Smart Structures
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Week - 01
Lecture No - 01
Introduction to Smart Structures (continued)

Welcome to the first lecture of this course. We will start with a basic introduction to the smart structures.

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So, these are these are the items that we will deal with for first 3 weeks. We will at first see what smart structures are and then we will talk about some classifications, key elements of smart structures and then we will see some of the traditional actuators and sensors and then we will see smart materials and we will have a comparison of smart materials, actuators and sensors in terms of their properties. After that we will talk about advantages of smart material actuators and sensors, then we will see control methodologies and strategies, we look into the integration issues. After that we will talk about major barriers to smart structures and then we will see some of the applications.

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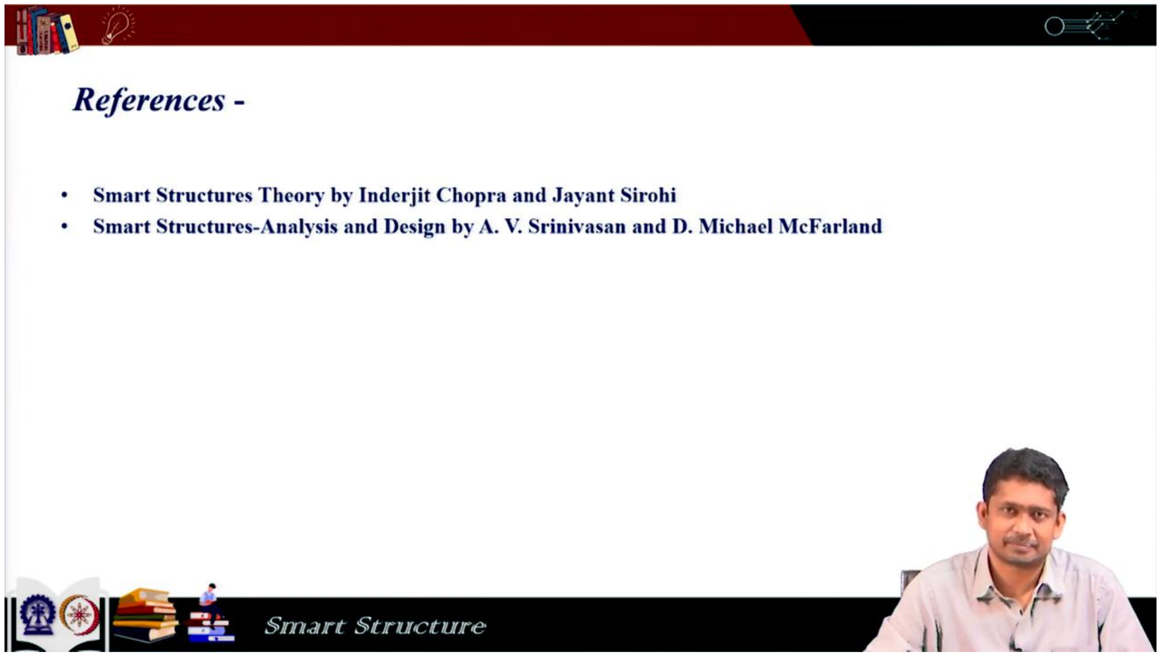

For this we will refer to the books Smart Structures Theory by Chopra and Sirohi, Smart Structures Analysis and Design by Srinivasan and McFarland.

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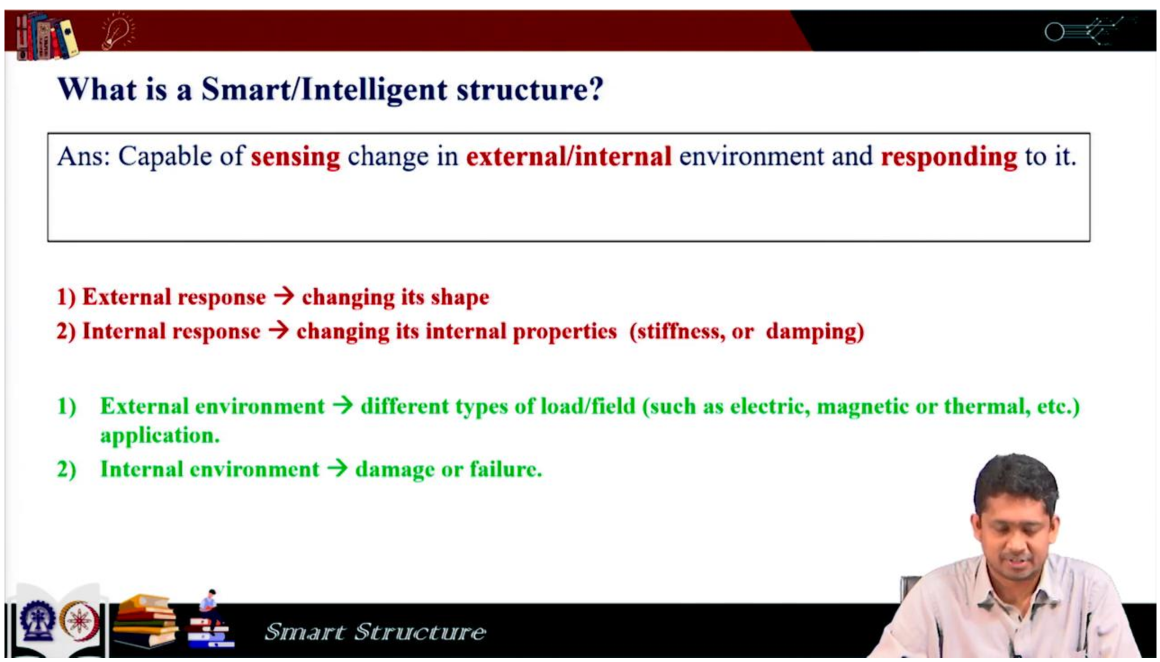

Smart structures are capable of sensing change in external or internal environment and responding to it. So, here we have two kind of conditions, one is external condition, one is internal condition. External condition refers to change in load or any external field like electric field, magnetic field, thermal field and so on.

For example, if we think about an aircraft, so when it is flying if it encounters a gust that is a external change. And if there is any change in it is internal properties like if there is any damage or failure that can be an internal change. Similarly response also can be internal or external. If we again go to that aircraft example, so when the aircraft encounters gust it might want to change it is shape. The wing might want to change it is shape just to alter the aerodynamic load. So, that can be an external response. Internal response can be in terms of changing internal properties like stiffness, damping and so on.

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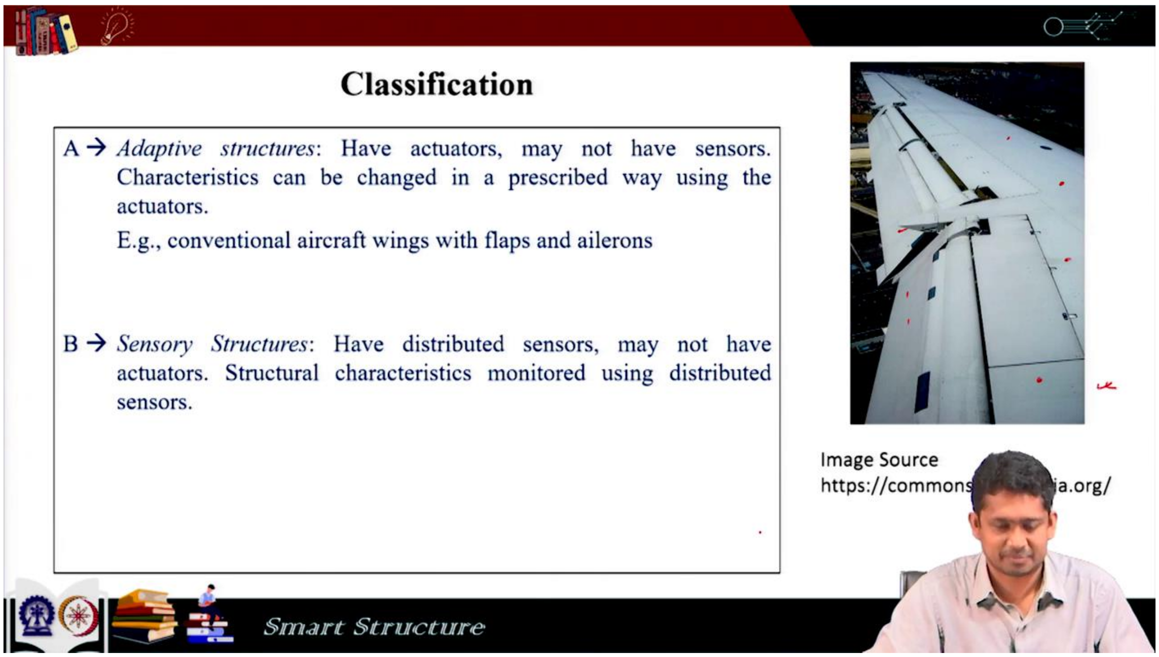

Now here we look into some of the terminologies, we can find it in the book of Chopra and Sirohi. So, there is something called adaptive structures. Adaptive structures have actuators and may not have sensors.

And these actuators are used to change the characteristics of a structure in a prescribed way. For example, we can see an aircraft wing here. It has several control surfaces. Now the pilot gives command and accordingly the control surfaces activate and based on their action the lift, rolling motion and many parameters can be changed. Sensory structures are at the other end they may have sensors, but they may not have actuators.

Again in this aircraft wing, if we have several sensors placed at different places and these sensors might measure parameters like strain, acceleration, temperature and so on. Now based on their measurement and using proper algorithms, the damages in the wing can be monitored in a real time or in a near real time sense. So, that is a sensory structure. Here the goal is mainly monitoring.

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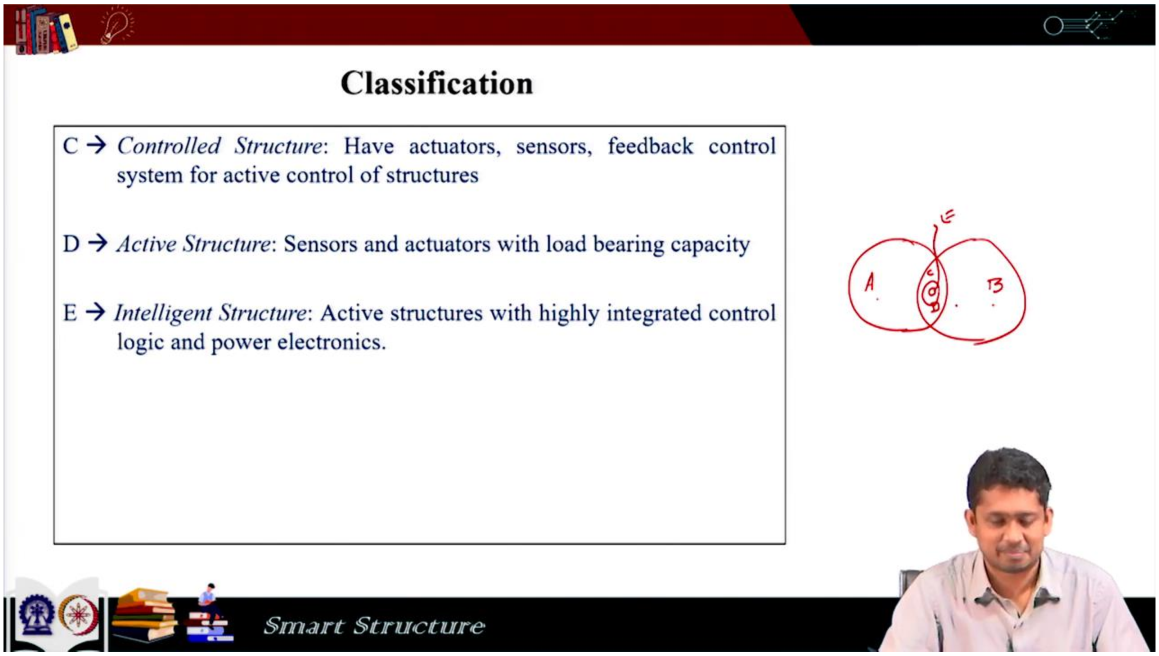

So, we have an active structure and we have something called sensory structure. So, active structure in this side, sensory structure is at this side, it has actuators may not have sensors, it has sensors may not have actuators. Now in this overlapping zone, we may have structures which have both sensor and actuator. So, this kind of structures sense some change using the sensors. Again the change can be external or internal and then through feedback control strategy, the actuators may be actuated and based on the actuation signal, the structure can adapt itself to the change. So, that is a control structure.

So, this entire thing is control structure. Again, this control structure has sensors and actuators which have some kind of load carrying capacity then we can call it an active structure and again within this active structure, if it has highly integrated control logic and power electronics then we can call it intelligent structures. So, this is a kind of hierarchy of different types of structures. So, as we can see that as we go towards from A to B towards D, C, E, the smartness increases.

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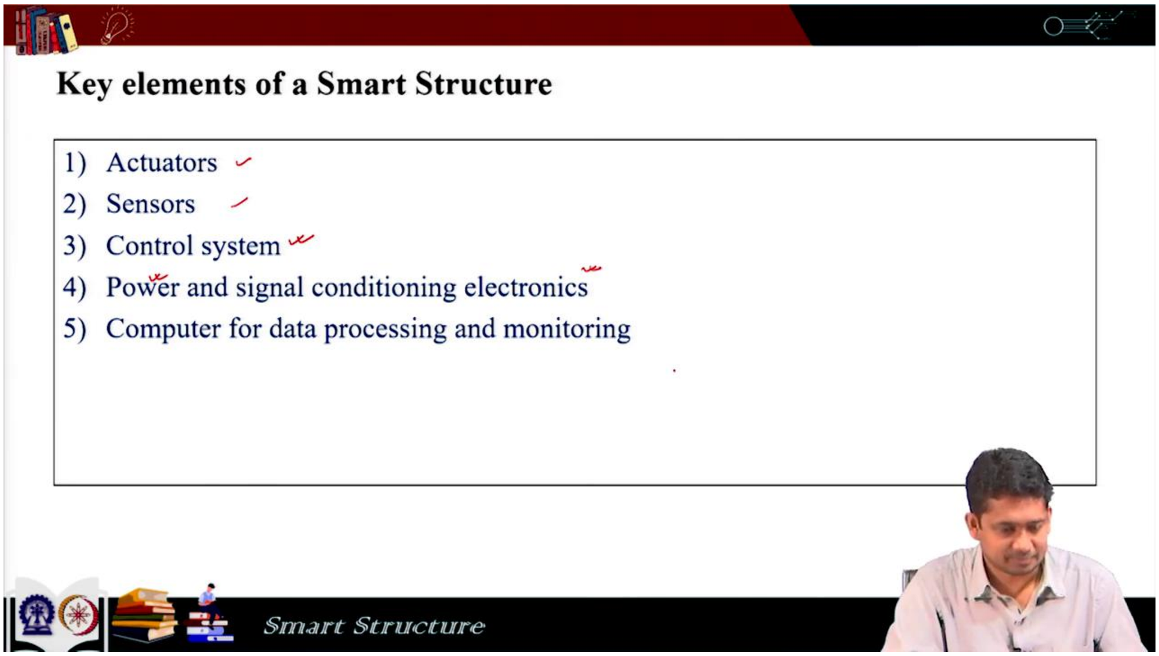

So, based on this discussion, we can say that we need quite a few components for smart structures. It needs actuators, sensors. It needs a control system. So, the control system takes the sensor data and then actuates power and signal condition electronics is needed. So, even in this power supply, some kind of smartness can be brought into. Nowadays with tremendous advancements in technologies, generally the sensors actuators and the associated equipments need much less power.

So, the idea is that if these are fitted to a structure then and if the structure is vibrating then can we harvest some energy from the vibrating structure and use it to power our equipments. So, that is an area called energy harvesting. We will talk about that as the course progresses and we need computer for data processing and monitoring.

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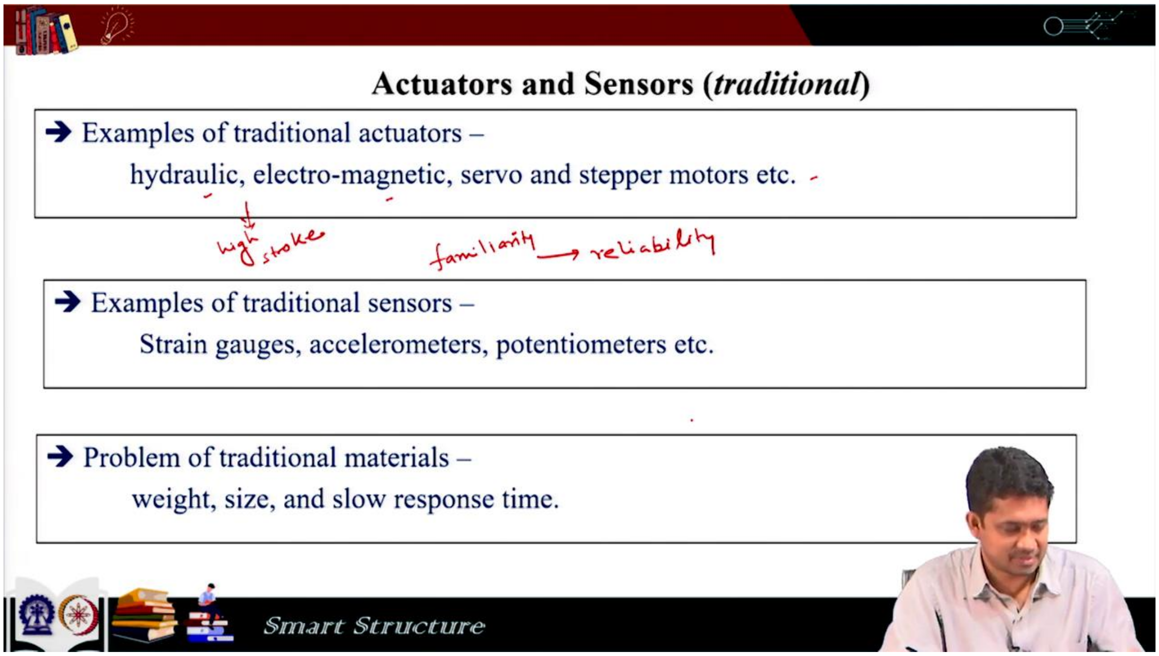

So, here we have examples of traditional actuators and sensors. Traditional actuators can be hydraulic actuators, electromagnetic actuators and servo and stepper motors.

Now, these actuators generally have high stroke. So, as compared to the smart material actuators which we will discuss, these generally have higher stroke and examples of traditional sensors include strain gauges, accelerometers, potentiometers. Now, these sensors and actuators are in use for a long time. So, we are quite familiar with their properties and they have they are quite successful. Now, this familiarity leads to reliability also.

However, the problem is that generally these sensors actuators are bulky. Their weight is more and their response time is quite slow. So, if you want to go more sophisticated applications where need faster response time, we may want to go for smart material sensors and actuators.

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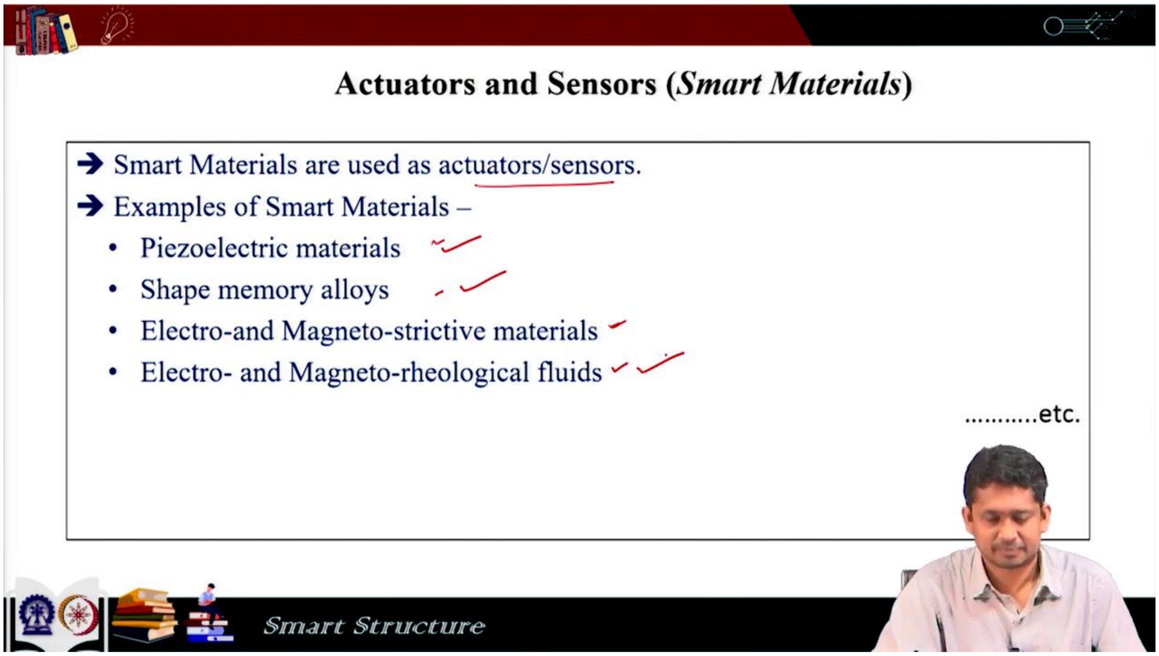

Smart material actuators and sensors as the name says, they are made of smart materials and smart materials have very unique properties which makes them good candidate for actuator sensor material. So, here are some examples of smart materials, piezoelectric materials, shape memory alloy, electro and magnetorheological fluids, electro and magnetostrictive materials and electro and magnetorheological fluids. So, in this course we will talk about these three materials in more details.

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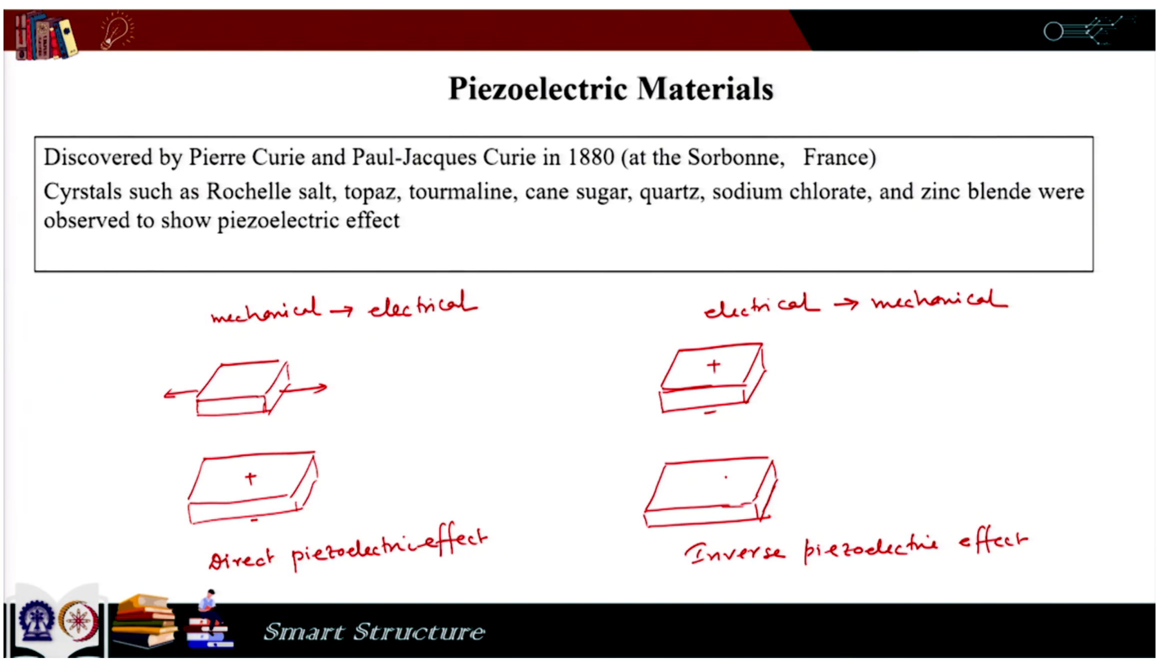

So, let us have a quick overview of these different materials and then we look into their comparisons and some applications. So, in piezoelectric materials, piezoelectricity refers to a property where if I have a piezoelectric object then if I give it strain, it expands and because of this, it generates electricity. So, we can find a potential difference across the two surfaces and that is the effect of giving mechanical input to it. So, here the effect is, input is mechanical and it gives electrical response.

So, that is called direct piezoelectric effect. Similarly we can do something opposite also if we have a piezoelectric material and if we give voltage to it and then it can have a mechanical response in terms of expansion or contraction. Now, whether it expands or contracts, it depends on how the material is polarized, what is the direction of the voltage, their property of the material and so on we will discuss it when we talk about piezoelectric materials. So, here the input is electrical, the response is mechanical and this is called inverse piezoelectric effect. This is called direct because this was observed before and this is inverse because this was observed later.

Now, this direct effect makes these materials a good candidate for sensing application because if we know the amount of voltage that we are getting here or the electric charge, we can do some calibration and find out what is the amount of strain. And this inverse effect makes them good material for actuation. We can give electrical signal and we can give get mechanical response. These materials were invented by the Curie brothers in 1880 and the effect was found in crystals like Rochelle salt, topaz, tourmaline, cane sugar, quartz, sodium chlorate and zinc melt.

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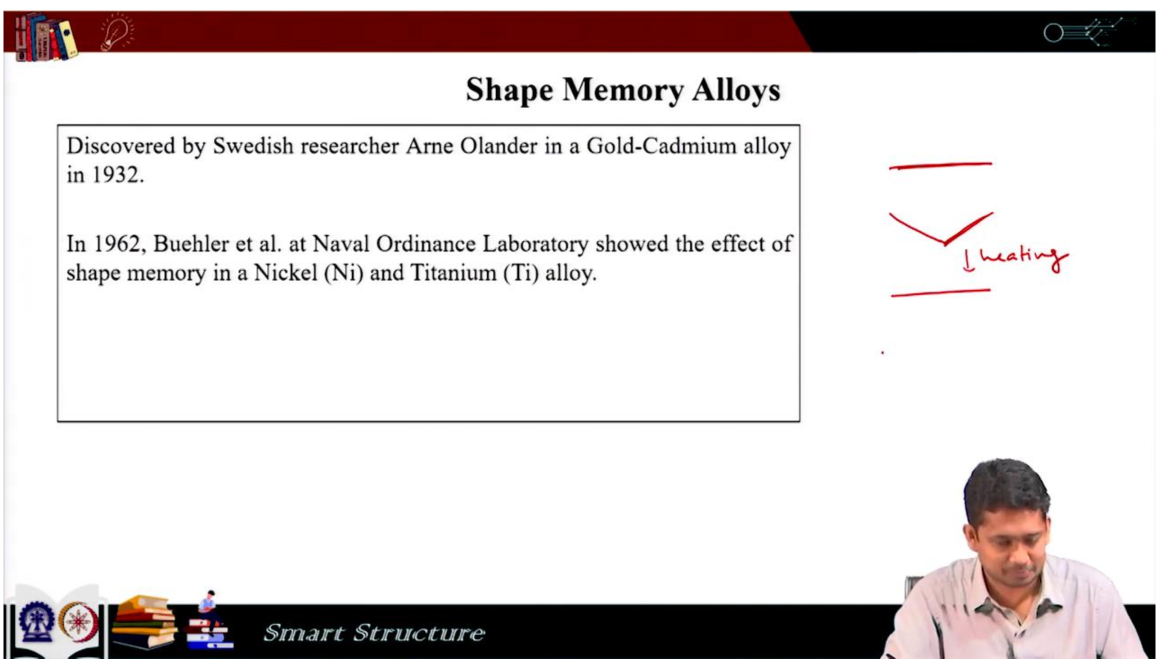

Shape memory alloy shows some interesting property. These materials show some kind of memory. So, if we have a shape memory alloy wire and then if we deform it then the deformation might look permanent, but then if we heat it, the material again regains its shape. So, by heating the material goes back to its original shape. So, we can say that the material has some kind of memory. It can remembers its previous shape just the application of it triggers its memory and it comes back to its original shape.

So, these materials were discovered by Swedish researcher Arne Olander in a gold cadmium alloy in 1932. And 30 years later Buehler and others at naval ordnance laboratory showed the effect of shape memory in a nickel and titanium alloy Nitinol. And so, because of this memory these materials are quite used as an actuator. So, these materials are kept deformed in this way and just by giving heat input, it tries to regain its shape and that generates actuation force. Similarly this material exhibits something called super elasticity also. That makes them ideal for using as a damper also.

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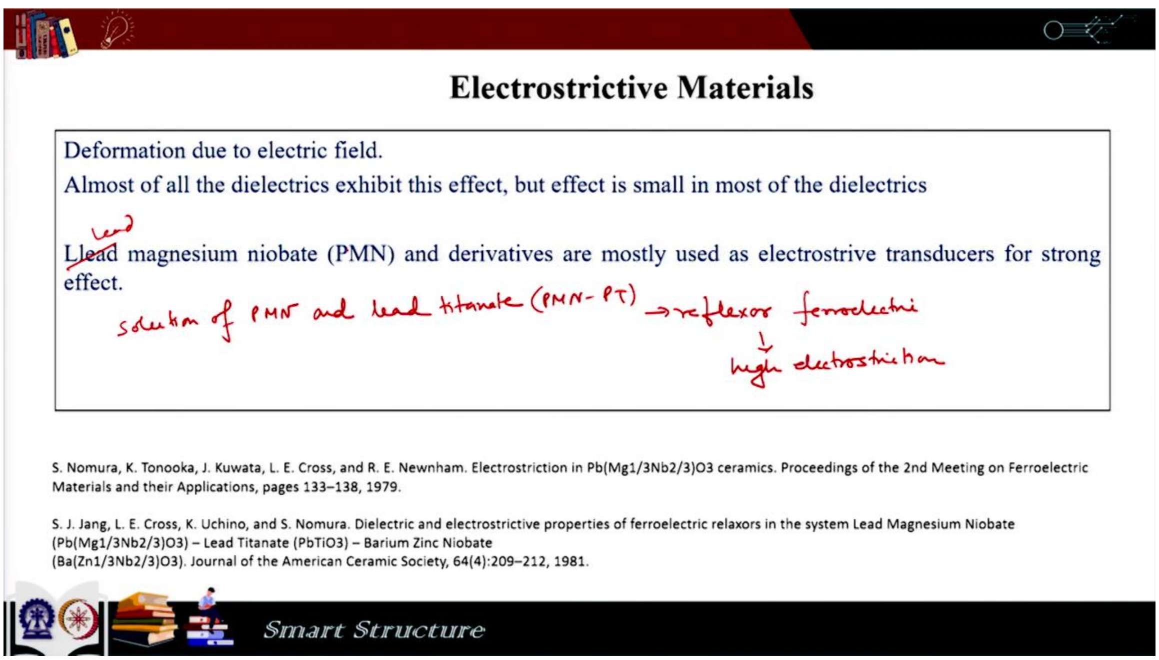

Now, we will talk about electrostrictive materials. Electrostriction refers to a phenomena where deformation is induced due to an electric field. Now, these materials are exhibited by dielectric materials and almost all the dielectric materials show some amount of electrostriction. But the effect is not that significant in all the materials.

Lead magnesium niobate and derivatives are mostly used as electrostrictive transducers for strong effect. Now solution of this lead magnesium niobate and lead titanate which we also call PMN-PT this is called reflexor ferroelectric and they show high electrostriction. So, these are quite popular materials for use as electrostrictive actuators. So, these materials because we see we get a mechanical response by giving electrical field. So, they are generally used as actuators.

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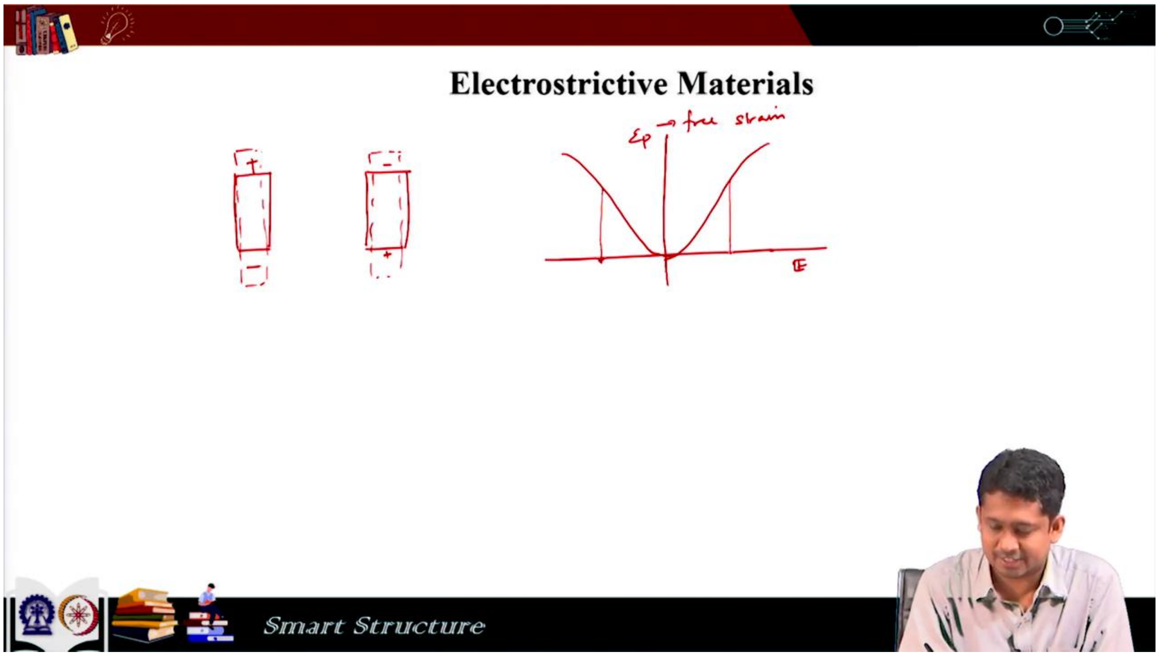

In electrostrictive materials if we give electric field like this then generally we get a response in this form. Now if we just give a opposite field or if we change the direction of the field, there also we get similar response. So, here the response is not the dependent on the direction of the electric field. So, if you plot the free strain versus electric field graph it looks something like this. So, it is symmetric with respect to this line.

Now here again we are talking about one more term which is free strain. Free strain is just the strain that we get if we do not constrain the material. So, if we keep the material unconstrained and then if we give the electric signal then the amount of strain that we get is called the free strain. So, whatever free strain we get at this side, the same free strain we get and the side also. So, it is not dependent on the electrical signal direction.

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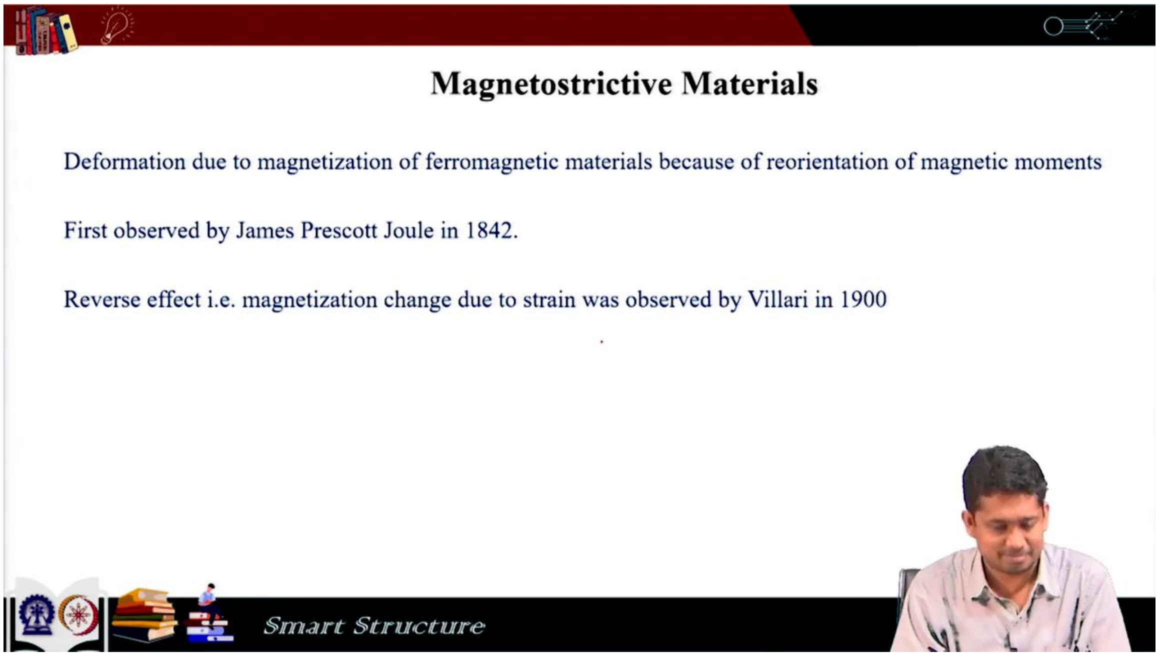

Now there is something called magnetostrictive materials and they are the magnetic counterpart. Here we get deformation due to magnetization of ferromagnetic materials because of reorientation of magnetic moments. It was first discovered by James Prescott Joule in 1842 and the reverse effect where magnetization change due to strain was also observed. That was by Villari in 1900.

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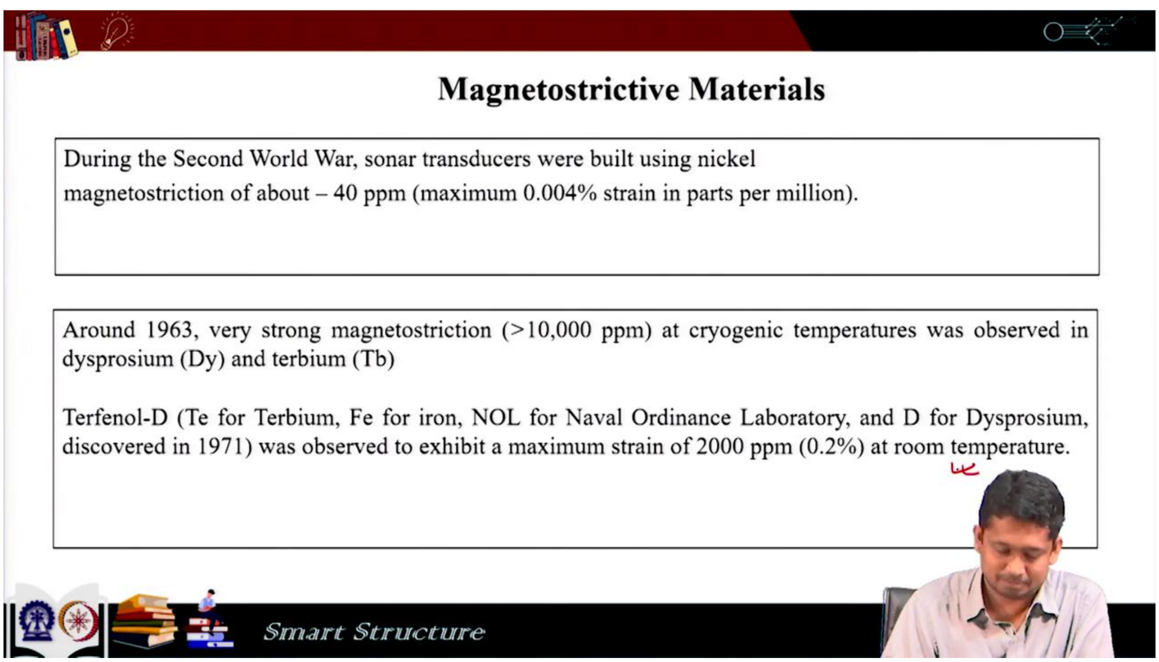

So, here we will see some applications of magnetostrictive materials. During Second World War, sonar transducers were built using nickel where we find magnetostriction of about 40 ppm. So, here maximum 0.004 percent strain in parts per million was observed. Then in around 1963, strong magnetostriction more than 10000 ppm at cryogenic temperatures was observed in materials dysprosium and terbium. So, there was a good amount of research in finding out materials which shows high magnetostriction.

However, here although the magnetostriction was high it was in cryogenic temperatures. So, then there is another material Terfenol-D where magnetostriction is observed, I mean, of 2000 ppm at room temperature.

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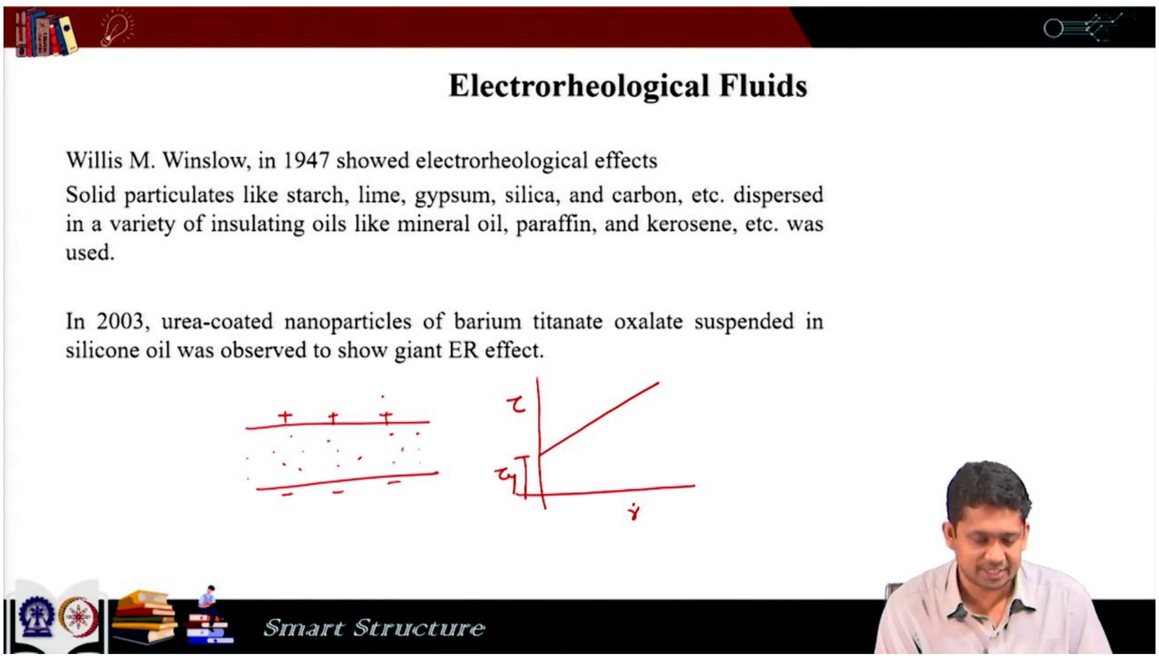

Now, we will talk about electro rheological fluids. Electro rheological fluids has its damping which can be controlled by electrical signals. So, in electro rheological fluids we have a fluid in which there are solid particles and there are electrodes at the top and bottom.

So, by giving electrical signal, the damping can be controlled and so in this material, an ideal graph looks like this. This strain rate and this is stress graph. So, this shear strain rate, this is stress graph and that looks like this. So, this is called yield stress. So, for the flow to happen the yield stress has to be overcome and this yield stress can be controlled by this electric field also.

So, these have quite a good amount of application in damping. So, this effect was showed by Williams M Winslow in 1947 and the effect was showed in solid particulates like starch, lime, gypsum, silica and carbon which was dispersed in a variety of insulating oils like mineral oil, paraffin and kerosene. Then in 2003, urea coated nanoparticles of barium titanate oxalate suspended in silicon oil was observed to show giant electrorheological effect.

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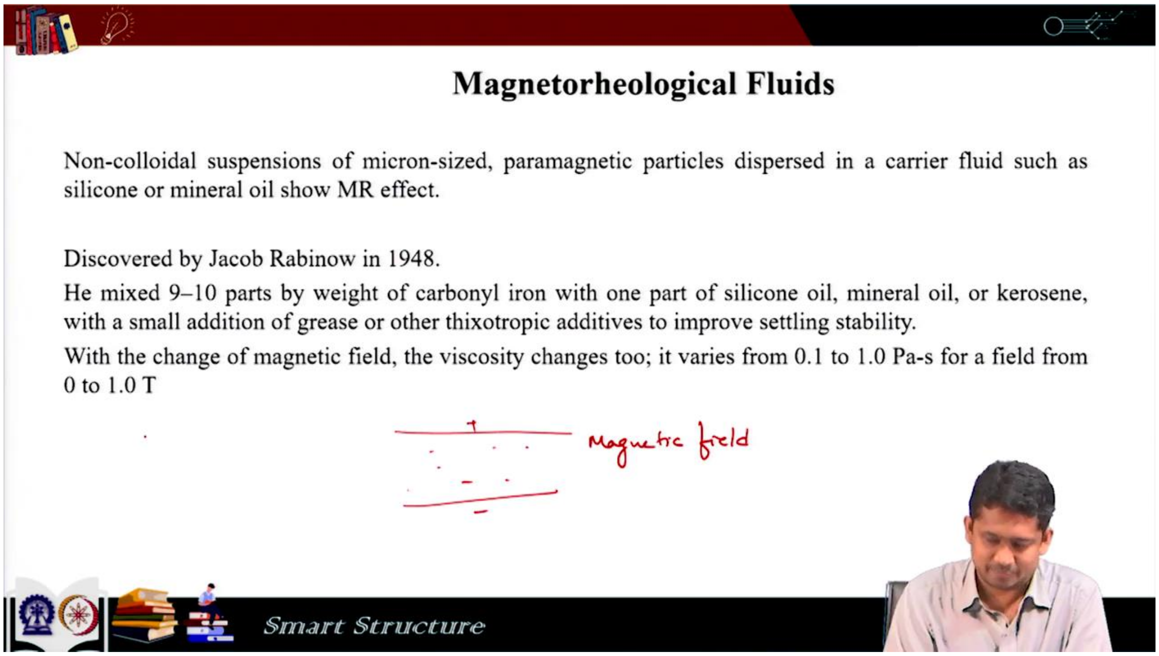

In magnetorheological effect, the effect is same, but instead of the electric field we need a magnetic field here. So, we need a magnetic field and this effect was found in non-colloidal suspensions of micron sized paramagnetic particles dispersed in a carrier fluid such as silicon or mineral oil and it was discovered by Jacob Rabinow in 1948.

He mixed 9 to 10 parts of weight of carbonyl iron with one part of silicon oil, mineral oil or kerosene with a small addition of grease or other thixotropic additives to improve the settling stability. With the change in magnetic field the viscosity changes to and it varies from 0.1 to 1 PAS for a field from 0 to 1 T.

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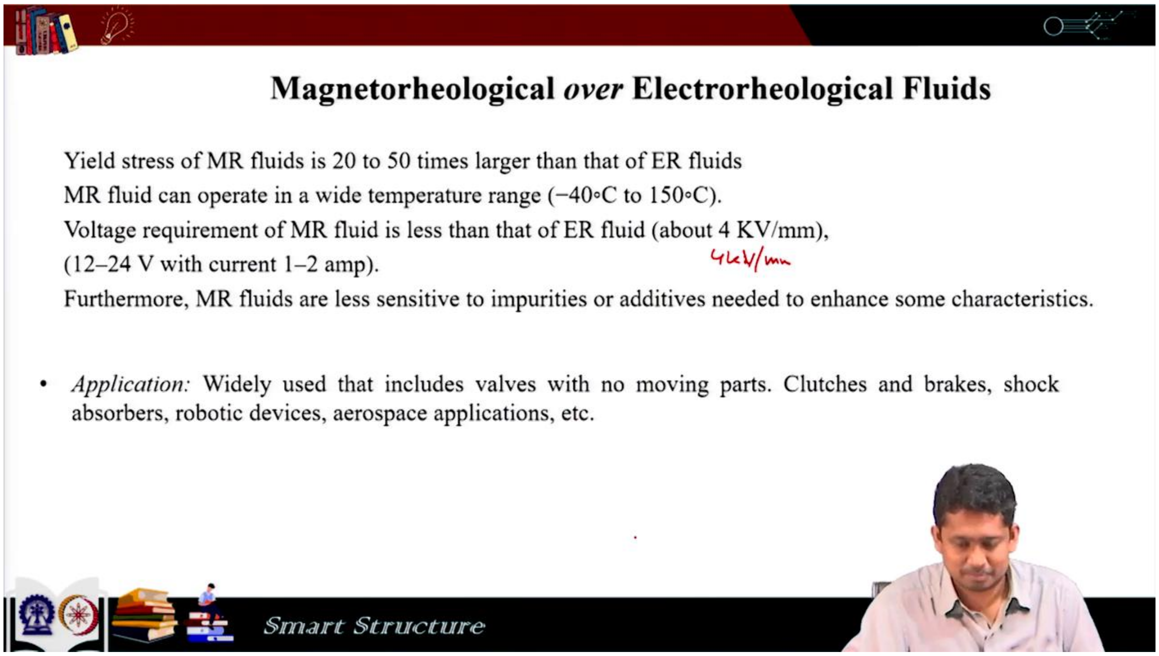

Here we have a comparison between the MR and ER fluids. MR fluids find more application than the ER fluids and there are quite a few reasons behind that. First of all, the yield stress in MR fluid is 20 to 50 times larger than the ER fluids and ER fluids operates in a wide temperature range minus 40 degrees to 150 degrees centigrade. The voltage requirements of MR fluid is less than the ER fluid. So, it is about 4 kilo volt per millimeter and the voltage of 12 to 24 volt with current of 1 to 2 amperes. Furthermore, MR fluids are less sensitive to impurities or additives needed to enhance some of the characteristics. Wide applications are there. This includes valves with no moving parts, clutches and breaks, shock absorbers, robotic devices, aerospace applications and there are many others applications as well.

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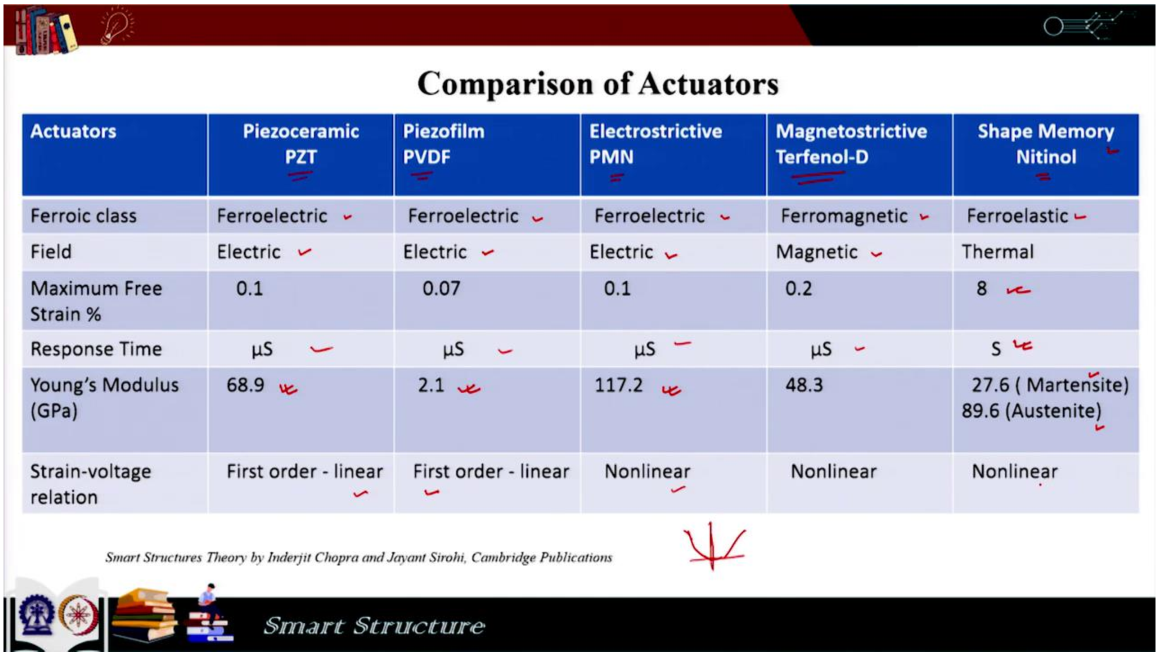

Comparison of Actuators

Actuators	Piezoceramic PZT	Piezofilm PVDF	Electrostrictive PMN	Magnetostrictive Terfenol-D	Shape Memory Nitinol
Ferroic class	Ferroelectric	Ferroelectric	Ferroelectric	Ferromagnetic	Ferroelastic
Field	Electric	Electric	Electric	Magnetic	Thermal
Maximum Free Strain %	0.1	0.07	0.1	0.2	8
Response Time	μS	μS	μS	μS	S
Young's Modulus (GPa)	68.9	2.1	117.2	48.3	27.6 (Martensite) 89.6 (Austenite)
Strain-voltage relation	First order - linear	First order - linear	Nonlinear	Nonlinear	Nonlinear

Smart Structures Theory by Inderjit Chopra and Jayant Sirohi, Cambridge Publications

Here we will see comparison of different smart material actuators. So, we have here piezoelectric materials. Now piezoelectrics are available in various forms. So, there can be piezoelectric crystals, there can be piezoelectric ceramic materials which are polycrystalline.

We will talk about what these means later on and there can be piezoelectric polymers. Now, among the piezo ceramics, PZT is the most widely used and among the piezo films PVDF is most widely used. We will again look into this in more details and there are electrostrictive materials PMN. We talked about. Magnetostrictive materials we are considering Terfenol-D here and for shape memory alloy, we are considering Nitinol here.

If we look at their ferroic class, then PZT is ferroelectric and PVDF is ferroelectric, PMN is ferroelectric and Terfenol-D is ferromagnetic and Nitinol is ferroelastic. Now, PZT materials they need electric field for actuation. PVDF need electric field for actuation and electrostrictive materials need electric field for actuations. Magnetostrictive materials need magnetic field for actuation.

Shape memory alloys need thermal actuation. Then if we look into free strain, then the maximum free strain produced by piezo ceramics are 0.1 percent, piezo films are 0.07 percent, electrostrictive PMNs are 0.1 percent, magnetostrictive materials are 0.2 percent and shape memory alloy is 8 percent. So, we can see that shape memory alloy has much more maximum strain as compared to the other strains. Now, we will if we look into the response time, the piezo ceramics, I mean, first 4 materials have much less response times. They are all in microseconds, whereas, in shape memory alloy the response time is in seconds. So, in first 4 materials we get less strain, but the response time is much less.

So, it is faster i.e. response is faster. In shape memory alloy, we get much more strain, but the response is slow. If we look at the Young's modulus, then piezo ceramics show Young's modulus of 68.9 gigapascal and PVDF shows 2.1 GigaPascal. So, there is the very big difference. So, that is why there are different applications. For some kind of structures, PZT is good. For some kind of structures, PVDF is good and we look into some examples. Electrostrictive materials even higher Young modulus, more than 100 gigapascal, magnetostrictive materials around 50 and shape memory alloy. The shape memory alloy remains in 2 phases, martensite phase and austenite phase.

Again we look into what this phase means when we talk about shape memory alloys in details. We have seen that shape memory alloy comes back to its original shape and that is possible because it does a phase transformation. Now among these two phases, martensite has much low elastic modulus 27.6 gigapascal and austenite has much higher.

It is close to 90 gigapascal. If we look into the strain voltage relationship in piezoelectric materials both PZT and PVT it is first order linear and then in electrostrictive materials it is non-linear. We have seen that, it is the phase strain is kind of this. So, it is a non-linear behavior. In magnetostrictive materials, it is non-linear. In shape memory alloy, it is non-linear.

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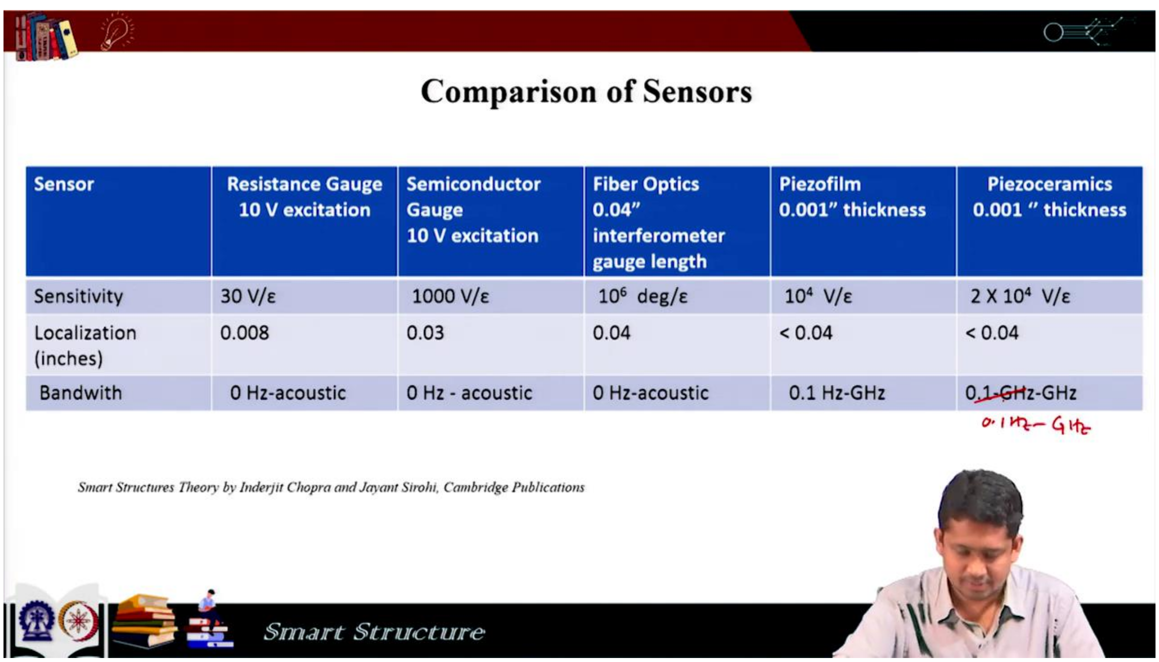

Sensor	Resistance Gauge 10 V excitation	Semiconductor Gauge 10 V excitation	Fiber Optics 0.04" interferometer gauge length	Piezofilm 0.001" thickness	Piezoceramics 0.001 " thickness
Sensitivity	30 V/ε	1000 V/ε	10^6 deg/ε	10^4 V/ε	2 X 10^4 V/ε
Localization (inches)	0.008	0.03	0.04	< 0.04	< 0.04
Bandwith	0 Hz-acoustic	0 Hz - acoustic	0 Hz-acoustic	0.1 Hz-GHz	0.1 GHz-GHz

Now here is a comparison of the sensors. For sensors, 5 sensors are chosen, resistance gauge which has around 10-volt excitation, semiconductor gauge around 10-volt excitation, fiber optics 0.04-inch interferometer gauge length, piezo film 0.001-inch thickness and piezo ceramics 0.001-inch thickness. The sensitivity for the first kind of sensor is 30 volt per epsilon where epsilon is a strain, semiconductor gauge it is 1000 and then fiber optics it is 10 to the power 6 degree per epsilon, piezofilm it is 10 to the power 4 volt per epsilon, piezoceramics it is 2 into 10 to the power 4 volt per epsilon. If we look into localization the resistance gauge the localization is accuracy is 0.008 inches, in semiconductor gauge it is 0.03, in fiber optics it is 0.04, in piezofilms it is less than 0.04, in piezoceramics it is less than 0.04. If we look at the bandwidth then resistance gauge operates in a bandwidth of 0 hertz to the acoustic range same with semiconductor gauge and the fiber optics. In piezofilms it is 0.1 hertz to the gigahertz range and now we look into a comparison of different sensors.

So, here 5 kind of sensors are chosen, resistance gauge with 10 volt excitation, semiconductor gauge with 10 volt excitation, fiber optics 0.04 inch interferometer gauge length, piezofilm 0.001 inch thickness and piezoceramic 0.001 inch thickness. Sensitivity of the first kind of strain gauges 30 volt per epsilon, here epsilon is a strain, semiconductor gauge it is 1000 volt per epsilon, in fiber optics it is 10 to the power 6 degree per epsilon, piezofilm it is 10 to the power 4 volt per epsilon, piezoceramics 2 into 10 to the power 4 volt per epsilon. If you look at look into the localization accuracy, resistance gauge has 0.008 inches, semiconductor gauge it is 0.03 inches, fiber optics it is 0.04 inches, piezofilm less than 0.04 and piezoceramics it is less than 0.04. As far as the bandwidth is concerned, resistance gauge operates from 0 hertz to the acoustic range, semiconductor gauge and fiber optics also operate in the same range, piezofilm operates from 0.1 hertz to the gigahertz range and piezoceramics operates from 0.1 hertz to the gigahertz range. And again these comparisons can be found in the book of Chopra and Shirohi.

This brings us to the end of this lecture. We will continue from here in the next lecture.

Thank you.