Vibration Control
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Module - 7
Principles of Active Vibration Control
Lecture - 6
Magneto-rheological (MR) Fluids

This is Dr. S. P. Harsha from Mechanical and Industrial Department IIT, Roorkee, in the course of Vibration Control, we are mainly discussing about the active vibration control. And in that we are discussing about this smart materials, that how these materials can really behaved as a smart, when they are treating as the sensor or the actuator or the entire we can say the control unit together. So, in this we discussed almost about the piezoelectric feature, we discussed about the ER feature which the electrorheological features in that particular fluidic part.

And then we can straightaway used as the vibration controlling feature, so in the today's lecture we are going to discuss about the Magnetorheological fluids. As we can see that in the electro rheological fluids have certain limitations towards that, and we will try to see that they be overcome in this magnetorheological fluids. And with there are certain excellent properties of this ER fluid, like they can be used straightaway as the ER clutches, ER breaks. Or even we can say that the electrorheological vibration dampers, can also be effectively used under there, we can say either the shear modes or any kind of modes features are there. So, in the magnetorheological fluid at as the name itself speaks that we have, again same the rheological particles are there, or we can say the properties of the particles, the rheological and the magnetic field is being applied.

So, it is a type of the smart fluid, in a carrier fluid usually a type of we can say the non conducting oil, and when it is being subjected to the magnetic field, the fluid greatly increases it is apparent viscosity. And to the point it is becoming a viscoelastic solid, importantly the yield stress of the fluid when it is being active, we can say active means it is on situation. The state can be controlled very accurately by varying the magnetic field intensity, so the upshot of this we can say that is the fluid ability to transmit the force can be straightaway controlled with electromagnet, which gives rise to it is many possible control based applications.

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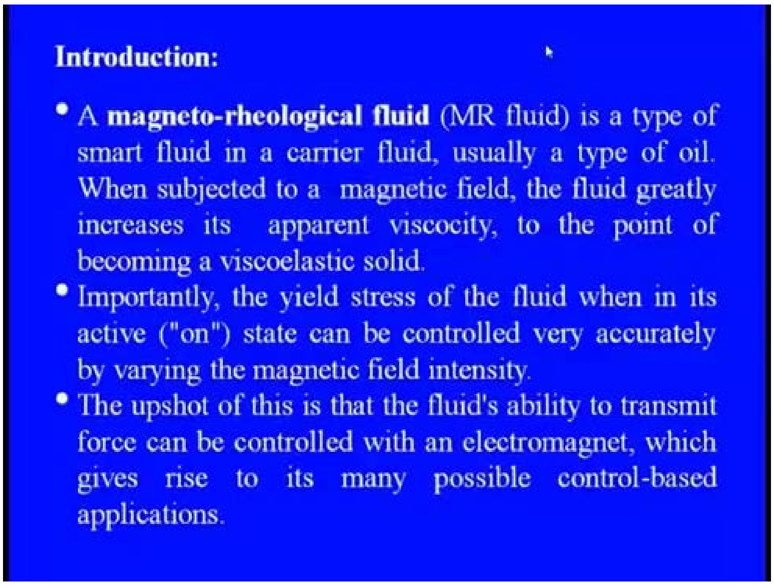

Introduction:

- A **magneto-rheological fluid** (MR fluid) is a type of smart fluid in a carrier fluid, usually a type of oil. When subjected to a magnetic field, the fluid greatly increases its apparent viscocity, to the point of becoming a viscoelastic solid.
- Importantly, the yield stress of the fluid when in its active ("on") state can be controlled very accurately by varying the magnetic field intensity.
- The upshot of this is that the fluid's ability to transmit force can be controlled with an electromagnet, which gives rise to its many possible control-based applications.

So, straightway what is the strength of the electromagnets are there accordingly you see here, that transmission force can be it effectively controlled there itself. So, MR fluid if we are just talking about, when electric field the electric field is applying and we are getting the apparent viscosity which is being increased right from liquid to solid. The same thing is happening here, when the magnetic field is applied, the apparent viscosity is been increased and then it is forming from liquid to solid, so how they are being different.

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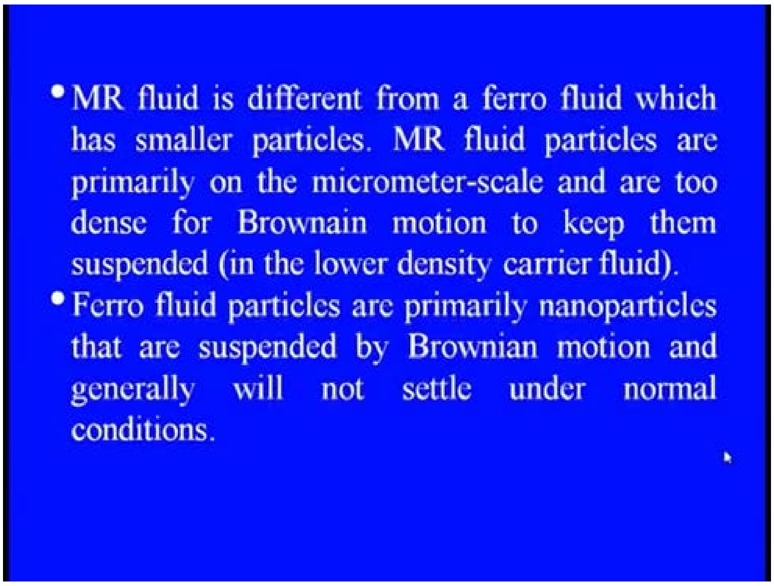

- MR fluid is different from a ferro fluid which has smaller particles. MR fluid particles are primarily on the micrometer-scale and are too dense for Brownain motion to keep them suspended (in the lower density carrier fluid).
- Ferro fluid particles are primarily nanoparticles that are suspended by Brownian motion and generally will not settle under normal conditions.

So, MR fluid is different from, a Ferro fluid which as a smaller particle, and again the MR fluid particles are primarily on the micrometer scale and are too a dense, for Brownian motion to keep them suspended. That means, we need to check it out, that it has to be suspended in the lower density carrier fluid. And Ferro fluid particles are primarily the nanoparticles that are suspended by the Brownian motion, and generally will not be settled under any normal conditions. So, we are going to discuss about that when we have the electrorheological fluid or the magnetorheological fluid how you see the things are being different in these cases.

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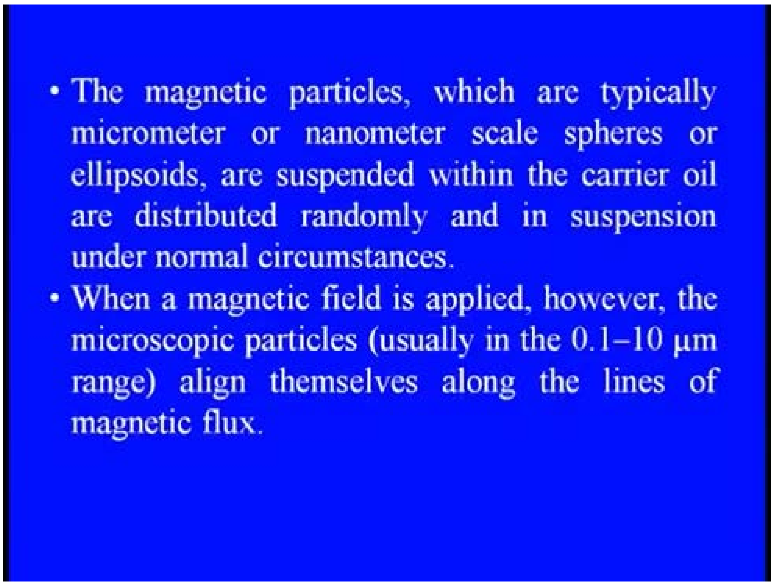

- The magnetic particles, which are typically micrometer or nanometer scale spheres or ellipsoids, are suspended within the carrier oil are distributed randomly and in suspension under normal circumstances.
- When a magnetic field is applied, however, the microscopic particles (usually in the 0.1–10 μm range) align themselves along the lines of magnetic flux.

So, the magnetic particles which are typically we can say of the size of micro or nanometers are just the spheres or the ellipsoids. So, when we have the ellipsoids or spheres of the size of these nanoparticles, they can be suspended within the carrier oil and then are being distributed randomly as per the viscous or any orientation feature. and also when we have a normal circumstances we know that, the random orientation of these magnetic particles are pretty common, in any kind this conducting, and the non conducting oil like the carrier oil. But, when the field is on, means the magnetic field is being applied even this microscopic particle may be from 0.1 to 10 micrometer range align themselves, along the line of the magnetic flux.

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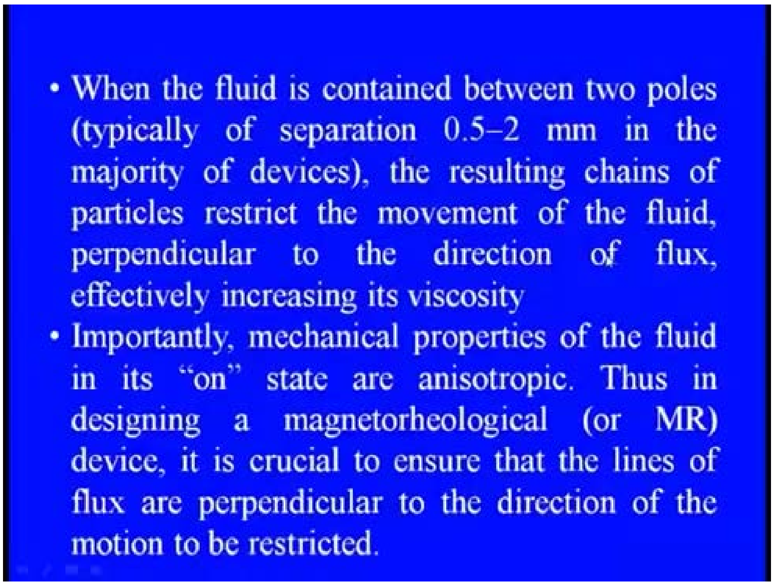

- When the fluid is contained between two poles (typically of separation 0.5–2 mm in the majority of devices), the resulting chains of particles restrict the movement of the fluid, perpendicular to the direction of flux, effectively increasing its viscosity
- Importantly, mechanical properties of the fluid in its “on” state are anisotropic. Thus in designing a magnetorheological (or MR) device, it is crucial to ensure that the lines of flux are perpendicular to the direction of the motion to be restricted.

And when the fluid is contain between the two poles, say which is being separated in between 0.5 to 2 millimeter, there is a chain of the particles which restrict the movement of the fluid. And the absolutely they are aligned perpendicular to the direction of flux, and that is why there is an effectively increase in the viscosity of the part. And moreover the mechanical property of fluid, when it is in the on situation, the states are anisotropic thus designing of this MR magnetorheological devices.

It is crucial to ensure that these lines of the fluxes, the flux whatever the lines are there they must be perpendicular to the direction motion which is to be restricted. So, say that we just want to restrict or we just want to put the resistance in one direction, the applied magnetic flux should be perpendicular to that direction only.

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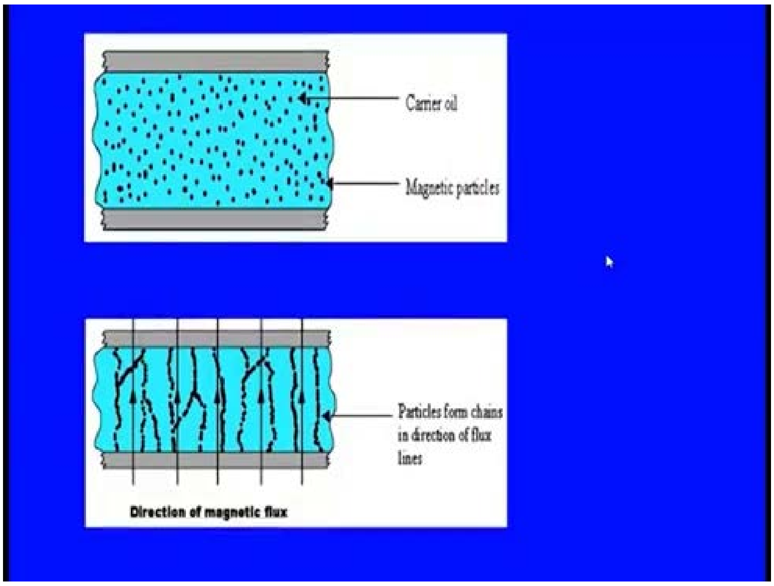

Just like you see these, we have the carrier oil which is showing there by the green part and we have the magnetic particles, which are being randomly oriented. Now, we want that they should arrange in the column wise side, not in the row side, then the particle which are being forming the chains in the direction of flux lines, these are the direction of my magnetic flux which is just perpendicular to these lines. And they are just forming the entire column wise structure, so from the liquid to solid phase, we can simply see that when it is on, then we have a streamline structure. And when it is not on, then we have the randomly oriented these fluid fluidic particles.

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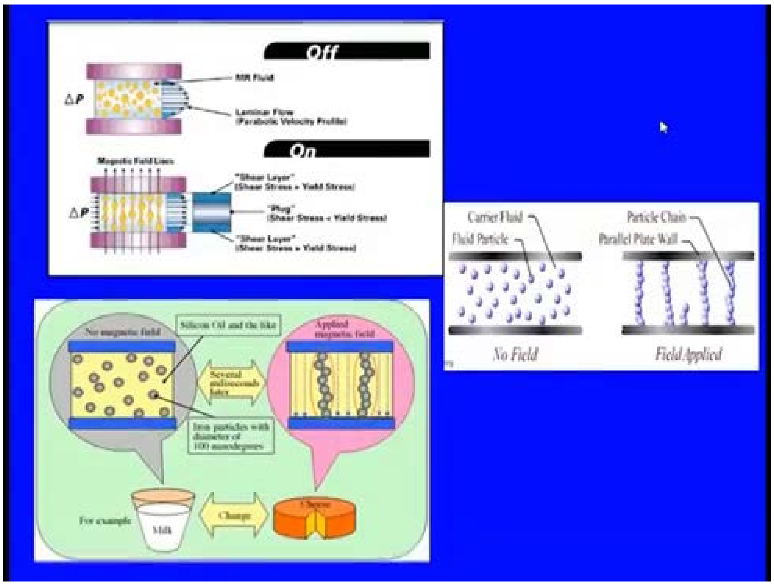

Or even rather we can be even see here, when no field is applied this is what the random orientation in which this the carrier fluid is there, and these particles are there, and when the electric field is on that, how the orientation is straightaway changed, because now we want the resistance in this direction, the vertical column directions. Or even we can see on other way, when this is what the change of pressure is there, when it is off these magnetic this MR fluid and this is what you see we can say a laminar flow parts are there.

So, there is a clear we can say a parabolic velocity profiles are there along with that when it is off, but when it is on, that this is what my magnetic field lines along with that. So, the orientation of along these all the particles just aligned with this part, and we can say that at this part we have the shearing layer, in which the shear stress which is more than the yield stress. And also we can say that this part which being there, it is a just plugging feature and we can get straightway the shearing layer on just top and bottom.

So, if you look at this with the perfect laminar feature, because of the part here we have this part here straightaway, so on top and bottom the shear stresses are dominating there itself, the shearing mode. Or else even we are when we are looking towards this part when you have the entire feature the particles are being there, and the carrier oils are there straightaway they are forming these columns of the chains, along when the field is being applied. So, we can say simple example, one is the milk in which you see the all the particles in the water which is a carrier form, is being you just randomly oriented.

And when the magnetic field is on, the entire milk is being converted into the cheese, this is one way through which we can simply explain, that the liquid form of the fluidic nature. How it is being converted into the solid form in which all the magnetic particles are being aligned, and they are just showing the resistance in the direction where, when they are being aligned there. When we want to see resistance in the this column direction, we can simply put the column feature or we want the resistance in the this direction where the rows are there, we can frame the rows along these particular layers. So, this is the basic we can say principles which we can straightaway adopted there.

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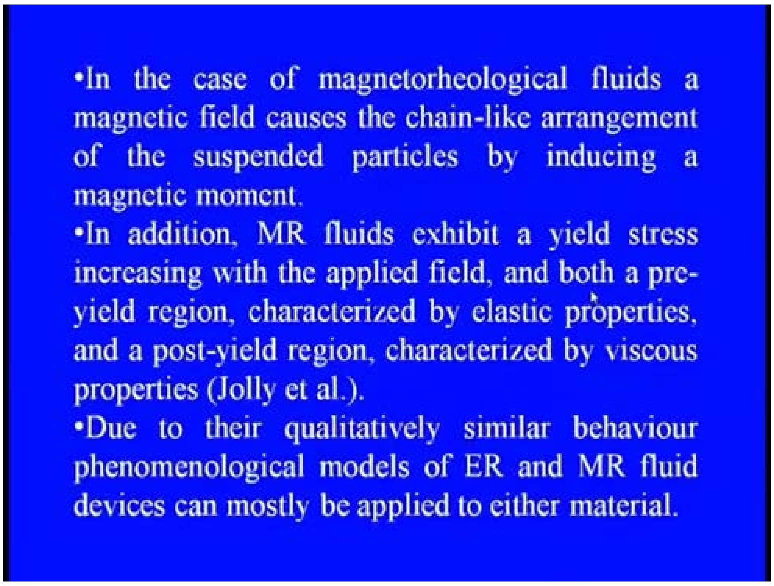

- In the case of magnetorheological fluids a magnetic field causes the chain-like arrangement of the suspended particles by inducing a magnetic moment.
- In addition, MR fluids exhibit a yield stress increasing with the applied field, and both a pre-yield region, characterized by elastic properties, and a post-yield region, characterized by viscous properties (Jolly et al.).
- Due to their qualitatively similar behaviour phenomenological models of ER and MR fluid devices can mostly be applied to either material.

So, in case of magnetic rheological fluid a magnetic field, which simply causes the chain like arrangement of the suspended particles by simply inducing a magnetic moment, or the fluxes there itself. And they can also exhibit the yield stress, which is being increasing with the applied field strength, and both we can say a pre yield region can also be characterized by the elastic properties. And the post yield region can be characterized by the viscous properties, so in the Jolly et al paper this simply shows that, when we just want to see the elastic and the viscoelastic this the viscous feature, we can simply see that what exactly the yield the pre yield and post yield regions are there, how the behavior is there. So, due to their qualitatively similar behavior, which is simply phenomenal mode of ER and MR part, we can say that they can these devices can be mostly applied to either of material. Now, we are discussing about the modes of the operations what are the basic modes in that?

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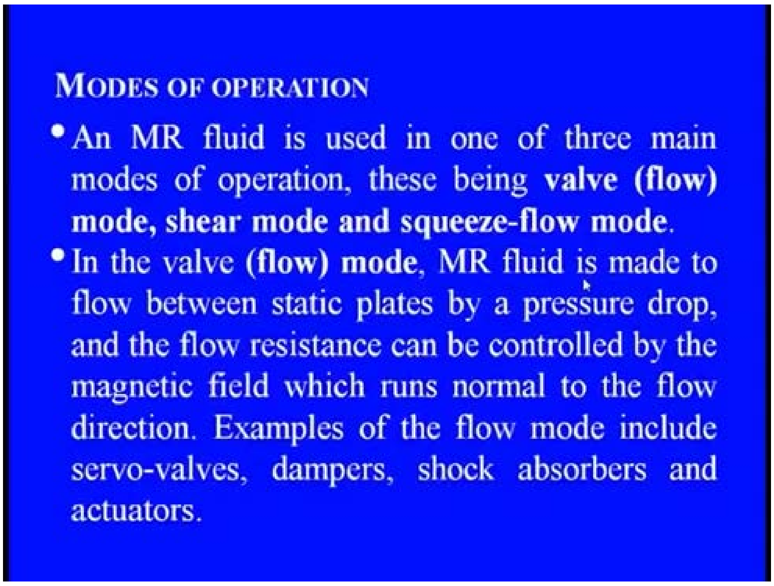

MODES OF OPERATION

- An MR fluid is used in one of three main modes of operation, these being **valve (flow) mode, shear mode and squeeze-flow mode**.
- In the valve **(flow) mode**, MR fluid is made to flow between static plates by a pressure drop, and the flow resistance can be controlled by the magnetic field which runs normal to the flow direction. Examples of the flow mode include servo-valves, dampers, shock absorbers and actuators.

So, an MR fluid is used in one of the three modes of the operations, where you see the directional features are being important. So, first mode is we can say the flow mode or we can say sometimes it is a valve mode, second mode as we discussed previously the shear mode. And third mode in which the MR fluid is basically under a operations it is the squeezed flow mode, so when we are talking about the flow mode, means the valve mode, the MR fluid is made to flow between the static plate by a pressure drop.

And the flow resistance can be controlled by the magnetic field, which runs normal to the flow direction, then only it is being effective and we can get a proper resistance. Few of the examples of flow mode is the servo valves, dampers, shock absorbers and even the actuators.

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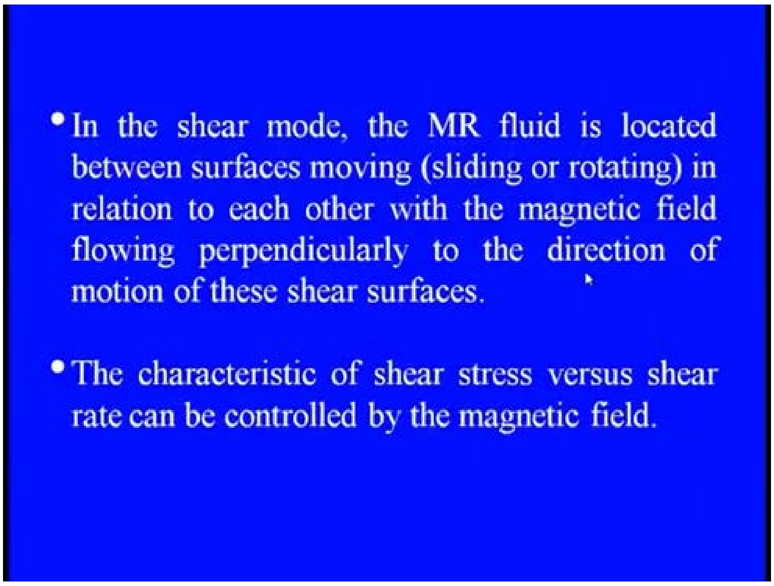

- In the shear mode, the MR fluid is located between surfaces moving (sliding or rotating) in relation to each other with the magnetic field flowing perpendicularly to the direction of motion of these shear surfaces.
- The characteristic of shear stress versus shear rate can be controlled by the magnetic field.

In shear mode the magnetic rheological fluid is located between this surface, moving we can say rather the sliding or rotating surface. In relation to each other with the magnetic field which obviously, flowing perpendicular to the direction of motion with these shearing features. And the characteristic of the shear, stress versus shearer we can say rate because when the shear stresses are being there the environment, the rate of shear strain is always being there with that. And it can be straightaway controlled by the strength of this magnetic field, and the last board we are saying that the squeeze mode.

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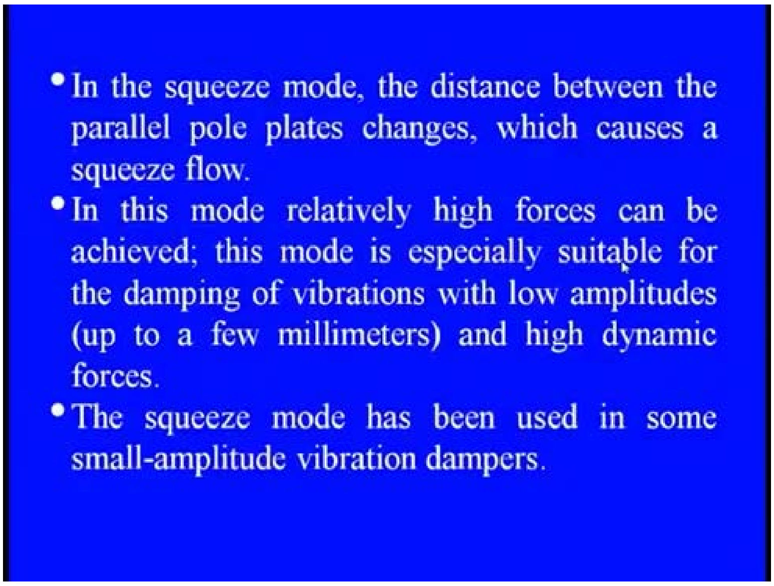

- In the squeeze mode, the distance between the parallel pole plates changes, which causes a squeeze flow.
- In this mode relatively high forces can be achieved; this mode is especially suitable for the damping of vibrations with low amplitudes (up to a few millimeters) and high dynamic forces.
- The squeeze mode has been used in some small-amplitude vibration dampers.

The distance between the parallel pole plates changes, and when the distance is being changes they are simply causing the squeezed, we can say form with the magnetic particles. And in this mode relatively high forces can be achieved, because when you are squeezing the things, the reaction features are being quite reactive. And this mode is specially suitable for damping of vibration with the low amplitudes, and high dynamic forces.

Because, we know that when we are just going up to the few millimeters of the amplitude of this part, and even you see the forces are quite significant, this squeezed part can be effectively absorb the energy against that. And the squeeze mode has been used in some of the small amplitude vibration dampers, because of it is real operational features there itself.

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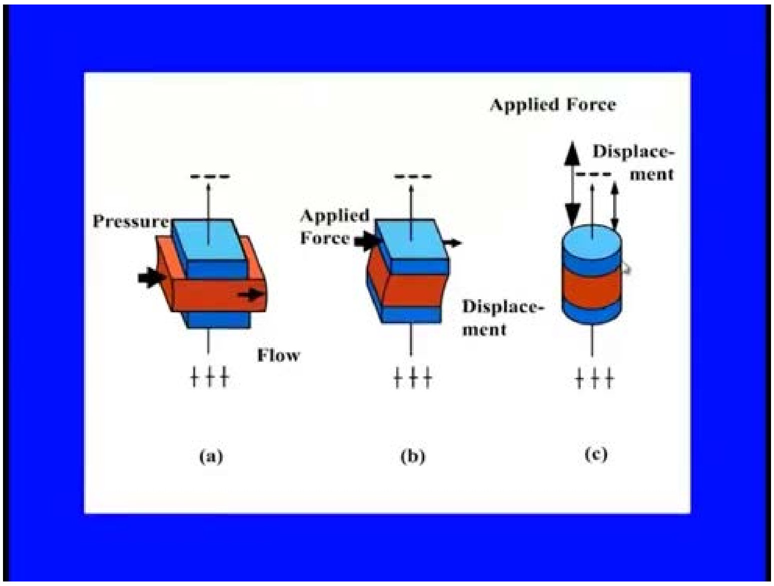

So, you can see that all three modes can be straightaway shown there, when you have a flow mode means the valve mode that, they are absolutely moving in this way, and the pressure which is like the magnetic field which is being applied normal to it. And we can get just the flow features, when you have the shear mode as per the name itself, they are being just parallel to this, either in the rotational or any part we have the shear force in that. And third it is when you have the squeezed part here, the displacement is this is just they are just changing the distance and because of that you see, their squeezing features are being occurred at the magnetic particle. And through that you see the high force with the low amplitude applications can be straightaway occurred there, or else rather we can simply explain with this way.

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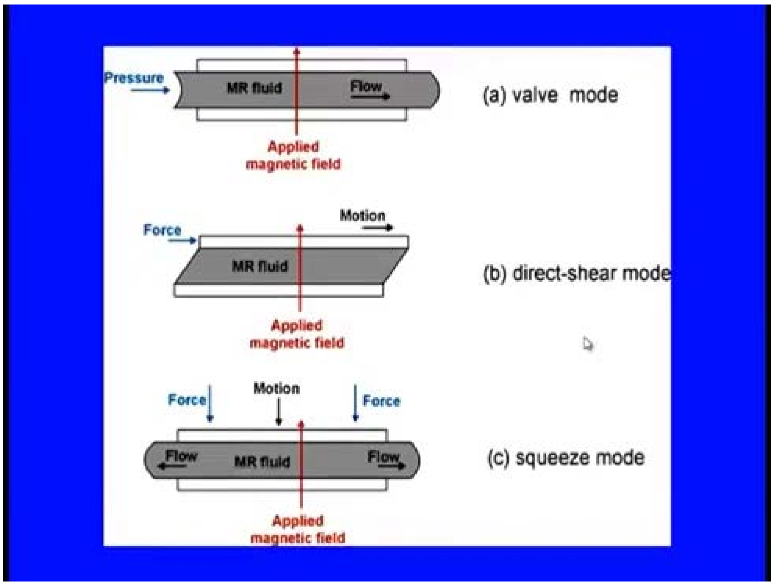

When the MR fluid is being there you see, this is my applied magnetic field and when we are just simply dragging this direction, the flow certainly, they can be streamlined in this particular channel form. And when you have the shearing part here, this is what my motion and so this is a parallel or the rotating motion and the magnetic field which perpendicular of this, we can get the shearing features at this particle part. Or else you see here when the forces are being acting in this way, means when it is just squeezing, changing it is size between the two plates.

We can get this is what the flow is and the motion is like that, and we can get the squeezing action there itself, when we just want according to the application or even you see here with these particles which we are generally using, this is what the direction of this part, the flow part and the vertical magnetic field is being applied in the flow shear or we can say these squeeze mode operations. So, according to the action of these we can say magnetic the field or whatever the particle featured.

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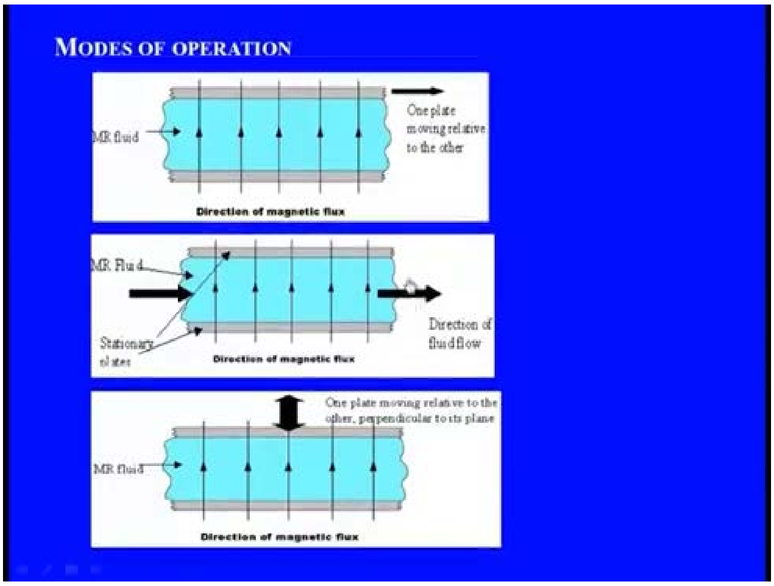

MODES OF OPERATION

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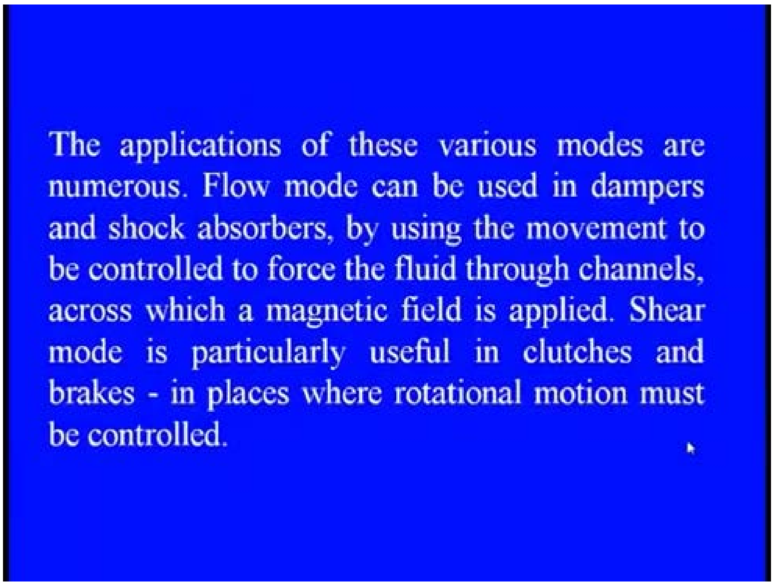

The applications of these various modes are numerous. Flow mode can be used in dampers and shock absorbers, by using the movement to be controlled to force the fluid through channels, across which a magnetic field is applied. Shear mode is particularly useful in clutches and brakes - in places where rotational motion must be controlled.

The application of these various modes are being chosen, so flow mode can be used in damper, and shock absorber with the use of the movement to be controlled to the force and flow through the channels, across which the magnetic field is being applied. So, this is a very smooth we can say part, in which where we just want to absorb or to dampen out, the vibration this is one of the perfect part to be applied there. The shear mode which is we can say particularly useful in clutches and the breaks, and in places where you see the rotational motion must be controlled, it is perfect the shear motion. Because here it is ultimately putting the parallel forces in the rotation, or you see here in that particular sliding actions.

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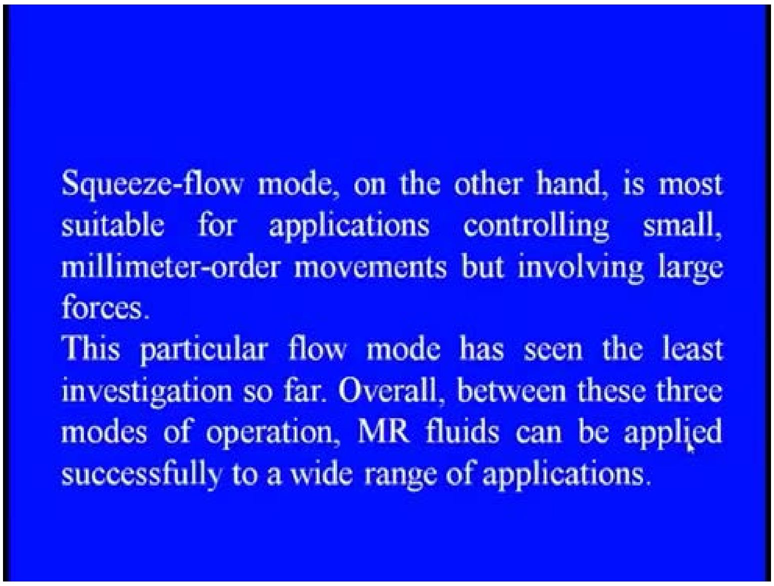

Squeeze-flow mode, on the other hand, is most suitable for applications controlling small, millimeter-order movements but involving large forces.

This particular flow mode has seen the least investigation so far. Overall, between these three modes of operation, MR fluids can be applied successfully to a wide range of applications.

And squeezed flow mode is the most suitable application controlling the small or we can say the millimeter order movement, but involving the huge amount of the excitation forces. So, this particular flow mode has seen, at least we can say investigation in various part where in straightway, we can straightway control the high excitation forces with the low amplitude feature. So, MR fluid can be applied successfully to the wide range of applications according to the service condition, applied features. And where we just want to control the entire say vibration or the excitation features, so the first, as far as the vibration control problem is concerned they can be act as the damper.

So, MR dampers have clear object of a intensive studies from both the point you see, their interesting physical features and also due to the potential applications to control damping in mechanical system. Because, the essential characteristic of the MR fluid is their ability to reversibly change, from free flowing linear viscous liquid to semi solid having the controllable yield strength in millisecond. And when they are exposing to a magnetic field, they can be clearly controlled the yield strength even within the fraction of the milliseconds.

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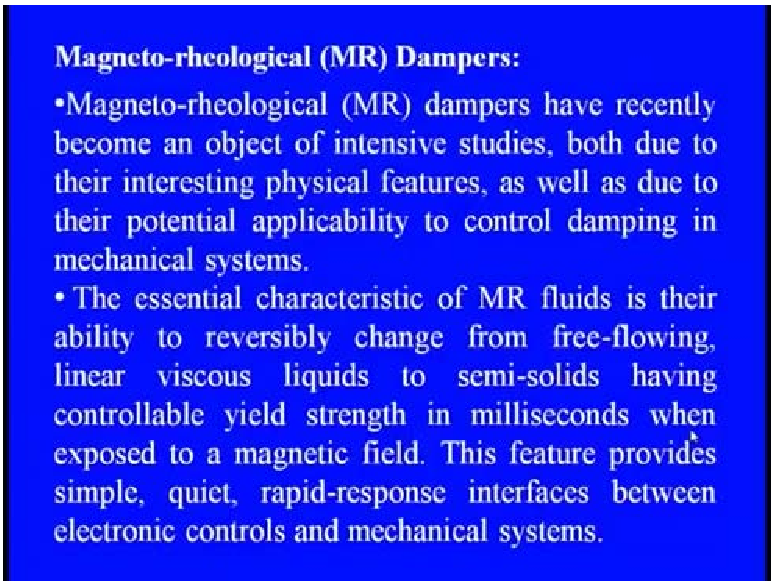

Magneto-rheological (MR) Dampers:

- Magneto-rheological (MR) dampers have recently become an object of intensive studies, both due to their interesting physical features, as well as due to their potential applicability to control damping in mechanical systems.
- The essential characteristic of MR fluids is their ability to reversibly change from free-flowing, linear viscous liquids to semi-solids having controllable yield strength in milliseconds when exposed to a magnetic field. This feature provides simple, quiet, rapid-response interfaces between electronic controls and mechanical systems.

So, this is the pretty clear, we can say a physical characteristic is there in which we can say that, they have clear ability to reversibly change, right from free flowing to semi solid part. And this feature provides a simplest quite rapid response interfacing between the electronic controls, and the mechanical system motion part you see here.

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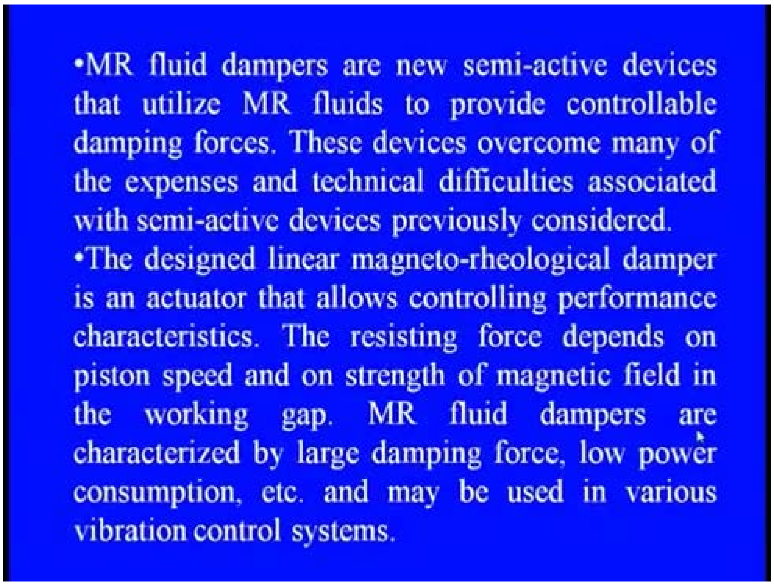

- MR fluid dampers are new semi-active devices that utilize MR fluids to provide controllable damping forces. These devices overcome many of the expenses and technical difficulties associated with semi-active devices previously considered.
- The designed linear magneto-rheological damper is an actuator that allows controlling performance characteristics. The resisting force depends on piston speed and on strength of magnetic field in the working gap. MR fluid dampers are characterized by large damping force, low power consumption, etc. and may be used in various vibration control systems.

So, these dampers are we can say new semi active devices, which utilizes MR fluid to provide controlling damping forces. And these devices overcome many of the expenses and the technical difficulties, when which are being associated with the semi active devices. The design of this linear magnetorheological damper is nothing but an actuator which allows controlling performance characteristic, in which we can say that the resisting force depends on the piston speed, and the strength of the applied magnetic field.

Because, in that working, whatever the particles are there they are being straightaway provide, the resistance according to their chain structure, but it is depending on that what exactly the piston speed is there. And what is the strength of this magnetic flux field, so these dampers can also be characterized by the large damping force low power consumption, and maybe we can say used in various this vibrating controlling systems.

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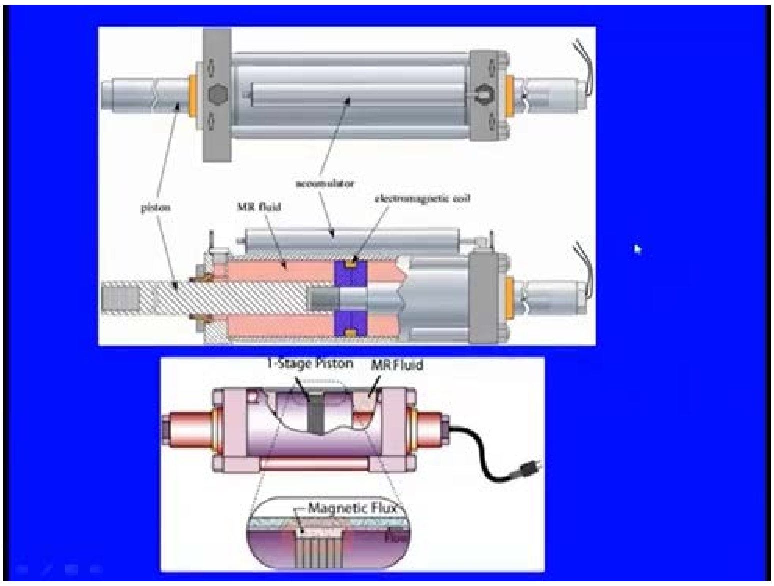

As you can see here, in this we have the MR fluid here we have the piston, because as I told you that it is straightaway depending on the piston speed. So, what exactly the piston speed is there what is the flux, the strength of the magnetic flux and with that you see here these magnetic this field. Under these the electromagnetic coil the strengthen can be provided and these are what we can say the accumulator through which we can accumulate.

Or rather we can say that in this piston form there is a clear the magnetic flux which is being we can say straightaway applied and these MR fluid which is there in between that, can be straightaway provide a good damping devices towards that. So, this is what you see the basic arrangement in which we have the piston part, so how the piston, what the movement is there and then according to the strength, the strength of this magnetic field we can have a good damping featured in that. So, when we are talking about this principle, the as a damper part we can simply go with the various mathematical models.

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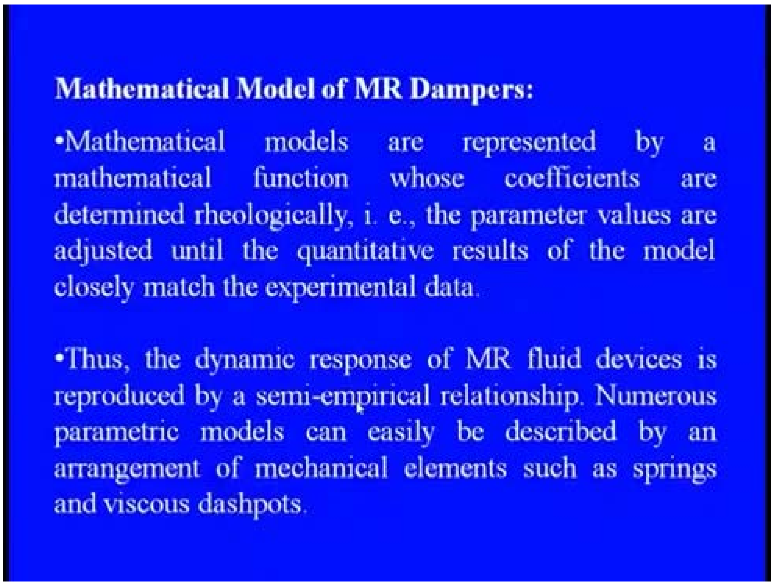

Mathematical Model of MR Dampers:

- Mathematical models are represented by a mathematical function whose coefficients are determined rheologically, i. e., the parameter values are adjusted until the quantitative results of the model closely match the experimental data.

- Thus, the dynamic response of MR fluid devices is reproduced by a semi-empirical relationship. Numerous parametric models can easily be described by an arrangement of mechanical elements such as springs and viscous dashpots.

Through which we can represent the mathematical function whose coefficients can be determined using the rheological part that means, the parametric value which are being adjusted until the quantitative results of the model, are not closely matched with the datas. So, when we are talking about the damping part, the dynamic response of these MR fluid devices is reproduce by the semi empirical relations. And then you see we can simply use the various parametric model, through which we can justify the arrangement of mechanical elements in that the spring or viscous dashpots together.

So, the first model is coming under this magnetorheological fluid damper is the Bingham model, as we discussed in the electro rheological fluid, that when the fluid is being under the shearing action, there are two feature, it is not a Newtonian feature. There are two feature after the yield limit, there is a clear relation between the shear stress and the rate of shear strain, so you see here we have clear Bingham nature itself. So, here also when we are applying the magnetic field on these polarize particles, we can have a similar part of relations.

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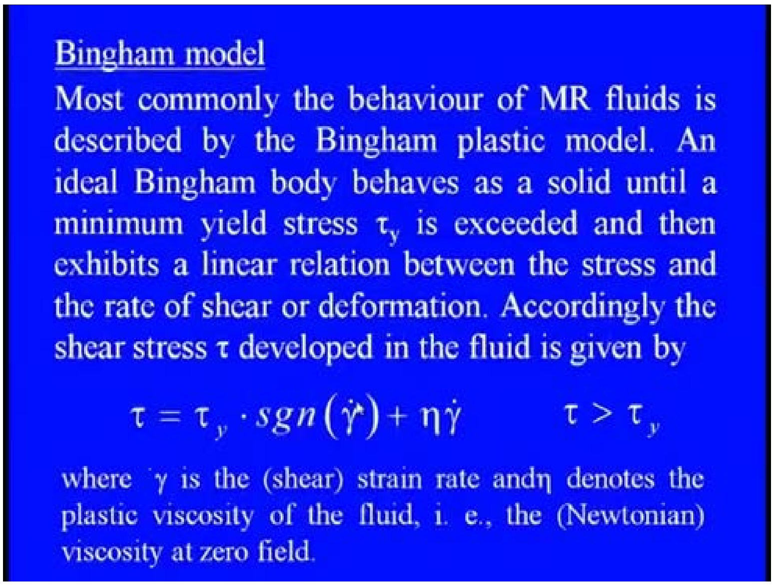

Bingham model

Most commonly the behaviour of MR fluids is described by the Bingham plastic model. An ideal Bingham body behaves as a solid until a minimum yield stress τ_y is exceeded and then exhibits a linear relation between the stress and the rate of shear or deformation. Accordingly the shear stress τ developed in the fluid is given by

$$\tau = \tau_y \cdot sgn(\dot{\gamma}) + \eta\dot{\gamma} \qquad \tau > \tau_y$$

where $\dot{\gamma}$ is the (shear) strain rate andη denotes the plastic viscosity of the fluid, i. e., the (Newtonian) viscosity at zero field.

So, most commonly behavior for this MR fluid is described by the Bingham plastic model, an ideal Bingham body behaves as the solid until it is reaches up to the minimum yield stress say tau y. And when it is being exceeded there itself, then they are simply exhibiting the linear relation between the stress and rate of the formation or the shearing part. So, this is one of the relation for the Bingham part that even we are applying the load up to a certain limit means, before it is reaching to the yield point, there absolutely the solid nothing is being happening in that.

But, after that there is a clear elastic behavior is there, so we can say that it is something of viscous and elastic part, so they are almost similar to viscoelastic feature of the materials. And then we can go with the same kind of the relation that the shear stress tau, which is being developed under the action of this magnetic field with the nanoparticles, we can say tau is nothing but equals tau y. That is my minimum yield stress, at which there is a conversion from solid to liquid phase or we can say to non Newtonian, to we have some kind of the linearity.

So, we can say tau is equals to tau y sign of this gamma dot plus eta gamma dot, where we know that the gamma dot is nothing but equals to the rate of shear strain and the eta is clearly showing the plastic feature of the viscosity of the fluid. That is we can say that, it is the viscosity is having at the 0 field which is simply exhibiting the Newtonian part, so we have a clear plastic viscosity means, the non Newtonian feature of this. So, we have both the tau y sign gamma dot, which is showing a linearity feature in the stress with the shear strain. And eta gamma dot is showing that rate of shear strain is there, but this is absolutely absorbed with the viscous plastic nature or we can say whatever the these solid features are there, before the yield limit.

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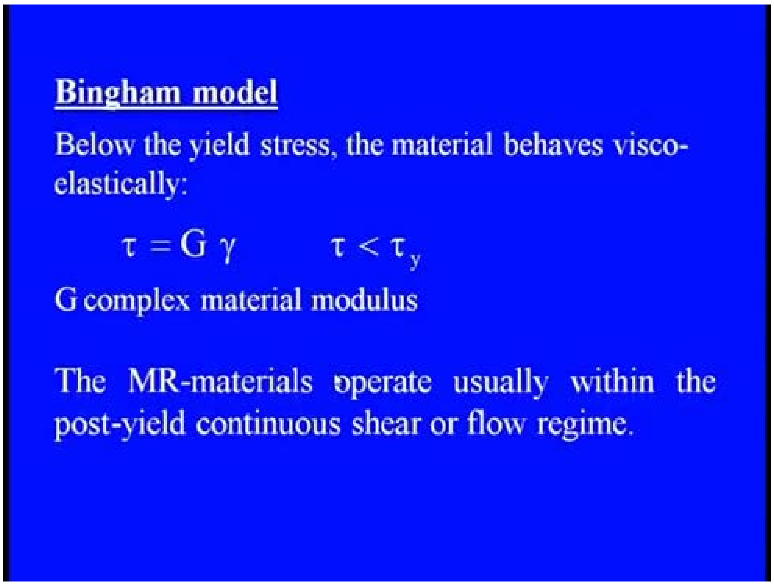

Bingham model

Below the yield stress, the material behaves visco-elastically:

$$\tau = G\,\gamma \qquad \tau < \tau_y$$

G complex material modulus

The MR-materials operate usually within the post-yield continuous shear or flow regime.

So, in the Bingham model we can say, if we are just going below the yield stress, then certainly as I told you the material is behaving like the viscoelastic feature, where we can say that the tau is proportional to the g into gamma. The g is not the shear modulus, the g is here the complex material modulus right now here, though it is the shear modes are there. So, we can simply defined the shear strain rate of shear strain, within the we can say the below yield stress this relation is clearly showing. that the MR material operate usually within the post yield continuously shear or we can say flow regime.

So, we need to check it out that, what exactly the regimes are what is the reason it is below yield point or above yield point. If it is below yield point then the tau is equals to g into gamma and if it is above yield point, then certainly we can say that, this is absolutely showing the f equals to the same the linear behavior of that.

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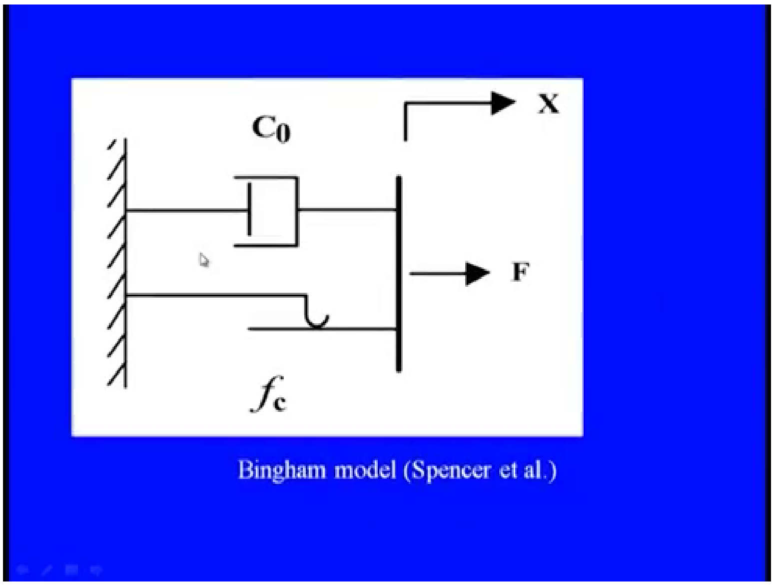

Bingham model (Spencer et al.)

So, this is what the Bingham model which is giving in the excellence paper of the Spencer et al, in which it is there that whatever the forces which is being excite the system, just flowing in that we have a clear C 0 part that is the minimum viscous part, showing the plastic viscosity there itself. And then you see here after that we have a clear proportion, the after yield point we have clear elastic features in that, in which we can say that it is simply the tau y sign, we can say gamma dot. Means we have the yield and we have the rate of shear stress is linearly varying with the shear stress part.

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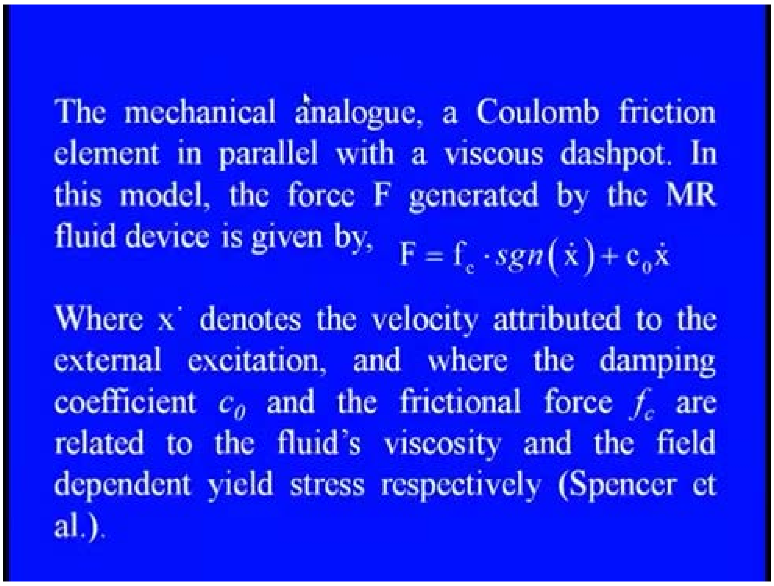

The mechanical analogue, a Coulomb friction element in parallel with a viscous dashpot. In this model, the force F generated by the MR fluid device is given by, $F = f_c \cdot sgn(\dot{x}) + c_0 \dot{x}$

Where x˙ denotes the velocity attributed to the external excitation, and where the damping coefficient c_0 and the frictional force f_c are related to the fluid's viscosity and the field dependent yield stress respectively (Spencer et al.).

So, we can even put the mechanical analogue of such behavior with the coulomb friction element, which is parallel just with the viscous dashpot. So, in this model when we are just talking about the coulomb friction features in that, the force F which is generated by this magnetorheological fluid device, can be obtained as the f c sign of X dot plus c 0 x dot. Where we know that, the X dot is absolutely the velocity part associated with the damping available, and which is attributed to the external excitations.

And the damping coefficient c 0 and the frictional force as f c are simply related to the fluid viscosity, and it is the field is depending on the yield stress respectively. So, this is what we have the two things together, we have the damping which is absolutely the function of the fluid viscosity. We have the frictional forces, which depends on the field, what exactly the yield stress fields are there together. And along with that, we are saying that this f c means the frictional forces it is just varying with these sinusoidal features sign omega or sign we can say X dot.

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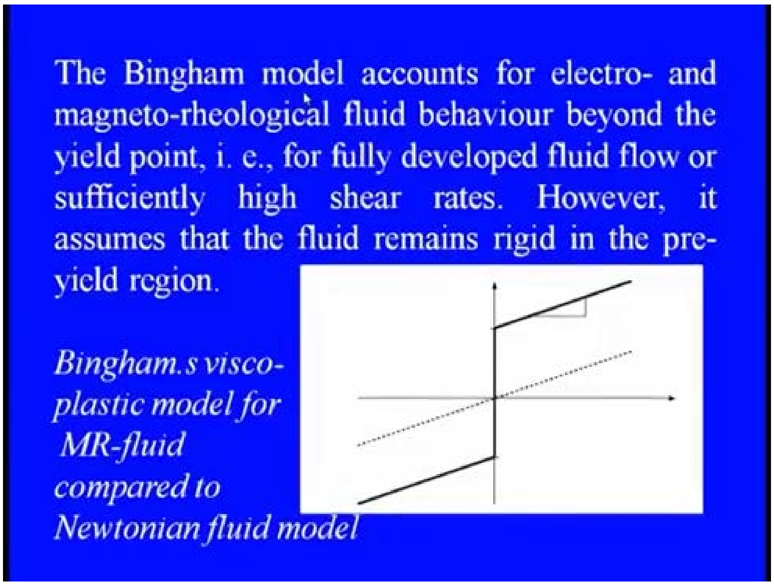

The Bingham model accounts for electro- and magneto-rheological fluid behaviour beyond the yield point, i. e., for fully developed fluid flow or sufficiently high shear rates. However, it assumes that the fluid remains rigid in the pre-yield region.

Bingham.s visco-plastic model for MR-fluid compared to Newtonian fluid model

So, when we want to represent the real character of these MR fluids we know that, the Bingham model which is very close to that is simply accounts for electro or magnetorheological fluid behavior, beyond the yield point. That means, when fully developed fluid flow is there, or we can say if it is whatever the shear stresses are there if they are sufficiently high. Then only we can say that, we can just go for the real fluid behavior, but also we assumes that the fluid remains rigid in the pre yield stress region.

So, as you can see that on the diagram, this is clear that right from you see 0 to up to this ((Refer Time: 28:58)) point the viscous part is so dominating, that it is not exhibiting any kind of the flow part. So, whatever the energy which is being there, it is being dissipated or absorbed at that point and beyond yield point, then this we can say the linear region the elastic features are there. So, viscoelastic model for the MR fluid is clearly showing that, if we have these Bingham models are there, then we need to show with this part, first go straight and then you see the linear propagation is there. And if you have the Newtonian fluid model, which can right from 0 to just proportion they are absolutely showing the linear relations between this stresses, and shear strain part or else even when we are trying to see on the experimental features, then also with the flow and velocity.

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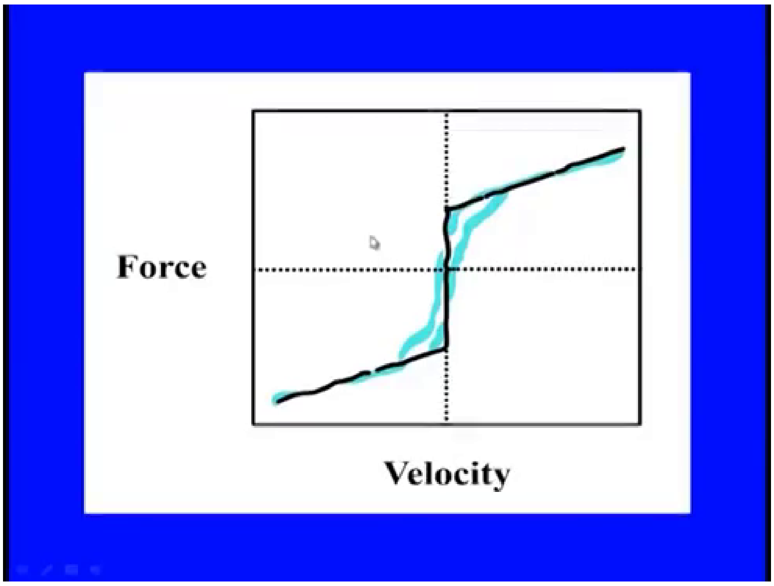

You can see that how the damping is being featured out here, so this is what, this is the green line is clearly showing that, how the real variation is there in the force to the velocity or the movement for that part.

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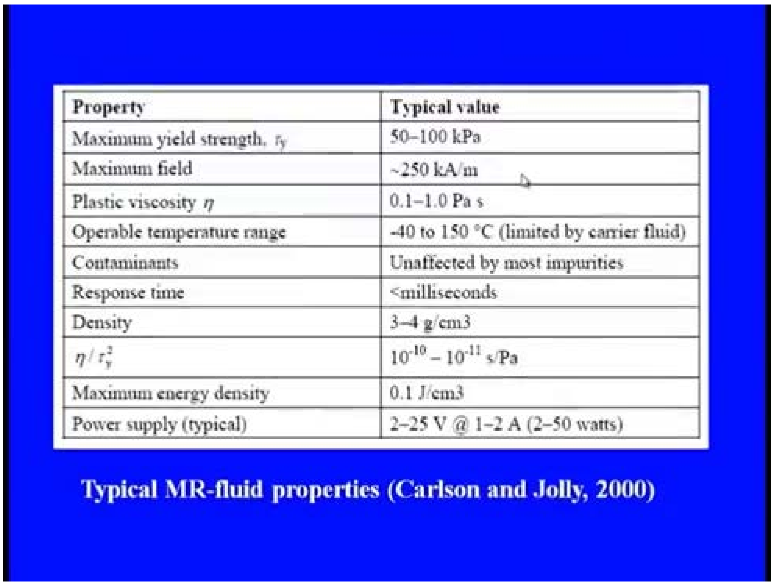

Property	Typical value
Maximum yield strength, τ_y	50–100 kPa
Maximum field	~250 kA/m
Plastic viscosity η	0.1–1.0 Pa s
Operable temperature range	-40 to 150 °C (limited by carrier fluid)
Contaminants	Unaffected by most impurities
Response time	<milliseconds
Density	3–4 g/cm3
η / τ_y^2	$10^{-10} - 10^{-11}$ s/Pa
Maximum energy density	0.1 J/cm3
Power supply (typical)	2–25 V @ 1–2 A (2–50 watts)

Typical MR-fluid properties (Carlson and Jolly, 2000)

So, when we are going with the MR fluid there are various properties, which are being documented by the Carlson and jolly in the paper in 2000, in which we have the with the typical MR fluid. We can get the minimum yield strength almost up to 100 kilo Pascal where the maximum field can be there of 250 kilo ampere per meter, the plastic viscosity which is the basic property before yield limit, can be there 0.121 Pascal into second. And it can be operated in the temperature range of almost we can say up to 150 degree Celsius and minimum even up to minus 40degree Celsius.

The response time is always less than milliseconds that is the beauty of the system is, we can immediately get the response when it is being acted there. The density is almost 4 gram per centimeter cube and then you see when we are trying to relate the plastic viscosity with this yield limit. Then we can have almost 10 to the power minus 10 to minus 11 second per Pascal and then you see all other properties all these power supply for this making all that part is almost near about the 50 Watts and then we can get the maximum energy density like that. So, this was the first model, which can simply show the real character of the magnetic magnetorheological fluid, which can be act as a damper also.

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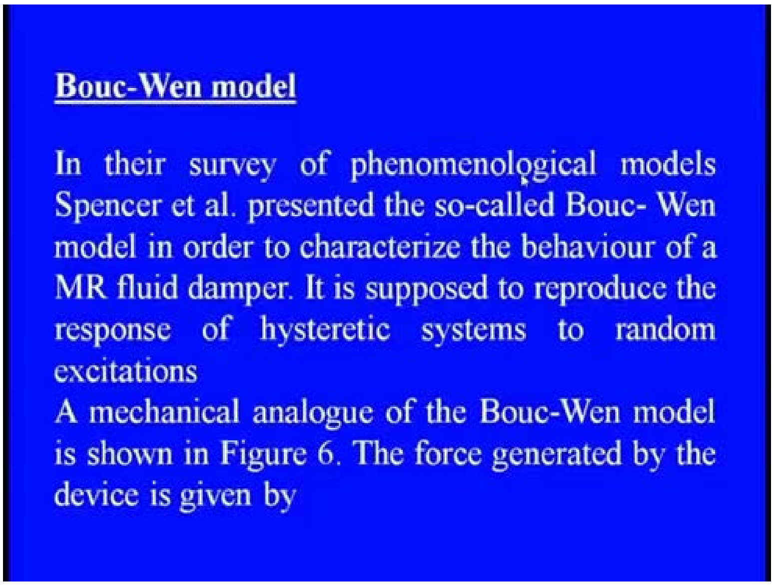

Bouc-Wen model

In their survey of phenomenological models Spencer et al. presented the so-called Bouc- Wen model in order to characterize the behaviour of a MR fluid damper. It is supposed to reproduce the response of hysteretic systems to random excitations

A mechanical analogue of the Bouc-Wen model is shown in Figure 6. The force generated by the device is given by

Second, further we can say that more refined part is the Bouc-Wen model, so Bouc-Wen model is just we can say one of the most refined model, which is even presented by the Spencer in their paper. And in this model you see here we just want to characterize the behavior of this MR fluid damper, so again we need to reproduce the response of the hysteresis system to the random excitation. So, we can say that we can straightaway put a mechanical analogue of this Bouc-Wen model.

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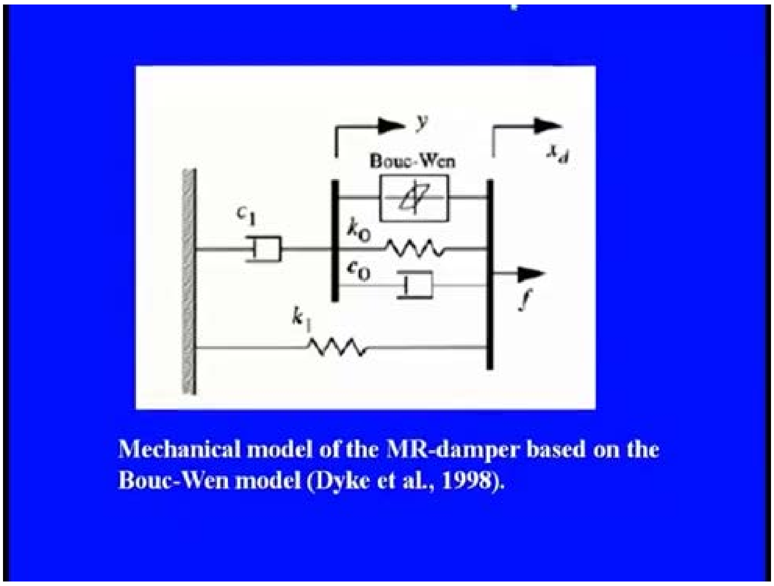

Mechanical model of the MR-damper based on the Bouc-Wen model (Dyke et al., 1998).

In which you see here, the force is generated by the device can be represented like this, here we have the same the spring feature, we have the damper feature together. But, this is what you see the Bouc-Wen model, in which here we are saying that the displacement is y and the entire this the total damper movement is x d. When the external force is being applied, there are three main devices which are being acted together, according to the Bouc-Wen model c 0, k 0 and this device in which we are saying that what exactly the hysteresis part is there in that. So, these three you know like features in which we are just trying to consider, or we can say we are just trying to put the response from the hysteresis system from the random excitations.

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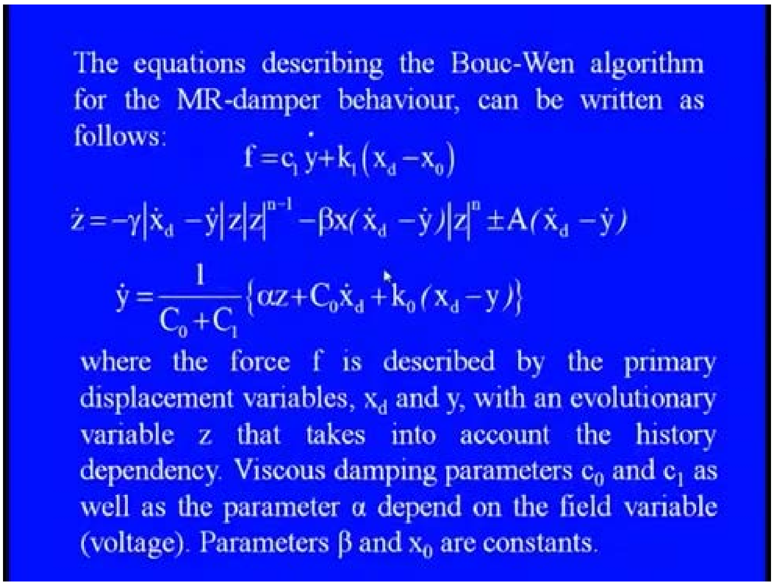

The equations describing the Bouc-Wen algorithm for the MR-damper behaviour, can be written as follows:

$$f = c_1 \dot{y} + k_1 (x_d - x_0)$$

$$\dot{z} = -\gamma |\dot{x}_d - \dot{y}| z |z|^{n-1} - \beta x (\dot{x}_d - \dot{y}) |z|^n \pm A (\dot{x}_d - \dot{y})$$

$$\dot{y} = \frac{1}{C_0 + C_1} \{ \alpha z + C_0 \dot{x}_d + k_0 (x_d - y) \}$$

where the force f is described by the primary displacement variables, x_d and y, with an evolutionary variable z that takes into account the history dependency. Viscous damping parameters c_0 and c_1 as well as the parameter α depend on the field variable (voltage). Parameters β and x_0 are constants.

So, we can simply write the mathematical relations which can describe the Bouc-Wen algorithm for the MR damper behavior. So, first is the primary displacement variable say f, small f which is nothing but equals to the c 1 into y dot means whatever the real character of the damper at that time, which is related to we can say it is all the damping parameters.

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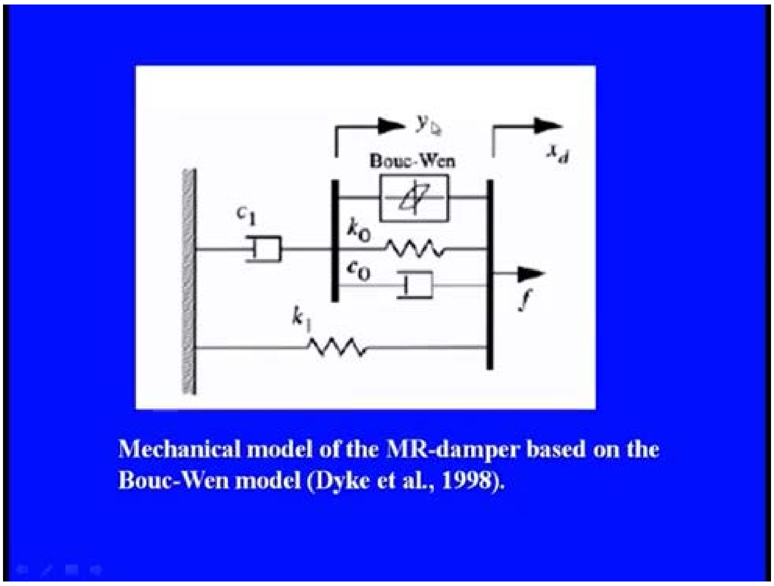

Mechanical model of the MR-damper based on the Bouc-Wen model (Dyke et al., 1998).

So, c 1 if you look at, c 0 was the first damping, c 1 was the damping which was you see here the outside part and this c 1 is related to the displacement y.

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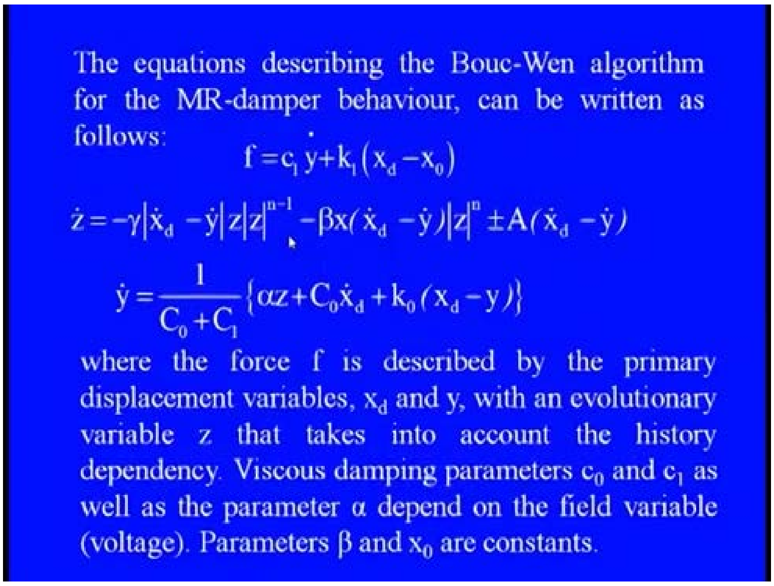

The equations describing the Bouc-Wen algorithm for the MR-damper behaviour, can be written as follows:

$$f = c_1 \dot{y} + k_1 (x_d - x_0)$$

$$\dot{z} = -\gamma |\dot{x}_d - \dot{y}| z |z|^{n-1} - \beta x (\dot{x}_d - \dot{y}) |z|^n \pm A(\dot{x}_d - \dot{y})$$

$$\dot{y} = \frac{1}{C_0 + C_1} \{ \alpha z + C_0 \dot{x}_d + k_0 (x_d - y) \}$$

where the force f is described by the primary displacement variables, x_d and y, with an evolutionary variable z that takes into account the history dependency. Viscous damping parameters c_0 and c_1 as well as the parameter α depend on the field variable (voltage). Parameters β and x_0 are constants.

So, we have the damping force from the c 1 is c 1 y dot, so we have when we are just trying to show the force in terms of that, we have the c 1 y dot damping force plus restoring force is there due to the relation in between the x d, that is we can say whatever the variable features are there in the displacement part and x 0 is the initial part. So, the difference of the damping and the initial part is just giving into k 1, whatever the stiffness feature is there is giving the restoring forces.

And when we are going with the evolutionary variables, we simply account whatever the previous dependency features are there z dot is nothing but equals to minus gamma x dot d minus y dot into modulus of z into z to the power and minus 1 minus beta x by x d dot by. When we are just trying to compute these coefficients, again beta and this whatever the x 0 which we are applying here, they are the constraint part we are just trying to put the conditions.

So, beta into x dot d minus y dot z to the power n plus minus a x dot d minus y dot n, so we can say that, we can straightaway get these two coefficients, according to what the application means way, what the boundary conditions are there, and what you see the operating features are there together. And the y dot which was there initial first part you see that what exactly the velocity component is nothing but equals to 1 by C 0 plus C 1 and C 0 and the C 1 are nothing but the viscous damping parameters.

And we have into alpha z and alpha is nothing but the field variable which is absolutely depending on the applied voltage into z. And z you see as I told you that this is what the evolutionary variable depending on how the dependency features are there on the previous part, into c 0 x dot d because the c 0 is just moving with the x d. So, we have the viscous forces with that plus K 0 into X d minus y here, because now the displacement which we are considering here is the y.

So, these three equations, which are being formed by the Bouc-Wen is simply showing the relations of all these parameters, when the entire fluid damper model is behaving under the excitation force f, and when we are trying to make the predicted part between the experimental.

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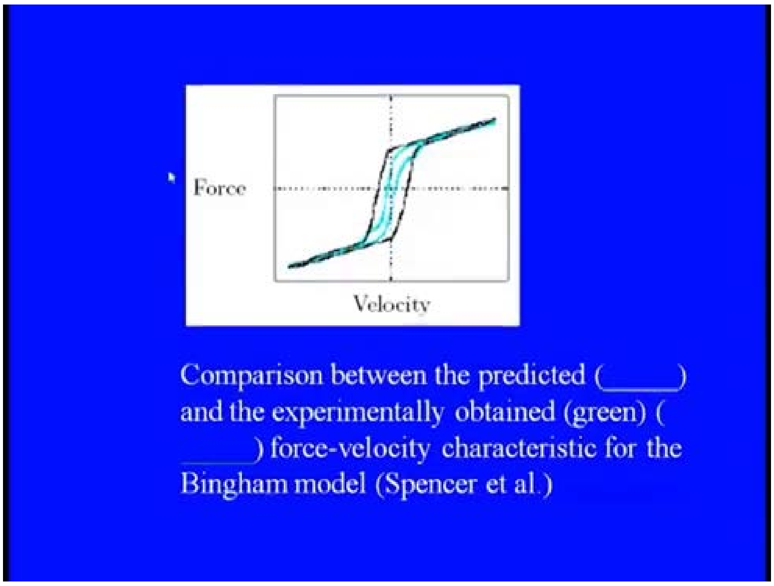

Comparison between the predicted (_____) and the experimentally obtained (green) (_____) force-velocity characteristic for the Bingham model (Spencer et al.)

And we can say this theoretical part in the Bingham model, we can clearly as I shown there, this is what my hysteresis loop when the entire feature features are there in that. So, experimental features as it is a clear showing the non-linearity, when the green part when the experimental feature are there, so when we are going to the application of this MR fluid.

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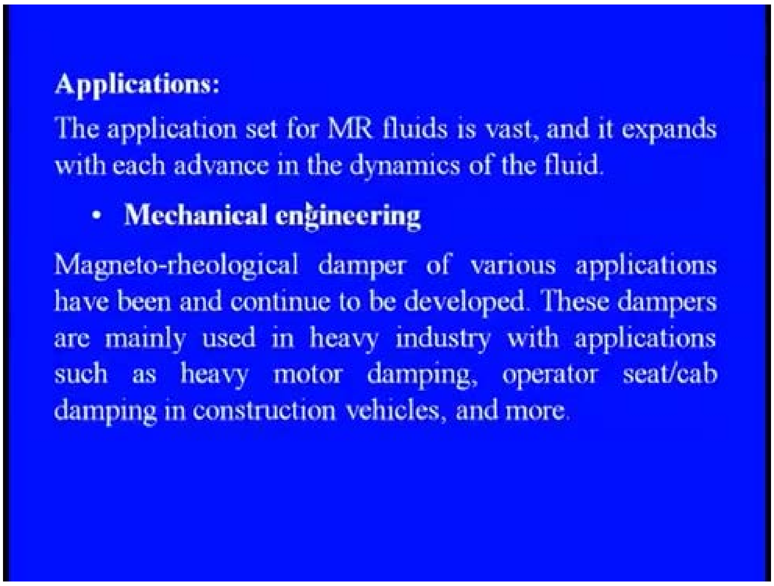

Applications:

The application set for MR fluids is vast, and it expands with each advance in the dynamics of the fluid.

- **Mechanical engineering**

Magneto-rheological damper of various applications have been and continue to be developed. These dampers are mainly used in heavy industry with applications such as heavy motor damping, operator seat/cab damping in construction vehicles, and more.

Then certainly first thing is coming in mechanical engineering, these damper of the various application have been there, and it is still the various compact, and the robust features are being even added and they can be use. So, these dampers are mainly used in heavy industries with the application as heavy motor damping, or we can say operator seat or cab damping in the construction vehicles. Or there are various thing where the response time is required minimum, and there you see immediately we need to act these features.

((Refer Time: 37:49)) Even in the military and defense part in which various researchers have been already put their efforts, and they are straightway using the fluid bullet resistant part in that. And the various all terrain vehicles which employed the dynamic MR shock absorber or the dampers as straightway using. The human prosthesis in which the MR dampers are utilized in semi active, the human prosthesis in which, whatever the leg features are there, they can be act as the integrated part in between that.

Much like those in use used in these military or the commercial helicopters, a damper in this prosthetic leg can be straightaway decrease the shock, which is being delivered to the patient leg when it is being jumping or any dynamic access are being happened. The sudden jump or sudden we can say impactive force, which result in the increase with the mobility and the agility for the patients. So, this is one of prosthetic feature in which the leg or somewhere, when the dynamic access are continuously being happened. The MR dampers which can be embedded to the real material I can exhibit a real good time, just like with the minimum response time.

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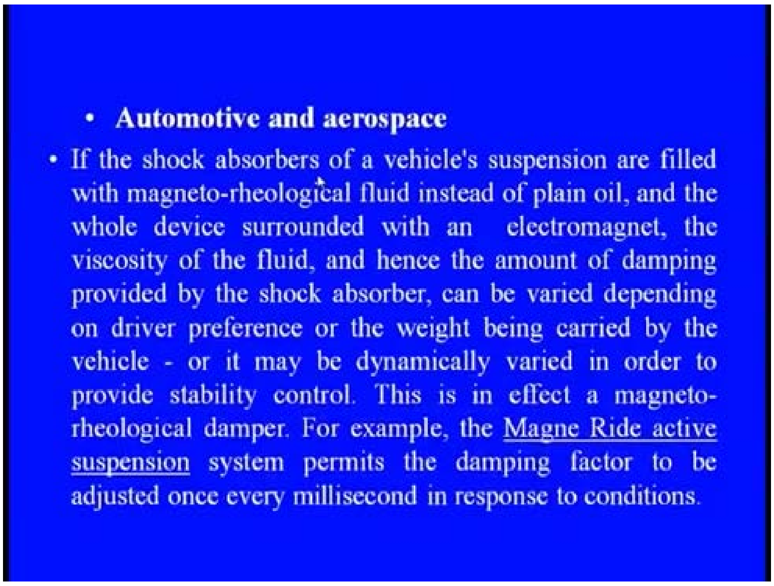

- **Automotive and aerospace**
- If the shock absorbers of a vehicle's suspension are filled with magneto-rheological fluid instead of plain oil, and the whole device surrounded with an electromagnet, the viscosity of the fluid, and hence the amount of damping provided by the shock absorber, can be varied depending on driver preference or the weight being carried by the vehicle - or it may be dynamically varied in order to provide stability control. This is in effect a magneto-rheological damper. For example, the Magne Ride active suspension system permits the damping factor to be adjusted once every millisecond in response to conditions.

Automotive and the aerospace, if the shock absorber of a vehicle suspension are filled with this MR fluid instead of the plain oil, then the whole device surrounded with an whatever we can say the electromagnet. The viscosity of fluid can be enhance the amount of damping provided by the shock absorber, can be varied depending on the driver performance or we can say weight which is being carried by this vehicle. And also we can say that the dynamical variable in the order to provide the stability control, these MR dampers are perfect.

So, this is in effect of the magnetorheological damper for which we can say that, the magnet ride active suspension system can be adopted through which we can permit the damping factor, which can be adopted or which can be adjusted in every millisecond response according to the condition. So, they are so quick in their response, so whatever the conditions are being changing like the operating, or we can say the boundary conditions, they can be immediately adopt and respond in corresponding way.

So, that is why wherever we require such kind of applications, right from automobile to aerospace to helicopter damper or even for the military, and all others part or even for where the human responses are requiring more the MR damper can be straightaway embedded to the system and then here we can get such kind of things.

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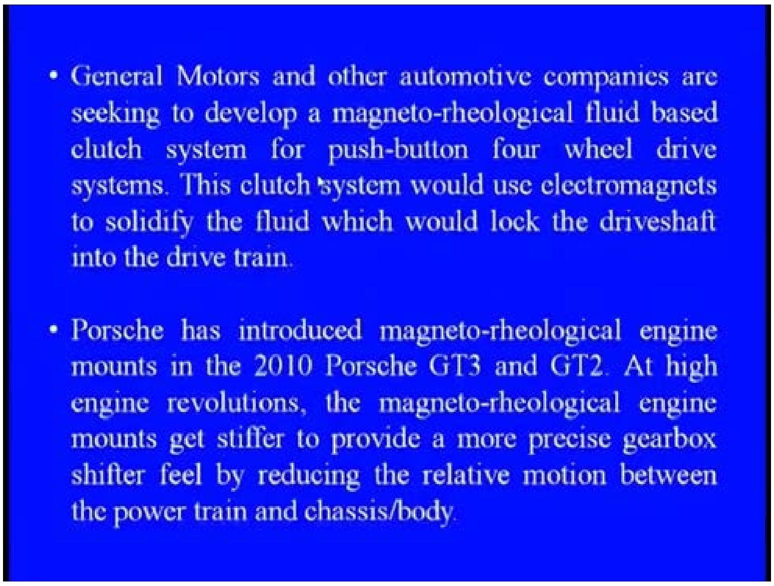

- General Motors and other automotive companies are seeking to develop a magneto-rheological fluid based clutch system for push-button four wheel drive systems. This clutch system would use electromagnets to solidify the fluid which would lock the driveshaft into the drive train.
- Porsche has introduced magneto-rheological engine mounts in the 2010 Porsche GT3 and GT2. At high engine revolutions, the magneto-rheological engine mounts get stiffer to provide a more precise gearbox shifter feel by reducing the relative motion between the power train and chassis/body.

So, in even in the general motor and other various big companies, they are developing the magnetorheological based clutch system, for push button four wheel drive systems.

Because, this clutch system can be used as just the electromagnets to solidify the fluids, which can lock the entire driveshaft into the we can say the drive train, and whenever it is being required they can be engaged and disengaged accordingly. And Porsche has introduced is one of his paper, the MR engine mounts which we just discussed in the previous case even the ER fluids can be also used as the engine mount.

And at the high engine revolution these MR engine mounts get stiffer to provide a more precise gear, stiffer feel by reducing the relative motion between the power train, and the chassis or entire body itself. So, they can be act as a good damper even for heavy machinery and in the quick response time, they can give the entire features, though you see here there are various other models like the lie model. And various other models are more refined models are available, but we need to restrict over this part, because we need to featured out. That along with these the flow characteristic of the magnetorheological fluid as we are just using the damper part, but we need to check it out that you see here, all the time we cannot be replaced.

Because, you see here the whatever the electromagnetic fluxes are being created, they can also effect the various other properties of the surrounding part. So, you see a triply we cannot use these features, for controlling the vibration through the damper. So, you see here in the last 2 lectures, right from ER damper to MR means electrorheological fluid damper and MR, this magnetorheological fluid dampers, they have an excellent properties, according to the resistance which is being provided to the system.

And it is absolutely based on the applied electric or magnetic field, and even in now a days you see here, because of their sensitivity and quick responses, because their responses are in milliseconds only. Though you see MR fluid is more quicker than the ER fluid, but since if we compare with the other sensor and actuation feature there response time is very fast. So, we can adopt these things, but again we need to check it out that, where it has to mount and what are the service and the operating conditions.

So, that the there should not any damage because they can be effectively use against shock absorber both the dampers, because they are showing based on their Bingham model characteristics. They are almost exhibiting the viscoelastic features, in which you see we have both before yield and after yield point, there is a clear solid and liquid features are there. Means when the magnetic or electric field is on, they are almost exhibiting, when electric field is on it is just exhibiting or the solid features in which you see here, all the particles the polarized particles are aligned.

In that direction where the resistance is being required, and you see all the field which is being there on outside, it should be perpendicular to that part. So, this is the basic concept you see and some general mechanism, but you see still more and more research is being going on according to that where we where we require, the clear configuration and the control of the dynamic forces. How we can adopt to these electrorheological or magnetorheological fluid dampers. Now, in the next lecture we are going to discuss the another form of these application of this electro or magnetic field, in the electro restrictive and magneto restrictive the material part. So, how we can again put the restrictive features by applying these magnetic, and the electric field there itself. We are going to discuss in detail, basic mechanism and their applications.

Thank you.