Smart Materials and Intelligent System Design
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Lecture – 03

Good morning to all of you in the MOOC course on Smart Materials and Intelligent System Design. In this a series, the first module in which I am talking about the overview of smart materials, on that we have already discussed about the piezoelectric materials.

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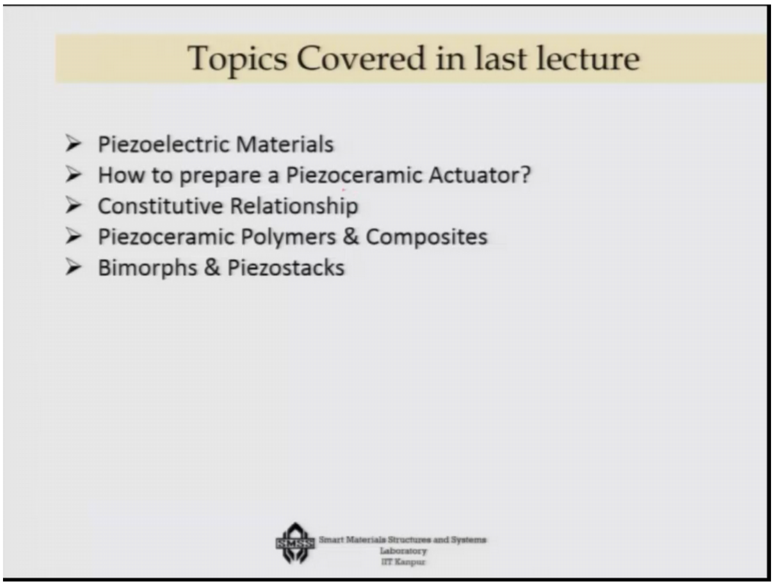

Also I told you about how to prepare piezoceramic actuator, I have discussed about the constitutive relationship of piezoelectric material, which is very much similar which I will be talking about today also for magnetostrictive materials. And, I have also discussed about piezoceramic polymers and composites, basically I told you that the necessity for this kind of systems are more from the sensor point of view and also to embed them in structural systems.

And also I have touched about the issues of bimorphs and piezostacks. So, with a broad overview with you on piezoelectric materials, we will now talk about the magnetostrictive materials.

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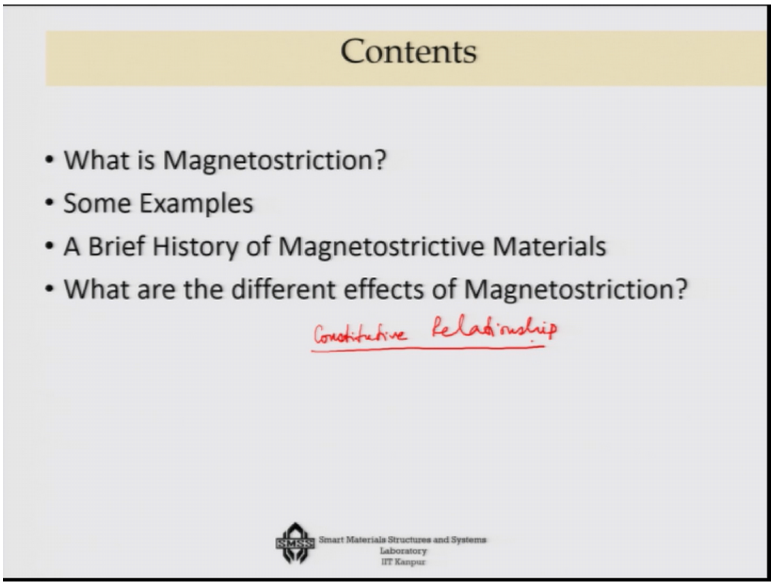

In this series what I will be talking about is that: what is magnetostriction first of all and, then I will show you some examples, where we can apply these magnetostrictive principles. And we can develop transducers based on that, a brief history of magnetostrictive materials that timeline, how things are evolved and what are the different effects of magnetostriction along with I will also talk about the constitutive relationships in this as well of the magnetostrictive material.

So, let us first start with the our first aim to understand that: what is magnetostriction? The magnetism itself is considered to be a magical power, for a very very long time, it seems that Cleopatra is used to take bath, on ferromagnetic beats considering that she will be you know ageing process will not happen to her. So, this is how the kind of superstitions or believes that were there on magnets in the people.

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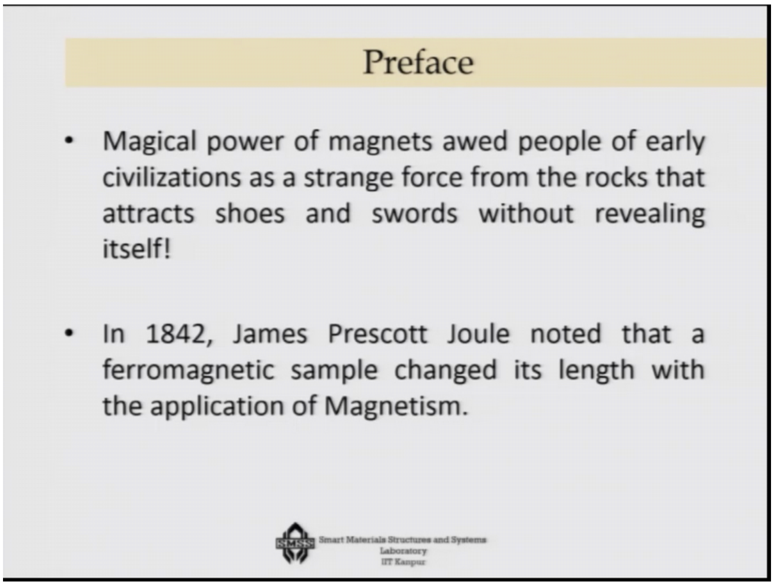

But what interesting thing was only discovered around 1842 by James Prescott Joule and he noted that a ferromagnetic sample a change its length with the application of magnetism. So, that was something new; earlier people knew, that how magnetism is generated in a ferromagnetic material to some extent empirically, but that is also changes its length was not known to people.

The ferromagnetic materials can change its length, you know while subjected to the magnetic field, that was a new discovery by James Prescott Joule and that is the beginning of magnetostriction. Now, what is magnetostriction? When, if you know about the domain theory that, you have studied in your school days about the presence of you know magnetic domains in a magnetic material.

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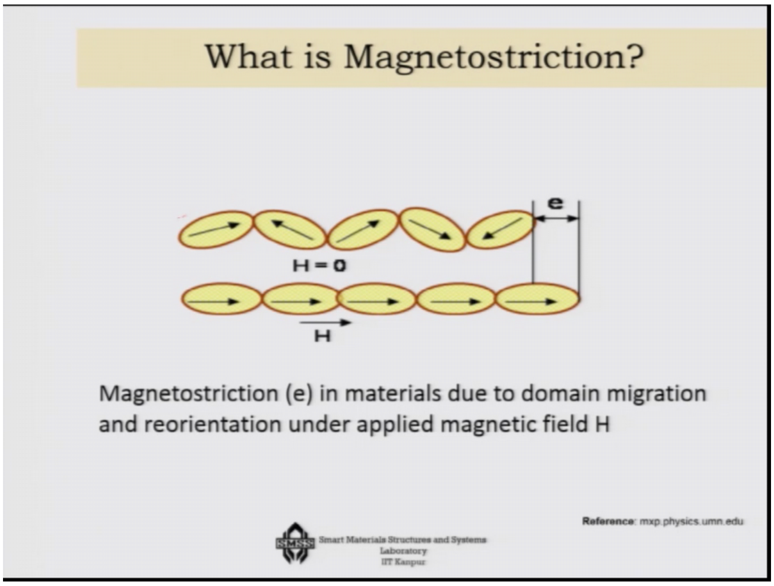

Then a each one of these beads are actually this magnetic domains, and the direction of the domain you know, magnetism is shown with these arrows, which is very similar to when I have shown you about the dipoles you know direction of polarization. Now, in general when H equals to 0 these domains are all placed in a manner that it is a north-south, north-south combination, but they are not aligned. So, they are very randomly placed, if I apply a magnetic field what will happen all this domains will flip and they will align themselves in a particular direction.

The moment this will happen you will see it is like a kind of a twisted chain and the moment, you know you are actually applying some kind of a force; in this case you see magnetic force this chain unfolds. So, as a result this magnetostriction is going to happen; that means this whole sample is going to change its length. This particular process we also say that this is due to domain migration and reorientation; that is the way we technically define this term. So, under the effect of magnetic field when there is a domain migration and reorientation of the magnetic domains, that actually causes the magnetostrictive effect in such a system.

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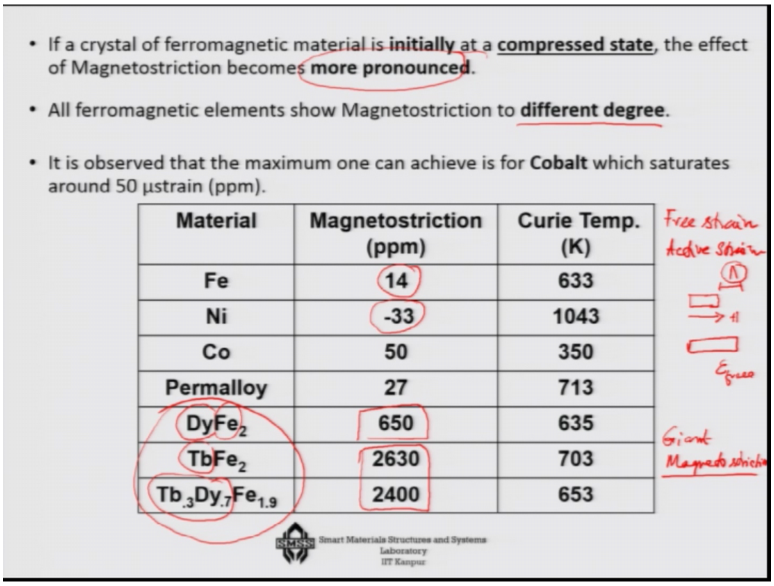

If this effect it is observed that if the ferromagnetic material is initially at a compressed state then the effect is more pronounced. Well it is naturally so, because when it is at a compressed stage, then these domains are all much more you know constricted in a smaller area. Now, the moment you are applying the magnetic field, assuming that you have enough magnetic field available with you this compressive you know confinement actually is taken over. So, it comes back to its general normal size and, then as the magnetic field is applied further, it expands until all the domains get nicely oriented in one direction. So, as a result that affect becomes much more if it is initially compressed. So, that is one technique that people do.

The point is that is the magnetostriction uniform in a all ferromagnetic material; no, different ferromagnetic materials show different degree of magnetostriction. For example, iron which was the first one to be noted by Joule that shows only 14 parts per million; you know like a strain that you can produce. So, it is a active strain will always tell this in terms of free strain, these are the terms that we will continuously deal with free strain or active strain.

So, what it means is that if I do not apply any other external force, then let us say I have a sample of any smart material, in this case it is a magnetostrictive material and I have applying a magnetic field. And, what is the free expansion that is going to happen to the system. So, that is what is our free strain, we usually denote it by lambda or epsilon phi. So, that is the free strain that is in 14 parts per million in the case of iron.

And in the case of other materials like I will come to nickel later on, cobalt it is 50 parts per million; permalloy 27 parts per million. Towards the end of the last century, or you know even today what is happening is that new materials people are actually designing. And, in these materials the effect of magnetostriction is actually much-much higher, you know sometimes it is even 100 times more than what we used to see in the as old magnetostrictive materials.

So, what is the tricks for that; well, if you look at it that in such materials along with a ferromagnetic material like let us say iron, you are also using another material from the periodic table which is far away, in a periodic table. These are called rare earth materials like dysprosium, like terbium or a combination of terbium and dysprosium. So, this kind of materials show large you know what we call giant magnetostriction and, this is the latest development in terms of the material advancement.

Now that is one point, the other point is that in among all these materials nickel shows negative magnetostriction. So that means, most of this materials, if I apply magnetic field it will expand, but there is this anomaly there that is nickel that in state of expansion it will compress, if I apply the magnetic field. And this has to do with the orientation of the magnetic domains in nickel. So, that is an anomalous behavior.

The other interesting point here is the Curie temperature. If you remember, I told you that for piezoelectric materials, there was a Curie temperature beyond that temperature; if you heat up the material it will not show the piezoelectric property. Similar, to this for the magnetostrictive material also if you exceed all this temperatures you know for various materials, they would not actually show the magnetostrictive effect That means, even if you apply magnetic field the domains basically will be so, much thermally agitated that they will not be able to align themselves towards the direction of magnetic field. And, hence magnetostrictive effect will not come up. So, this is a point we have to keep in our mind.

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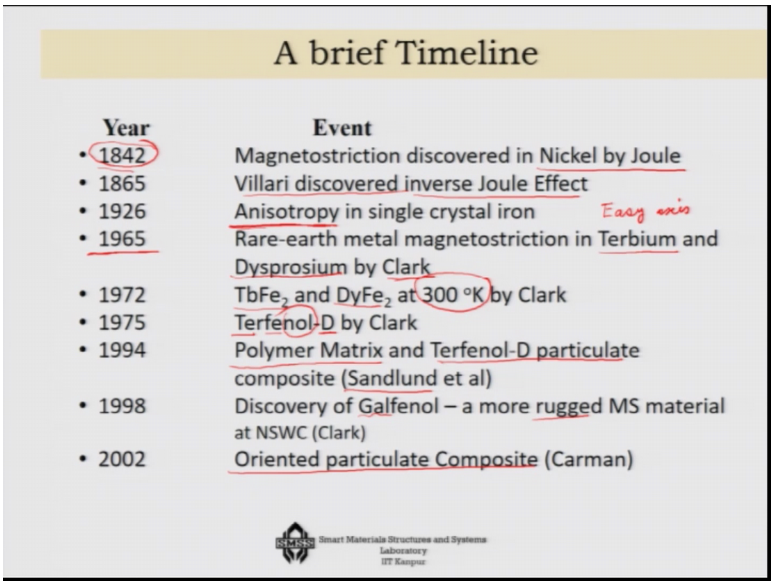

Now, let us just look at a brief timeline, how this magnetostrictive materials evolved. As I told you that around 1842 James Prescott Joule first discovered it in nickel, and later on in other ferromagnetic materials. Now, 1865 Villari rediscovered what is known as inverse of Joule effect. So, just like piezoelectric material where we have seen that if you know apply mechanical force, it was generating charge. In this case, first effect was of course, the indirect effect. That means, if you apply the magnetic field it was changing its length, but later on it was found that if you change length it will change its state of magnetisation which is: what is the Villari effect.

And then people also find that this effect is very important that this effect is anisotropic. Now, what do you mean by isotropic and anisotropic is the same, that the way we discuss it in the context of solid mechanics that, these magnetism magnetostrictive effect has a directional dependence; so, it is not that in every direction you will see equal amount of expansion. They there are certain directions for example, we call them to be the easy axis; along the easy axis you will see, that maximum actually deformation takes place or maximum change of length takes place.

So, and in other direction it is less. So, there is an anisotropic so, that was discovered by people. And then I was telling you that as late as 1965 imagine that 1842 the effect was discovered, but as late as 1965 people first found out that if you use terbium, or dysprosium you will see much larger effect of magnetostriction, this was discovered by

Clark at the naval ordnance laboratory of USA. And later on Clark himself have shown that if you make an alloy of terbium, iron and dysprosium iron, then the you can improve this effect in the sense that terbium or dysprosium on its own shows the magnetostrictive effect at very low temperature.

But you can bring it to a considerably high temperature by making an alloy with iron. So, thus actually terbium, and iron and dysprosium, this three materials are added finally, and the naval ordnance laboratory name goes inside it and the material that is used commercially today is called Terfenol D which is a magnetostrictive material. People just like the ceramic things started thinking about can we make a polymeric fashion of it, because that is important for productization. So, 1994 polymer matrix and Terfenol D particulate people have shown like Sandlunds and others that you can make a composite out of it.

Also Terfenol D one of the problem with these material is its machinability. So, from that point of view instead of terbium it was found out that, if you add gallium then you get a new material called Galfenol and that is a more rugged magnetostrictive material. And also people have worked on magnetostrictive particles vary 5 nano particles and then orient them at the particulate composite phase itself. So, these are various advancements that are happening in the realm of magnetostrictive materials.

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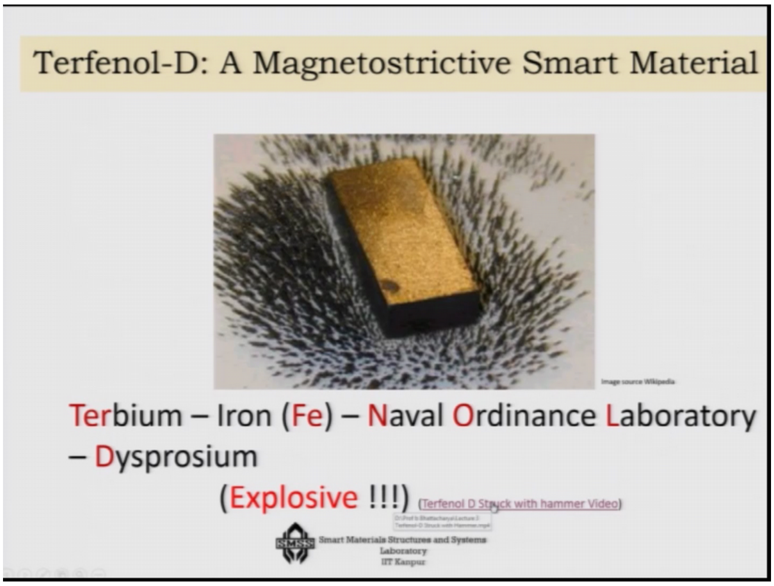

This materials in comparison to their are the piezoelectric counterparts, they are actually very high energy content they have in fact, they is they are like you know quite explosive in this particular small video, you see that if I strike a Terfenol D material with hammer you will see that how explosive this whole system becomes. So, you can see that the energy density is phenomenally high in this particular system.

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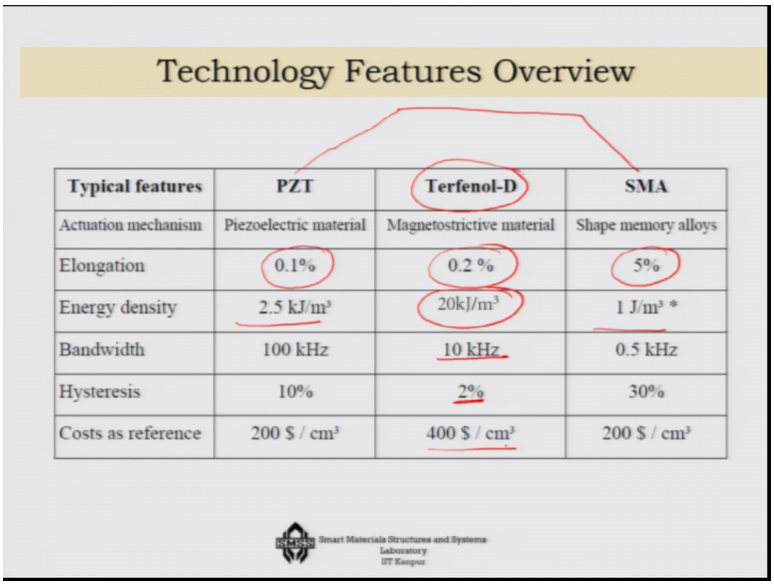
Technology Features Overview

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	20kJ/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, that is the Terfenol D, now let us compare this particular smart material Terfenol D with respect to its two other counterparts in the two sides, that is a piezoelectric material and a shape memory material. Now, if you consider in terms of the elongation or the maximum strain, that you can get from this materials you would see that piezoelectric materials give only 0.1 percent of strength where as magnetostrictive material is much better it gives 0.2 percent, and shape memory alloys gives much higher 5 percent of strength. So, that is something which is to be noted that Terfenol D is better in terms of active strain.

Energy density wise you can see that this is twenty kilo joule per meter cube, which is much-much higher than the piezoelectric material, or the shape memory alloy. Bandwidth is not as high as piezoelectric material it is slightly lower. So, this is 10 kilo hertz hysteresis is much less, but the cost is much high. So, this just gives you a kind of a comparison between the two.

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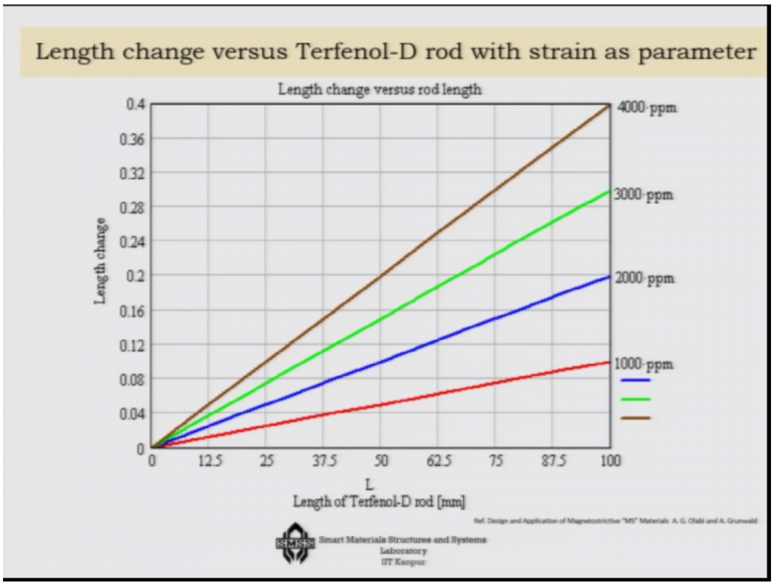

Now, I am continuously telling you about parts per million. So, what does; that means, in terms of giving you some kind of a physical idea about parts per million. So, in x axis I have given you the length here in millimeter. So, this is in millimeter so, let us say if I choose hundred millimeter of a Terfenol D rod and, I told you that it shows about 2000 parts per million if it is not compressed. Then that would mean that the change of length will be something like 0.2 millimeter. So, that will give you some kind of an idea about how small is this change of length. In fact, if it is piezoelectric material it will be how much something like you know 0.09 or so, ok.

So, it is even smaller and if it is you know shape memory alloy, it will be something like right, now it is 0.4 is the maximum here, but it may go something like 0.5 millimeter or so, that is the highest we are talking about. So, you can get an idea about what is the length change, can you see it with naked eyes well unless it is a high frequency vibration, or situation like that you cannot see it otherwise except for shape memory alloy, where sorry electrostrictive polymers you really cannot see most of the cases, that this change is happening. But, you can feel the presence, if you can develop a dynamic situation like vibrations etcetera. Now, if you look at the you know stress strain relationship in these materials that is also very interesting we often call it as a butterfly curve.

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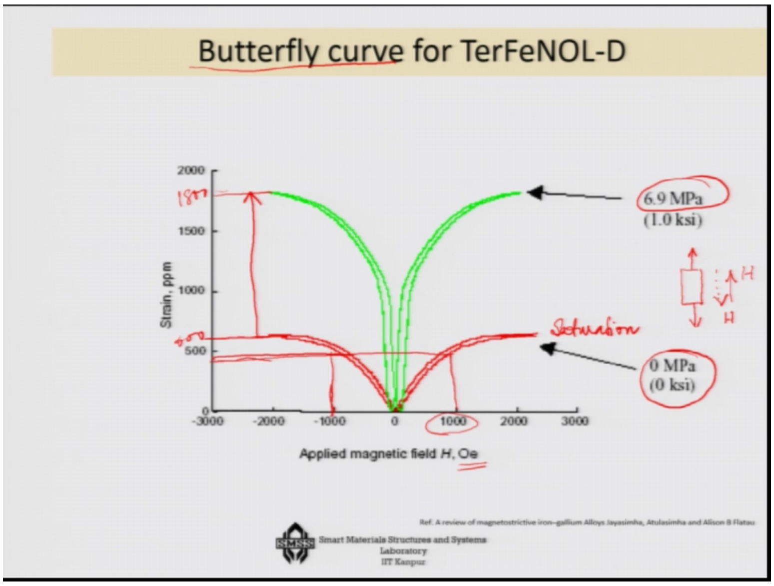

So, what does this butterfly curve means, if I consider the smaller one where it is not compressed, you look at it that if I apply positive load and stress it, I am going to get positive strain in the system. So; that means, if you take a small sample of the Terfenol D rod and, if you apply tensile force you are going to get tensile strain which is fine you know it happens.

But interesting thing is that in this case this load is not coming first of all, not by a physical load, but by a magnetic field. So, this is an o state as you have seen. So, if I apply a magnetic field and that magnetic field matches with the direction of orientation in a manner, that it actually you know gives you the tensile stress, then it is going to expend fine. Now, what if I change the direction of this magnetic field to the reverse direction ok, in the case of piezoelectric material, if I change the direction of voltage it immediately starts to compress.

But in this case if I go to a minus 1000 ok, if I look at it well it is exactly the same as it was at plus 1000 so; that means, it is still giving you positive strain. So, that is important that magnetostrictive materials they always expand, no matter whatever is your direction of the magnetic field. The other thing that you can see here is that if I increase the you know pre stress level from 0 MPa to 6.9 MPa I am increasing look at the maximum strain value something like say 600 here. And it is it will be going something like say you know 1800 here. So, it increases this much if I actually I was telling you know that if

I apply a pre stress on the system. So, that is something that we also try to take advantage of.

And one last point here is that, if I increase the magnetic field am I going to get continuously magnetic active strain, or free strain out of it no beyond a certain level you see this saturation is occurring. So, that is technical saturation of the system; that means, beyond that strain you are not going to get any more strain out of the system, why because all the domains are aligned by them, that picture I will show you soon that you know how this domain change.

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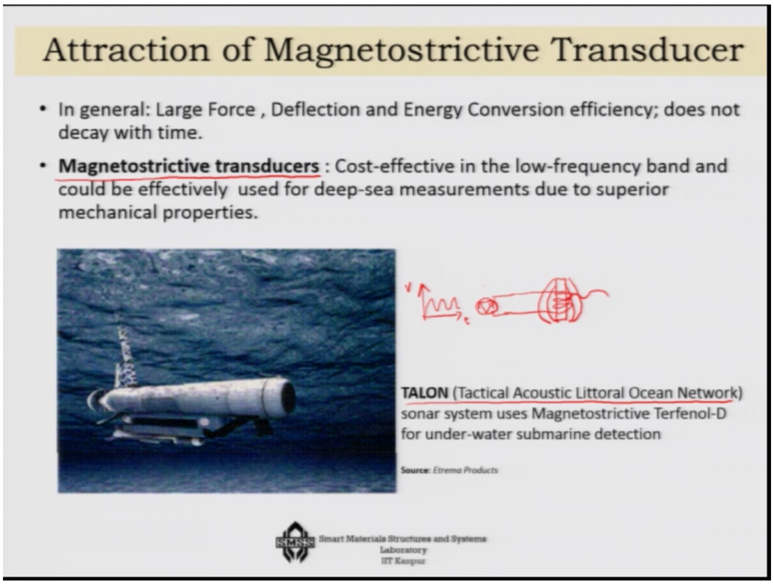

Now, where can we apply such a system, one of the most important application of such a system is in terms of you know tactical acoustic littoral ocean networks talon. So, this are you know sonar systems, sonar systems are used for defense purposes say for example, if there is a underwater attack of any submarine, or any such thing. Then this kind of systems this sonar systems, what it does is that it actually converts the you know the mechanical field of wave in terms of change of magnetization, and that change of magnetization actually generates a pickup voltage in the system.

So, thus you can actually develop a magnetostrictive transducer by using you know the magnetostrictive material in it. So, if you remember earlier we have used piezoelectric composites ok, in this case we are using a magnetostrictive material. Let us this is a block of magnetostrictive material, in which an wave is hitting though we expect this material to actually vibrate int his manner ok. Now, let us say as it is vibrating mechanically deforming. So, its state of magnetization is changing, if we have a coil here a coil like this which we call a pickup coil ok.

So, in this pickup coil the state of magnetization will be changing in this material because of its change of length. So, this pickup coil if it is you know attached to signal analyzer, what you are going to see is that the signal is going to get changed. So, you are going to essentially see in the time domain you know in terms of the current change, or you can convert it to voltage change equivalently and, you can see that there is a wave or a vibration coming up in the system. So, thus you know you can actually develop a transducer using the magnetostrictive material.

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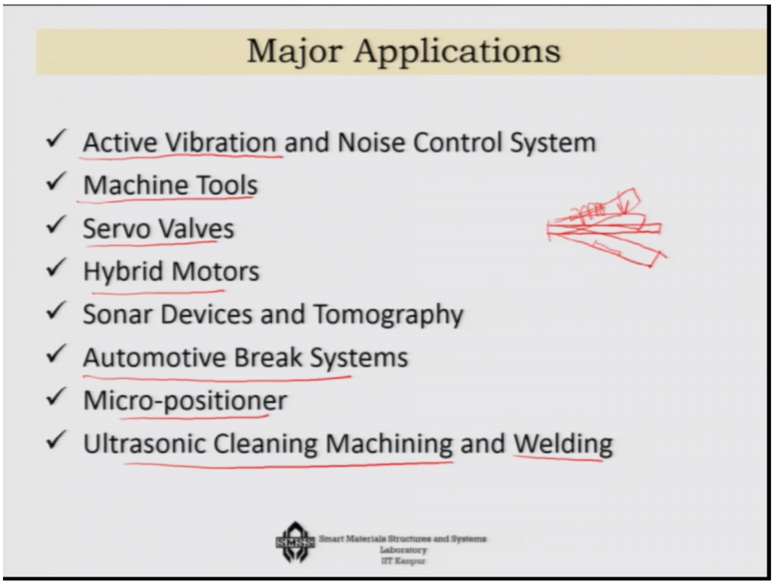

What are the major applications of this system, one of the major application today is not just for transducers, but for active vibration and noise control. So, in this case what we do is that we you know, if suppose there is a vibration or a noise happening ok. So, noise is nothing, but a high frequency vibration. So, let us consider that a system which is vibrating at a very high frequency and, it is creating noise etcetera I want to control this for various reasons like structural purposes comfortable situations etcetera.

Now, if I use a magnetostrictive material in it so, suppose I am using a magnetostrictive material, then and if I actually have a coil around what will happen is that, I can give you know whenever it is expanding I can give a compressive stress. So, that it is forced to go back to its neutral situation. So, like that in the other direction also I can do the same thing. So, that is how the active vibration control happens. So, this essentially forces this situation back to the neutral location.

Machine tool scatter in a very similar manner, you can control servo valves it is also used for all of type of valves, hybrid motors sonar devices, I have already told you automotive break systems and micro positioner very similar to the servo valves. And, also for ultrasonic cleaning of machine, where you need to generate high frequencies and also for ultrasonic welding purposes you can use a similar you know magnetostrictive material. What is the one of the advantage of this material, what piezoelectric material is that piezoelectric material, because it is basically capacitor in nature, it may actually get discharged with respect to time, but magnetostrictive material would not do so, so it is actually more rugged.

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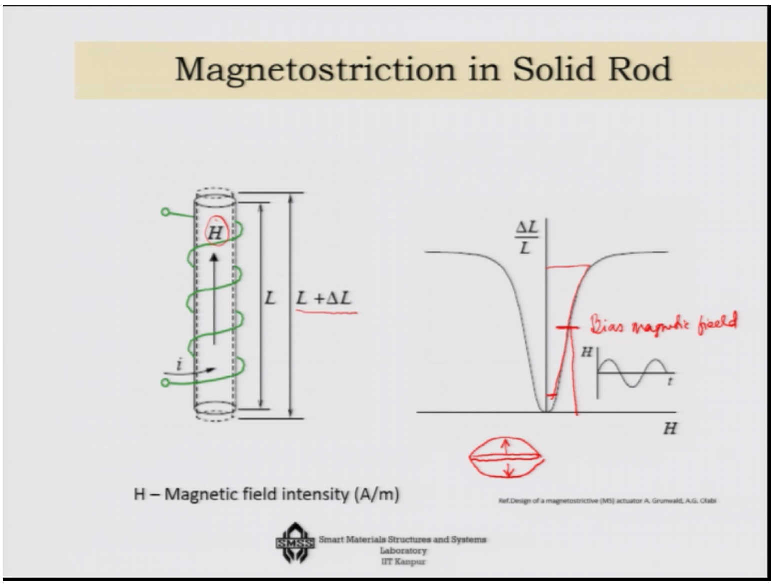

Now, this is what is you know like what happens, if I apply a magnetic field of intensity H and I told you that it will change its length no matter whatever is the direction, it will change its length to L plus delta L and you can see that this is how this change of length is happening to the system. Now, the reason why I am showing it is that, can we develop you know alternating modes in this system; that means, if something only expands you cannot actually get a like if you consider that earlier example that both positive and negative displacement; that means, tension and compression for a system, how can you get if it only expands you cannot get it right. So, in order to get that what we do is that we pickup somewhere we apply a bias you know magnetic field.

So, if I apply that then the system is already you know it is going to expand to this particular value and, then you know it with respect to this if I reverse the magnetic field, what is going to happen is that it is going to show you know the both sides expansions and as a result you can generate vibrations in the system. So, this is actually something like it operates against a bias magnetic field. And only then the magnetic field value increasing, or decreasing you are either expanding, or you are contacting in a relative sets. So, that is what you know is the trick that we use.

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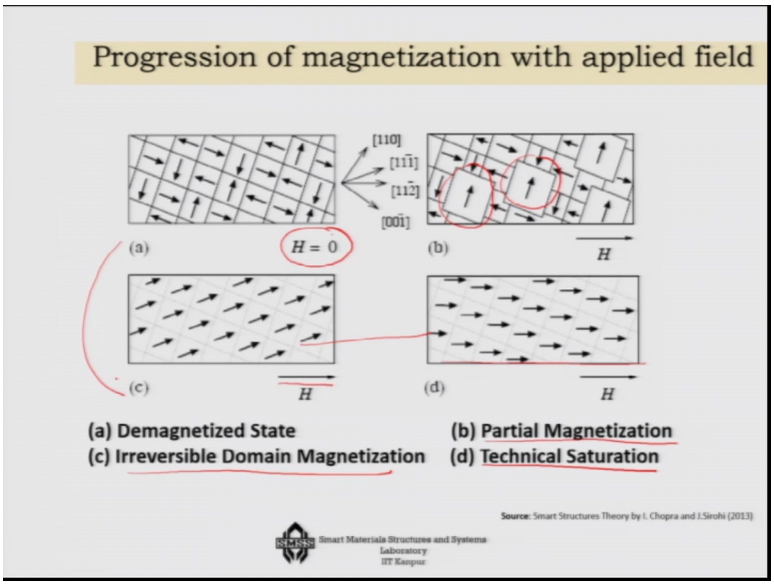

Now, if you look at it in that what is happening microscopically is that, when there is no magnetic field the domains are randomly aligned, as I am increasing the favourable domains are increasing in size ok. So, that you can see that there is a partial magnetization state favourable domains are increasing. Beyond a certain magnetic field these all this domains are aligned, they did not aligned directly with this, but they will be aligned towards this magnetic field and that is what is irreversible domain magnetization.

If I increase further then all of them will actually go and perfectly aligned with H, and that is the technical saturation. From this direction to this there is not much of a change, but you know from here to here from state a to c you get maximum part of the magnetostriction.

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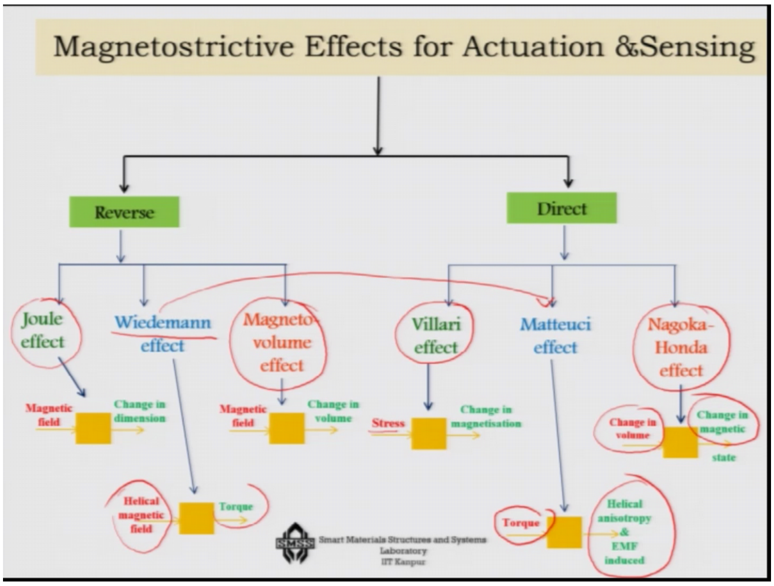

So, this magnetostrictive effect then we can actually distribute it into several effects ok. The first effect that I told you is a reverse effect the change in length that is Joule affect. What if instead of change in length the volume changes then it is called magneto volume effect and, what if you know I do not want to change the length, but I want to twist it. So, application of helical magnetic field can do that ok, that is also known as Wiedemann effect.

And from the direct effect point of view now, if I stress it the change in magnetization will take place that is Villari affect, if I actually apply a volumetric stress then there will be it is called Nagoka Honda effect, where there is a change in magnetic state also. And finally, just like the Wiedemann effects counterpart is called Matteuci effect, where if I apply a torque I am going to see helical anisotropy and EMF will be induced in the system. So, there are so, many variations thirty six variations which are very common in the magnetostrictive material.

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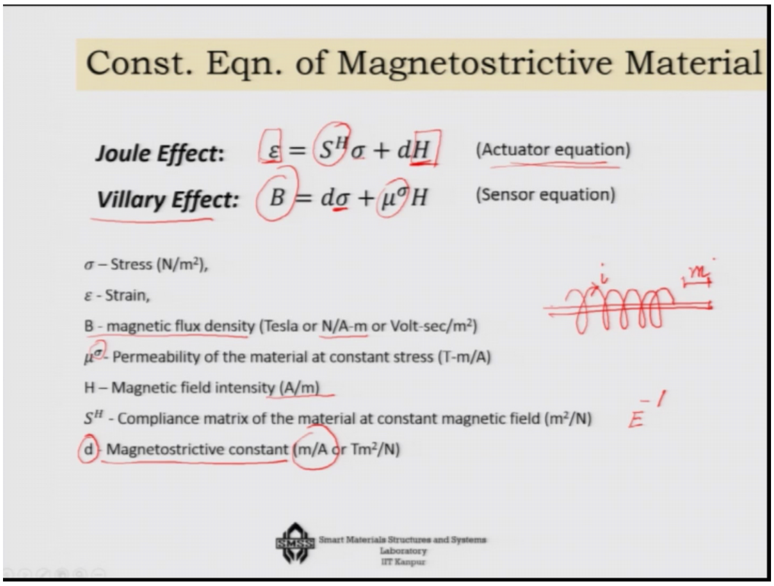

If I now come to the constitutive equation of magnetostrictive material, then two of them that I have chosen one is the joule effect and another is the Villary effect in the joule effect what is happening is that and, we call it as the actuator equation that if I apply the magnetic field I am going to get the state. Remember as usual if I apply stress I am going to see the stain and that is not a smart behavior, that is just that any material would behave, but if I apply a magnetic field and if I get an actuation strain, that is what is important and that is used in actuators.

Similarly in terms of you know if I apply a stress and, if I see that there is a change in magnetization. Not through the application of magnetic field, but through the application of stress, then that is known as the Villary effect and these two equations look very similar to their counterparts of piezoelectric materials. So, if you look at them that B here is the magnetic flux density. So, that is a new thing to ask which is generally measured as Newton per ampere meter and, instead of permittivity we have a permeability here, which is measured at a constant stress.

And then H is the magnetic field intensity as ampere per meter or Oersteds we use such units for measuring the H, so that is for the magnetic field intensity S H is the compliance it is a reverse, or inverse of the you know modulus of elasticity and d is the magnetostrictive constant. Just like piezoelectric constant we have a magnetostrictive constant here whose unit is meter per ampere.

Now, you see instead of voltage we are giving here ampere, because you need to give current in the coil right. So, it is most favourable if I actually give you know if I use current as the input, and expansion of the system you know that in terms of meter. So, that is why meter per ampere is used in this situation.

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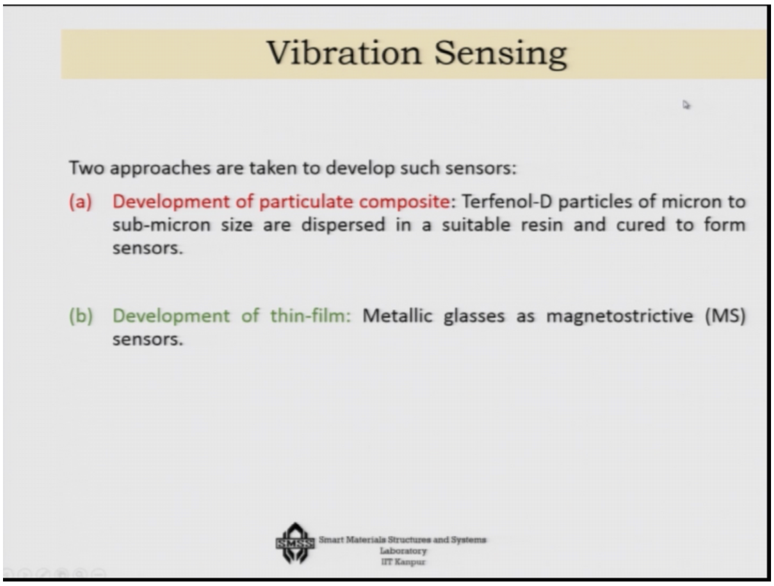

Now, there are two ways I will show you. So, one I told you for the actuator for sensing applications either you can develop you know particulate composites. So, Terfenol D particles are mixed, in a suitable resin system and cured to develop a sensor, or you can develop actually a thin films like metallic glasses as magnetostrictive you know sensors.

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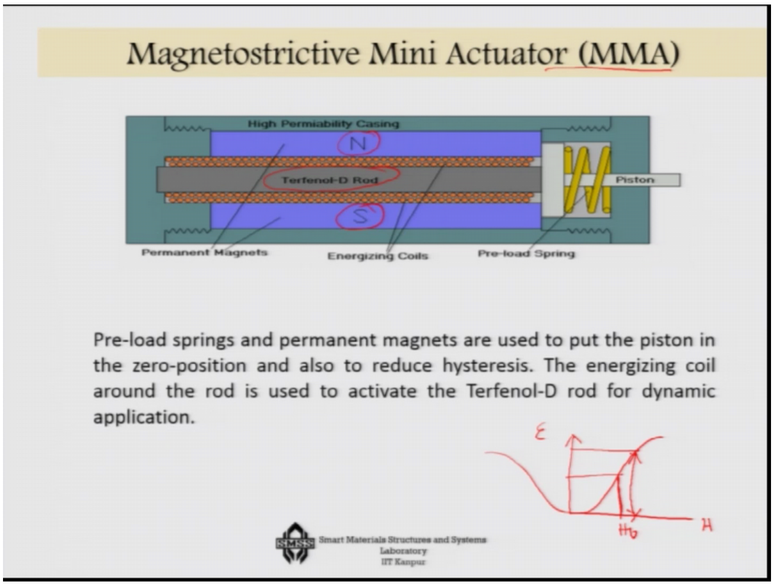

So, these are two ways and in terms of actuators there is one actuator which is very common it is known as magnetostrictive mini actuator. So, what you do here is that you have a Terfenol D rod here and, then you actually have the energizing soils here. So, the coils basically give the magnetic field. Also you give a bias magnetic field, as I told you that this bias magnetic field allows it so, if you still remember H versus the magnetostriction plot let us say you remember that butterfly curve.

So, in order to give this bias magnetic field H b that is why we are using this thing and, then across this bias magnetic field we actually oscillate the current. So, that I get you know this variation of strain in it. So, that is what is used in this magnetostrictive mini actuator.

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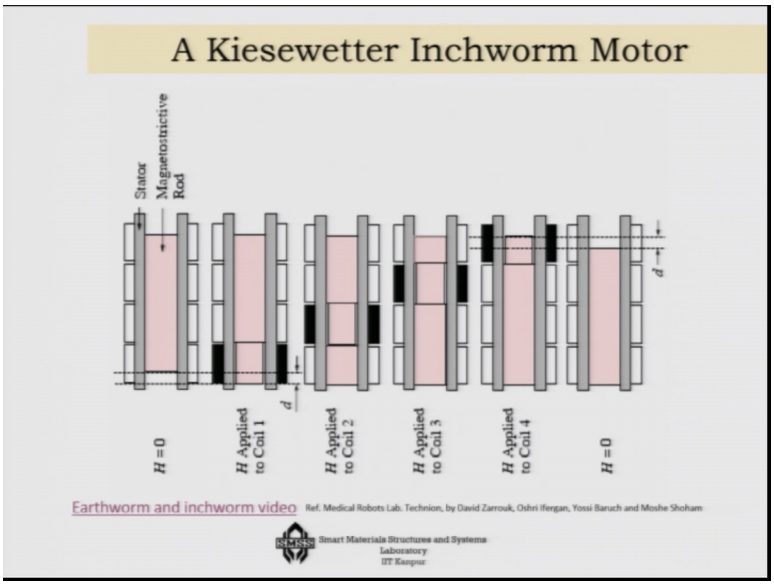

There is another very interesting application that you can do using it, you look at this that you can develop a inchworm, which is very similar to some of the earthworm motions by using magnetostrictive material.

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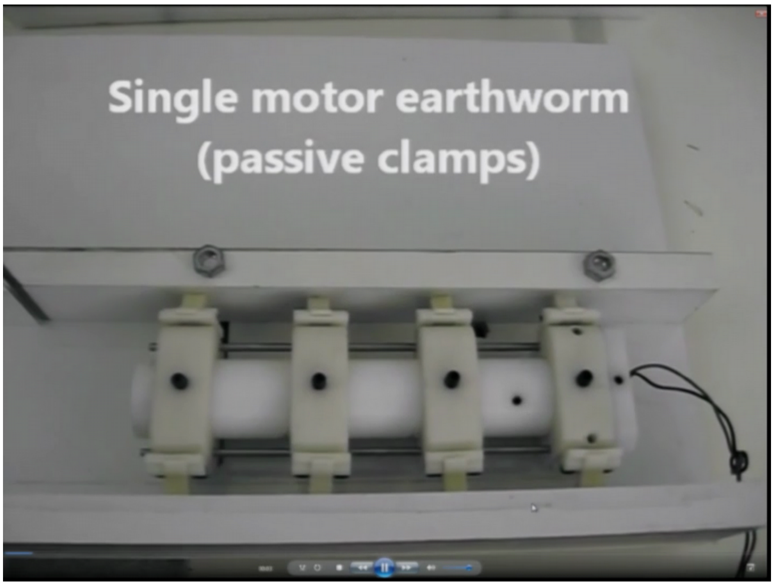

Look at it that how people have developed this product, where you know you are applying the magnetic field and, essentially these expansions are happening in each one of these elements and they are you know sequentially in touch with the valve.

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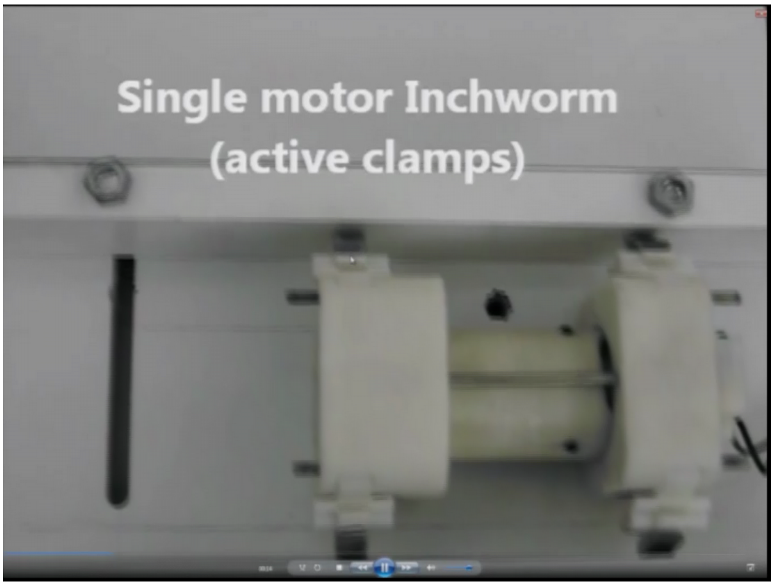

And you know that is happening in a sequential phase, one is touching one is opening up. So, clamping de clamping and the whole system is having a forward motion. So, that is something that you will find in this type of a system.

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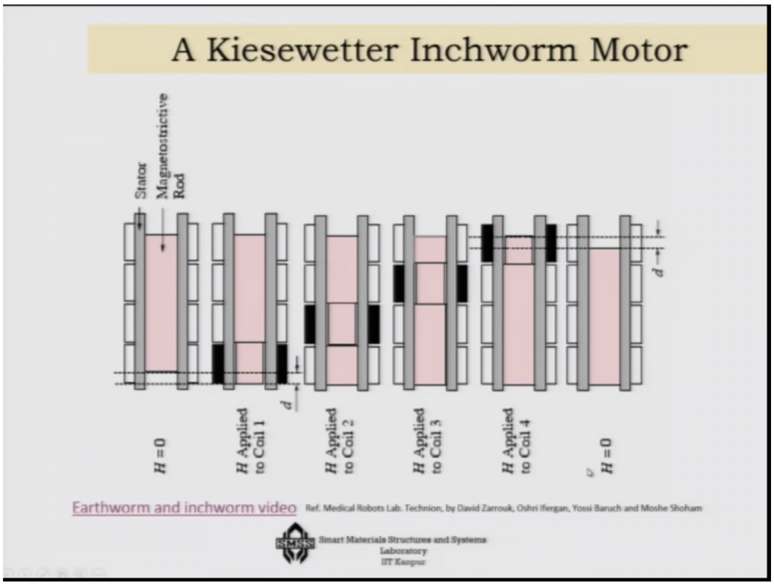

So, these are some of the interesting applications of the magnetostrictive material.

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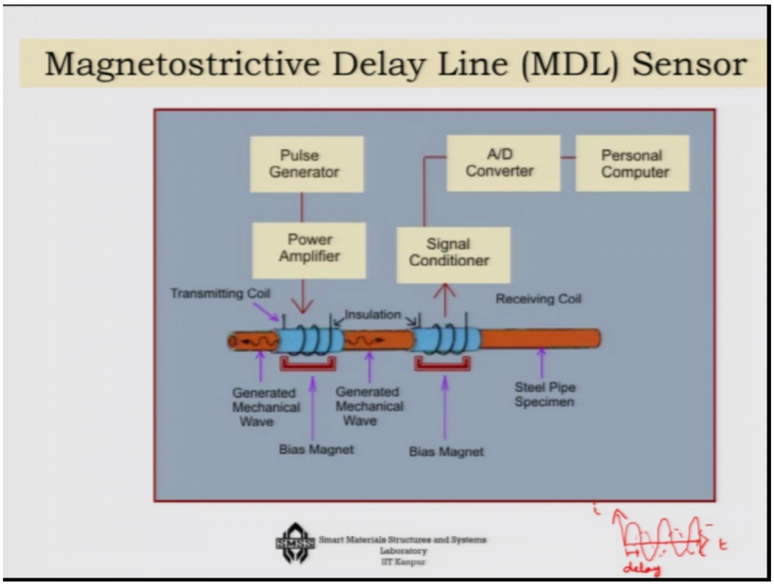

One interesting application is in terms of pipeline sensing, it is also known as magnetostrictive delay line sensor. So, what you have here is that once again you have these you know coils here and, this is a transmission coil and you have a receiving coil at the other point. So, as you are applying an electromagnetic field, what is going to happen is that a vibration is happening and that vibration mechanical vibration is travelling along the pipe.

Now, the same signal that you are giving here, you can in no time you can get the same signal back here. So, the you know electromagnetic wave you can transport in no time, but the actual mechanical vibration signal will get a delay and this two if you actually plot one with respect to the other let us say you know, one signal which is coming so, it is a time versus i. So, let us say one signal is the electromagnetic exercitation that you are happening that is happening here, and another if you try to get the pickup coil current, you will see that there is a delay in the whole system.

So, that delay is because the mechanical signal takes some amount of time to travel and generate this. Now, this delay can actually be a parameter, if there is a crack then this delay will be more.

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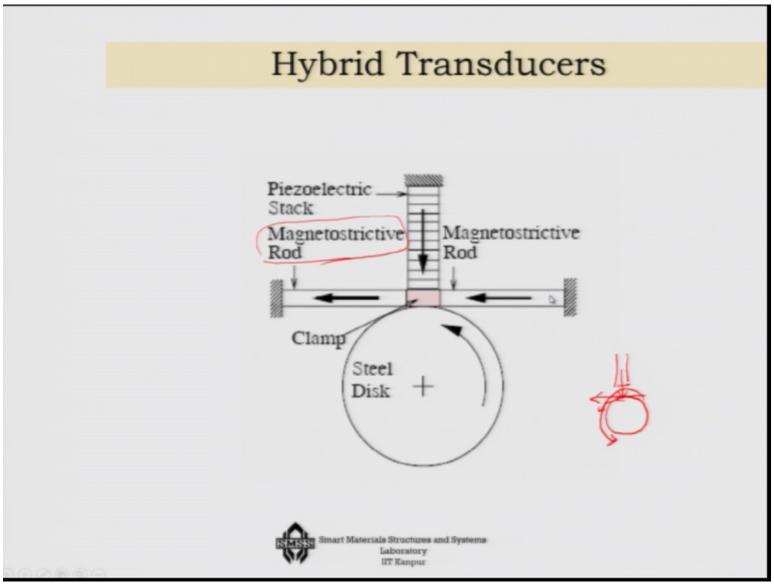

So, that way you can actually detect cracks in the pipeline. Now, you can also develop another intelligent application of the system, which is known as hybrid transducers for hybrid transducers what we have is we have a magnetostrictive rods we know that is a horizontal part and we have piezoelectric stack which is vertical.

So, what is happening is that by controlling, these piezoelectric stacks you know motion and in combination with the magnetostrictive rod, you can actually you know first of all this will make sure that if it expands it is going to touch the system. At that time with the help of magnetostrictive rod, you get a pushing force. So, it starts to rotate, but if it is in touch with it cannot rotate so, you immediately switch it off so, that it goes back ok. So, the system goes back and this whole thing starts to rotate. So, that is one of the you know use of a hybrid transducer of piezoelectric and magnetostrictive system.

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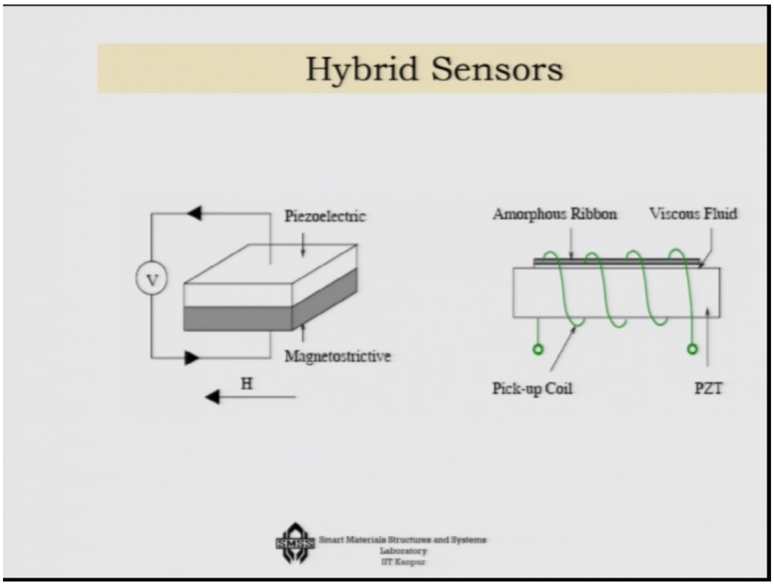

There are many other uses like material which is by more partly piezoelectric partly magnetostrictive, you know amorphous ribbons with viscous fluid in it on a piezoelectric beam so, you can produce many such hybrid effects by using both of them. So, this is where we would like to put an end.

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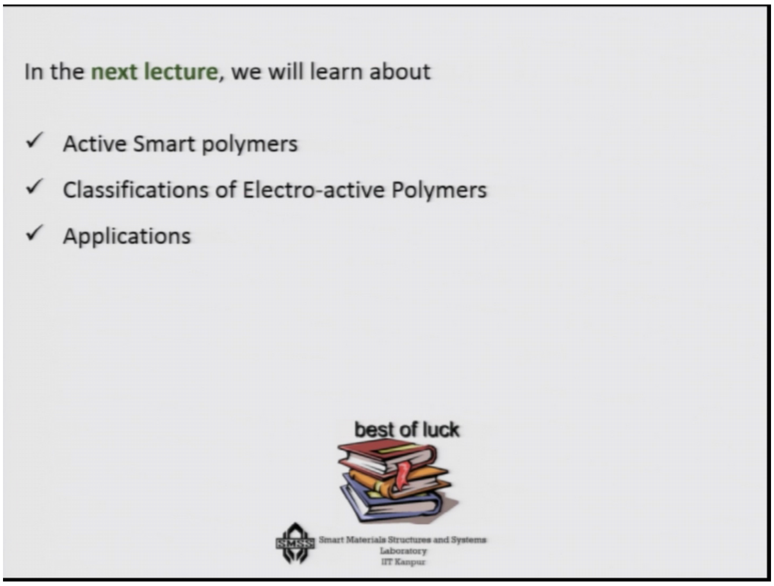

In the next lecture we will talk about active smart polymers classifications of electro active polymers and their applications.

Thank you.