Nature and Properties of Materials
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Lecture 25
Smart Materials 3

Today, I am going to talk about another type of smart material, which is known as magnetostrictive smart material. So in the earlier material that I have discussed with you that is the piezo electric material, electric field and mechanical field were coupled in that particular system which means by using electric fields we have generated mechanical deformation. And similarly, by using mechanical force we have generated electric voltage.

But the magnetostrictive material, this electric filed is to be now replaced by magnetic field. That means by using magnetic field, we will generate mechanical deformation and the other one that is mechanical deformation or force say mechanical force will create a change in magnetization, unlike the charge generation here it is change in magnetization, so this is the 1st one is our direct effect just like very similar to the piezo electric material, this is our direct effect and this is our reverse effect okay, so this is what we are going to study in today's lecture.

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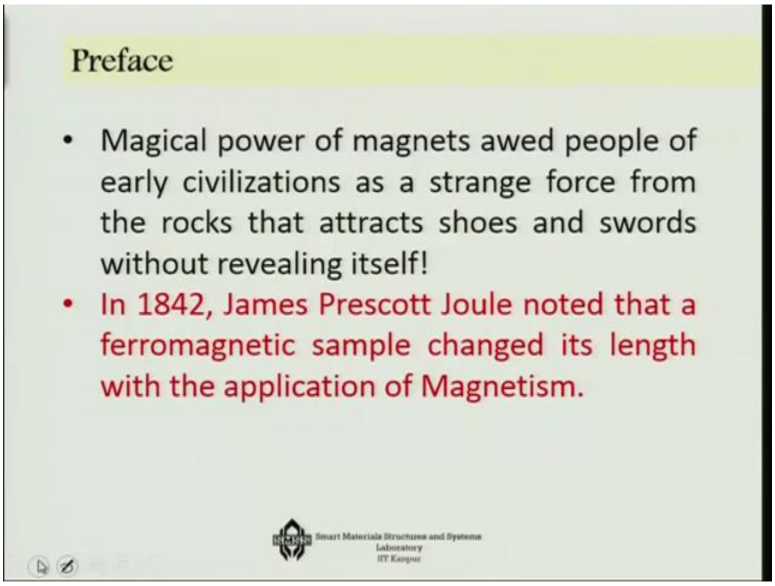

Now, magnetic force is something which was in the deep history it was always considered to be a very mystic kind of a force because if you want force you see which you cannot actually visualize it or visually determine that the force is there, but the forces can be very considerable. So this is what we know is considered to be a magical power of the magnet and that awed of people of early civilizations as if it is a of strange force which comes from the rocks basically, these magnetites are available in the rocks.

If you go through the stories of Arabian nights, you will see that Sindabad's story of that rock attracting ships is also a very similar version. So the rocks that attract shoes and swords without revealing itself, so people considered it as a magical power. Now that is about the magical power of the magnet, but James Prescott in 1842 noted another interesting thing of the magnets and that is, if you take a ferromagnetic material and if you apply the magnetic field on it, it actually changes its size or length.

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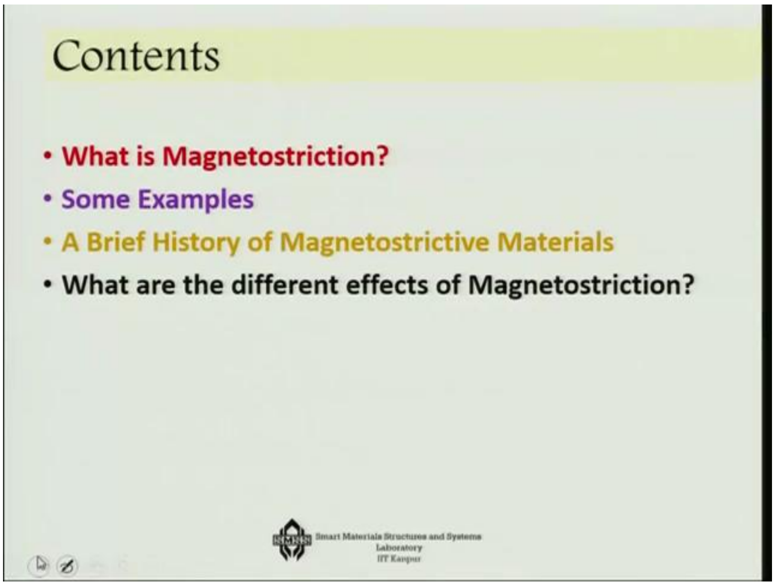

That change in length is very small in iron, but nevertheless it changes its length and this was discovered in 1842 by James Prescott Joule, other day I told you that is the beginning point of the magnetostriction. So what I am going to talk about today is that what magnetostriction is and there are some examples and which will help us to understand the phenomena, a brief history of magnetostrictive materials and what are the different effects of magnetostriction, so that we develop a bit of background about it.

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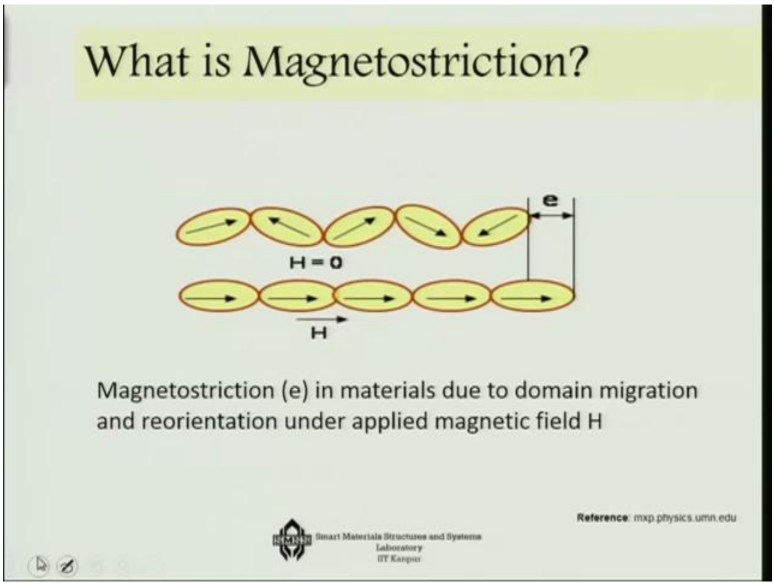

Now, what is the magnetostriction? Magnetostriction material is something which refers to the change in the size of the system due to domain migration and reorientation under applied magnetic field. For example, you consider the 1st case where a magnetic material as is always having dipoles magnetic dipole in it and each dipole has its own direction, but these directions are very randomly aligned, so that means in terms of North-South suppose they are very randomly aligned.

And that is as there is no applied magnetic field, the moment you apply the magnetic field, they will all get properly aligned and that would create an expansion in the system, as a result you are going to observe the magnetostriction in the system. So, this kind of mechanical deformation which happens due to domain migration and reorientation in this type of a material under applied magnetic field H that is what is actually magnetostriction. There are 2 terms here which is important, one is called magnetostriction, and another is called giant magnetostriction.

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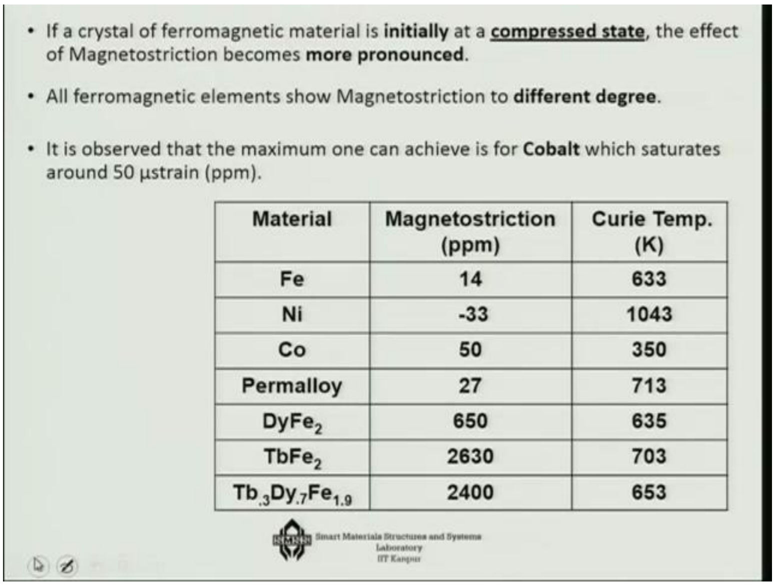

Material	Magnetostriction (ppm)	Curie Temp. (K)
Fe	14	633
Ni	-33	1043
Co	50	350
Permalloy	27	713
$DyFe_2$	650	635
$TbFe_2$	2630	703
$Tb_{.3}Dy_{.7}Fe_{1.9}$	2400	653

While magnetostriction is true for all the materials, but a subset of that shows a very-very large magnetostriction and that is generally referred in the literature as giant magnetostriction. Now if a crystal of ferromagnetic material is initially at a compressed state, it is found that this effect is actually more pronounced. In fact, there is another reason in which this effect can be utilized a bit in a compressed state or if you use a biased magnetic field, you can actually generate both expansion and contraction otherwise, magnetostrictive effect basically creates expansion in the system.

All ferromagnetic elements show magnetostriction to different degrees, but all of them show magnetostriction. And it is observed that out of the general paramagnetic materials, it is cobalt which shows the maximum magnetostriction, which is about 50 micron strength where it actually saturates. Now, you may see that there are some materials which show actually negative magnetostriction. So what it means is that if positive magnetostriction means expansion, then negative magnetostriction is some of the rarer cases where you see that by using magnetic field, you can even contract the system.

However, all these 14, minus 33, 50 in a in absolute scale, these are all very low, even Permalloy which is 27 is very low. But it is with the discovery of the later phases of magnetostrictive material like Dysprosium and iron alloy or terbium iron alloy or terbium dysprosium and iron alloy you will see that in these cases magnetostriction is quite high. And the other interesting thing is that very similar to the piezo electric material, which has a Curie temperature what it means, is that beyond that temperature the piezo electric property gets lost.

Very similar to that, magnetostrictive material also has a Curie temperature beyond which the magnetostrictive property gets lost. And that Curie temperature actually is varying for different materials, but on an average for this giant magnetostrictive materials, these are actually 600 plus in terms of Kelvin that means it is about 300 degree or so. So what it essentially means up to 200 degree or 250 degree, this system will work very well.

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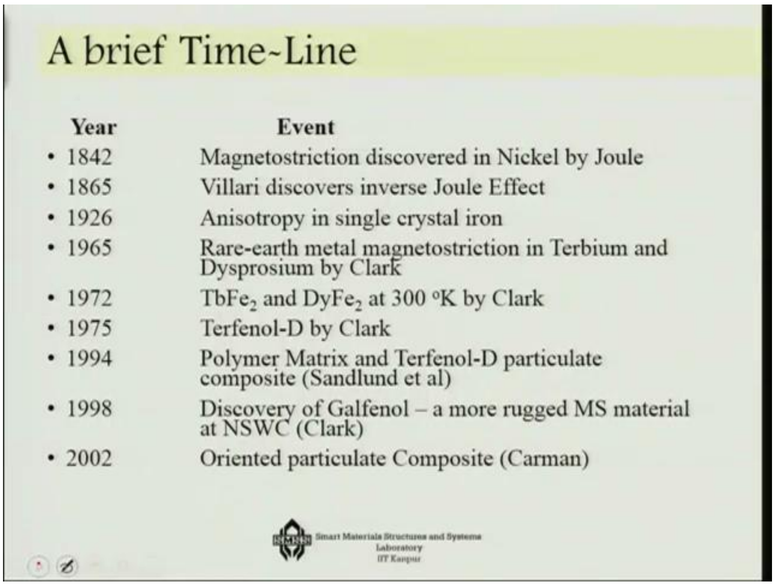

Now, we talk about a brief timeline of the magnetostrictive material as I told you that James Prescott Joule first discovered magnetostriction in Nickel and that was Joule's discovery that is in 1842. In 1865, the reverse effect that came into the notice of Villari, so he found out the inverse of the Joule effect. And 1926, people were able to see this anisotropy in single crystal iron due to the development of material science.

In 1965, for the 1st time beyond the general ferromagnetic materials, people found magnetostriction in rare earth metals like terbium and dysprosium, this was initially found out by Clark and then other people in the Naval ordinance laboratory. It was later on 1972 it was found out that instead of using pure terbium or dysprosium, if you use terbium iron compound or dysprosium iron compound, you can actually get magnetostriction at a up to a much higher degree of temperature.

And then on this terbium iron compound if you add a little bit more dysprosium, you are going to get a much larger magnetostrictive effect and Terfenol-D which was actually discovered by Clark. And later on people found out that if you use polymer matrix and the particulate composites of Terfenol-D, you can make nice composite out of it and you can give nice shapes to the system. Later on, there was another material instead of terbium it was found that if you use gallium and then iron and then Galfenol is a new material that is actually more rugged magnetostrictive material it was developed in NSWC by Clark and that was found to be a much more rugged magnetostrictive material.

Also, people have worked on oriented particulate composites, where this magnetostrictive materials are properly oriented to get maximum kind of displacement or matriculation shape change out of it. So the one which is mostly used is Terfenol-D. And as you can see the name itself tells us what is the composition of it.

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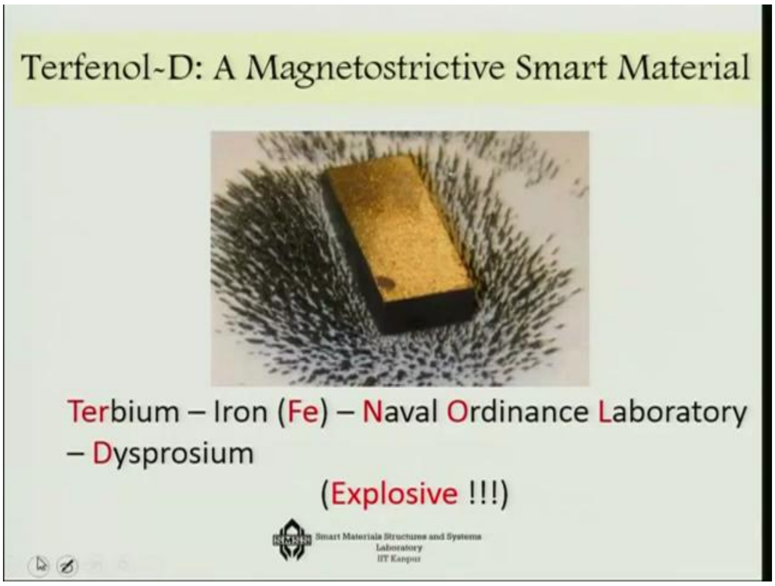

Because there is this Fe which is the iron, then Ter is the terbium part, so it is a terbium iron compound to begin with and this NOL is nothing but Naval Ordinance Laboratory of USA, who claim the 1st people to discover it. And D is the Dysprosium, so that is how this Terfenol-D name actually appears, it looks very shiny and in fact, it is very-very explosive. This is a small video in which you can see that if you hit this magnetostrictive material with a hammer, it is releasing huge amount of energy. So that is basically the energy density is very-very high in this magnetostrictive material.

(Video demonstration for Terfenol-D)

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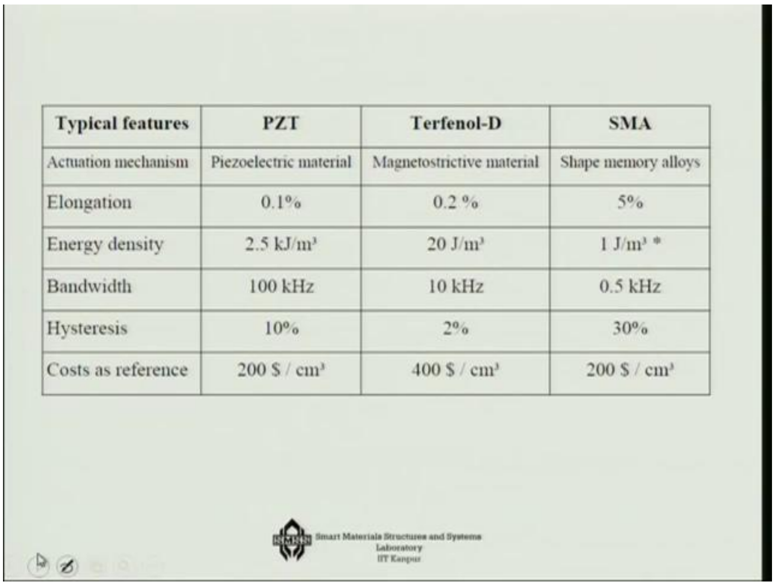

Typical features	PZT	Terfenol-D	SMA
Actuation mechanism	Piezoelectric material	Magnetostrictive material	Shape memory alloys
Elongation	0.1%	0.2 %	5%
Energy density	2.5 kJ/m³	20 J/m³	1 J/m³ *
Bandwidth	100 kHz	10 kHz	0.5 kHz
Hysteresis	10%	2%	30%
Costs as reference	200 $ / cm³	400 $ / cm³	200 $ / cm³

So where we are in terms of the performance comparison between magnetostrictive material and shape memory alloys, et cetera. Now, is it the actuation because of this piezo electric actuation? For Terfenol-D, it is a magnetostrictive material so it is a magnetostrictive actuation and for SMA it is a thermal driven process generally. So the elongation if you compare, you would see that Terfenol-D gives a medium performance, not as high as SMA, not so low as the piezo electric material.

In terms of the energy density that it shows is somewhere around 20 joules per meter cube which is quite high. And in terms of bandwidth once again it is in the middle like 100 kilo hertz by piezo electric material or shape memory alloy as 0.5 kilo hertz, this fellow shows about 10 kilo hertz. And the hysteresis is about 2% in the whole thing, so it means it behaves in a very linear manner. And cost wise also, it is actually double the cost of Terfenol-D, but it is easier to actually fabricate them, so in terms of that it is easier sometimes than the PZT or other counterparts, so this is a relative comparison between these materials.

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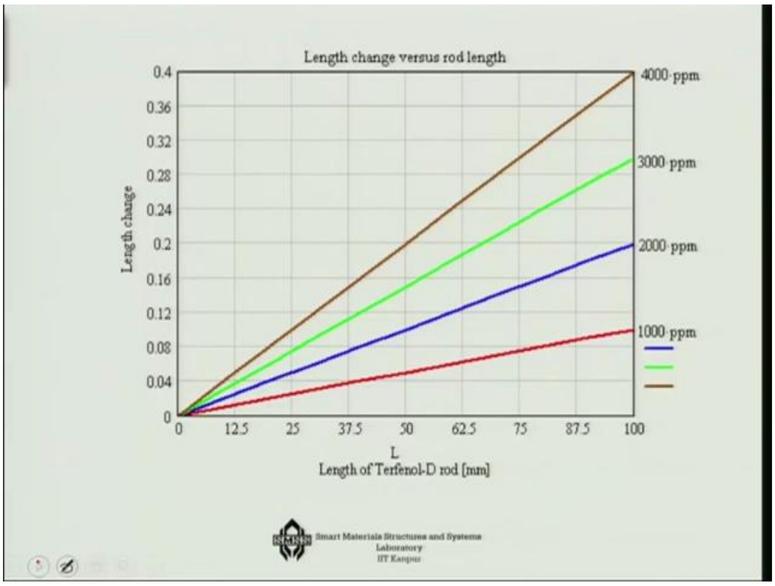

Now, I told you that magnetostrictive materials shows something like 2000 parts per million or little more than that in terms of the strain that tip strain, so how much does it mean in terms of the change in length? So let us say, I choose a 100 millimeters of a beam and I apply these materials over it and then if the full strain if something like 200 parts per million.

And if you just join it you are going to see that it is slightly lower than 0.2, but between 0.16 and 0.2 to that is the change in the absolute length that you can expect in such situations from this material. So this gives us an approximate idea of the type of change that you are going to see in this material.

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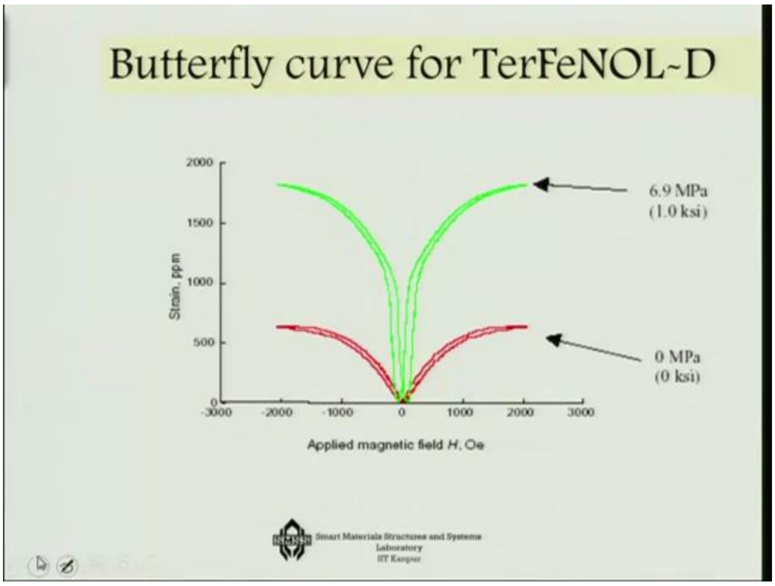

Another interesting thing is that the Terfenol-D has a butterfly curve okay because you can see that the shape here is like a butterfly. Now, in this butterfly curve what we are trying to show is that if you change the magnetic field, you are going to see that there is a reversal, but that reversal is not in terms of sign change, so you can see that with respect to positive voltage you get some shape, with respect to the negative voltage you get the reverse shape in the magnetostrictive material.

However, the point that is interesting is that in all the cases you are only getting positive strain, only expansion. So how can we generate a kind of a tension compression sequence, so that vibration gets generated in the system because it is a butterfly curve, it does not go to the other side.

To do that, what we use is a bias current and also we actually operate it across the bias current suppose somewhere this is what is made biased magnetisation and then we keep that fixed and then we actually take a bandwidth on which as we change this bias, it is going to show relatively either less strain or more strain, thus you can generate your own magnetostrictive transducer, so that is the advantage of this system.

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Now, what are the attractions of this magnetostrictive material? Surely so many people are working on it, there must be something which attracts them. One I already said the large force generation, the other interesting point is that its signals does not decay with time, so it actually unlike the piezo electric materials where the discharge happens very fast, it does not get discharged so to say very fast.

So, if you consider a magnetostrictive transducer to apply, it will be cost-effective in the low-frequency band and could be effectively use for deep sea measurements due to their superior mechanical techniques. There is one such transducers that is TALON that is Tactical Acoustic Littoral Ocean Network TALON software sonar system that uses magnetostrictive Terfenol-D for underwater submarine detection like Etrema products visibility, you will see this type of applications into it.

Magnetostrictive are actually transducers are very active in terms of sensing very small displacement and converting them to very good significant amount of change of magnetisation or change of voltage. So that is why as transducer, these things are used in various sub-sea applications. Now, magnetostriction in a solid rod, how would it happen?

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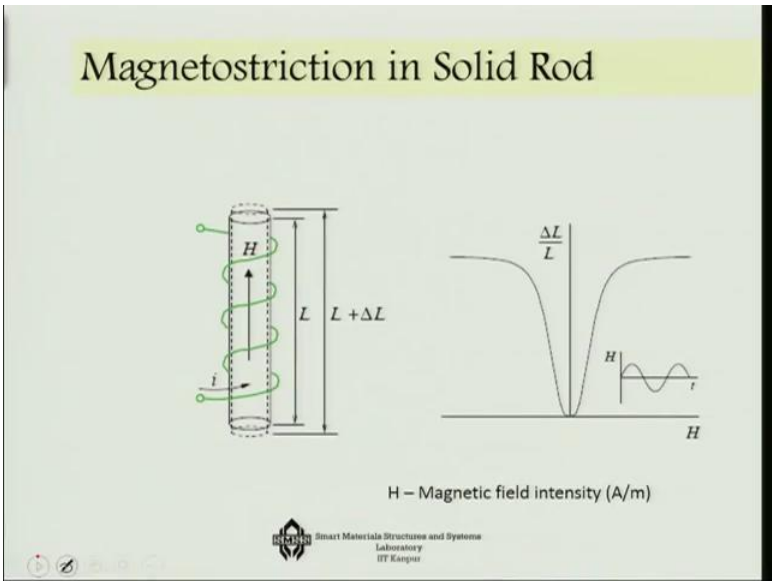

So if I consider a solid rod and if there is a solenoid worn around it, and in that solenoid let us say I am applying a current I, which is going to generate a magnetic field H on the core that you can see here, let that core be magnetostrictive core. Then due to the application of this current, the magnetic field will create an expansion initiate and it will become from L to L plus Delta L.

And if you plot this Delta L over the length, what you are going to see and that if you actually plot with respect to the change in magnetisation, you are going to see that famous butterfly curve, which says that even if we actually change this magnetic field from positive to negative side, still we are always getting expansion in the system.

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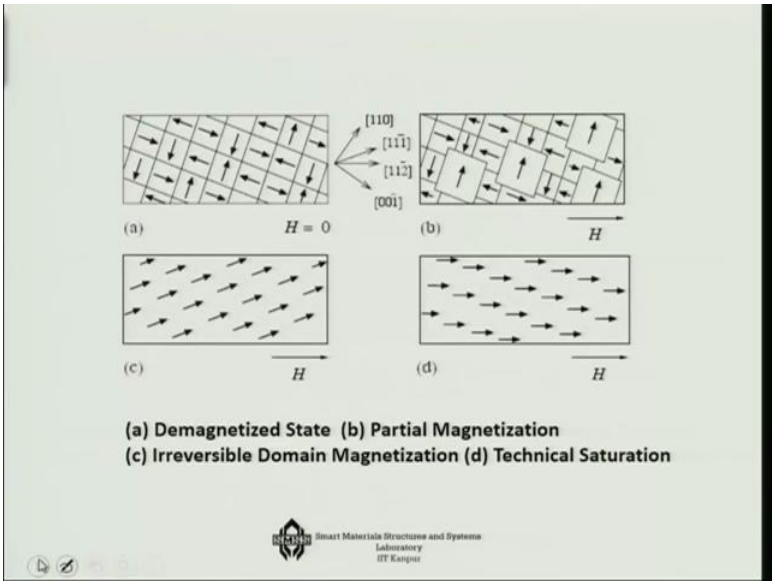

Now, if I vary the magnetic field in this type of a system suppose initially there is no magnetic field, so you can see the domains here which are very arbitrarily aligned. Now, the moment we apply the magnetic field, what will happen is that there are some axis which are known as easy axis, so if my magnetisation favors the easy axis, then the grains will be growing along the easy axis as it has grown in this case. And then you will further if you increase the magnetic field intensity, what you will see is that all the magnetic dipoles got very nicely aligned.

And this if you increase further, the intensity of the magnetic field you can almost make all the magnetic field dipoles to be parallel to the system. So starting from the basic demagnetized state plus for a Terfenol-D material, you can get reasonably good change in shape by following these steps. Now, just like piezo electric we have 2 effects like one is direct effect, another is reverse effect.

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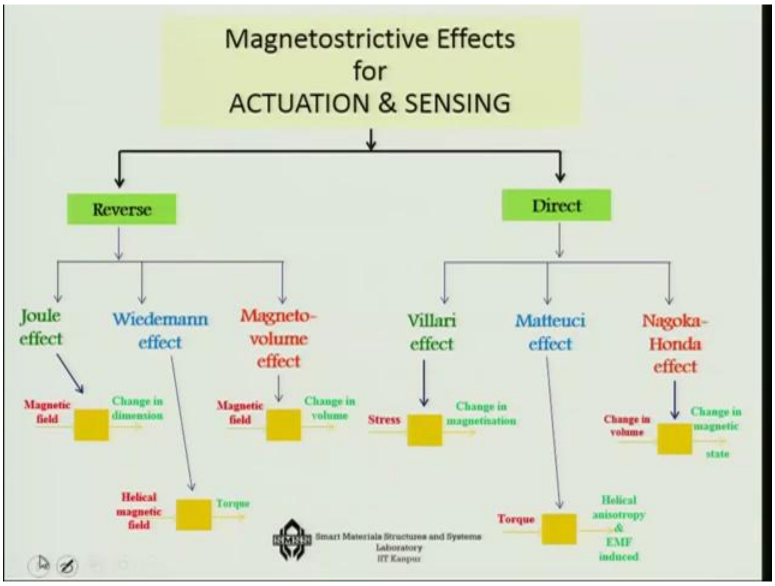

Something very similar is they are also for the magnetostrictive materials for example, if you look at the reverse effect that it creates there is this joule effect that joule has discovered okay that the magnetisation is changing the length, then there is this Wiedemann effect in which he showed that this if this magnetic field is helical in nature, then it will not create length rather it will create torque and then the magneto volume effect in which if you change the magnetic field, you are going to see a good change in the magnetic volume of the system.

Now, all this change of volume if you say or change in dimensions, et cetera, all these can be used in terms of developing actuators for the system. But what are we going to do for developing sensors for the system? Then there are 3 techniques that you can use, one is called the Villari technique, Matteuci effect and the Nagoka-Honda effect. The Villari effect actually what it does is that if there is a stress change, then there will be a change in magnetisation in the system.

The Matteuci is very strange, if you actually apply torque then you are going to see the helical anisotropy and EMF induction in the system, so that is what our Matteuci effect is. And the Nagoka-Honda effect, in this actually if there is a change in the volume in the system, then there will be a change in the magnetic field of the system, so that is Nagoka-Honda effect. But mostly what we use are the Joule effect, Wiedmann, Magneto volume effect and Villari effect of the system.

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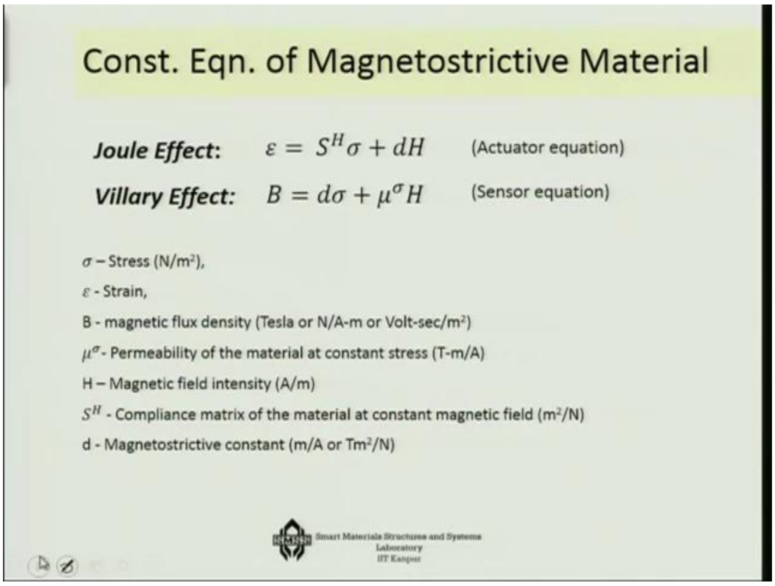

Now, if you look at the constitutive equation of magnetostrictive material then there is 2 important one, one is from the direct effect point of view and that means where you are using the mechanical force field and you are getting the change in terms of the electrical or magnetic field change, so which is what you can use in terms of the mechanical force field change for example, Villari effect you can use in terms of developing the sensor here.

And other one is where there is a application of the magnetic field and you are getting a change in terms of the mechanical strain, which is what is used in terms of the actuator equation. Now, if you look at each one of these equations, in the Joule effect you can see that the mechanical strain can be either related to the mechanical stress, which is the normal Hookian part. Also, you can use the magnetic field intensity along with d, d is nothing but magnetostrictive constant, and you can use that in order to generate the mechanical strain in the system.

Similarly, if you look at the Villari effect which is more used for sensor development, here if there is a change of magnetic field intensity then there will be a change in the magnetic field displacement which is fine, but in addition if there is a change in stress or that means if there is a change in strain also, then also there will be change in the magnetic flux density B and that can be captured in terms of change of voltage through a pickup coil, et cetera. So that is what is the constitutive equation, which looks linear but it is actually linear in a very small range and this is used in terms of developing actuators and sensors.

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What are the major applications? We can use this material for active vibration and noise control system, for machine tools , for servo valves, hybrid motors, for sonar devices and tomography, automotive break systems, micro-positioning and ultrasonic cleaning in for machining and welding, so there are varied applications in which actually you can use it. The initial application was in terms of sonar devices, but now you see there are so many different applications of these magnetostrictive materials.

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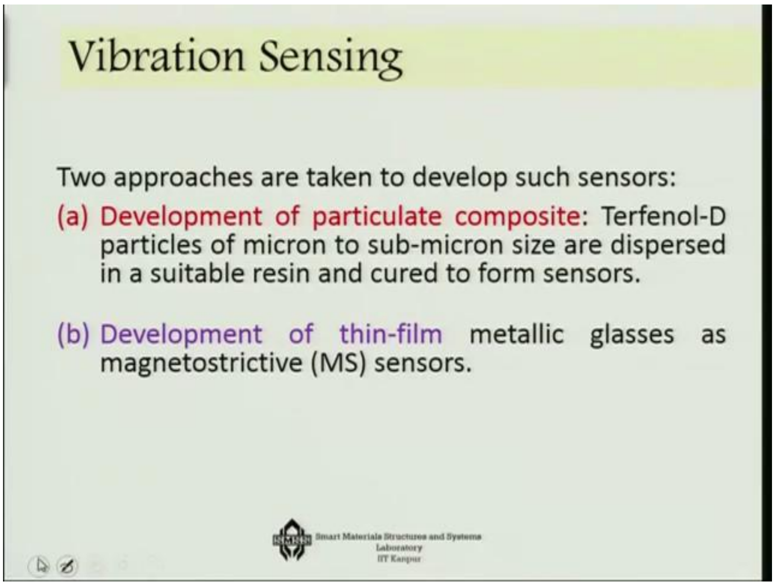

In terms of vibration sensing there are 2 approaches, one is to develop particulate composite like Terfenol-D particles are milt of micron to sub-micron size and are dispersed in a suitable resin and cured to form sensors. And the other one is the development of thin-film met glasses metallic glasses as magnetostrictive sensors, so these are 2 different approaches for developing such sensors.

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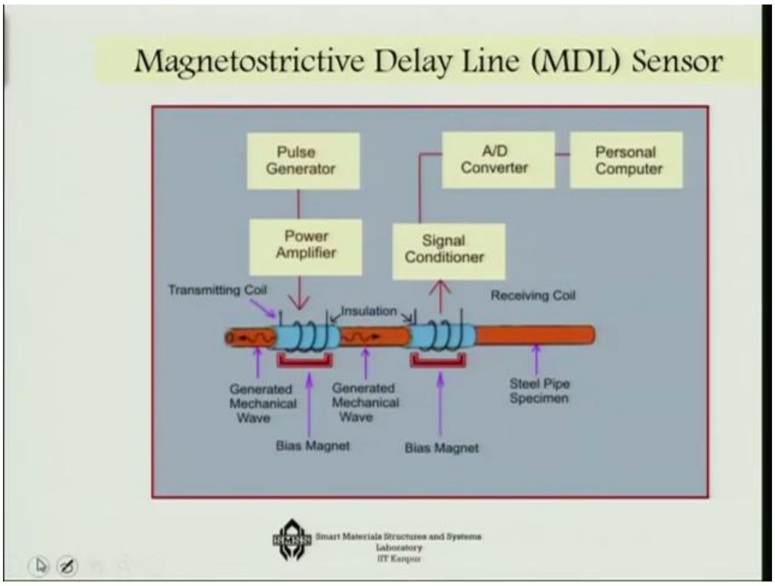

One such typical sensing I am showing you her, which is the magnetostrictive delay line fencing, so what happens is that there is one area where you have applied the magnetostrictive material, you have applied this biased magnetic field which is generating mechanical wave and that mechanical wave is travelling, then at another point you are actually picking up the signal.

And then you are finding out that what is the delay in the arrival of this signal through the pipe and is the instant the signal transfer from point A to point B due to the electromagnetic effect because the signal which is coming through the pipe, there will be a delay in that pipe and that delay will be more and more if there are cracks inside the system and that is why this delay can be a measure of the cracks, etc or the defects in the pipe.

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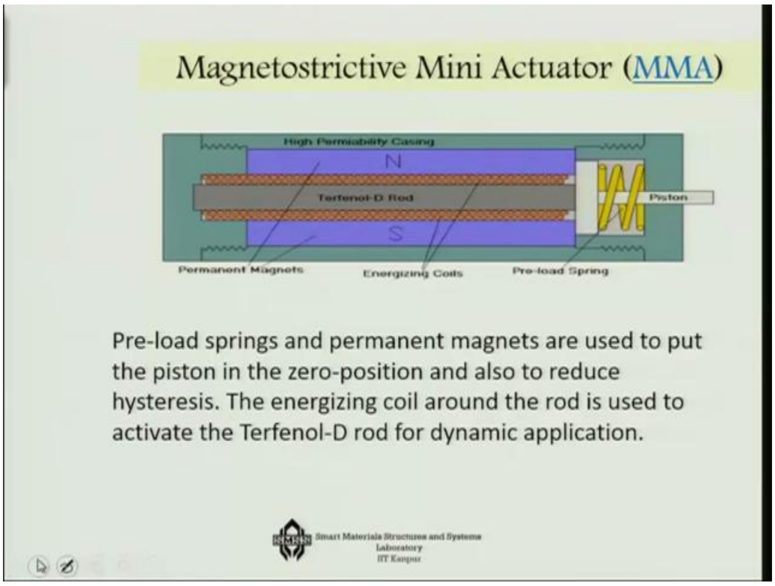

This is another application of magnetostrictive system, it is called Magnetostrictive Mini Actuator or short form MMA, is been developed by (())(27:17) groups in University of Maryland. What you will see here is that there are these permanent magnets there on the 2 sides and there is this Terfenol-D rod in the middle. And as you are applying this electric field and the permanent magnet already gives a bias to the system, so by applying the electric field on top of that you can actually move to and fro the system.

And this spring actually makes sure that you get more or less linear response for a good range of this, so that is how you develop this magnetostrictive mini actuator which you can use for vibration control. There is another interesting way in which you can use it, it is called Inchworm motors like a Kiesewetter inchworm motor.

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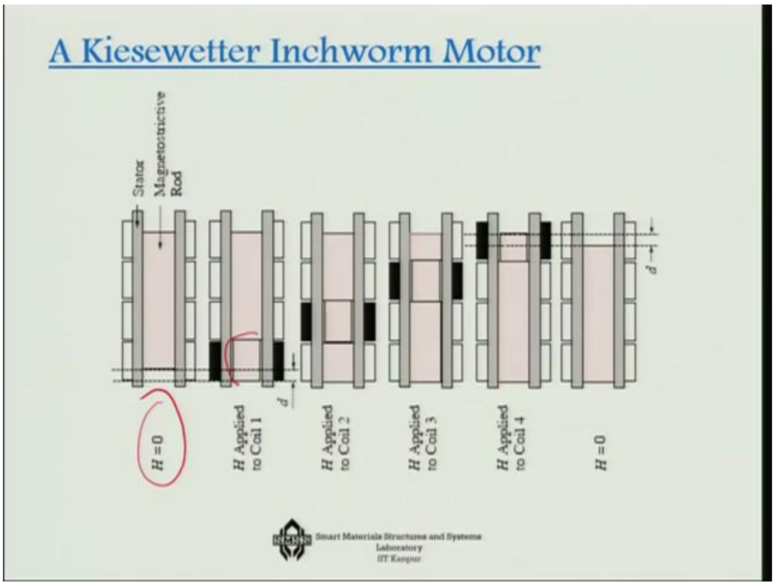

And you can see here that initially there is no magnetic field, then you apply the magnetic field at this level and then you remove, you do it here so when you are applying it here, you are getting a deformation. Our task is by applying it repeatedly at different levels okay, we are actually shifting the position in such a manner that this displacement comes here itself, so that you are able to make some kind of inchworm movement in the system by repeated application of managing field in to a series of magnetostrictive materials, it is a very innovative concept.

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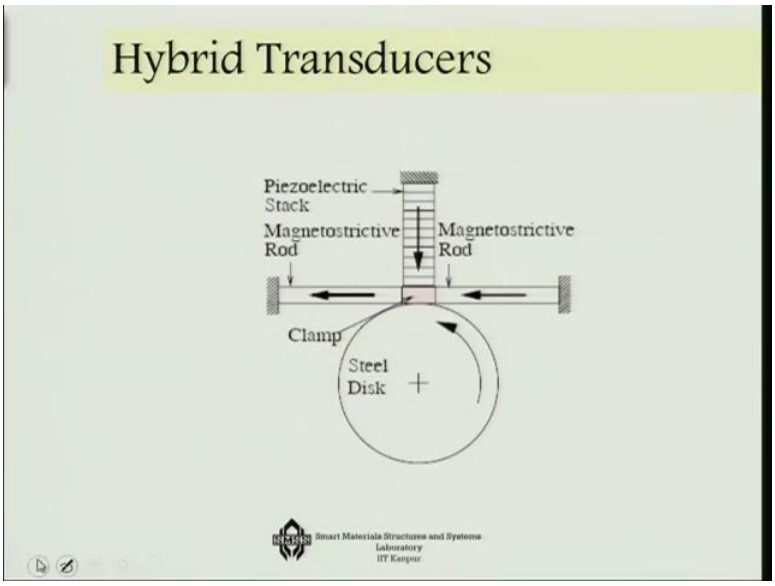

There is something like hybrid transducers also. In this case for example, there is a steel disk okay and this steel disk has clamps here okay and there is a piezo electric stack here so and also these are magnetostrictive rods. So that means if I apply magnetic field, they are actually going to give some kind of a a force here which will generate torque and about the moment about the Centre and then that will keep the rotation of the disk.

But if you want to control that rotation, then you use the piezo electric stack which will work like a clamp and it will time to time it can actually stop the disk or slow down the disk. So thus, with the help of these 2 you can generate various uniform motions in the steel disk system.

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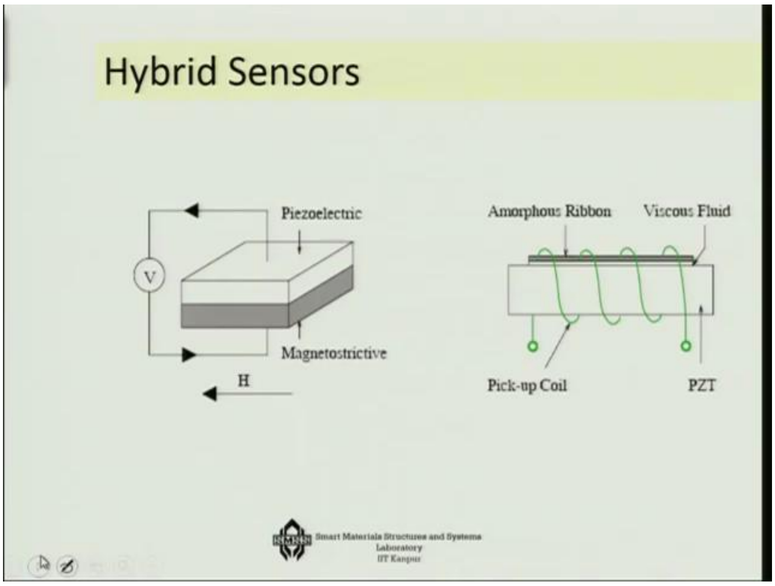

Similarly you can have hybrid sensors like partly piezo electric and partly magnetostrictive. Or you have amorphous ribbon, which is magnetostrictive and then you have pickup coils and also you have the PZTs. So the idea in this type of systems is that magnetostrictive sensor can be used in one part of a strain generation whereas, in the other part you can use piezo electricity thus you can use magnetostrictive material for a large range.

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So this is where we will close this discussion on magnetostrictive material, the references that you can use are Anjanappa's papers on magnetostrictive particulate composites, Dapino's paper on Magnetostrictive sensors and also the Carman and Micknight's paper on oriented Terfenal-D composites. In the next lecture I will talk about Active smart polymers, thank you.