Machinery Fault Diagnosis and Signal Processing
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Lecture -06
Engineering Applications of Vibration

This lecture is on engineering applications of vibrations, so far we have studied about the basics of engineering vibration. Today we will see in this class what are the basic engineering applications of vibration and towards sometimes in the middle of the class we will see how vibration is used for the health monitoring of machines or condition based maintenance of machines ok.

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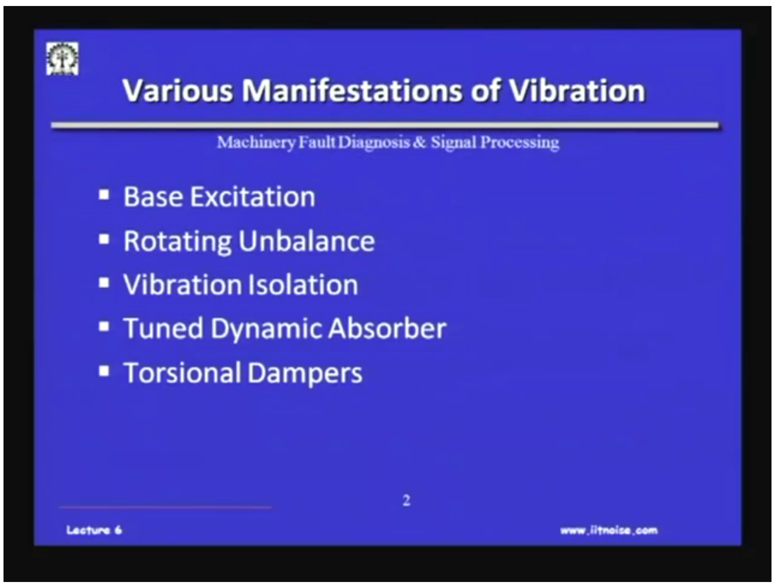

Some, of the topics which we will be discussing today are essentially what happens during the case of a base excitation.

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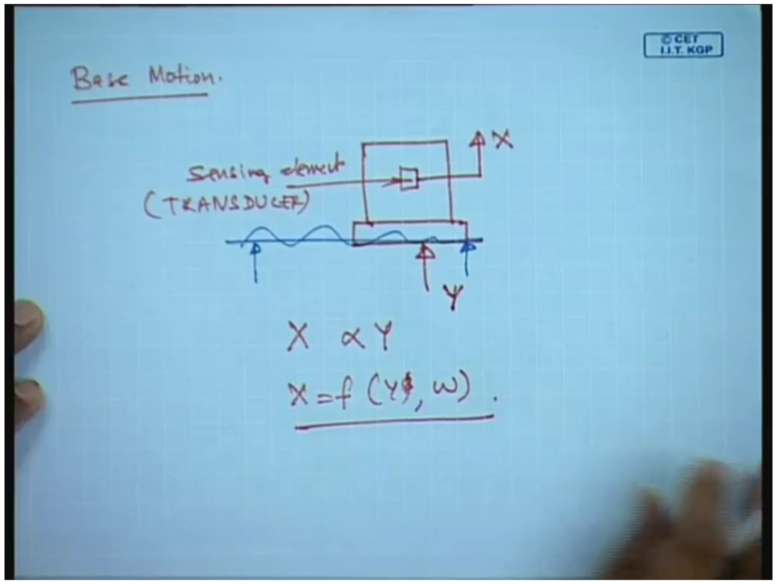

For example if you have a surface and because of certain forces there is a motion on the surface and how by putting a sensor you can measure this motion Y and sense it as a response X of the sensing element. In the base of this motion, easily and typically when we have a vibrating surface we try to know what Y is, how do you do that we put a sensing element X or what is it which will be essentially housed in a transducer.

So, it is personal to Y or what is the relationship between X, Y as a function of the frequency etcetera okay. So, once I can measure X, I know how it is related to Y okay and that is what we are going to study in the base excitation.

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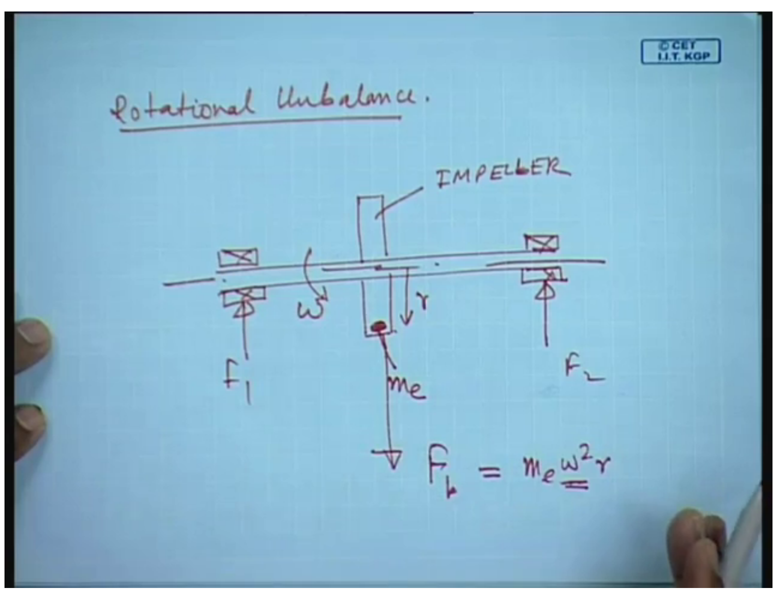

Another very important applications of or unwanted vibration is this rotational unbalanced. Essentially what we have is any shaft which is supported on bearings. Suppose it carries a set of blades like in an impeller and if this undergoes rotation, imagine in this impeller if there is an unbalanced mass m or m e this unbalance was at a radius of r from the axis of rotation of the shaft.

You can imagine the unbalanced radial unbalanced force F unbalanced will be m e Omega square r where Omega is the speed of rotation. Now you see this unbalanced force because of the centrifugal action of the unbalanced mass is proportional to Omega square, Omega is the rotational speed it is almost very small if m e is small r is small and Omega is small but even if m e and r small but Omega is large.

Like in the case of gas turbines now rotating at 30,000 rpm a small amount of unbalanced mass is going to give rise to unbalance force and what will happen essentially is because of this unbalanced force there will be forces coming up to this bearings okay. That dependence this F1 and F2 depend on the position of the impeller and so on and further this will be complicated if there are sets of impedance.

Like in a gas turbine as you will see there will be different stages of compressors. So, one set of compressor having a lot of vanes in that impeller. And if one such vane has an unbalance it is going to lead to unbalanced force and this unbalanced force in different planes is going to give rise to couples and then this is going to have a complicated effect in the life of the machine. It is going to affect the bearings; bearings will be subjected to fatigue failure.

There will be clearances will increase and it is going to complicate the matter okay. So, we should try to avoid this problem ok.

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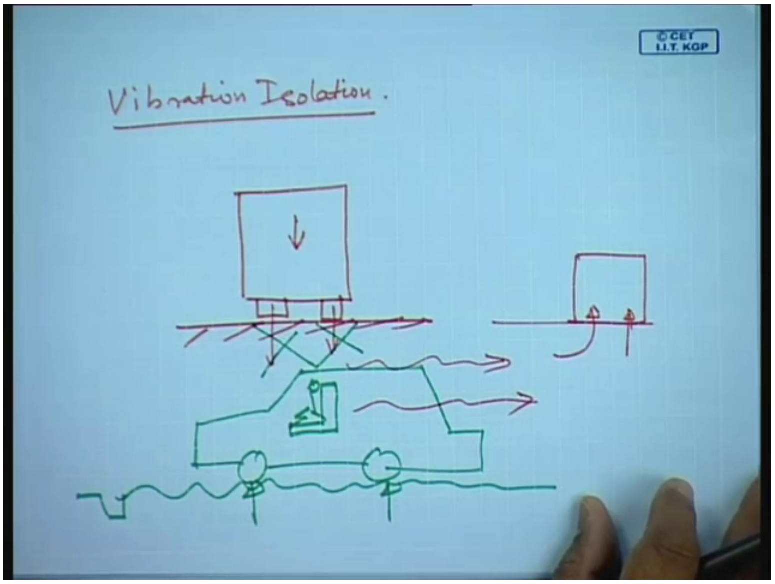

Now another situation we have in the engineering application is vibration isolation. Where in suppose I have a machine which is put on the foundations because of the dynamics of the machine certain forces are being subjected to the ground and this ground is going to then vibrate and this waves will get transmitted and then at some other place I have another machine and they are going to affect this machine's operation.

So, I have to devise a mean wherein I reduce this energy which is getting transmitted from one machine to another, this is one way of looking at it. The vice versa also happens for example you are driving on the road on a vehicle and there are a lot of roughness potholes etc. So, these are going to give rise to forces okay. And these forces are going to get transmitted and then you are going to get a sense of vibration to the human being who is sitting in the car.

And obviously we would like to isolate this frequency which is coming from the ground this motion which is coming from the ground by a proper selection of what is known as the vibration isolators. We will discuss about them in subsequent sections. So, the vibration isolation is another serious problem in engineering a vibration and then we will see how we can avoid it, how we can reduce it and so on.

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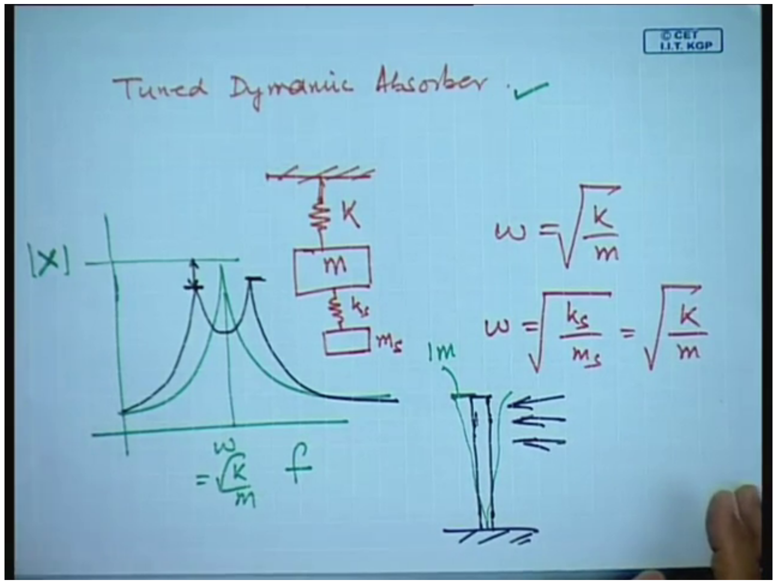

Another application of vibration is this Tuned Dynamic Absorber, what happens suppose I have a body suppose I have a body which has a mass m and stiffness k, so, Omega = root over k by m okay this is the primary; this is its natural frequency and this is the primary mass. Now this system if I see the response of this system I will get a natural frequency response at its natural frequency which is omega = to root over k by m.

And say for example this amplitude X which I have got here is something which I do not like I would like to reduce this vibration amplitude. So, what I could do is I could attach to this system another system wherein this Omega is also equal to its ks and ms. so, this system now is going to have a response which will look something like this.

Because there are two bodies there will be two natural frequencies and there will be a natural frequency shift. And most important thing is this amplitude of vibration has reduced. So, the primary mass though the natural frequencies have shifted then but the amplitudes of vibration has reduced. And particularly this has applications in for example large skyscrapers for example because of the wind blowing you talk about the tall hotels in Dubai or the skyscrapers of New York or San Francisco etcetera.

When this wind is blowing these skyscrapers have a motion I mean and this at the top could be about 1 meter imagine are a hundred storeys building on the top it is swaying about 1 mete. And this kind of motions could be arrested suppose we put such structural tune dynamic observers in the structure itself. So, that they are going to arrest these motions and reduce the amplitude of oscillations. This is one application of tune dynamic absorber, lot of applications of such tuned dynamic absorbers in automobiles.

For example if you know the drive shaft or the propeller shaft propeller shafts also undergo a lot of torsional oscillations. So, we can put such torsional tuned damping absorbers to reduce those oscillations at the natural frequencies, because by tuned dynamic absorbers we can reduce the oscillations of the primary mass because of the resonant frequency of the secondary mass.

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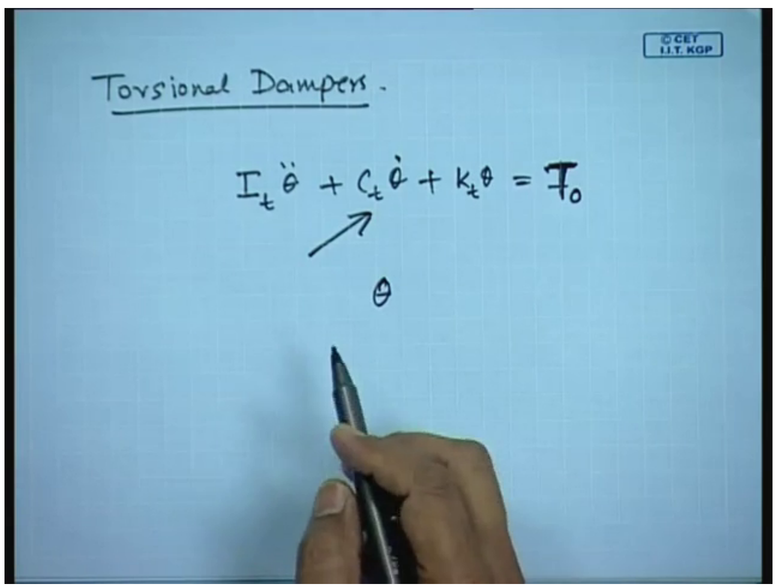

Another engineering application is this Torsional Dampers you recall you know I had written this equation I t theta dot + Ct theta dot double dot sorry Kt theta is equal to some function, forcing function, torque. So, by introducing this damping term in oscillating systems by having a torsional damper I could reduce the oscillations of the rotational response of the system.

For example the crankshaft of an engine which is under here which is having rotary motion and its torsional oscillations could be reduced by putting a torsional damper. So, these are the some of the applications and we will see some practical examples now.

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To begin with if I look into this case here, in the case of a tractor platform isolation here we have a tractor. For example of course this is the platform where you put the foot in case this is a mean my younger days you know ways to test on a tractor. And this is a platform here and if the driver sits here because of the engines dynamics okay.

None of the vibrations from the engine should get transmitted to this platform to seat etc. so, how do they arrest that if you will look closer here there are actually what are known as the anti vibration rubber mounts in this location here between the platform and the chassis of the tractor. The chassis of the tractor is actually supporting the engine.

So, the forces from the engine because of the engines excitation and engines acceleration forces and the inertia forces the engine excites the structure. So, this chassis is going to have large motion and if this platform was rigidly connected to the chassis it is, it all this energy is going to get transmitted to the platform. Instead we put a flexible element you can think of it as a structural fuse or you can think of it as a structural impedance mismatch.

The energy which is analogous to an electrical circuit, if I put an; if I have an impedance mismatch in the system the current is not going to flow. And the power flow will not be at maximum, and same is happening here also. The mechanical power flow is reduced by having an impedance structural impedance mismatch which is created by this vibration isolator.

So, depending on the payload being subjected to the isolator depending on its mass the frequency of operations. I can decide on the natural frequency of the oscillator. I can decide on the stiffness characteristics of this oscillation of this oscillator, this is another such view of this Isolators. And these Isolators just need not be elastomeric or a polymeric amounts.

They could be also spring mounts because you know this elastic mounts they wear out with time the elastomers sometimes they react with the oil and they lose their property. Sometimes they react with the saline atmosphere etcetera around you and then they will lose their structural stiffness and their bonding strength.

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So, sometimes in many harsh applications people use ah other kind of monster, I will come to later on. Now this is the case of a gas turbine you know where in there turbine rotates at about 30,000 rpm and then there are series of such impellers which will be the compressor and then the turbine. And this compressor there could be many such blades in the veins in the impeller.

And if one such set of compressor ring undergoes an unbalance it is going to give rise to a radial force. Suppose another one has another amount of unbalance it is going to give you a radial force. So, there could be a couple, so in this couple this is there going to give rise to a lot of forces though this turbine is put on a structure here on a platform and this platform is rigidly mounted to the hull of the ship or fixed to the wing of the aircraft.

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So, now this is a closer view of this compressor imagine this all of these rotate at 30,000 rpm or 20,000 rpm. Imagine if one such vane either has a small amount of unbalanced mass, you can imagine the kind of forces which are coming on to the bearings which are supporting them. So, on unbalance at high speeds is very, very dangerous.

And in fact this amount of unbalance depends on the severity of the machine suppose. It is a very high speed machine will have serious consequences. So, reliable you are talking about the high speed machining operation where we have a spindle and there is an amount of unbalanced mass on the spindle suppose. You are doing a vertical boring and if there is an unbalanced mass and because of this there are radial forces you will never get a true bore okay.

So, they will be overlaid on the bore, so all these are going to affect the performance of your output of the machine. It could be a machine surface, it could be an gas turbine, it could be an effect on the it will affect the bearings. So, these are actually the causes by which the machines fail or the reasons behind which machines fail. If one such unbalance goes unnoticed and we only get woken up when the bearings fail.

But the problem could happen usually has created this. So, it is very I mean people do that once they install a machine they ensure that the machine is balanced perfectly tool it's operating speed. And in the subsequent classes I will also be telling you how to do a field balancing of such a large gas turbine or a fan which is rotating and rotating at high speeds.

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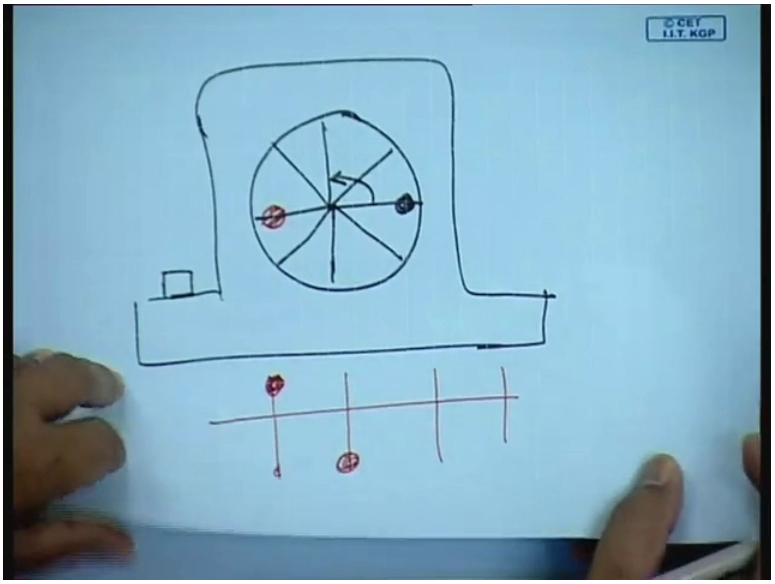

Basically you know what happens I should briefly tell you here in the radial plane for example if this has lot of; you can call it vanes, blade whatever if there is a small amount of unbalanced mass and this is rotating. And in this machinery and this of course there in the casing etcetera, okay. And I measured this response here by some technique. If I can find out this amount of unbalance and if I know the location of this unbalance physically with respect to put a certain marker in this well.

I could put a correction mass okay in a single plane and then I will have a balanced rotor or a balanced disc. But if there are multiple such disc along as along the length of the shaft I have to make sure that each one of them is balanced.Otherwise I have a balance here okay if I have a balanced mass unbalanced mass here and a balanced mass here, I may be balancing it in one plane but the couples will still be there. Now this is also something which we have to be careful about.

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Another application or I should show you this anti vibration mounts, for example this is a set up from our lab. When you have the system running there will be lot of forces coming on to this structure. And this structure will eventually transmit to the foundation. So, these are what are known as anti vibration mounts. You can see one mount here, another mount here, so imagine if next to this machine, I had a very sophisticated laser based measuring systems okay.

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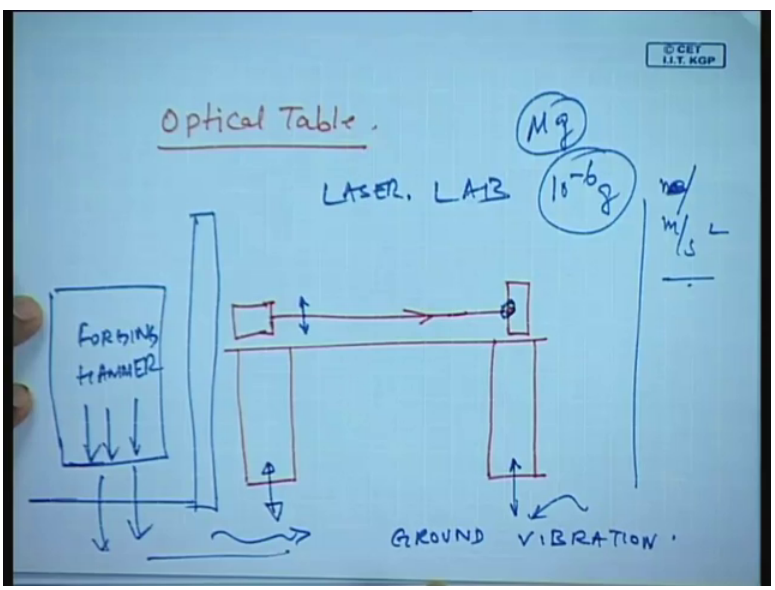

Optical tables were in, now this is the table okay and there is a laser beam being produced and then it has certain target which it has to hit or strike. If there is a small amount of oscillations because of certain ground vibration, so what is going to happen? That this source is also going to have a motion. So, I can never hit my target by laser beam and there are many engineering applications wherein lasers are used.

Lasers are used in nano microscopy, lasers are used in machining, lasers are used in surgery imagine if such laser beam mean if imagine a doctor coming to your eyes to do a little laser surgery and his hands are shaking okay. And bring it back here in an optical measurement table because I have a hard; imagine you have a larger forging hammer in your workshop next door okay.

Of course you have made a nice building and then there are nice walls etcetera. So, the workshop and then you have a lab here, here being a laser lab okay because of the forging hammer a lot of forces are coming and then these forces come to the ground. and then this are going to get transmitted through the ground and then the laser.

And this is a not a science fiction it does happen there has been instances in a way where I have a measured vibrations of the level of micro g. Micro g is 10 to the power minus 6g okay. In fact wherever when we have laser based measurements the vibrations have to be less than 10 to the power minus 6g okay meters per second square or whatever that lower vibration level okay.

But question is how do I achieve it suppose I have been forging hammer next to it or I will try to give you a more realistic picture. I had visited a lab where we are doing some oscillation selector for a laser machining a laser measurement system laser microscope to be precise. In this building there was an elevator each time the elevator was going up and down the shaft they were having problems in their laser based measurements.

Because you know once we have an elevator going up and down the shaft because of the elevators movement the vibrations were getting transmitted from the elevator shaft through the foundation to the laser lab ok. And the measured vibration levels were even 10 to the power minus 6g and that is small enough to create problem in nearly the best measurements ok.

So, as an engineer as the vibration specialist we have to decide among what is known as this Isolators. Isolaters is both for motion and both for forces because then you think about earthquakes when earthquakes occur why do buildings fall because excessive forces have come to the foundation ok. So, we have to design and decide on Isolators.

Vibration is the motion is one, next thing I will talk about cases when we have impulses nuclear blast shock waves ok. What happened when we have shock waves, what happened when we have a missile firing on the deck of a ship ok? So, how do we address that the ship should not rock ok, other electronics and the in the equipment in the control panel should not get affected.

Because once we have such shock waves coming in they are going to give rise to fatigue loading. Shock coming once or coming twice repeated shocks they will induce fatigue load on the machine and then the structural components maybe the electronics holders would fail. Imagine a printed circuit board ok wherein we have lot of solders and this printed circuit board is kept on a platform where in very close to it you are firing on the side.

And there is no protection to arrest the vibration because once we fire this missile and these forces are going to excite the solders and solders will give away eventually ok and then we all have a component failure. So, the reliability of the equipment has to be and so also ensure that they do not fail under repeated shock loading, repeated forces, repeated motions, so this has to be also ensured.

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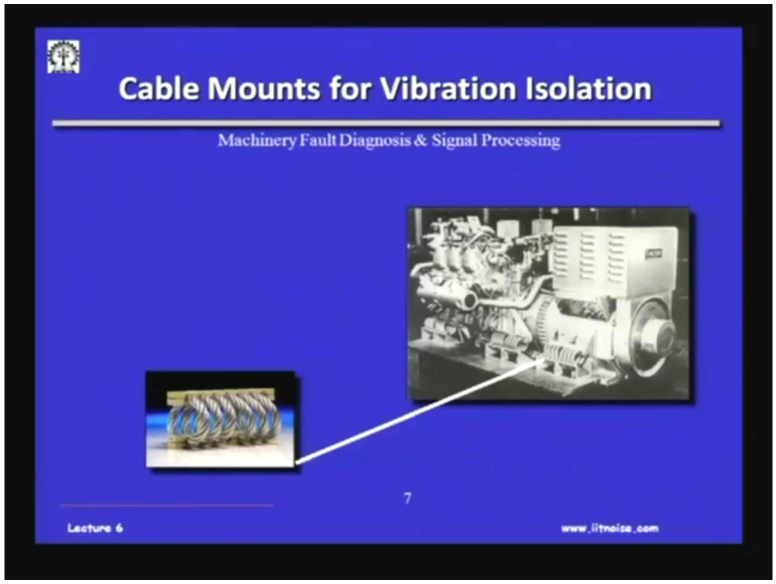

I just another one example which are talking about and you must have seen this, when we have this generator driven by an engine. And because of this motion of the engine because engine itself because of the inertia forces and the gas forces are going to have only you must have studied in your dynamics of machines that some of these forces are not balanced ok. Whatever we call a perfectly balanced machine.

But then there are some orders at which balancing forces are there and these forces will also excite the foundation and this has to be isolated by I could have elastomer mounts. But nowadays you know people are using cable mounts you know this cable mounts it can flex in both directions longitudinally, transversely. So, it can take up forces in any direction because if I was talking about an anti vibration mount which you will see.

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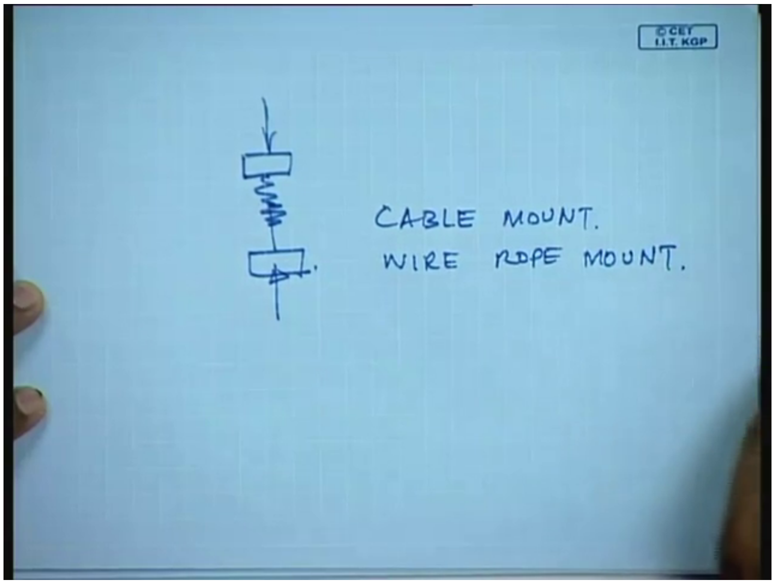

That the mount which we have is usually in one direction say okay. But suppose the motions are in three directions it becomes very cumbersome to put you know three Isolators in three directions rather the convenient way of doing it is through cable mount or sometimes in people also known as wire rope mounts. Because of the fact that there are no elastomers here, so they can be subjected to weather conditions.

And in a saline atmosphere in an oily oil mist full at atmosphere, so, they will not wear out with time and because of these are made of high stand stainless steel they will not corrode. They can take more loads for the same available space. So, cable mount is people are particularly in the defense they are using a lot of cable mounts because it can serve a lot of harsh environment.

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This is another case of a missile launcher and then here you see again the cable mounts have been put here and such a system could be put on the deck of your ship. Then once you have the missiles firing none of the motions are going to go through the deck to the other systems in the ship okay. Because you know you will see we will be doing some numerical, how to do we calculate the stiffness? How do we estimate the damping? How do you estimate the payloads of the mounts?

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Well this is from a catalog of a manufacturer of Isolators; I will just show you some of the examples here. These are the normal helical Springs which are used as mounts and some of these are actually pads where they are in there are pockets here. So, when you compress them they are going to flex in and take in the load. These are the cable mounts.

And these are some of the conventional spring helical mounts and they could be a series of such springs and then there could be damping associated with damper associated with it and so on.

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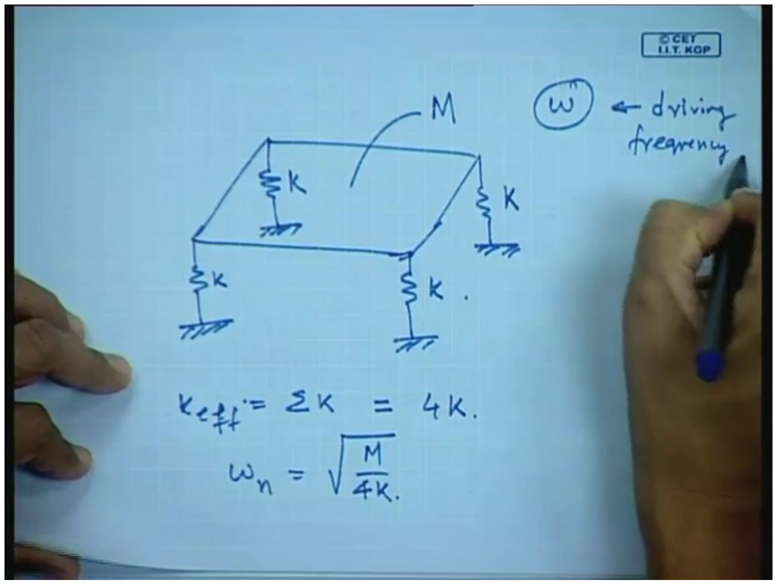

I will now give you a typical example as to say for example I have a machine, I will just draw the base of the machine and suppose it is put on four Isolators. And then there is this machine has a certain mass m and each one of them has a stiffness k, so, springs and parallel the effective stiffness is nothing k effect is nothing. But summation of the case and this will be four k's okay and the natural frequency of this system will be M my for K okay.

Now imagine the question is what is the motion of this? or the vibration which is transmitted to the ground because of this system. And this system say for example it is rotating at a certain speed Omega there is the rotating component which is rotating at the speed Omega and we known as the driving frequency.

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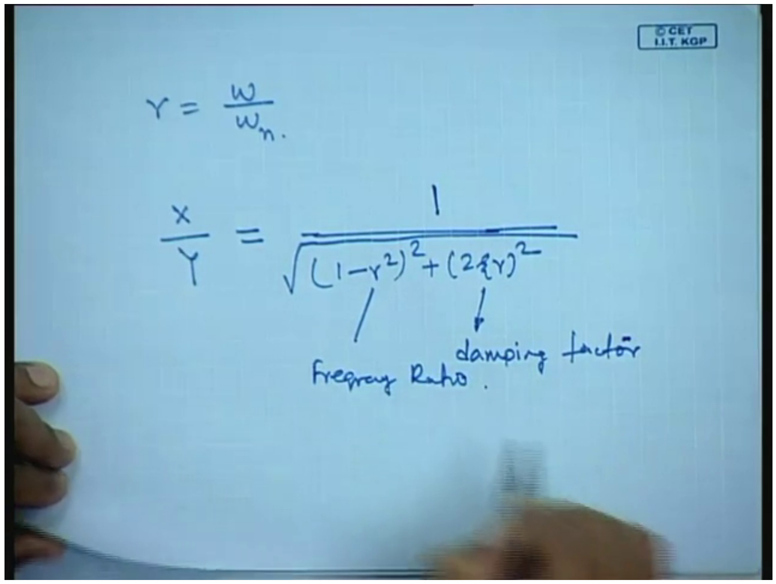

So, we will define a ratio r is equal to Omega by Omega n, so the ratio which is transmitted on the displacement is actually given by where Zeta is the damping coefficient factor and r is this the frequency ratio.

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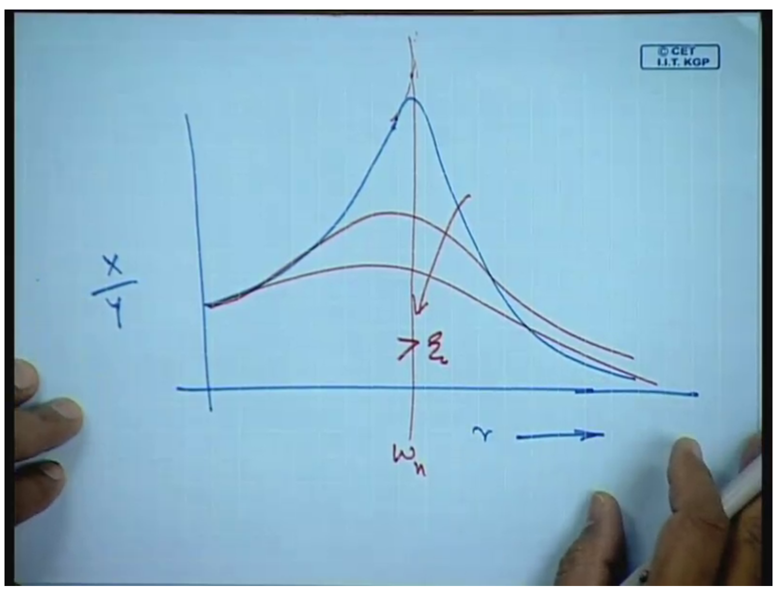

Now if I plot this what happens is if we look at the typical recent response plot? Now if I increase the; if the damping reducer is very less, what happens is this amplitudes go up okay. And if I increase the damping okay, so at t resonance I can always reduce the motion vibration motion by introducing damping okay. Now how is that done actually we can there are many ways to introduce damping.

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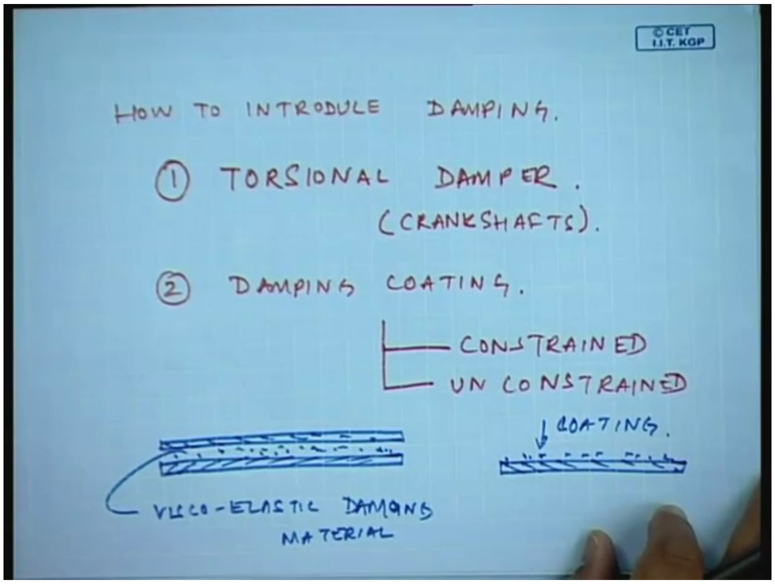

In rotational systems they use what is known as torsional damper particularly in crankshafts of engine another is by damping, coating or sandwich beams and they are both constrained and unconstrained. So, basically if I have a surface, sheet metal in the constraint layer damping, what I could do is I could have another thin structural material. And here I will put a visco-elastic elastic damping material.

So, because of the relative motion of these two members there will be an hysteresis loss. And then the energy will be damped the energy will be reduced and then the oscillations of vibration will reduce this is one. Another is just coating with the unconstraint. We just pay coated with a damping material which is known as the kind of a coating commercially of damping paints are available to measure such are to put on the structures to reduce the motions at resonance.

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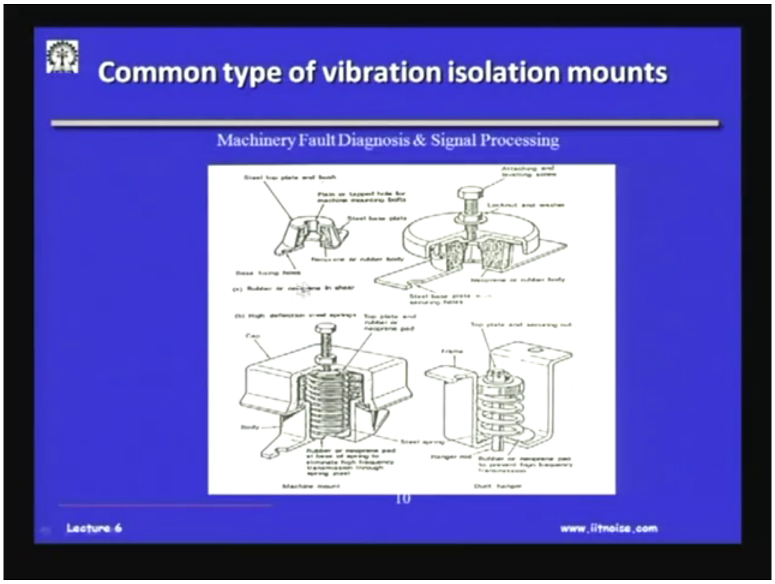

Coming back to this figure here so this is how the structure of the internal of vibration isolator looks like. This is a steel base plate and here there's a neoprene rubber body which acts which gives stiffness and sometimes also gives some inherent damping in it and so one component of the structure is attached to the base.

And another component is attached to the top and same is true here wherein we have the neoprene pad or rubber pad on top of it we also have an helical spring. So, depending on the payload we can; if the payloads are more we can have a bigger helical spring if the payloads are less even sometimes the pads are good enough to take the payload okay.

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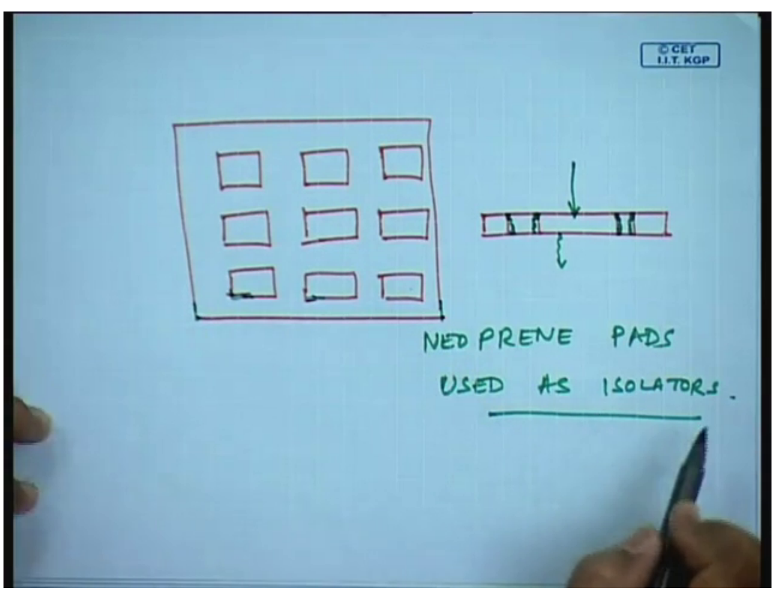

And as I am telling you in the previous diagram some of these pads they have what is known as they are not a thick rubber sheet instead there are pockets. So, what happens when there is a load because of this pocket if you look at the sectional view? So, I am just drawing say two pockets they will flex in so because of a load they will try to move in okay and then try to take the load and then try to because we have to arrest motion.

So, they will flex and take the motion and then less will be transmitted so such are the neoprene pads which are used as used as oscillators.

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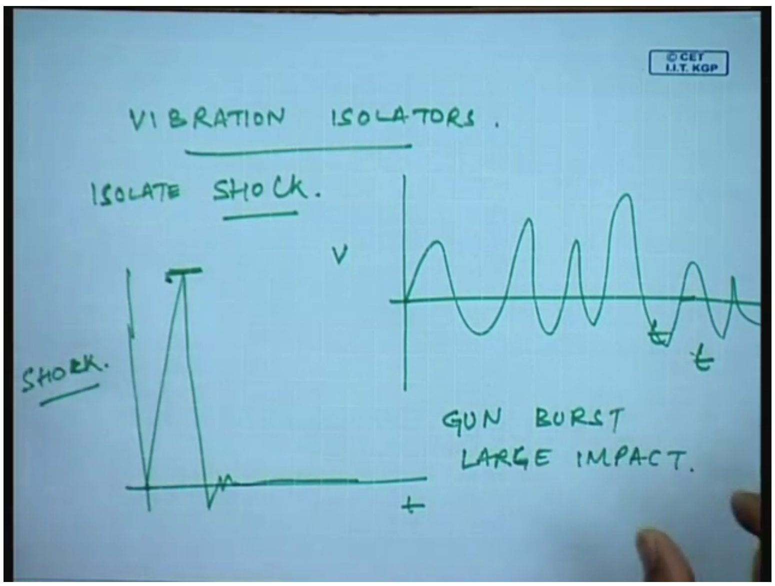

Now such vibration isolators are sometimes used to, in engineering to isolate shock. Now what is shock? For example you know you would have studied about the vibration where in the time domain I have a series of you know I can break them into in time domain and there will be lot of frequency components of such a time history of the Virgin signal. But a shock on the other hand is a large motion occurring for a fraction of a time okay and this amplitude could be very, very high.

For an example an impact like okay like a gun burst large impact they happen only one in a given period of time they are not repeatedly we never have repeated shots. For an example a large earthquake initial wave is a shock. So, such shocks have very, very large amplitude so immediately what happens, the how we isolate this suppose if a subject my equipment to such shocks they are going to get damaged because of this high oscillations.

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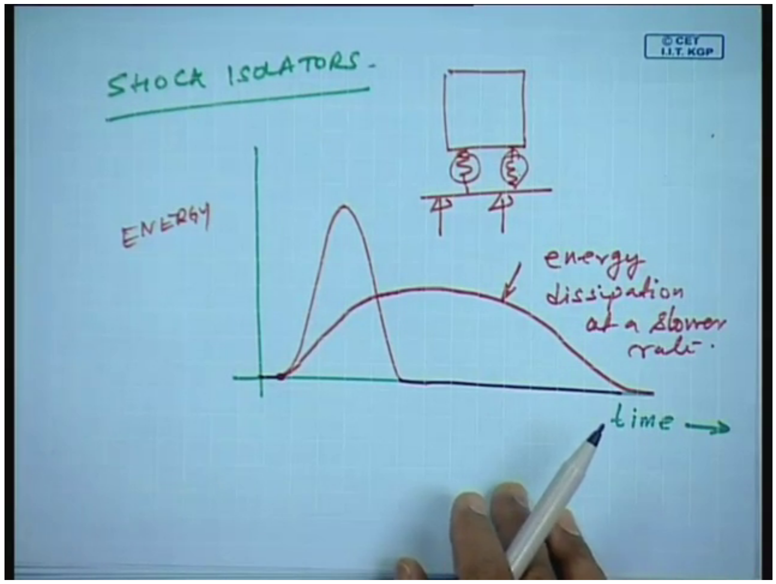

So, in such a case what if you look at the energy point of view in shock Isolators look at the time. I will; the energy is like this to begin with, in shock isolation we try to reduce the and this energy there is no Isolators this energy would straight go into your component and damage the component. So, in shock isolation what we do through this oscillator try to take in all that energy and it is the same energy.

But dissipate it at a less, lower amplitude with a longer time, so, the energy you know the area of these two curves should be the same. So, energy dissipation at a slower rate okay, so, if I have a very fast moving object shocks are coming here, so this Isolators are shock Isolators actually try to take this energy and then the same energy goes into the system but at a reduced amplitude. Because I cannot eat up energy and has to anyway going.

But I will give it at a much slower rate, so, this is how because how does that happen this happens by having provisions for this, Isolators to flex to move. Unless they move they cannot take up that energy. Instead if they have a rigid connection everybody everything would go in, so, this is a soft connection here, this is the soft connection here okay.

So, they will have low motions and sometimes this cable mounts are also used in shock isolation system but we just saw the example of them as a missile launcher. So, such foundations are also put with cable mounts which also act as shock isolators okay. In, of course you know this is not a class in vibration because you know in engineering shock and isolation or vibration isolation is a course by itself and I am sure the teacher must be covering all this there.

But this is of course on a condition monitoring and the reason behind telling this is once you go to the machines to do CBM it will invariably come across these elements and we have to do measurements around these elements. Because these are the elements wherein the energies go in and go out okay. Because of an unbalanced I will see the forces coming at the bearings. Because of a forging hammer I will see energy coming into the system at the Isolators okay.

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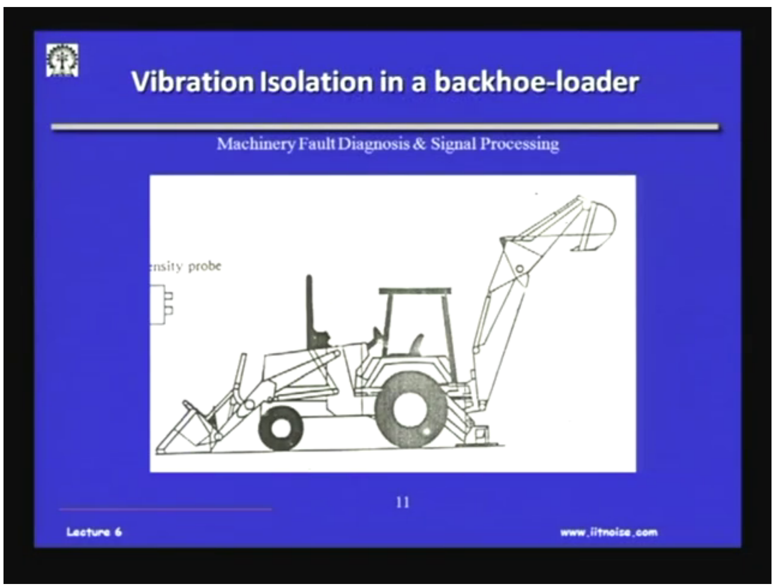

So, this is another example which I will use on a backhoe loader okay typically a backhoe loader or a truck. Essentially there are two strong components one in this engine and the chassis and if you observe and this is the unit where the operator or the driver sits and this is a cabin okay. And invariably now this construction equipment be it a bulldozer, be it loader they are always subjected to harsh vibrations because of the terrain.

Because of the work nature, because shovel, have to etcetera, so, this poor operators are really subjected to very harsh levels of both vibration and noise. So, these cabins you know them may look very robust but they have to they have actually supported on four mounts. And again our vibration Isolators come into play there and want us to decide on good amount of our so naturally.

This is one example we are talking about say a truck you almost have seen a truck going on the highway but the cabin where the driver sits actually sits on the chassis and this cabin is actually mounted on the cross frames or the cross frames and the longitudinal rails at four mount locations. So, no matter what comes through the road because of the pot holes because of high speeds, because of undulations on the road.

All this motions would normally come into the driver or to the driver seat. Imagine I will just give story here. See, these the driver gets excited by a forcing frequency and if you think of a human body as a mechanical system, the internal organs are supported in a fluid and then they oscillate. So, these internal organs also have a natural frequency and this natural frequency is about 2 to 5 Hertz very low frequency.

But imagine from the road if I have a forcing frequency of 2 to 5 Hertz's coming into the seat on which the driver is sitting then what is going to happen the driver is also going to have a resonant at 2 to 5 volts and the driver will have a nauseating feeling and maybe he will fall sick, he will throw off. And I am sure all of you must have experienced this while going in those in a state transport buses where in the there is not good amount of isolation through this seat and the bus floor.

We are almost rigidly bolted you would have noticed and then you will be saying people feel uneasy when long distances and such buses. sOn top of it if you think of the luxury buses nowadays when there are a good amount of cushions in the seat go to amount of isolations they reduce this energy coming in from the road and affecting the passenger or the driver.

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So, I will just show you one example here in this backhoe loader here this is a particular case wherein if you can see this, this actually this yellow one is the chassis of the cab ok and are the backhoe loader and this is the cabin. And this is the isolator it is nothing but a thicker rubber pad and here we are actually trying to measure the motion these are the accelerometers which are used to measure the motion of the chassis. This is in a particular direction.

This is the transfer this is a longitudinal and this is the vertical direction and there is another accelerometer here to measure the response at the mount location on the cab side. So, the effectiveness of this oscillator or the vibration transom stability can be checked by seeing the ratio of these of the difference within these two levels. And this difference is large then this oscillator is doing a good job, so, this is how the Isolators are actually evaluated and then we can also design as to what kind of isolators is to be taken in.

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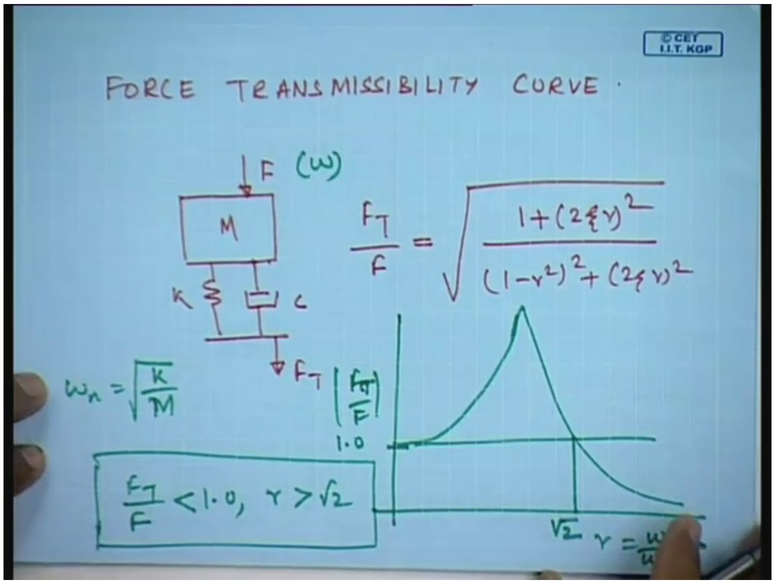

And if you look at the force transmissibility curve suppose I have a body which regenerates and force F and there are certain stiffness damping etc and this is the transmitted force FT okay. If you calculate this force transmitted to the applied force this applied force or the force which is originating because of the dynamics of the machine is given by okay.

And if I was to plot this curve where r = Omega by Omega and Omega n = K by M and Omega is the forcing frequency okay. So, this is 1.0, so this is FT by F and this is a plot and this value is root 2 okay, no matter whatever is the damping. So, at a frequency of Omega by Omega or Omega is equal to Omega n by root 2 or more so that means if the frequency of driving frequency is more than the root to the natural frequency.

The force transmitted will be less than the applied force F. so, the FT by F will be less than 1 for r greater than root 2 and this is a very, very fundamental design equation which all works and designers work with and so we can decide on of course in all these; because somebody asks you estimate me the values of k and c to be used in this machine where this machine operates at say 1,200 rpm.

So, 1,200 rpm means under 1,200 by 60 the forcing frequency I know the mass of the body I know how to find her stiffness and c depending on this equation okay. And sometimes I can go to the manufacturers catalog find out for different payloads what is the available stiffness or available damping and then select the Isolators okay. So, to summarize in vibration applications to engineering the cases of unbalanced.

The cases of base excitation, the cases of force transmissibility are very, very important tuned dynamic absorber and damping, tune dampers and vibrations occur around us everywhere. And these techniques which I told you are actually used to reduce the vibration levels. But sometimes we use them or we use them as an indirect means to estimate the condition of the machine because if there is an unbalance this will give rise to forces in the bearings.

If the Isolators are not working properly the vibration levels of the engine will go up. The dampers are not working, the torsional oscillations would be high and the crank shafts would fail in fact. Many of the industries you will see the crank shafts failing because the torsional oscillations were high they were either not arrested by the dampers you know particularly in ships these dampers are filled with oil somebody neglected filling up the oil dampers when dry and the effects happen okay.

So, we have to be careful as to how we can reduce this vibration levels. In the next class I will be talking actually you know I will be giving you more equations and will try to solve some problems in rotor dynamics. How actually rotor dynamics is an offset from vibrations and how actually rotor dynamics help us understand condition based maintenance okay.

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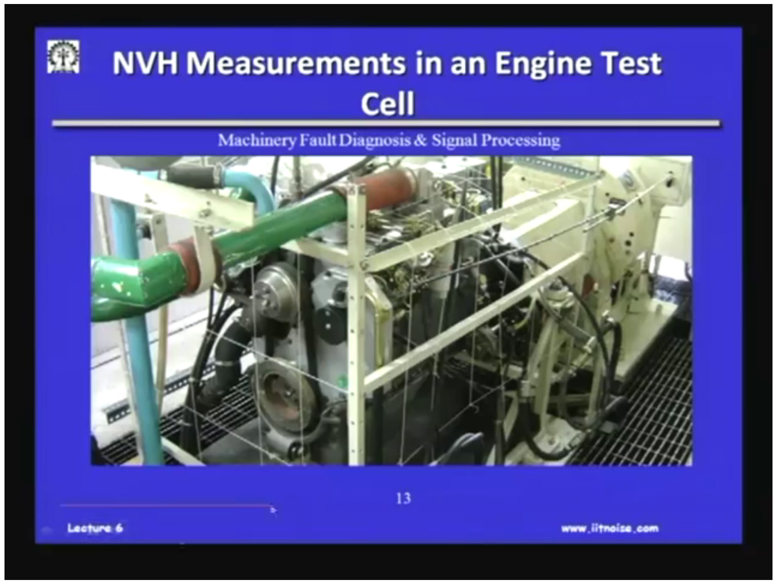

In closing this is one last slide wherein we will see the tuned dynamic sorry the torsional damper here on this engine and it will recall here in this engine we had done a lot of unconstrained layer damping to the oil sump to reduce the radiative vibration levels vibration and noise levels. This is actually in an engine manufacturers test cell we are doing the vibration study on the engine.

And in particularly this is the torsional damper because there is a crankshaft here and this is a 6-cylinder truck engine. So, these oscillations are reduced by having this torsional damper over here okay. Thank you,