Smart Structures
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Week - 11
Lecture No - 54
Introduction to Electro and Magneto Rheological Fluids

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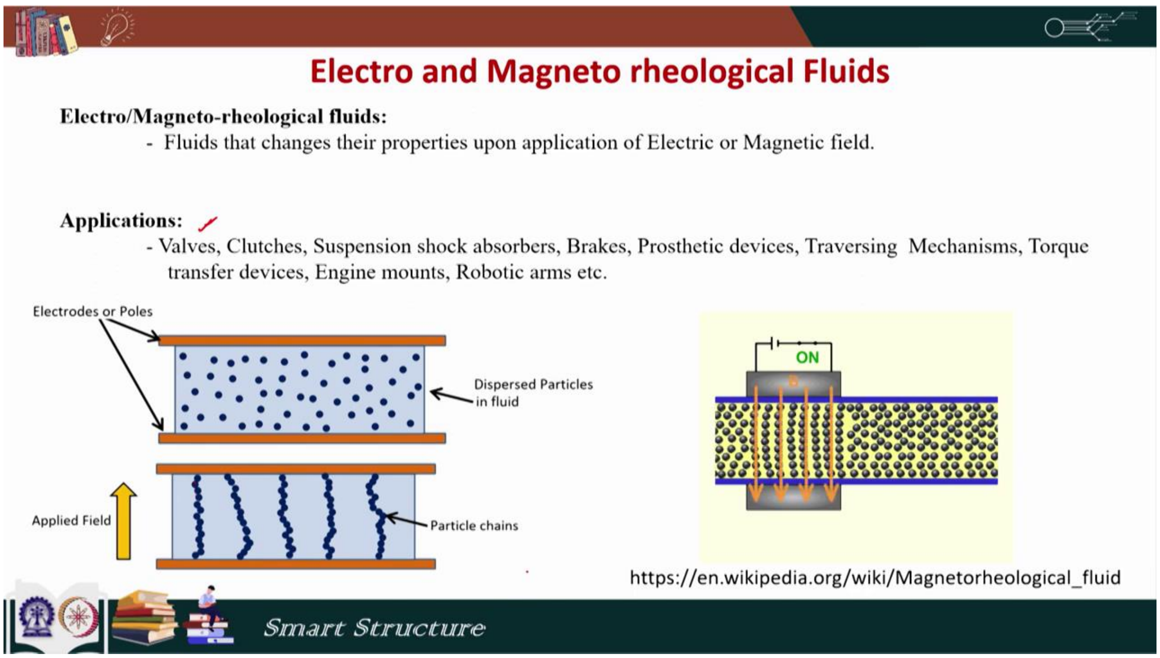

Today, we are going to start discuss another type of smart material and that is called electro and magnetorheological fluids. Now, these fluids are special fluids which shows some property change under electrical or magnetic field. So, when it shows property change under electric field it is an electroheological fluid and when it is under magnetic field it is magnetorheological fluid. This diagrams explains the behavior. Now, these fluids have a carrier fluid in which there are particles dispersed. Now, if I apply some field it can be electrical field or it can be magnetic field along this direction then this particle gets aligned and they form a chain like this.

Now, when they form a chain like this, the flow is blocked or the flow is reduced. So, these fluids by themselves are viscous fluids and on top of that they show the blockage of flow under the application of this kind of field. Now, this animation taken from Wikipedia shows it in a much better way. So, we can see that when there is applied electric field, these chains are forming and that is what is happening, I mean that is what we see as electrical and magnetic effects.

Now, the blockage of this flow that has applications as valves just by giving electrical or magnetic actuation, we can block the flow and their viscosity makes them ideal for application into shock absorption problems, damping problems and there are various other applications like brakes, prosthetic devices, torque transfer devices and so on.

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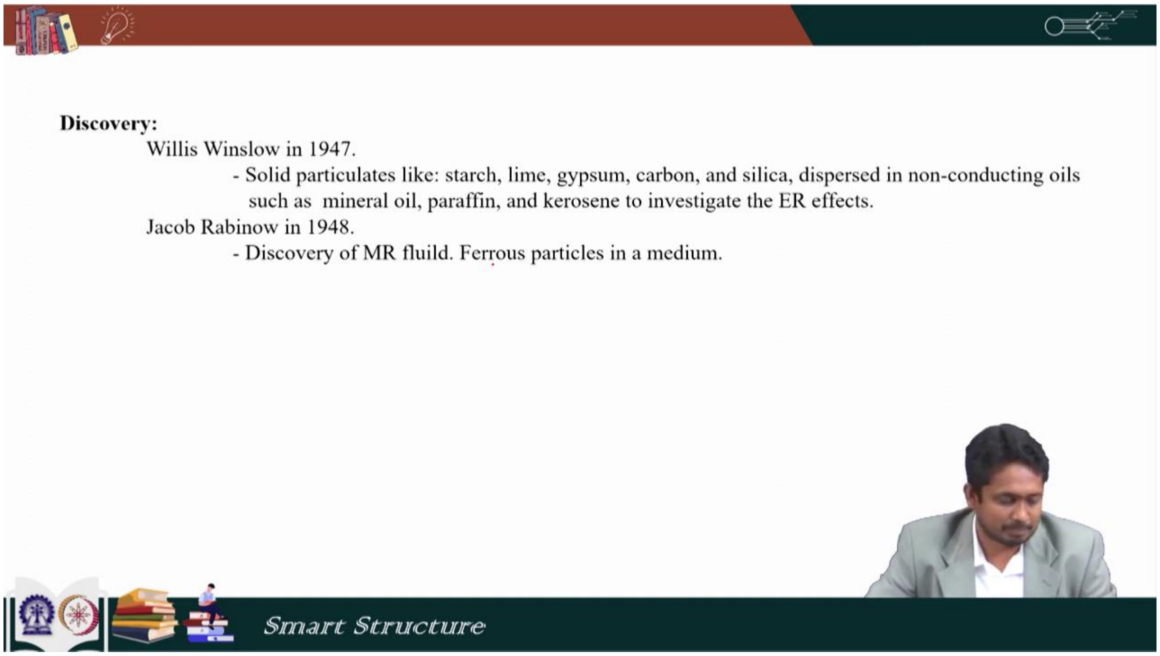

First in 1947 Willis Winslow discovered the electro rheological effect and that was discovered in a mixture of starch lime, gypsum, carbon and silica which were dispersed in non conducting oils like mineral oil, paraffin and kerosene. In 1948, the magnetorheological effect was discovered that was by Jacob Rabinow and that was seen in ferrous particles in a medium.

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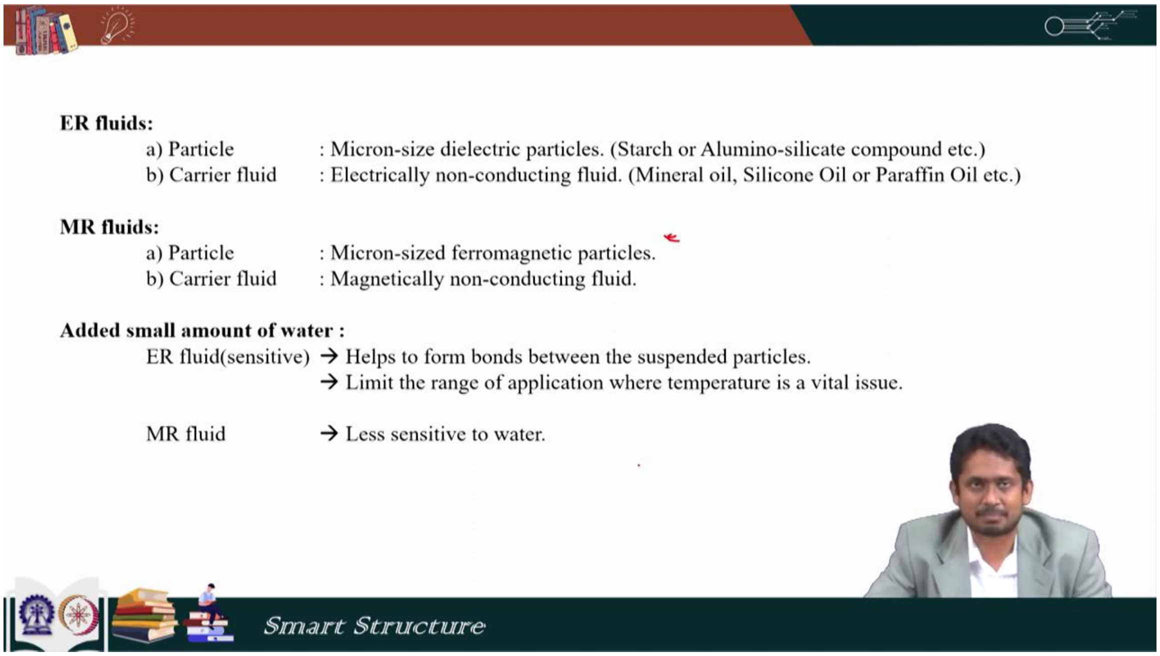

Now, here are some basic constituents. So, ER fluids have micron size dielectric particles like starch and amino silicate compound, electrically non conducting fluid like mineral oil, silicon oil, paraffin oil are the carrier.

In MR fluid micron size ferromagnetic particles are used and the carrier fluid is magnetically non conducting fluid. Now, if small amount of water is added then electrological fluids some significant change bond is created between the suspended particles whereas, MR fluid is relatively less sensitive to water.

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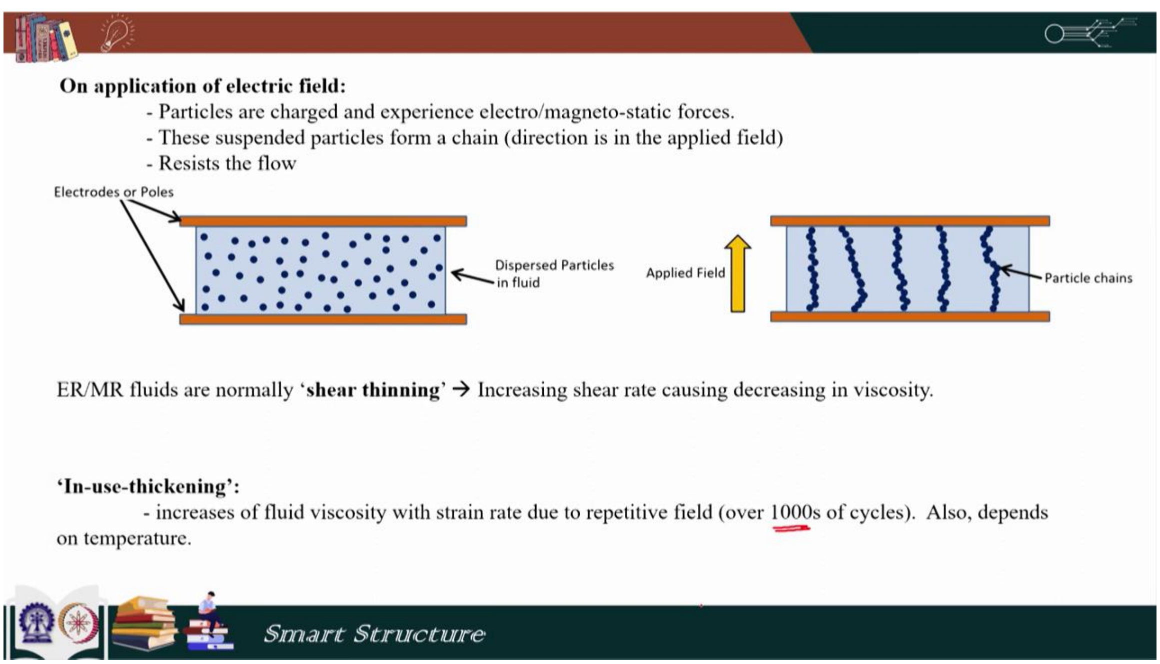

Again this shows the electro and magnetorheological effect. So, particles are charged. So, here it shows again the electro and magnetorheological effects this particle experience some force and because of the force, the alignment is done and its flocks the flow.

Now, this ER and MR fluids are generally exhibit shear thinning phenomena which mean that with increasing shear strain rate, the viscosity reduces. So, when the viscosity increases with increasing shear strain, the effect is called shear thickening. When it reduces with increasing shear strain rate that is called shear thinning. Now, ER and MR fluids are generally shear thinning materials. However, they display something called in use thickening that means, if these fluids undergo a lot of cycles that means, if the actuation is turned on and off several times, the electric or magnetic field is cycled several times then it may be large like 1000 or more. So, after that many cycles, the viscosity of the fluid increases and that is called in use thickening which means that after several use the viscosity increases. So, it is in use thickening.

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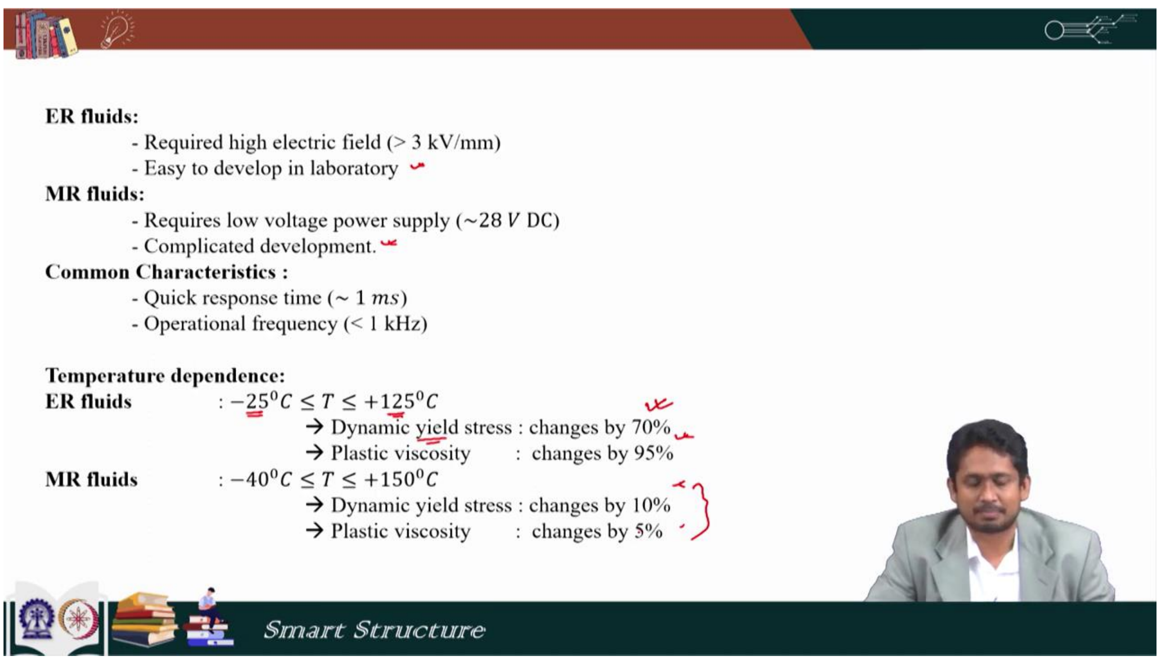

ER fluids generally require high electric field which is higher than 3 kilo volt per millimeter, but they are easy to form in the laboratory. MR fluids require low voltage power supply for example, DC voltage of 28 volt is ok for it that is why there is more focus on MR fluids now. However, their development is little bit more involved.

Common characteristics involved they are quick response in the range of 1 millisecond and operational frequency is generally limited to 1 kilo hertz. MR fluids are less susceptible to temperature variation for example, if we can see in case of ER fluids when there is a variation of temperature between minus 25 to 125 degree centigrade the dynamic yield stress changes by around 70 percent. We will come to what yield stress means. Plastic viscosity changes by around 95 percent. In MR fluids, in a similar temperature range, the change is around 10 percent or 5 percent. So, the sensitivity is less in case of MR fluids.

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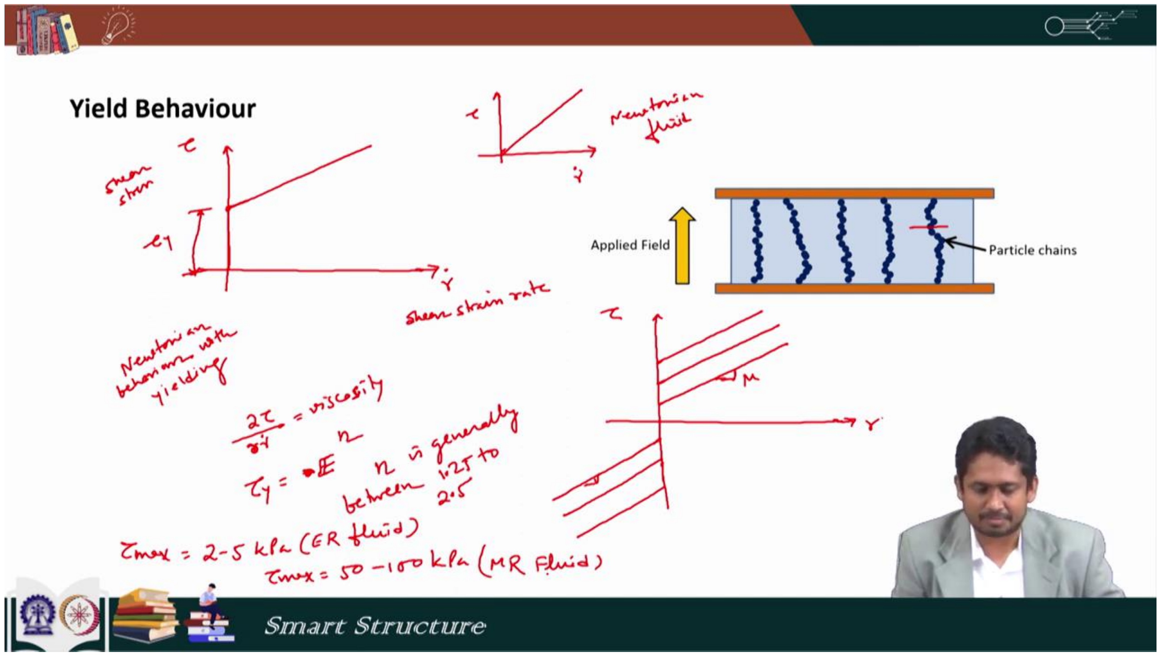

Now let us talk about yield behavior. So, as we have seen that under the applied field i.e. electric or magnetic field, this change forms and this change blocks the flow so that means, when you have this change formed if I want to make fluid flow over, it this change has to be somehow broken at least partially.

So, to overcome this block by the change, the shear stress here has to be more than the strength of this change. So, if I keep increasing the stress so, if I plot the gamma dot as the shear strain rate and along this axis if I plot tau the shear stress then until and unless the shear stress is of some value and that value is equal to the strength of the change, there is no flow possible. So, the graph just goes up like that. Once the stress is sufficient to cause the flow to overcome the resistance by the chain, the flow starts happening and the curve takes a shape like this. We know that in a Newtonian fluid, the variation of tau versus gamma dot looks like this.

In case of magnetic material we can get higher yield stress. In case of magnetorheological fluids the yield stress is more in case of electro rheological fluid the yield stress is relatively less. Now, if I apply more electrical field, the yield stress can be increased. So, if the field strength is more or the chain strength is more and accordingly, it needs more strength to break. So, if I plot again gamma dot and tau under a certain electric field or magnetic field this is a tau y and also if I reverse the flow diagram i.e. flow direction, the flow in the other direction is also possible. So, it is a same slope in the positive and negative direction because whether the flow is from right to left or left to right does not matter. And then if I increase the electric field or magnetic field, the yield stress increases, but the slope of the curve remains same and it goes on like this. Now, this slope of the curve is called viscosity as we know that del tau by del gamma dot is our viscosity and this yield stress as we have seen that it is a function of electric or magnetic field applied. So, as a function of that it can be written as E which means electric field to the power n, electric field or magnetic field that is to the power n.

$$\tau_y = \mathbb{E}^n$$

Now, n generally ranges between 1.25 to 2.5, but again, we cannot increase the yield stress infinitely. There is some limit. So, the maximum yield stress that is possible for electro-rheological fluid is 2 to 5 kPa for ER fluid and tau max the maximum yield stress possible is 50 to 100 kPa for MR fluid.

So, again we see that the yield stress is more for MR fluid and also it needs less voltage. So, that is why there is more focus on MR fluid nowadays. Now, we will look into the mathematical modeling of the behavior.

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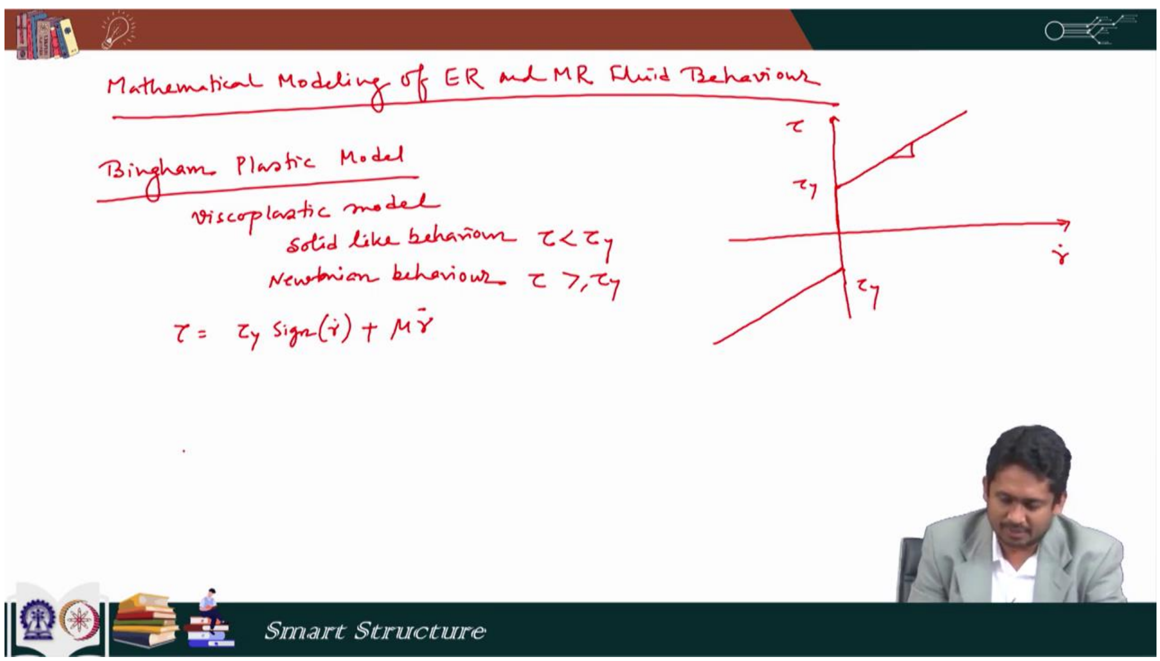

So, mathematical modeling of ER and MR fluid behavior and there are various models. The first one is Bingham plastic model.

This model is a visco plastic model. It shows solid like behavior when tau is less than tau y. So, if I plot it tau versus gamma dot, so, until and unless the stress is tau y, there is no flow. We know that in a solid if I apply stress it does not flow that is why till tau y it is a solid like behavior. After tau y, it is a Newtonian fluid like behavior.

So, Newtonian behavior when tau is greater than or equal to tau y. So, this is the same diagram that we drew while discussing about the yield phenomena and in the negative side also it is the same thing. If I want to write it mathematically, it looks like this. tau y sin of gamma dot plus mu into gamma dot. Tau y is this and we have tau y here. Sin of gamma dot means if the gamma dot is positive that means, we are here if the gamma dot is negative we are in this this side plus mu into gamma dot. So, mu is the slope here and that is our viscosity and the same slope is shown by this graph also. So, that is our Bingham plastic model.

$$\tau = \tau_y + \sin(\dot{\gamma}) + \mu\dot{\gamma}$$

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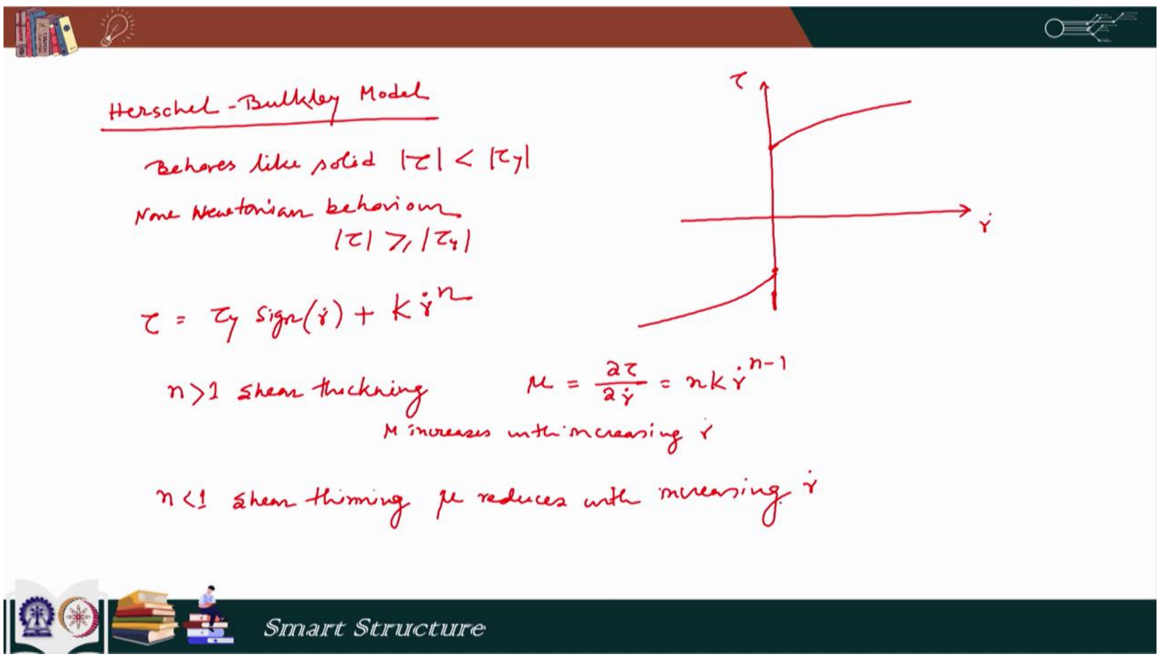

And then there is a model called Herschel bulky model. So, it again behaves like solid till tau is less than tau y. Now to be technically correct we should put a modulus sign here because the stress can be negative also. So, we can do the same thing here also considering the fact that the we can be in this side or in the other side of it. Now again the same thing we have gamma dot. We have tau. So, until and unless we are here no flow is possible, but the Herschel and bulk clay model says that after that the behavior can be non-Newtonian.

So, instead a Newtonian behavior the graph can be a curve. So, non-Newtonian behavior when tau is greater than equal to tau y and that is generally denoted as this tau y sin of gamma dot plus k gamma dot to the power n. So, as we can see that when n is equal to 1 that becomes the Bingham plastic model and that time the flow becomes Newtonian, otherwise it is a non-Newtonian flow. Now when n is equal to 1 it is a shear thickening phenomena because if we denote the viscosity mu and that as del tau by del gamma dot, we get this as n k multiplied by gamma to the power n minus 1. So, when n is more than 1, this quantity mu increases with gamma dot.

$$\tau = \tau_y \sin(\dot{\gamma}) + k\dot{\gamma}^n$$

$$\mu = \frac{\partial \tau}{\partial \dot{\gamma}} = nk\dot{\gamma}^{n-1}$$

So, that is why it is shear thickening because mu increases with increasing gamma dot and when n is less than 1 this quantity reduces with increasing gamma dot. So, that is shear thinning. So, mu reduces with increasing gamma dot. So, Herschel-Buckley model is a more generalized model. Bingham plastic model is a special case for it.

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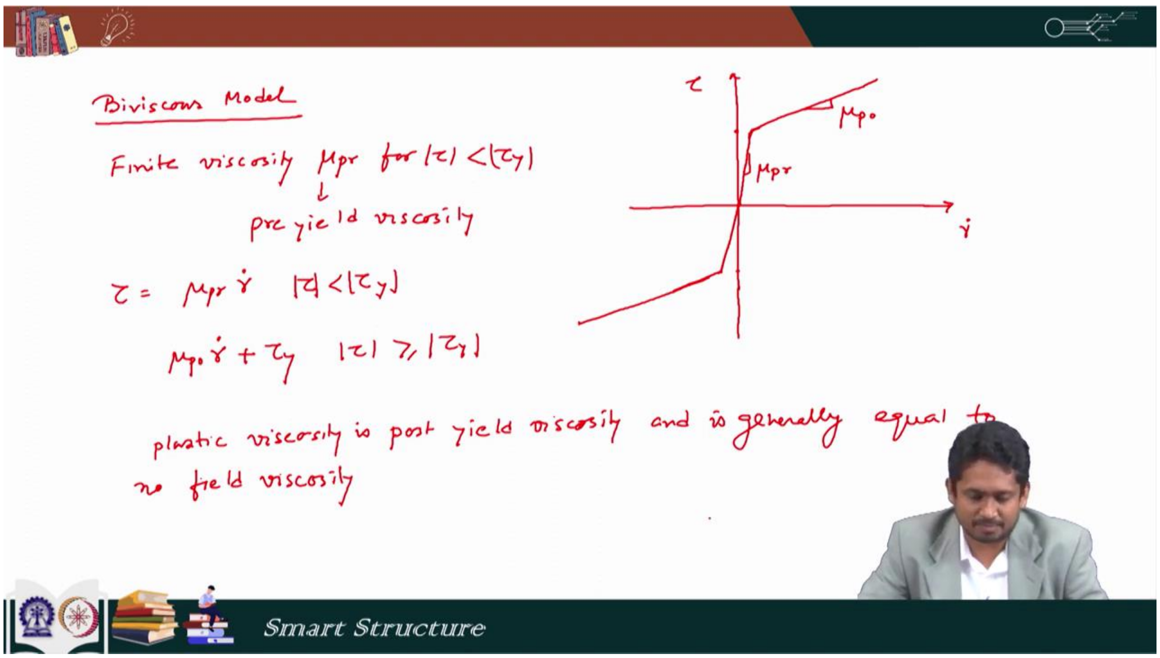

Then there is something called a Biviscous model. By viscous model, it considers a finite viscosity even before the fluid yields. So, previously in the diagram we we showed that until and unless the material yields, there is no flow. That means, the slope of this graph was infinite. Biviscous model says that it does not have to be infinite.

There is a finite viscosity although very high value till we reach the yield stress. That means, before tau y it shows some flow, but the flow is not too high, say small flow that is why the viscosity is too high here that is because even if the chain does not break at least it can deform. So, some flow is possible and it is same at the negative side. Then after the tau y is achieved, it gets the viscosity reduces and then it behaves like this. So, instead of this point lying on the tau axis, it lies somewhere here and that signifies some high amount of, but finite, viscosity between 0 to tau y and after tau y the viscosity is same.

So, this is finite viscosity which we denote as mu pr for tau less than tau y. So, the slope of this graph is denoted as mu pr. We can call it pre yield viscosity and then mathematically we can call it tau is equal to mu pr gamma dot when my tau is less than tau y. Again we should put the mod sign and it is mu post viscosity plus tau y. So, this viscosity we are calling mu po that means, post yield viscosity and it is same here in the negative side when tau is more than or equal to tau y magnitude wise.

So, here we are talking about two types of viscosities; one is pre yield and another is post yield. Now, a post yield viscosity is much lower than the pre yield viscosity and if I do not apply any electric field or magnetic field to the material, then the material flows in its own viscosity and that viscosity is generally equal to this viscosity po. It is called plastic viscosity also. So, plastic viscosity is the viscosity that is happening after tau y. So, the plastic viscosity is post yield viscosity and it is generally equal to or it is considered to be equal to for all practical purposes no field viscosity.

Now, in all these discussions, we have simplified the behavior, but in general, the behavior is not so simple in the pre yield region. The material shows significant amount of hysteresis.

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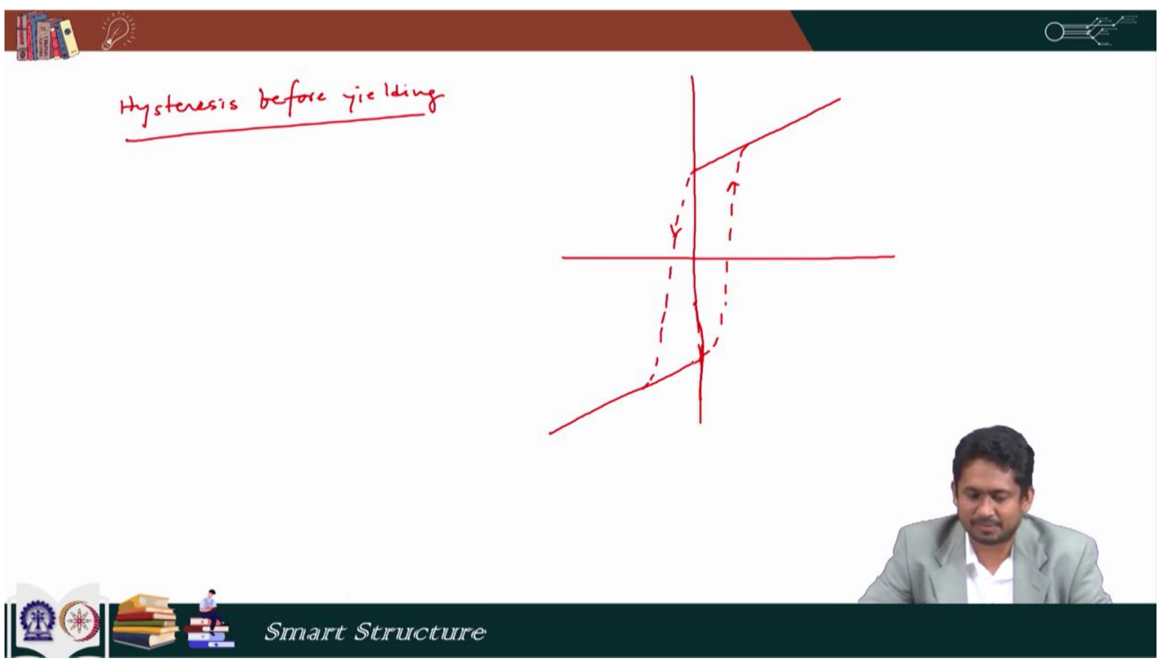

So, we generally see a hysteresis in the pre yield region. If I draw the same graph which we in fact, let us draw the Bingham plastic model which is a simplified one even in this graph and all these graphs are idealization in the pre yield behavior, generally what happens is the material shows hysteretic behavior like this. So, if I increase gamma, it goes to this curve in this way and it comes back in this way. So, in the pre yielding region there is a hysteresis and all the models that we talked about they do not include the pre yield hysteresis. They are much simplified model.

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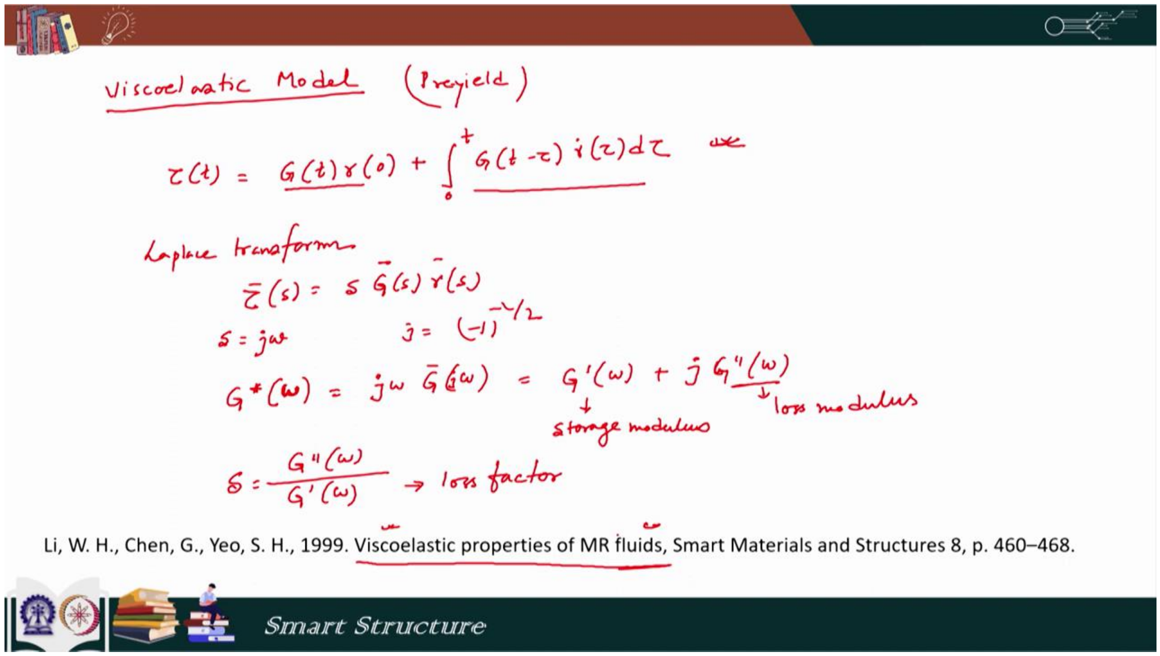

Now in many cases, especially in case of applications for damping or shock absorption, the pre yield behavior is very important and the pre yield behavior is more of a viscoelastic behavior. So, we can call it Viscoelastic model and that is pre yield. So, now, we are interested in pre yield viscoelastic model and those pre yield models are quite useful when we want to analyze this kind of systems for specially for damping applications. Now the word Viscoelasticity comes from two terms, one is viscous and one is elastic. Elastic means it is behaves like elastic solid. So, here the stress is proportional to strain. So, here we are specifically talking about shear stress. So, the shear stress is proportional to shear strain.

So, that is linearly elastic and in viscous material, the stress is proportional to the strain rate. In this case, we see both rate dependence as well as the dependence on the value of the stress. So, it is a combination of linearly elastic and viscous behavior. Now, for that there are various models of viscoelasticity. Now here we are going to talk about a viscoelastic model that has been shown in this paper and that is a quite popular model which is used for various applications and that is what we are going to discuss here. So, as per this model, tau t at any time t, the shear stress is a function of the shear strain rate at the previous time also. So, when you are talking about applications for vibration absorbers, the system is a dynamic system. So, they are time dependence. Now if I want to find out the stress at the present time t is a linear function of the strain at the present time t and also the previous histories and this integral is called a convolution integral as we know.

$$\tau(t) = G(t)\gamma(o) + \int_0^t G(y-\tau)\dot{\gamma}(\tau)d\tau$$

So, this is convolution in the time domain. Now if I apply Laplace transform to this equation we know that a convolution in the time domain is equal to a product in the Laplace domain. So, if I apply Laplace transform the equation looks like this where g bar is the Laplace transform of g and gamma bar is the Laplace transform of gamma and then if we consider S equal to j into omega. So, j is basically our imaginary number minus 1 to the power half then we can say that the quantity G star omega, we get a quantity G star omega and that looks like j omega multiplied by G bar of j omega we have G bar s. s is replaced by j omega that is that is this and if I multiply this s which is a j omega now and that product is called G star. Now this quantity is a complex quantity now which can be written as G prime omega plus j into G double prime omega.

$$\bar{\tau}(s) = s\bar{G}(s)\bar{\gamma}(s)$$

$$S = j\omega$$

$$j = (-1)^{1/2}$$

$$G^*(\omega) = j\omega\bar{G}j\omega = G'(\omega) + jG''(\omega)$$

This is called storage modulus. This signifies a linear elastic behavior and this is called loss modulus which signifies the viscous behavior and then we define a quantity delta equal to G double prime of omega by G prime of omega and that is called a loss factor. Now this quantity is this G's can be function of omega and also in ER and MR fluid based on the amount of actuation we are doing, amount of electrical magnetic field we are applying this G's can change. Now this paper shows some experimental results of how G is sensitive to those parameters. Now later on we will use this model to solve one of the problems where a structure would have ER or MR fluid layer as a component.

$$\delta = \frac{G''(\omega)}{G'(\omega)}$$

So, with this let me conclude this lecture here. Thank you.