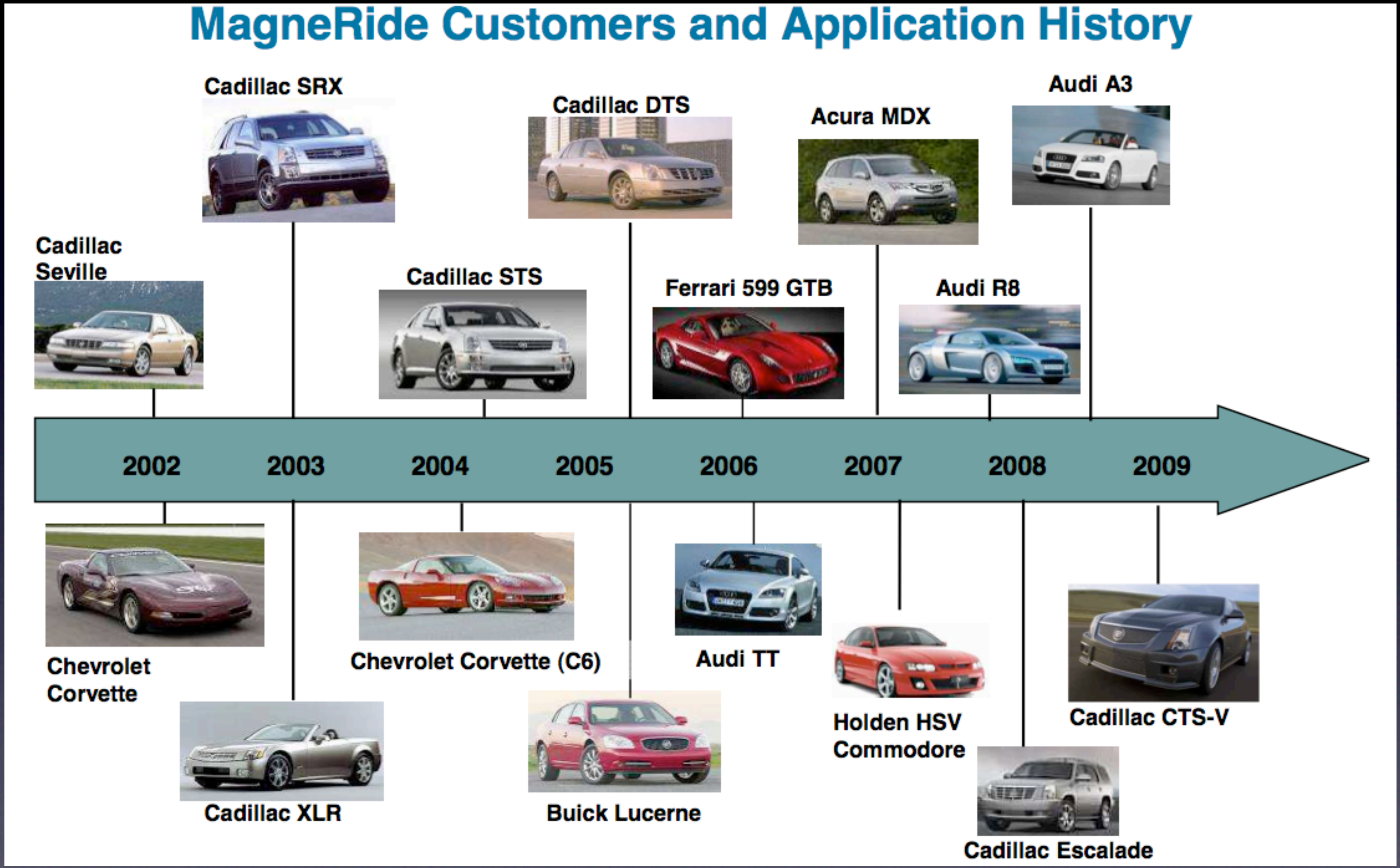
Air Lift Shock



Coil Over Shock

MacPherson Strut

Magnetorheological Fluid Applications



Magnetorheological Fluid Applications

Lord Corporation Video

Actuator Materials

- Shape Memory Alloys
- Magnetostrictive Materials
- Piezoelectric & Electrostrictive Materials
- Electrorheological & Magnetorheological Fluids
- Selection of Actuator Materials

Smart Systems

Smart Actuators

This innovation is tagged with

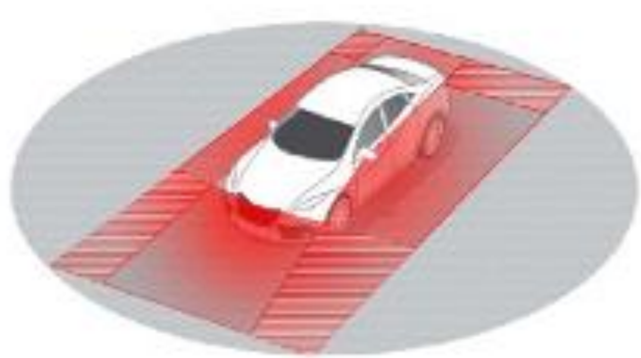
Electronic Control Units and Brushless DC-motors merge to integrated actuators creating subsystems of the future. Current products include engine cooling fans, electric oil/water pumps and other future applications. The Brushless DC cooling Fan is composed of a high efficiency compact motor with integrated sensorless motor drive electronics. Blade and shroud components are engineered and optimized with most modern CFD and FEM tools.

MAGNA

Smart Systems

Driver Assistance and Safety Systems

We combine technologies of camera systems, ultrasonic and radar systems as well as their functions to provide the driver active guidance in parking or reverse situations and enhancing field for view while increasing safety and comfort. Example innovations include 360° Panorama Vision, Forward Facing Imaging and Object Detection.



MAGNA

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Actuator Technologies

Type	Material	Driving Energy	Material Form
Shape Memory	Nitinol	T, S	Strip, Spring, Tube
Magetostriction	Terfenl-D	H	Rod, Stack, Wire
Electroreological/ Magnetorheological	Colloidal Suspensions	E, H	Viscous Liquid
Piezoelectric/ Electrostrictive	Barium Titanate Lead Zirconate Titanate Lead Magnesium Niobate	E, S	Disc, Plate, Stack, Tube, Cylinder

T - Thermal Energy, S - Mechanical Strain, H - Magnetic Field, E - Electric Field,

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Actuator Technologies - Performance Factor based Selection Criteria

Performance Factor	Shape Memory Alloys	Magnetostrictive	Piezoelectric Electrostrictive
Linear Displacement	High	Moderate	Moderate
Linear Force	Low	Moderate	High
Weight	Moderate	High	Moderate
Volume	Moderate	High	Moderate
Cost	Moderate	High	High

Actuator Technologies - Performance Factor based Selection Criteria

Performance Factor	Shape Memory Alloy	Magentostrictive	Piezoelectric/ Electrostrictive
Displacement (Bending)	High	Moderate	High
Force (Bending)	Low	Low	Moderate
Weight	Low	High	Low
Volume	Low	High	Low
Cost	Moderate	High	Low

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Actuator Technologies - Comparison of Properties

Technology	Displacement	Force	Hysteresis	Frequency Range
Shape Memory Alloys	500 µm (L=5 cm)	500 N	10-30 %	< 5 kHz
Magnetostrictive	100 µm	1,100 N	~ 10%	< 4 kHz
Electrostrictive	65 µm	9,000 N	1 - 4 %	< 1 kHz
Piezoelectric	100 µm (L= 5 cm)	20,000 N	8 -15 %	< 30 kHz

Actuator Technologies - Comparison of Properties

Technology	Strain	Strength (Mpa)		Operating Temperature Range
		Tensile	Compressive	
Shape Memory Alloys	5% (two-way)	900 -1,500	-	Up to 400^0C (Thermal Actuation)
Magnetostrictive	200 με 1 kA/m	28	700	Up to 300^0C (T_c=380^0C)
Electrostrictive	1,500 με 1 MV/m	11.7	300	0^0-30^0C (T_c)
Piezoelectric	1,000 με 1MV/m	75.8 (Static) 27.6 (Dynamic)	> 500	-20^0 - 250^0C (T_c=365^0C)

- Lecture 1: Introduction to Smart Materials and Systems
- Lecture 2: Sensor technologies for smart systems and their evaluation criteria.
- Lecture 3: Actuator technologies for smart systems and their evaluation criteria.
- Lecture 4: Piezoelectric Materials and their Applications.
- Lecture 5: Control System Technologies.
- Lecture 6: Smart System Applications.

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