Vehicle Dynamics
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Lecture – 06
Tire Mechanics - An Introduction

In the last class, we were looking at the tractor trailer, right and we were looking at breaking. We also looked at how breaking affects the performance as well as, in other words, the breaking distances as well as we saw how when a tire is locked, whether the front gets locked or the rear gets locked or the trailer gets locked, how that is going to have an effect on the vehicle motion.

So obviously, we also gave a sequence on how it should be locked and obviously, the breaking forces or the percentage of breaking forces which are distributed, would depend upon the W's that are acting as well as on this sequence which we set you know that should take place, okay. Without dealing much into that tractor trailer, you have done some assignments, so that will give you an idea. We will now move over to a very important and interesting topic on tires.

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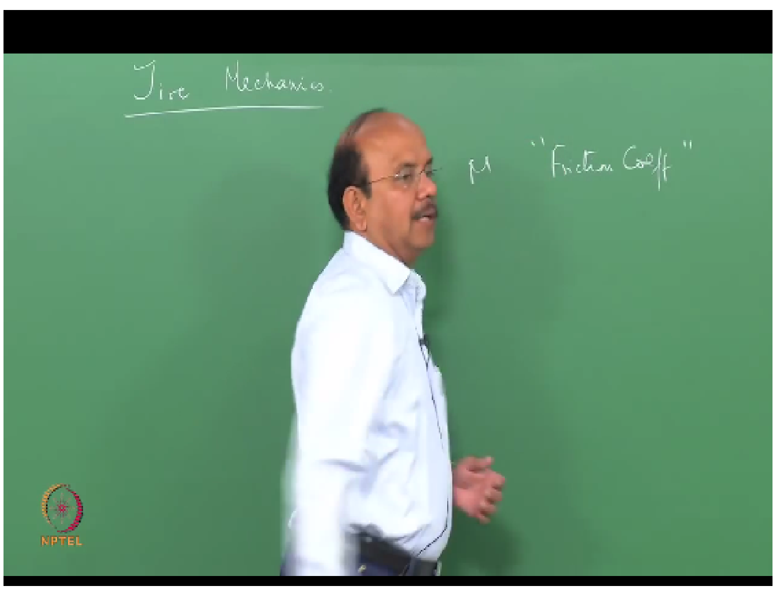

So in other words, we will understand what are tires and then we will go ahead and understand what is the mechanics of tires. Mechanics of tires is a very interesting topic as well as a difficult topic. Though one would say that what is in a tire, I see this everyday in every car, what is so important about tires. If you look at in automobile, there are 2 components which are extremely abused, abused to the greatest extent. One is the tire, the other is the piston rings, okay.

Both of them are abused, abused in sense that they are subjected to all sorts of loads, friction and so on in their lifetime and what happens between the tire and the road, is extremely important for the safety of the vehicle whether you are accelerating or breaking and whether you are taking a corner or manoeuvring the vehicle, for all these things what happens between the tire and the road, is important. So in other words, we have to understand this carefully.

In the last class, we said that we will dump all the effect, the effects that happen between the tire and the road in to one constant and we call this as mu and we said that this is friction constant or friction coefficient. I put that within the inverted commas, friction coefficient, because it is not as simple as what happens or what this equation says or what happens in just a block.

So friction coefficient is only a simple equation to depict the behaviour of the forces or depict the relationship between the forces but the phenomenon is very deep. We will answer the question, okay, one by one as to why or how this friction coefficient or friction is developed and how it enhances the grip and so on.

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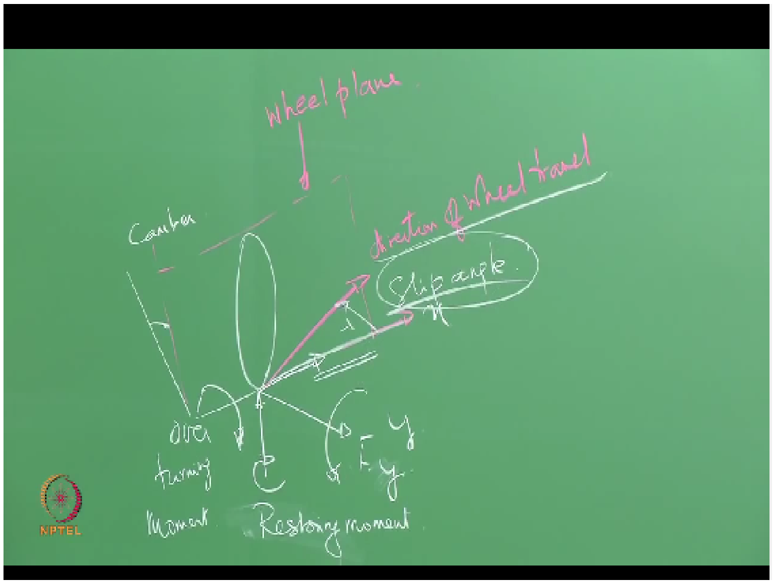

Now before we go further, let us look at just the forces that are acting on the tire. Since all of you know, you have done a course on automotive systems, you know what is a tire and so on. I am not going to deal too deeply into the specs of the tire and so on, but we will maybe indicate this as we go along. We will not go into the construction of the tire and other aspects of materials but we will suffice it to understand what all is required to understand, we will do that right now.

So first let us look at the forces that act on the tire. There is a longitudinal force, okay, which is in x direction, okay, but that force is exactly not along, look at that, it is not along the wheel plane. Suppose this is the wheel plane, okay, then you would see that the tire direction of rolling or the travel is not exactly along that direction but is at an angle which makes, let us say that this lambda or alpha and that angle is what is called this slip angle, why is it so, we will see that in a couple of lectures.

So the first thing is that, it is very interesting to note that the tire just does not, as it travels, it does not go along the plane. Let us say that the x direction is the direction perpendicular to the normal direction or normal to the wheel plane, okay. So in other words the tire does not travel along the wheel plane. So it takes a direction that is what I call as direction of wheel travel and that direction is at an angle of alpha or lambda which is called the slip angle, okay. That is the first thing.

There are a number of forces that act as well as moment that act on the tire. Of course, there is a longitudinal force, okay. We saw that the longitudinal force is along the x-axis, okay, but we modified it by saying that whenever a tire travels, it may not travel along the x axis, okay. Now the slip angle is necessary to generate what is called as a lateral force. If the lateral force is 0, slip angle becomes 0 and the vehicle or the tire travels along x direction.

So in other words, lateral force is developed because of the slip angle, okay. So we have a, let us call this as longitudinal force that is the Fx force, that is breaking acceleration and so on. Then we have the lateral force which is Fy, okay, which is the result of the slip angle. This, you would see that this is the result of what is called as slip. We will define all these things carefully.

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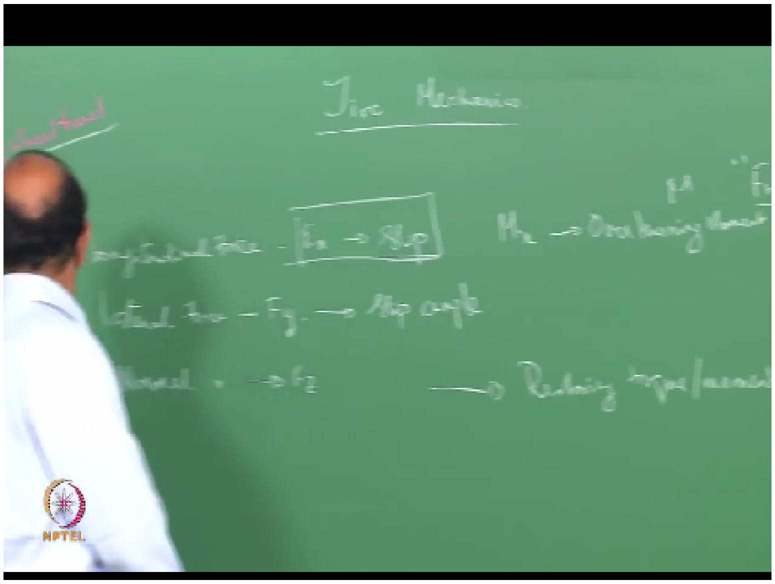

The longitudinal force is the result of what is called slip, very interesting when there is slip, longitudinal force is produced. When I say that, it really sounds, this is what an oxymoron rather that when you slip, what is this that there is a longitudinal force developed, how is that, that is what we are going to see. So there is a relationship between longitudinal force and what is called a slip, what is called slip I want to define that slip carefully as we go along.

So we have a lateral force Fy and that is due to what is called as the slip angle. In other words, when the lateral force does not exist, the slip angle does not exist and the direction of travel is along the x direction. Then of course we have what is called as the normal force. Normal force which is Fz is normal to the wheel plane, okay. That is the ground reaction as we called it in the last class.

All directions have an accompanying moment, okay. So let us look at the Fx first. That Fx force is accompanied by what is called as the overturning moment. I would call that as Mx and that is what is called as the overturning moment. You have a moment which acts along the Ez direction which is called as the restoring torque or a restoring moment. So here we have what is called as the restoring torque or moment and along the lateral direction, there is a force as well as a moment and the moment is nothing but the rolling resistance moment.

We said that that moment or rolling resistance torque is what can be converted into a force, okay, that acts in the x direction. So we said that they are equal, you cannot put both of them. So we said either there is a moment or there is a force. So when we analyse vehicular dynamics, the whole of the vehicle, then we replace the rolling resistance moment by means of the force in the x direction, this is what we saw in the last class, right. So these are the things that happen in a tire.

The question is how is developed, what is the mechanism of this development of these forces, okay, that is what we are going to see. One of you of course no how a tire is specified, okay.

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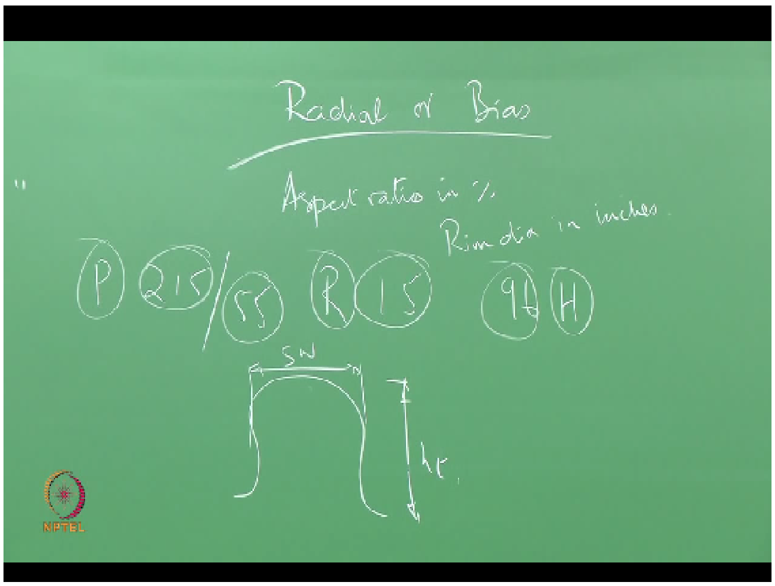

If you go to a shop to buy a tire, you would see that I want to say for example, you are buying a passenger car tyre, so you would say that I want a passenger car tire which is say a 215, okay and you would specify one more 55 or something like that 55 or 65/55 okay. Then you would specify R, okay and then you would specify another number 15, okay. This is what usually you would specify, right.

Sometimes you would go ahead and specify a number, okay and a letter. Each one of them have a meaning. P is the passenger car tyre, 215 is the biggest section width of an unloaded tire. Let us look at a section of the tire, okay. So that is a section of the tire. So this distance, okay, this is the section width, the maximum distance, okay or the maximum width is called as the section width. So you specify that section width, note that the section width specified in terms of mm, millimetre.

Then you have 55 45 65 whatever it is, that is what is called as the aspect ratio and it is in percentage. What is the ratio when we say aspect ratio, what is the ratio? The ratio of the height, here this height which I would call say, Ht, okay, to the section width, right. So it is a height, this height to the section width. So if I have a tire like this, then that is the section width, then that is the height, the ratio of the height to section width multiplied by 100, okay, that is what is called as the aspect ratio in percentage.

Lower the aspect ratio, okay it is called as the low aspect ratio tires, colloquially called as a low aspect ratio tires, 35 is a very low aspect ratio tires. In fact, if you see today many of the high-end cars, you would see that this height, you notice that they are very small, okay and these are low aspect ratio tires. These tires have a specific property or characteristics that it makes handling much safer.

On other hand, ride becomes quite wobbly or in other words, it has an effect on ride, a negative effect on ride and a positive effect on handling. So the low aspect ratio tires are compensated usually by a good suspension system, okay. R is what is called as the radial tire. Today, almost every or why almost all the passenger car tires are radial tires. We still have tires which are not radial in the truck segment, that depends upon the country, for example in North America, you have 90% or 95% of the tires are radial tires or even more.

But where as if you look at a country like India, maybe about 25% of the tires are radial tires and still what you call as radialization is going on where bias tires are converted into radial tires. We will see what is biased tire, what is radial tire again in the next class through some pictures. Just note that 2 types of tires are there, one is the radial tire and other biased tires. We will just see quickly a section and see what is the radial tire, but we will go from micro up, from micro to we will go to the macro, okay.

Now this is 15, is the rim diameter in inches, so that is the rim diameter in inches. Due to some peculiar history or legacy, you have mm combined with inches when you specify the tire. Then you have a load rating, you have a table from which you can find out the load rating of the tire, okay, and then you have what is called as the speed rating. So you have a load rating and a speed rating, okay. A quick look at the section before we go further and explain the micros.

That is a typical section, okay, cut section of a truck tire courtesy JK tyres, one of the leading manufacturers. We have a section of their tires. You would notice that there are a number of reinforcements, okay, there are a number of reinforcements, okay. You would also notice that these reinforcements in this tire are made up of steel, okay, and you would notice there are chunks of steel on either side, okay. Actually, that is what is called as a bead, okay.

So the rim is here, the tire sits on this rim and it is inflated, right. So there are number of parts of this tires, we will explain that in the next class. We will go into the details of what is the material that this tire is made of, how it works and then we will look at the different parts of the tires. The way the reinforcement is done is not, first of all, it is not a pure rubber, it has reinforcements, number one.

The way reinforcements are done, the tires are classified either as a radial tire or what is called as the bias tire. Radial or a bias tire, okay. Though you see that there are all steel radials, it is not necessary that all the reinforcements are made up of steel, okay. Some of the reinforcements, you see here, which is called as the ply, the reinforcements which come here, okay, section of which we will see in the next class, is made up of polyester materials and the belt as it is called, these are the belts, okay, the reinforcements are made up of steel.

So in other words, you can have a combination of materials which can reinforce this. So the reinforcements are basically made up of steel, nylon, polyester, rayon, and so on, okay. Before we deal deeply into tire per se, we will go from the material of the tire, then to the construction of the tire. This is just to give you a background. So let us now look at what are the materials and what or how does it behave, right.

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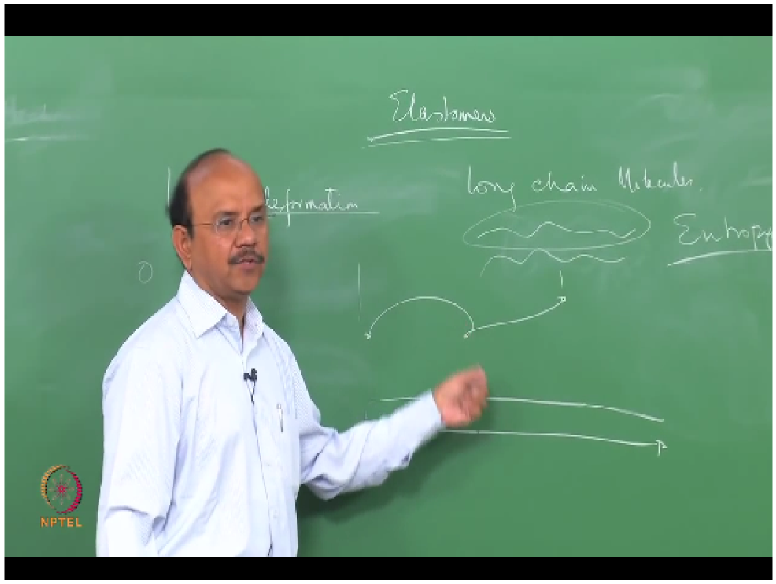

All of them, all the tires which are used in the automobile basically consists of what are called as elastomers. Of course, tires are classified into pneumatic tires which we use all the time or solid tires and are non-pneumatic tires which has very specific applications. But now we are, in this course, we are going to only see the pneumatic tires. So the first thing is that we should understand elastomers and how it helps the tires to develop the forces that are required for it to accelerate, break, take a corner, or manoeuvre and so on, okay.

So we will go into small bits of information which we will collect together in order to understand how a tire interacts with the road. In other words, we will understand the elastomers, we will understand the road, then we will understand how these 2 guys talk to each other in order to develop forces that are required, right, okay.

Now what are these elastomers. The elastomers are basically long chain molecules, okay, they are long chain molecules. Now these long chain molecules are vulcanised through what are called as the sulphur bonds. In other words, these long chain molecules do not exist. It is not that there is one long chain molecule and there is another long chain molecule, like that, okay. They are independent long chain molecules that exists, no.

These long chain molecules are bonded by what are called as sulphur bonds and that is what we call as vulcanization. Now if you leave this long chain molecule, okay, just leave it, it now what happens, it becomes something like a bundle of twine or wool or something like that, okay. It is very interesting to note how they behave independently and how that is different in their behaviour or what is the difference in their behaviour when it comes to these molecules, okay.

These molecular environments have other molecules as well. In other words, it is interesting to know the difference between how one molecule behaves how a number of molecules or molecular chains, okay, they behave, right, okay. Now if you look at one molecule, then the molecule can be like that, let us say that I take these 2 points and then I stretch it, okay.

When I stretch it, it increases, the length increases, okay. What is length, note that that is the original length, we call this as original length. Now when I stretch it, that is the final length. The first point you have to notice, is that this stretching is different from the stretching that you would notice in a metal.

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For example, if you look at steel, steel does not have molecules like this obviously and that the elastic behaviour of steel is due to what is called as lattice deformation. In other words, they have, depending upon the type of steel, the type of structure the steel, let us say that it is FCC and BCC or this is an austenite or is it FCC and so on, okay.

Now when you have the steel subject to a force then the lattice gets deformed and that is what we call as lattice formation and when we leave the forces, okay, the lattice goes back to its original position. So lattice distortions are deformations are responsible for the elastic forces that are developed in steel. You also know that the plastic deformation are due to a phenomena called slip and slip is due to the presence of dislocations and so on.

Look at this, so you have a wire. Say for example if you take the mouse, okay. Let us say that, this is the length from my left hand to right hand, this is the length of this long chain molecule as you see it outside. So now let us see what happens. When I stretch it, okay, look at how much I am able to stretch, look at how much my hand moves. Actually, I am not disturbing the bonds like what I did in the previous case, okay, but what I did was to straighten this out, okay.

Look at that difference. So the phenomena of deformation of an elastomer is different from that of steel and the phenomenon is controlled by with our entropy. Now you imagine that the entropy which you normally understand it to be what, higher the entropy, higher you imagine that very simple way of understanding, entropy is that higher entropy means that there is more chaos, more disorder and so on and so forth, okay.

This is what you roughly understand from your, let us forget about the mathematics. Here we say that it is the configuration which decides the entropy. When it becomes straight, the number of configurations that this molecule, macromolecule can take is limited, okay and so the entropy actually drops. So when I leave it, the entropy actually increases and so it goes back to this position.

So in other words, there is an entropy change that is responsible for the deformation of these macromolecules, okay. So at one level, you can imagine that these molecules are like a spring, okay. So you can say that I will fix it here, I will pull it, when I pull it, okay, it becomes like this and then when I leave it, it goes back to this position.

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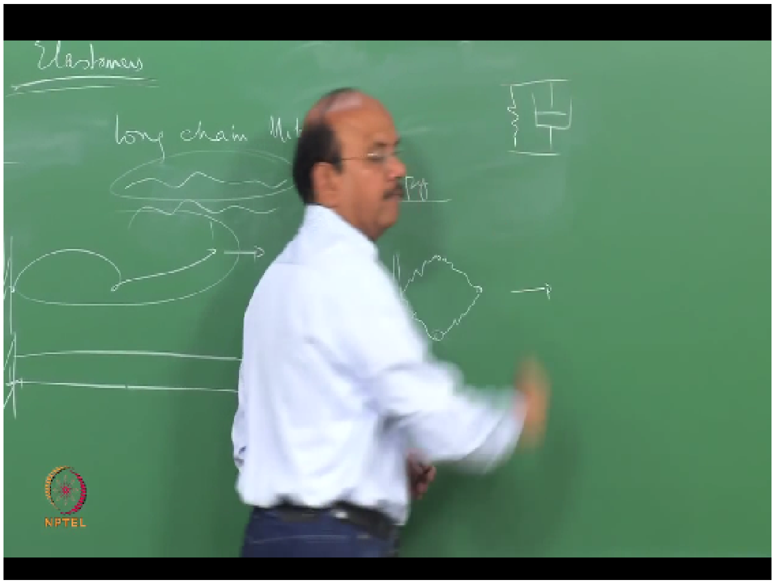

The same thing we can say or imagine the same situation when you have the springs which are bonded by sulphur. So if you have the spring bonded by a sulphur here, spring bonded by a sulphur here, the springs bonded by sulphur, the spring bonded by sulphur and so on, okay. This keeps increasing and so you apply a force, okay, a similar thing happens, fine. So this gives that kind of spring effect. So on one hand, this can be modelled as a spring.

Do not forget that there are long chain molecules, though they are bonded, okay, they are not arranged like happily like that, right. So when they are pulled, these long chain molecules start interacting with one another or with itself and so on, okay. In other words, the long chain molecules have, let us say some sort of a friction, it is actually not a friction, let us say that it is some sort of a friction between the other molecules, right.

So when I pull it, they also interact with other ones, okay and that gives a very interesting effect which is the viscous effect or the dashpot effect. You can, for a moment, imagine that these molecules are in a tube, this is called as a tube model and that elastomer consist of a number of tubes, okay, into which these molecules are placed and these tubes now start interacting and you can say that there is one more, okay the chain as it goes.

There is a tube like that and they start interacting with one another, right. So because of this interaction, I said, there is a viscous part. 2 factors become important in their interaction, one is what is called as the frequency and the other is what we call as temperature.

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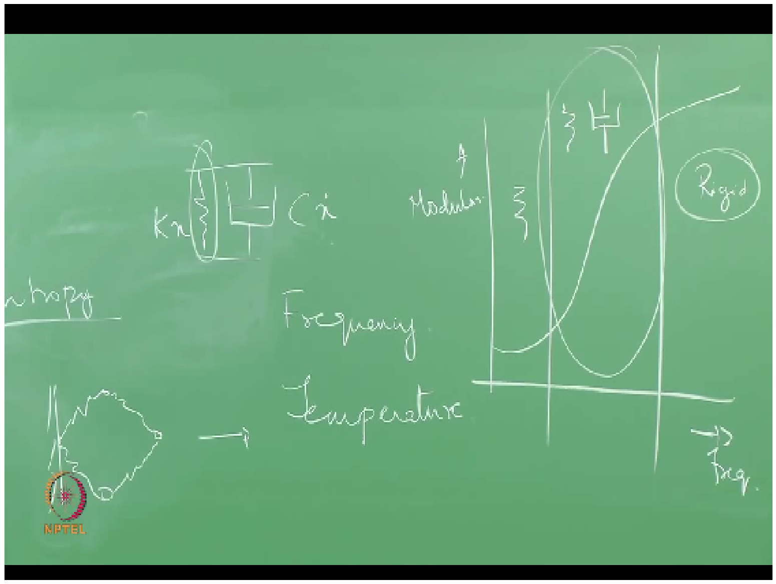

These 2 become important and interestingly, we will see that the mechanisms are similar and hence, there is a relationship between the 2. What do I mean by frequency? Frequency tells me how fast I am going to pull. Let us say that I am pulling it and releasing it. How fast I am going to do this, okay. I can do that slowly, okay and say one cycle per second, 10 cycles per second or I can do it in a very fast fashion, that I can just keep doing it at 10 to the power of 8, 10 to the power of 10 cycles per second.

Now what is the effect of this frequency on the mechanism just we said what we indicated right now that there are interactions. At very low frequency, since we had put a viscous affect which means that velocity has a role to play. At very low frequency, okay, the force that when you apply the force, okay, the chain have the time to react to that force and hence they would react to the force almost in the same fashion as you had applied it.

And since you are going to release the force again in a very slow fashion, okay, it has time to react and come back to its original position. So at low frequencies, the effect of time, I mean the time available is quite large and because of that the molecules have the ability to expand then come back. So in other words at low frequencies, it behaves something like a spring, okay and so all the forces are dumped into the spring.

So the force here is same. For example, a very simple model, the force here Kx, x is the displacement and for a dashpot, it is always Cx., okay. So the forces that act are able to get back or in other words, the whole rubber behaves like a spring. What happens when I increase it. Let us look at the other spectrum. The other end of the spectrum is that I am applying the force at a very high frequency.

So when I apply the force at a very high frequency, then the guy does not have time to get back to its original shape, okay. Because by that time, it gets back, you have applied the force again, right. It is a viscous effect we said. So what happens it would behave like a very stiff material because when you want to release it, it does not come back. When you want to again apply it, it will not again go back, so it would become very, very stiff.

So at very high-frequency, they behave as a very stiff material, okay. So in between the 2, at very low frequency, it is a nice spring, because the guy has enough time to recover and at very high frequency, he does not have time at all to recover, okay and hence it becomes very stiff and in between the 2, it has is a spring and a dashpot effect.

So, if I now plot, say for example, this frequency versus what we call as the stiffness, in other words modulus, how would it be that it will be like this, like this and like that. Here is the spring, here both the effects are there, the spring and the dashpot and here it is quite rigid, okay. Now clear. So these are the 3 affects. So to summarise at low frequency, the time required is good enough for the rubber molecules to come back.

And so they are springs and at higher frequencies, they do not have time and hence they become rigid. On the region of interest in this whole thing, is this, that is our region of interest. If I now plot a stress-strain curve for that region of interest which I would call as the viscoelastic region of interest, okay. How would it look like?

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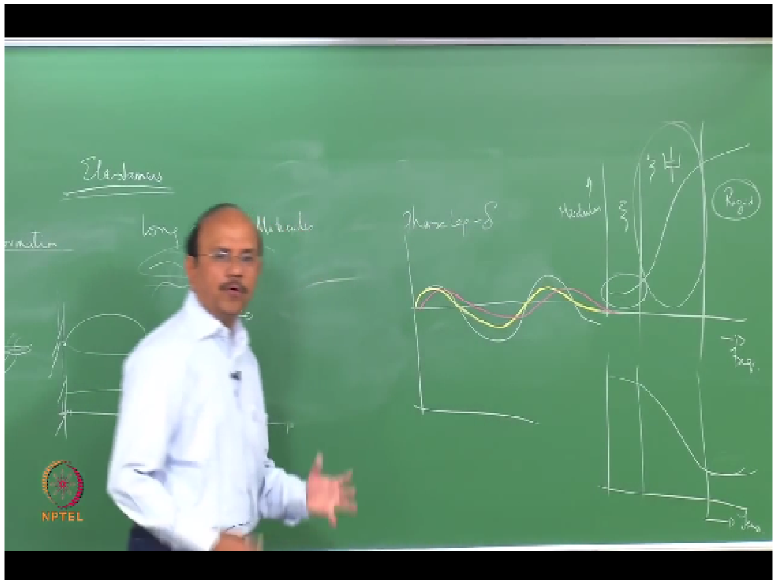

Let us say that I apply stress like this, okay, then the strains do not follow the stress. In other words, if it were to be an elastic material like steel, then so let us say that that is how the strains would be, pressure being the x modulus. On the other hand, here in this material, because of the viscous effect, there is a time delay between the stress and the strain or in other words, there is a phase lag, okay, between the stress and the strain, right.

So there is a phase lag between the stress and the strain and that is a very important, that phase lag is what gives you what is called as the hysteresis and is an important property of the rubber and which gives advantages and disadvantages in the case of functioning of the tire, clear. So in other words what does that mean. It means that when I apply the stress, the strain is not immediately developed, okay. It takes time to develop.

When I release it, okay, it does not immediately get back to its original position. It takes time for him to get back to its original position, okay. So this is a very important property which we will see more and more. We will recall this phase lag as delta, okay, this is the phase lag, we will call this as delta between the stress and the strain, right. Now let us look at the effect of temperatures and then get back to this again.

The temperature has just the opposite effect. When the temperature is high, the temperature aids these, let us say I am fixing the frequency, I am taking the temperature to be high. What would happen when the temperature is high, then it aids in the recovery of these molecules to its original shape and hence it would behave as if you are at a low frequency.

So if I now plot the temperature, at high temperatures, since it aids the molecules to recover, the modulus would be something like this. At very low temperatures, what would happen at very low temperatures, just the opposite, okay. The molecules are under difficulty to get back to its original position. So the modulus is high. Intermediate temperatures, the modulus is between the 2.

So if you compare this graph with this, you would notice that the temperature effect is the inverse of the frequency effect, okay. That is the inverse of the frequency effect. We will see that there is a relationship between the 2 which is called as the WL of relationships, okay, right.

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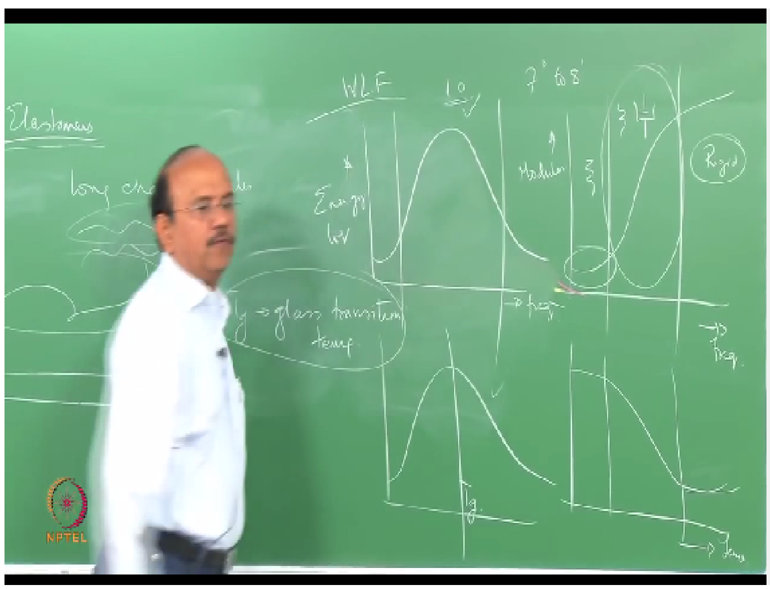

Now if I now plot for that frequency effect, let us say that I plot for the frequency effect, the energy loss versus the frequency, then the curve would look something like that. There is a region which is that central region, at which the energy loss is high, that is that region, okay, and that is the region at which we are going to use our tires. The same case, temperatures would also look something like this, right, clear, okay.

So the temperature also would have the same type of behaviour. There is one particular temperature of interest which is called as the glass transition temperature, popularly denoted by Tg. So Tg is the glass transition temperature below which the material is vitreous and above which, that is this region, above which the material becomes very soft, okay. so the glass transition temperature would obviously depend upon the frequency because both of them have an effect, right.

In other words, if I do a test at one frequency at A temperature and I now do with that same frequency at another temperature, the effects would be different, vice versa. If I do a test at one temperature with 2 frequencies, again the effect would be different. So there is an interaction between these 2. In other words, there is an equivalence between the frequency and the temperature. The equivalence is inverse.

So it is usually said that when the frequency increases by a factor of 10, there would be a change of temperature to 7 to 8 degrees. **“Professor - student conversation starts”** What is this change. When the temperature would increase or decrease, when I increase the frequency, what the temperature be, increase or decrease. Decrease. Decrease, okay. **“Professor - student conversation ends”**.

So you go this side in frequency, you would come the other side in the case of temperatures. There are equations for this and these equations are given by Williams, Landel and Ferry, this WLF equations. We will not go into the details, but we will understand this more physically, okay.

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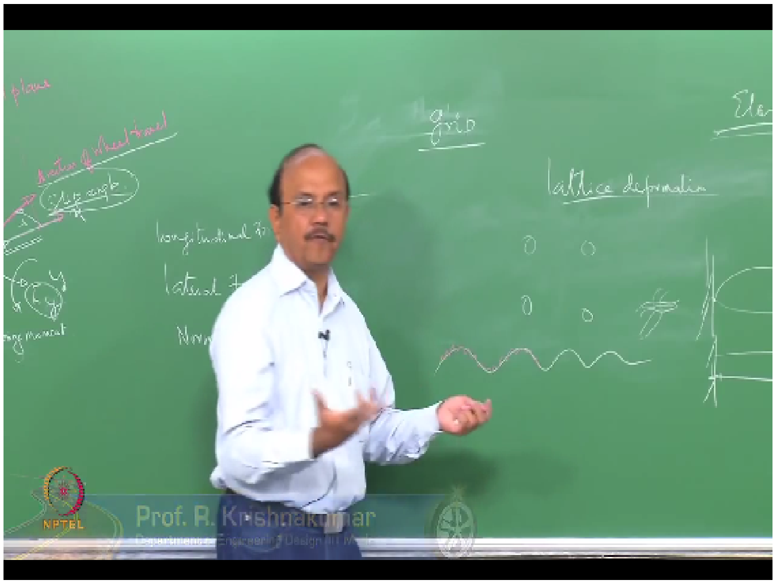

Now why are we talking about this. How is that the behaviour of an elastomer helps in the development of I say grip, that is the first question which we are going to answer. In other words, let us define what is meant by grip. So we are now going to the micro level. So in other words what we are trying to do is, we are now, that is the section and let us say that this is the tire, we are now going to go and sit at the interface between the rubber and the road and understand how this concept is going to be applicable at that circumstances.

One of the things we know about the road is that the road has what are called undulations. The undulations can be looked at from a macro viewpoint or it can be looked at from a micro viewpoint, right, okay. How does this rubber interact with the road is our next question? Given that we have these 2 kind of roughness, okay, that we will see in the next class.