Machinery Fault Diagnosis and Signal Processing
Prof. A R Mohanty
Department of Mechanical Engineering
Indian Institute of Technology-Kharagpur

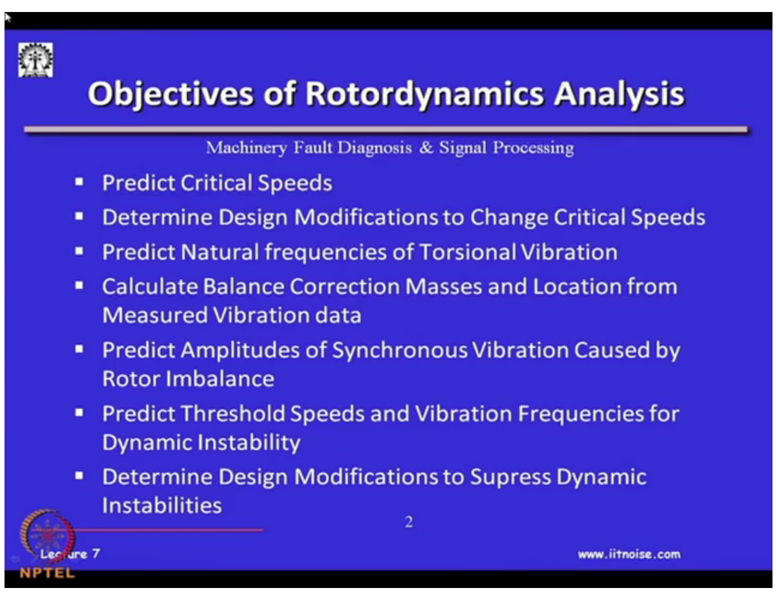
Lecture -07
Rotordynamics

Good morning, today we will discuss about Rotordynamics. As you know in any machinery rotating shaft is a very critical component. So, in this lecture on rotordynamics I will be just covering the basics of rotordynamics from a condition monitoring point of view. In fact the rotordynamics itself is a full-fledged at 40 hours of course and in this lecture of one hour we are just trying to discuss about the important aspects of rotordynamics.

And how actually the problems of unbalance in the rotor misalignment and the effect of the support stiffnesses play a role in the dynamics of the rotating shaft system okay and in practice we will be finding many rotor systems comprising of turbines compressors, ah pumps, impellers, sets of impellers ore fans with sets of loads and so on.

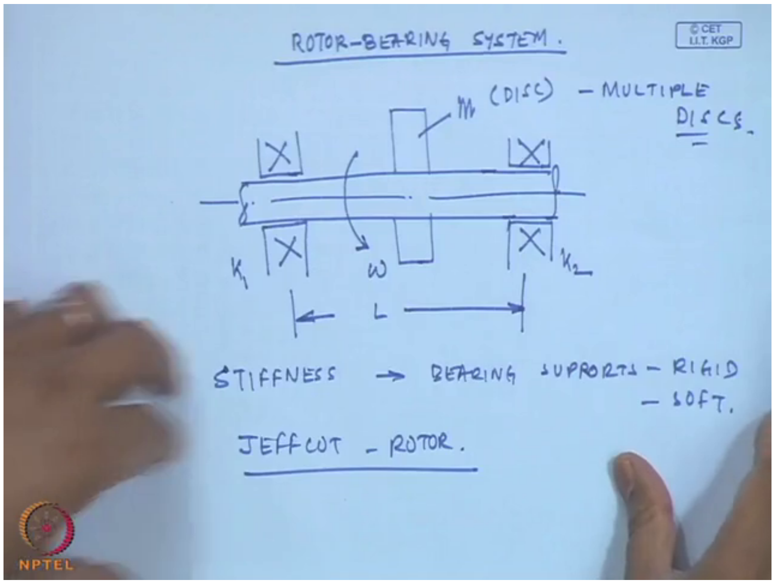
So, rotordynamics is very important that we understand the physics of such a rotating machines and then how do we try to control the unbalanced forces control the rotordynamic stability etcetera. Calculate the critical speeds and so on.

(Refer Slide Time: 01:38)



So, the basic objectives of rotordynamics is in a predict critical speeds and so on. But well, let me explain to you what this, what I mean by a rotor system

(Refer Slide Time: 01:52)

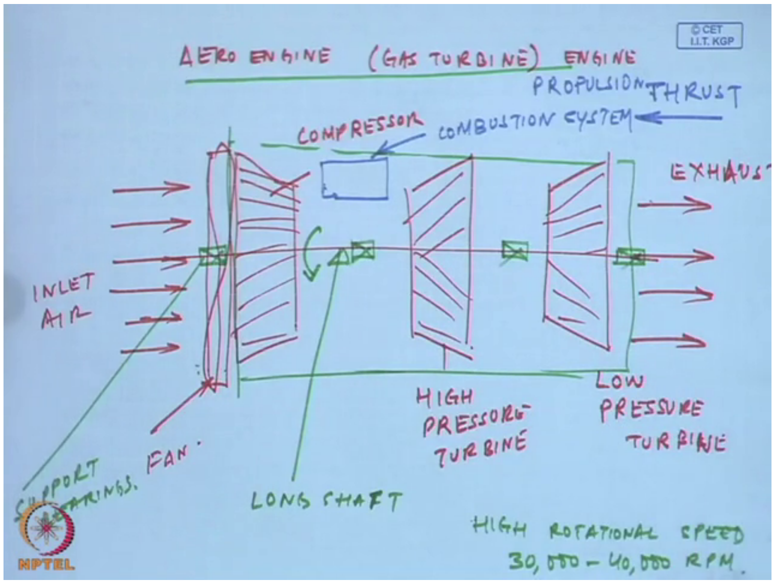


Have a long rotor which is essentially supported in some sort of a bearing and this is undergoing a speed of rotation Omega, rotating at a certain speed. And the span of the rotor okay, this bearings have certain stiffness say K1, K2 okay and there could be a heavy mass M on the rotor, so, if this rotor stiffness is a constant and stiff from the bearing support are rigid or soft.

When we have a rigid stiffness on the supports and the simple disc which is rotating this is basically a disc. We have the simple Jeffcott rotor many physics is understood by understanding the Jeffcott rotor where we have a rigid support stiffness. And then we have a certain disc which is rotating. So, when they are rotating we will have what is known as the critical speed; a certain speed at which the speed is equal to the natural frequency of the system.

And then we are going to have the condition of resonance, so, this is very, very important in the rotor systems I will have shown here one disc there could be multiple discs.

(Refer Slide Time: 04:33)



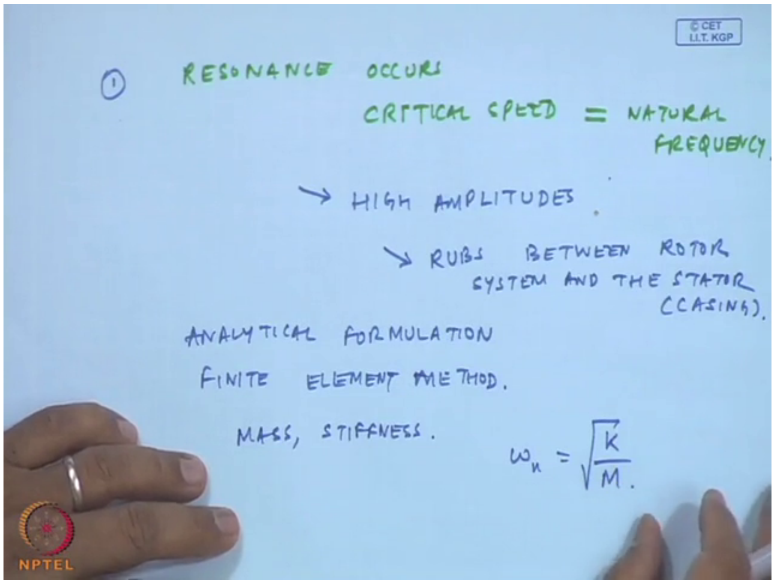
For example in actual conditions think of an aero engine for a aircraft engine which is essentially a gas turbine engine. So, we have a long system wherein we have the first stage this may be a compressor set. And then we have the high pressure turbine followed by another low-pressure turbine. We have the air coming in, inlet air may be some sort of a fan could be here, fan. This compressor that there are of set of vanes and same is true in the case of turbines.

And then we have the exhaust which essentially is the thrust to the engine for propulsion. Of course in between we have the combustion system of course; I am not going to do going the details of the gas turbine. But essentially our domain of interest is; this drawn here in red. And this portion here and this is this is the long shafts which are essentially; these are all supported on maybe bearings, intermitted bearings.

So, a typical gas turbine engine has this kind of a configuration where in; and the long shaft I have a compressor followed by a set of a couple of high pressure turbines, low pressure turbines and each of these system rotates at a very, very high rotational speed. And typically order of 30,000, 40,000 rpm, so you can imagine we have such an engineering complex system.

Wherein on a shaft I have sets of vanes or blades which are mounted on discs there could be multiple discs and they are rotating at a very, very high rpm. Now think of a scenario they could have many issues, one is what if the rotating speed it has a speed which equals to the natural frequency of the system okay then there will be condition of resonance.

(Refer Slide Time: 08:42)



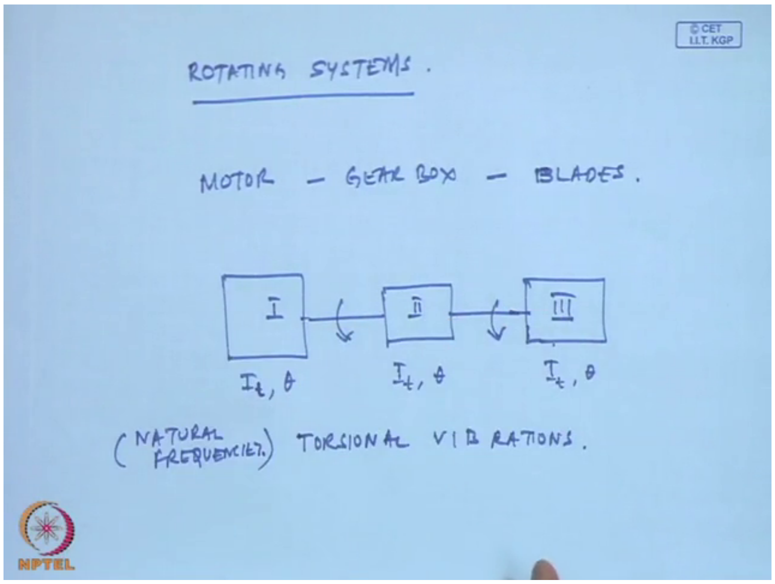
So, condition of resonance occurs when this critical speed is equal to the natural frequency of the system. So, when a, aircraft is rotating or sorry the engine is rotating and it is powering the aircraft and there could be conditions of resonance and because of this what would what could happen is there could be large amplitudes and large motions.

And this shaft because of resonance if it is having if it is going to have large motions okay it means to happen; if this was the casing okay and then this blade sets may touch the casing so there could be little rubs okay. So, this can lead to lot of things higher amplitude high amplitudes this could further lead to rubs between a rotor system and the stator in this case it is the casing.

So, lot of wear and tear will occur materials may fail components may okay and then this is one instances. So, by studying rotordynamics if you can physically model such a system through techniques of the analytical formation or through the techniques of or finite element method ok, we can try to estimate the critical speeds and avoid them during the operations. So, this is what is one of the, one of the important object is of studying rotordynamics.

The next determined design modifications to change critical speeds know we can change the; do certain design modifications, to change the critical speeds through these mathematical models, we can change the mass stiffness of the appropriate system and change the critical speeds you know Omega n = root over K by M, so, this we can play around as a designer, we can play around with the values of K and M and change the critical speeds.

(Refer Slide Time: 12:08)



We have in one case wherein there is lot of rotating systems, many rotating systems, subsystems in one unit. That could be for example a motor, driving a gearbox, driving a set of blades so and they are all rotating the shafts or rotating okay motor driving gearbox okay. All of them have a rotary inertia and then they have the corresponding; the rotary displacements etc. So, such subsystems okay can have the;

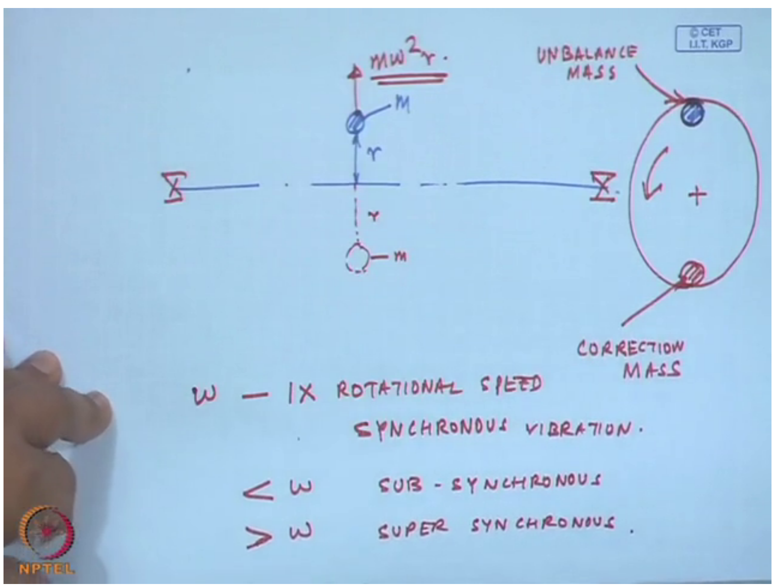
And then you have the natural frequencies like in the case of a linear system we had multiple degrees of freedoms. And every degree of freedom has a corresponding natural frequency when you have the torsional rotating systems, every subsystems of system one, subsystem two, subsystem three each of these subsystems can also be having natural frequencies and these are basically torsional natural frequencies.

And if we can predict them and then know them beforehand we can as designer or an operator ensure that we do not run the system at its natural frequencies. So, estimating the critical speeds in design modifications and then estimating the natural frequencies of torsional vibration is very, very important in the study of rotordynamics and the next would be in a rotating system.

You should think the case of an the gas turbane one we just talked about the small amount of unbalance in one of the vanes or the blades and once they rotate at high speed snow will be having very, very high unbalanced forces okay. And these forces are radial in nature and because of these unbalanced forces will be having forces are the bearing supports.

And sometimes these forces could be very, very high and then we have to ensure how to reduce these forces otherwise the bearings do not come off the supports or the bearings are not able to withstand such high forces. So, as a good designer we have to ensure that the unbalanced mass rotates at its center of rotation or everything is centered around the rotation and not away.

(Refer Slide Time: 15:09)



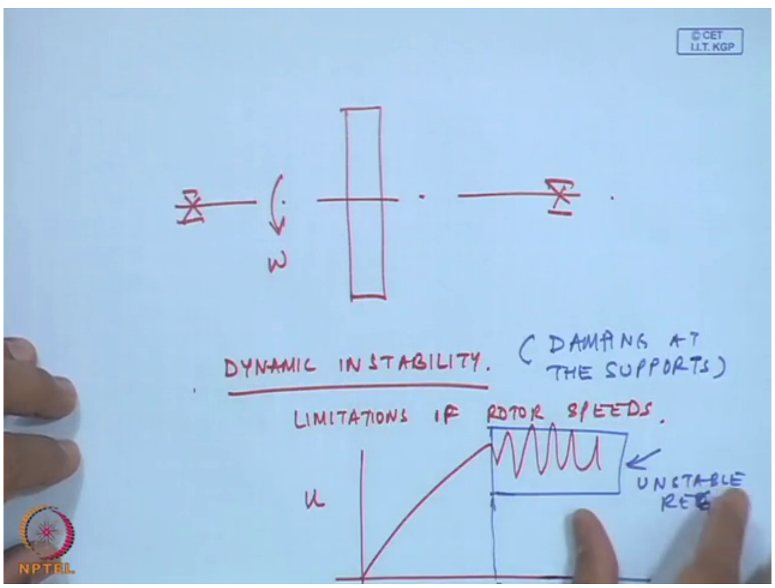
Suppose, I have an unbalanced mass M at a distance r, I am always going to have an unbalanced force m Omega square r and this is going to be harmful to my bearings if I put the bearings here. So, this has to be calculate the; we can do the balance correction and locate a location from the measure valuation data will when you talk about balancing in the few classes down the road.

We will see how we can balance such unbalanced forces either in signal plane or multiple planes and give correcting unbalanced masses. So, that the net effect is reduced for example in this case if I have an unbalanced mass at a distance r on this direction I can give another unbalanced mass on the same quantity distance r, opposite to, if I draw this plane, if you have an unbalanced mass, unbalanced mass here.

I can give a correction mass here okay; I can reduce this forces look at the net forces. And then another problem is you know we can also predict the amplitudes of this vibration caused by such rotary imbalance. Now I am having these two word synchronous, so, if any system is rotating at a particular rpm, we denoted Omega as one times X which is the rotational speed and any variation at this frequency is actually known as a synchronous vibration.

So, any frequency less than Omega is, sub-synchronous and any frequency greater Omega is super synchronous okay.

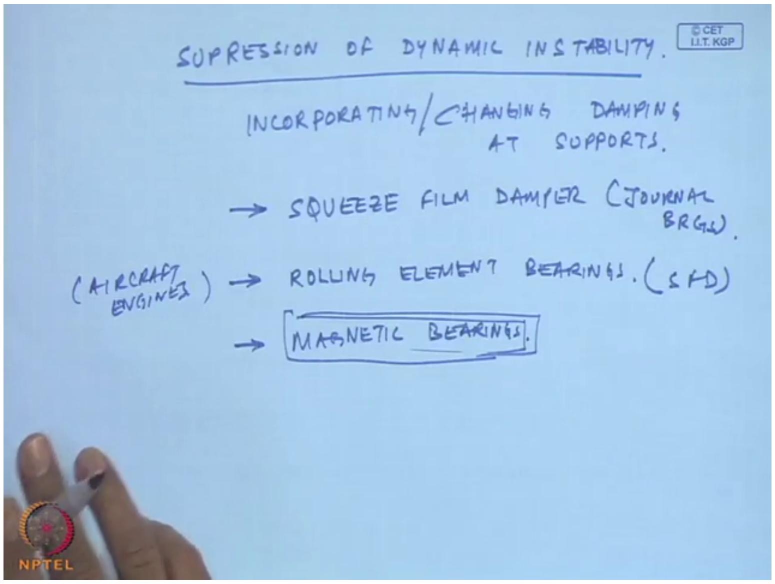
(Refer Slide Time: 18:13)



Later on you will see when this rotating shaft is rotating at a particular speed having disc okay. There will be speeds at which there were, lots of dynamic instability okay. And in fact this is one of the serious problems and the limitations of rotor speeds in particular if you if you plot it as Omega maybe the amplitude of; at certain speeds and what will happen okay.

These are the; which in this case if you increase the speed well, there is a critical speed beyond which we should not operate or if we have to operate it how this can be controlled and I just tell you right. Now by controlling the damping at the supports, we can control this dynamic instability in rotor systems.

(Refer Slide Time: 20:01)



And there are many ways to suppress this dynamic instability. This is essentially by designing or incorporating or changing damping at supports. And this has been possible by in a few; if you think of by a having discipline as a Squeeze Film Dampers in the case of journal bearings. And sometimes in rolling element bearings which are essentially very high stiffness bearings okay almost rigid supports.

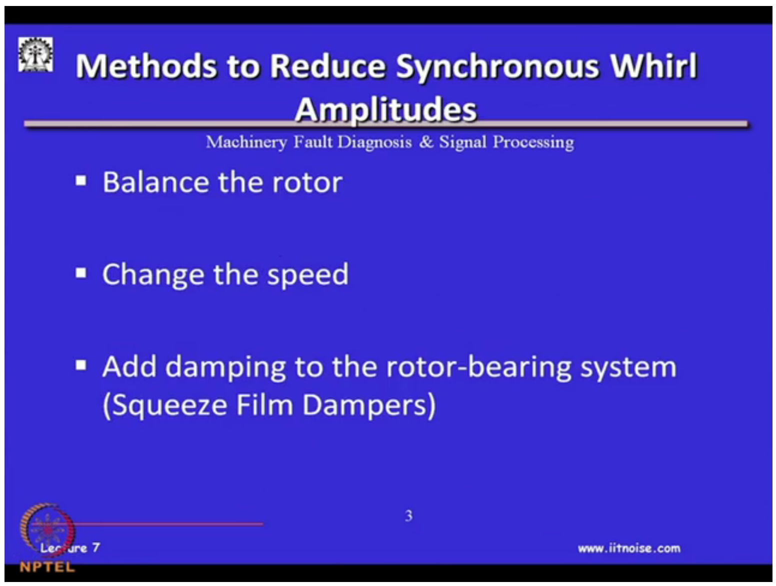
In some way by having an SFD Squeeze Film Dampers in the auto race some amount of damping control can be done. Of course I know people have used magnetic bearings to control dynamic instability in rotors okay. And that is still now in still in a research stage I would say or very few practical applications have come out of magnetic bearings to control the dynamic instability.

In small systems they have been successful but in large systems and there are other issues with using magnetic bearings. But traditionally squeeze film dampers have been used in the case of general bearings to suppress this dynamic instability. And though we use rolling element bearings some amount of SFD particularly in aircraft engines this has been done to support the dynamic suppress the dynamic instability.

So, to summarize the objectives or rotor dynamic analysis as I have the study here I predict the critical speed, determined the design modifications to change the critical speeds, predict natural frequencies of torsional vibration, calculate the balance correction masses and location from measured vibration data.

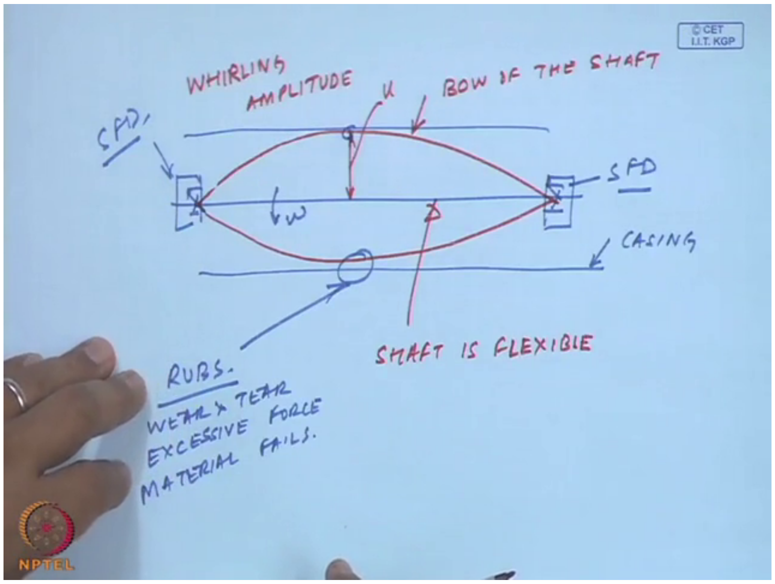
Predict amplitudes of synchronous vibration caused by rotor unbalance; predict threshold speeds and vibration frequencies for dynamic instability, determined design modifications to suppress dynamic instabilities.

(Refer Slide Time: 23:05)



Now there is a lot of things happen when we are rotating a shaft at it is at a particular Omega okay.

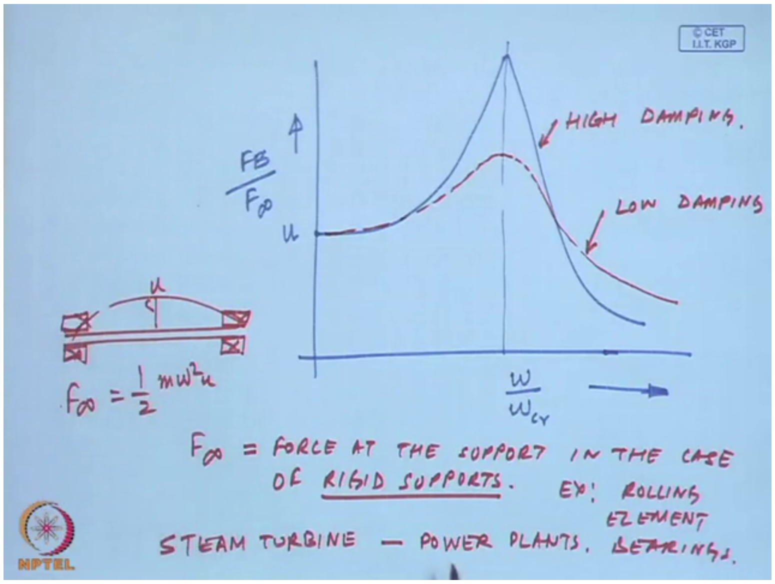
(Refer Slide Time: 23:20)



So, there will be a whirling of the shaft and this is the bow of the shaft. First assumption we have considered the shaft is flexible. So, that it can bow okay, so this fuel amplitude maybe if I denote it as u; our objective is to reduce the whirling amplitude because what happens if it swirls sometimes it may fall with the casing in a system but this is my casing. So, once it touches here these are the regions where ups are going to occur.

And this is going to clears wear and tear, excessive force and then material may feel okay. As I was telling you to reduce the synchronous whirling amplitudes I have to balance the rotor. so, that is unbalanced mass is a minimum, so the; does not fly out or avoid rotating at that particular speed Omega try to change the speed and if nothing is possible add this bearings we can use SFD, so that the support forces on to the onto the bearings is going to reduce okay.

(Refer Slide Time: 25:54)

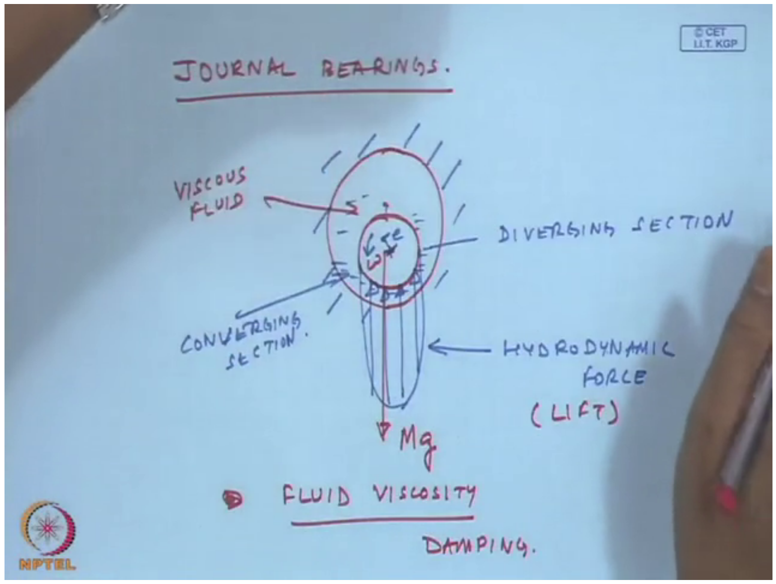


Now, if I think of a rotor system, suppose let me just draw this the ratio of the dynamic force to the forces on the supports when the supports have rigid stiffness and this is u and now if I increase the damping were f infinite is the force at the support in the case of rigid supports, example our rolling element bearings.

So, if I have a shaft which is supported on rolling element bearing okay and if this is going to have an amplitude u the F infinite any location will be half M Omega square u okay. And you can see for large machines this force is very, very high when in the M is high or at high speeds the forces are very, very high in case of a larger rotating systems when you are talking about say a steam turbine which is essentially used in the power plants okay.

Before if they were supported on rigid bearings like rolling element, bearings ball and ball bearings etcetera. The forces on the support would be very, very high and we have to and there is no way no mechanism no physics by which we can reduce this forces which are coming to the supports.

(Refer Slide Time: 29:11)



There are another way by which we can reduce this forces okay and that is where which is known as the journal bearings okay. But I should just give you an example in journal bearings essentially what happens I will come to the general bearing first, suppose I have a shaft which is rotating okay. And this is a filled with oil and because of the eccentricity between the center of the journal and the center of the shaft, I will have a converging diverging section okay.

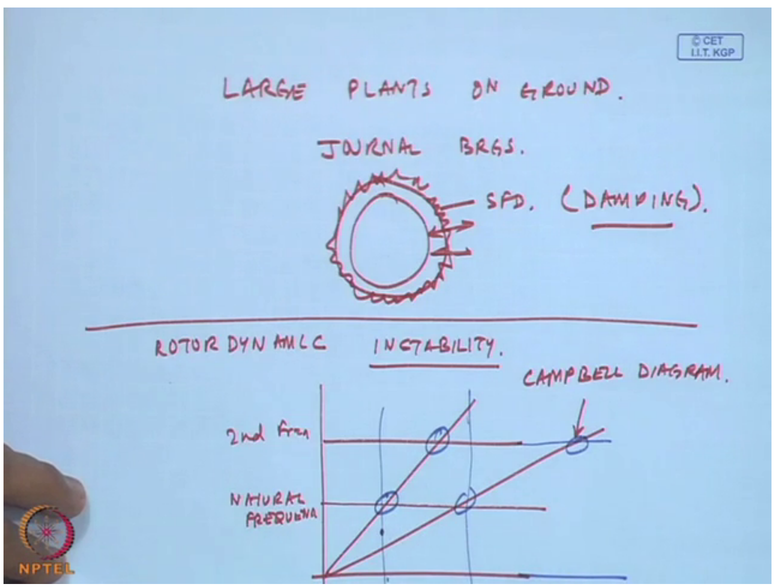
And this shaft is rotating like this and the journal is fixed. Because of this converging diverging section there will be fluid pressure. This hydro dynamic force which happens because of the converging section and the fluid viscosity the load of the shaft load which is coming Mg can be supported by the bearing forces because this will give a lift force. So, when I rotate the shaft at an Omega okay in a journal wherein it is filled with a viscous fluid because of the eccentricity e okay.

This fluid will develop try to build up a pressure and this pressure is going to act in the upward direction and support the weight which is coming at the support. So, in the journal bearings essentially the fluid viscosity comes into play and we can introduce damping okay. And thus reduce the force which is coming on to the bearing. If I go back to this plot here this is because of the journal bearing and this is because of the rolling element.

So, I can reduce the loads coming to the supports by introducing damping which is only possible when a general bearing. So, in any system like in the case of the steam turbines power plants if I have a large system or large shaft, a long shaft carrying a lot of discs of the compressors, turbines of etcetera. And if they were supported on rolling element bearings what would happen is lot of forces would come on to these supports okay.

Instead if I use a journal bearing and then in journal bearing is because the fluid is viscosity and the eccentricity of the shaft from the center of rotation, I will build up generate a fluid pressure, pressure up acting in the upward direction. And then this is able to support the loads coming onto the supports and reduce the forces and this can be very easily controlled by varying the amount of flow of a fluid flow the viscosity. It is a trans can be changed and then I can reduce the forces.

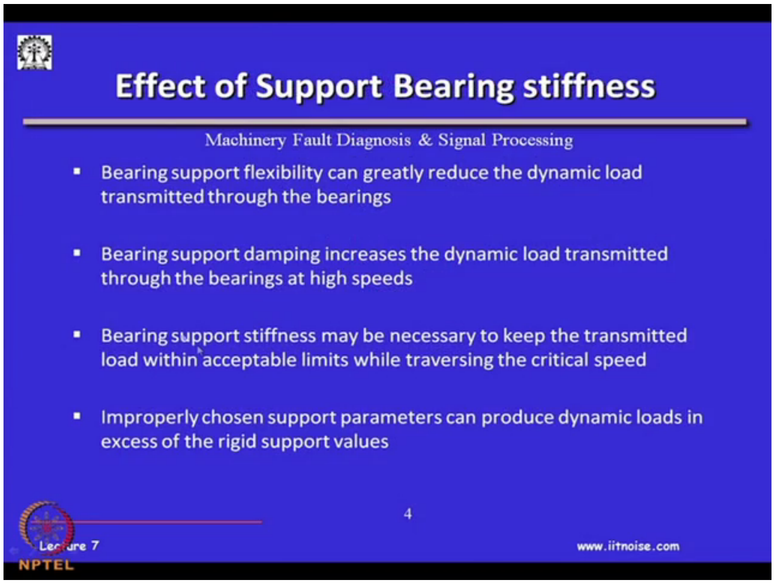
(Refer Slide Time: 33:46)



So, invariably in many of these stationary plants you will see that the large plants which are on earth on ground rather are the better what to use. We can have journal bearings okay which will try to reduce the forces coming on to them. And on these journal bearings if I have a squeeze film dampers basically I have a system wherein I am squeezing and having a vertical motion radially.

I can put the squeeze film dampers and basically and this is me to oscillate along the outer edge and then this basically this; I can introduce damping and it is in introducing damping at the supports, the load which is carried and supports does reduce and this is. So, our damping has a very, very important role in rural dynamics as to it can reduce the support forces it can control instability okay.

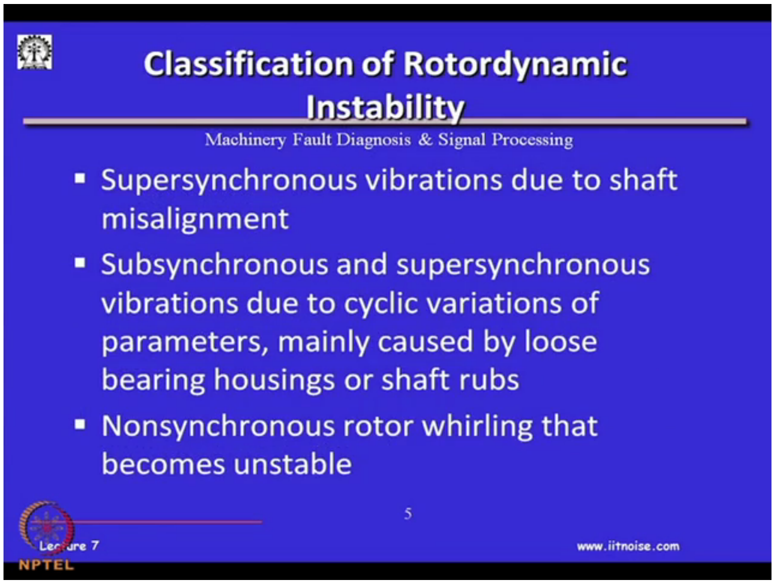
(Refer Slide Time: 34:58)



So, if I was to go back the effect of this support bearing stiffness bearing support flexibility can greatly reduce the dynamic load transmitted through the bearings. Like we just discussed by having the support flexibility properly selected, I can reduce the dynamic load which is transmitted through the bearings. Bearing support damping increases the dynamic load transmitted through the bearings at high speeds, as is also obvious from their plot.

Bearing support stiffness may be necessary to keep the transmitted load within limits while traversing the elliptical speed okay. Improperly chosen support parameters can produce dynamic loads in excess of the rigid support values. And imagine in the; suppose the; our chosen certain parameters are damping, so that the forces are very, very high then we are going to have a failure of the supports and this will not be accepted or allowed so how we can reduce that.

(Refer Slide Time: 36:03)

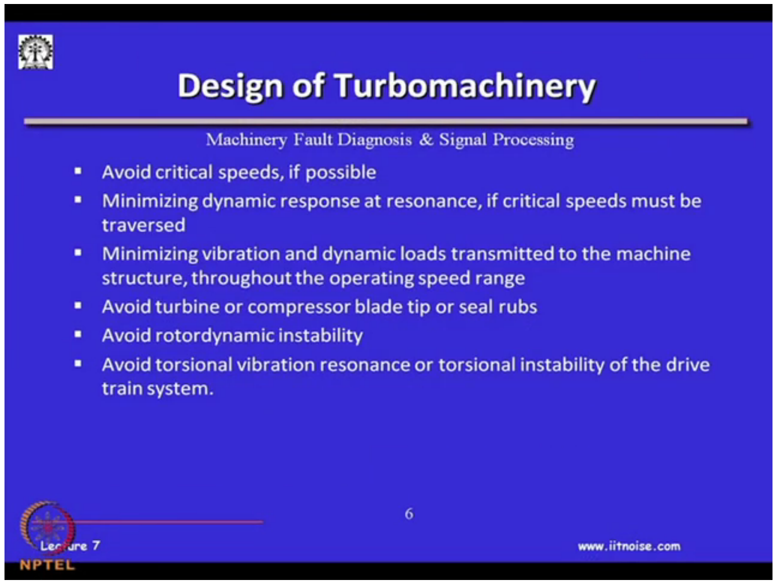


Now what do I mean by rotordynamic instability. Super synchronous vibrations due to soft alignment misalignment okay, soft synchronous and super synchronous forever since due to cyclic variations of parameters mainly caused by loose bearings of shaft rubs. Non synchronous rotor wailing that becomes unstable okay. So, these are the conditions where and we have to be careful to avoid such conditions.

So, we need to obviously have a shaft which is perfectly aligned we need to not have any loose components which will give rise to soft rubs okay. So, these are the conditions which we can avoid so that the dynamic instability does not happen okay. And with this I will tell you there is one suppose, I have this rpm and the first natural frequency, second natural frequency. So, there will be some frequencies and these are basically none of the Campbell diagram.

So, there are regions on which you know you would like to avoid operating at these zones okay. Where in your runoff speed should we solve that in a here operating at the speed at which you are below then this natural frequencies or operating at the speed you are in between these natural frequencies. So, these kinds of RPM which is natural frequencies plots are to be generated for multiple rotor systems are large rotor systems. So, that the conditions of resonances because of the critical speeds are avoided

(Refer Slide Time: 38:51)



So, with this basic understanding about the importance of support bearing stiffness and how support bearing stiffness's contribute to the overall forces which are coming under the supports. When we design a turbo machinery these are some of the things which one needs to keep in mind avoid critical speeds, if possible if you have to operate through the critical speeds in or traverse it very quickly.

Like in suppose a gas turbine you know we have to rotate at 30,000 rpm. Once you go from start to 30,000 rpm I am sure there will be number of resonances you have to pass through. So, quickly you need to change over to the resonance, quickly you need to move into the operating speed of 30,000. We cannot be moving or rotating constantly at the same natural frequency the; so, the ramp up or the speed up has to be very, very high.

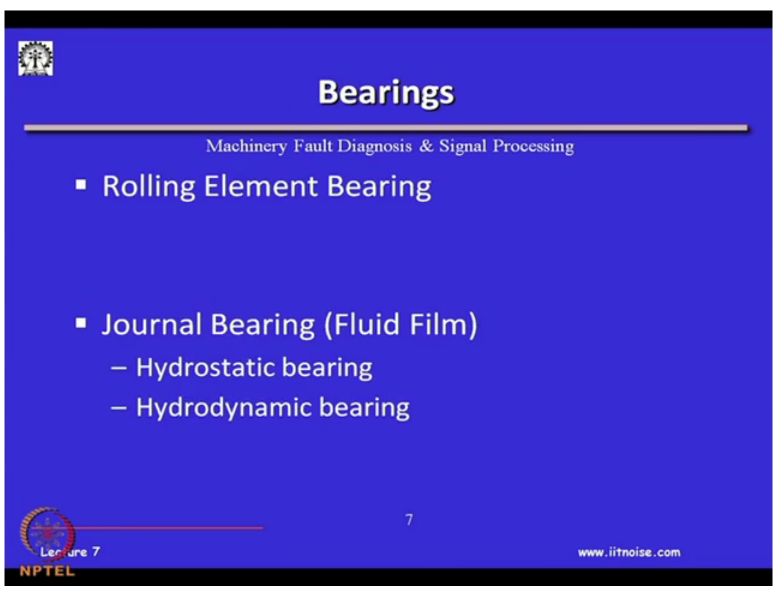
Minimizing dynamic response at resonance if critical speeds must be traverses or just what we discussed. We need to move up the speed increasing in canons very quickly. Minimize vibration and dynamic loads transmitted to the mission structure throughout the operating speed range. Avoid turbine or compressor blade tip or seal rubs, avoid rotordynamic instability, and avoid torsional reversing, resonance or torsional instability of the drive train system.

So, as you can imagine our turbo machinery is a very, very complex mechanism other than the you know the fluid mechanics operations, the fluid machines part of it wherein we have a certain energy coming in certain energy going out. And then we got a thrust but beyond that there is a lot of engineering into designing a, perfect turbo machinery as to its dynamics is concerned in terms of not rotating at its critical speed, how to avoid critical speeds, how to traverse up high speeds, how to avoid instability, how to avoid rotor rubs between the stator and the rotor.

So, these are and how to avoid multiple resonances and torsional systems. So, these are the complex issues of turbine machinery we can talk of our aircraft engine, steam turbine. Even a large set of pumps but these have to be taken into account you know this some of them are vertical and I mean if you go to many of the power plants particularly the hydropower plants you will see lot of the vertical maybe the couple on turbine etc.

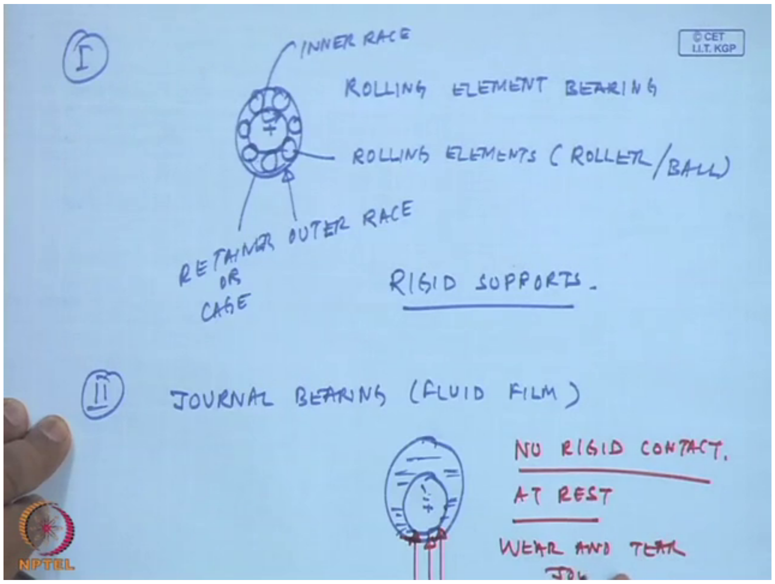
Vertical turbines the shafts are not horizontal but vertical, we have the effect of the gravity loads all together on the on the bearings. And how do how do you select the bearings it thrust bearing, the pivot bearings, the pad bearings etc. Now how do you have to take care of these issues so turbo machinery from our dynamics point is very, very complex thing as a designer people do take care of it. But then our goal in this class is how do we maintain and monitor the health of such a large complex turbo machineries.

(Refer Slide Time: 42:04)



So, just to recap now we have already discussed about the bearings. You know lots of bearings essentially are the two types the rolling element bearing or the journal bearing, a fluid film bearing.

(Refer Slide Time: 42:24)

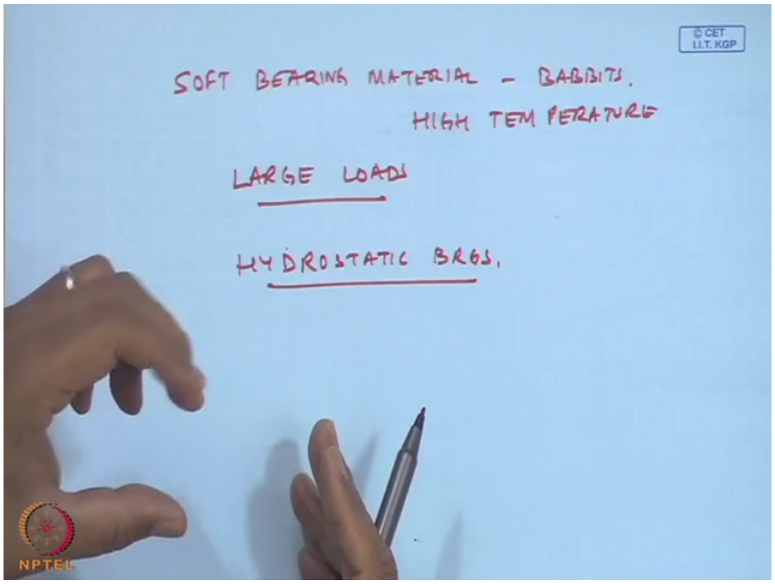


And as you know in the rolling element bearing we have the outer race, the inner race and the rolling elements which could be either a roller or ball and then they are supported by what is known as a retainer or a cage which ensures that they know two rolling elements come in contact with each other. And basically they are used for rigid supports, so in essence rolling elements are good where they did and the forces and the supports are less.

Because when the forces are very, very high because of the physical dimensions of the bearings they may not be able to support very, very high loads as in the case of the turbines which we discussed about. But the other kind of bearing is the general bearing or the fluid film bearings. Basically in the journal I have a shaft and because of this film and because of this convergent divergent section and because of the eccentricity of the shaft.

There is a pressure buildup and this pressure is actually supporting the soft okay. So, in no point in the you know rotation there is any rigid contact, no rigid contact between the shaft and the journal only may be at rest okay. This is in contact say every time you start or stop a machine the entire rotor system comes and sits on this. So, there is lot of wear and tear in the journal, wear tear in the journal.

(Refer Slide Time: 45:25)



That is what these journals are made out of soft materials, soft bearing material like Babbits which can be withstand a high temperature as well and which should be able to. So, because of the physics of the journal bearing they can support large loads. So, and basically all the steam turbines are etcetera on the gas turbines which are handbills we have journal bearings okay.

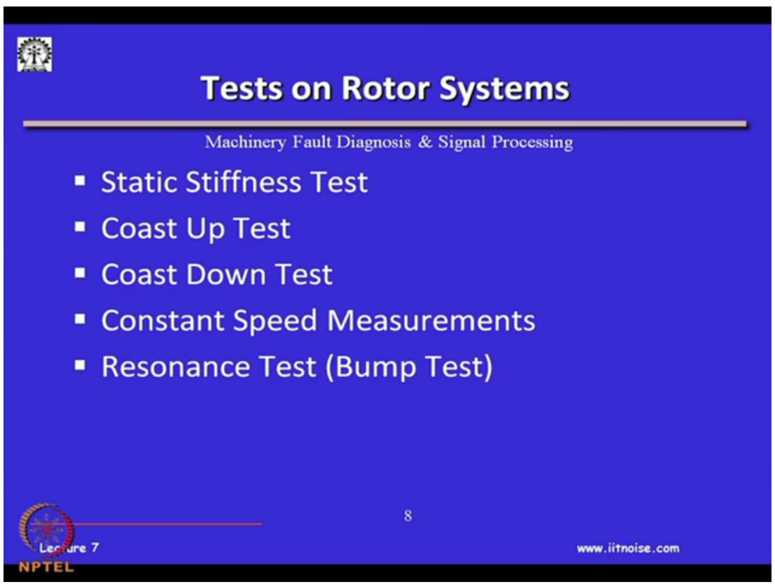
And basically what this film lubrication is the hydrodynamic lubrication which is talked. But in this journal bearings the pressure I was actually build up because of the eccentricity of the shaft and the journal. And because and thus creating a converging diverging section. But if I have the source of externally pressurizing the fluid and applying it to the journal I could be supporting the large loads which are coming like the bearing supports.

And such are the hydro static bearings and of course you know we are not going to go into details of the beings. But as supposed to harder dynamic bearings of the journal bearings there is never any contact between the shaft and the journal. So, very precise on instruments or equipment have such hydrostatic bearings where in we apply externalized pressurized oil or lubrication into the journal and the shaft.

And then but in our case we have the journal bearings or the rolling element bearings. So, in rolling element bearings if I in the outer race if I have some provision of adding a squeeze film damping arrangement wherein I can change the damping arrangements which is there actually in the aircraft engines, other than the rigid rotating element bearings.

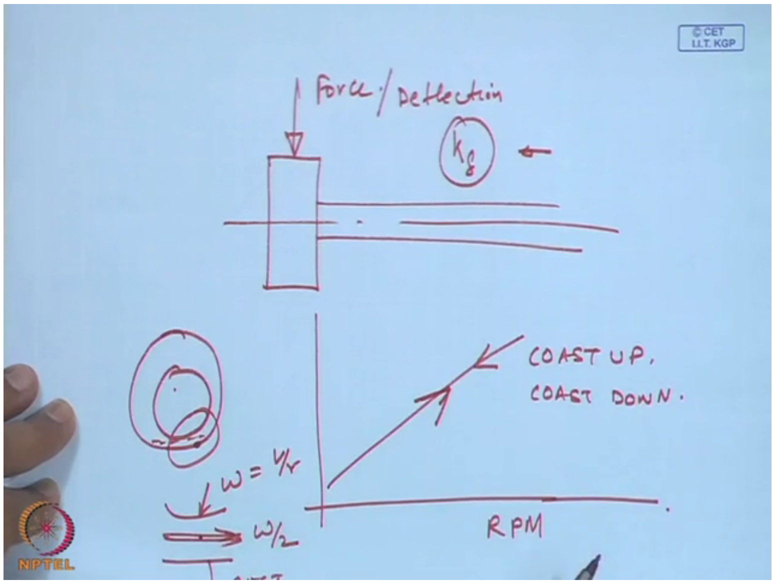
They also have a squeeze film dampers on the periphery which is which will not rotate but only oscillate and thus create this damping and as you know because of the damping the forces on the bearing support comes down. But when you talk about the journal bearing we can have the cases where in the because of the fluid wedge conditions the oil is lifted off of the oil picks up and gives a pressure and the support shaft is picked up it is held at a position.

(Refer Slide Time: 48:16)



But then in rotordynamics also we do a lot of tests on the systems to understand from a condition monitoring point of view or from dynamic analysis point of view. These are some of the tests which are done on the aerodynamic systems one is begin with is the static stiffness test or know what is known as the impedance measurements of the system.

(Refer Slide Time: 48:42)

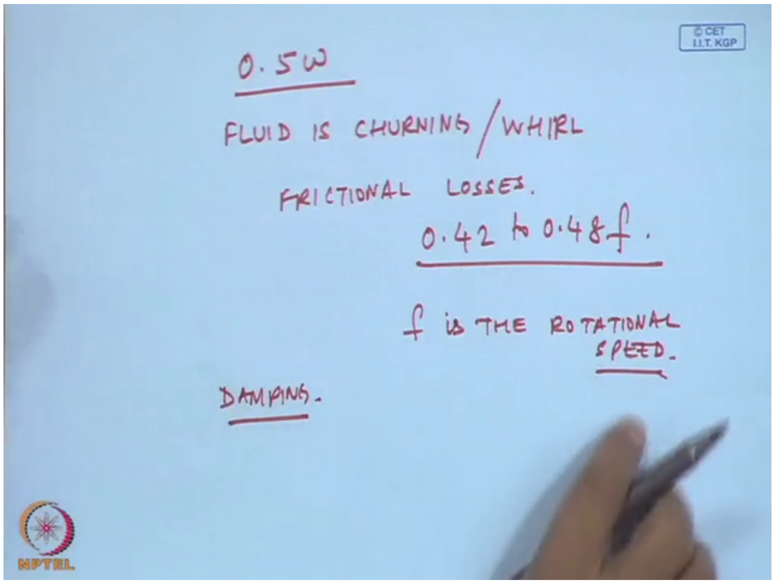


So, at the varying support stiffness at one location I can give a force and measure the deflection okay by having a transducer this deflection could be measured by LVDT or even you can put an accelerometer and then integrate it to get the deflection. So, just to know the static stiffness k delta, I can use such an arrangement where and we given a force method reflection and find out the static stiffness ok.

Many a times to understand the cases of the resonances we can do a course off test wherein we increase the RPM okay at a particular rate or come down from high speed goes down particularly in the case of the general bearing and very important thing happens like in this general bearing should think here basically the forces here at the largest okay and one is at rest and other is moving at a speed of Omega okay v by r linear speed.

So, there will be a point where in the entire film in the middle will be having a speed of Omega by 2 okay.

(Refer Slide Time: 50:40)

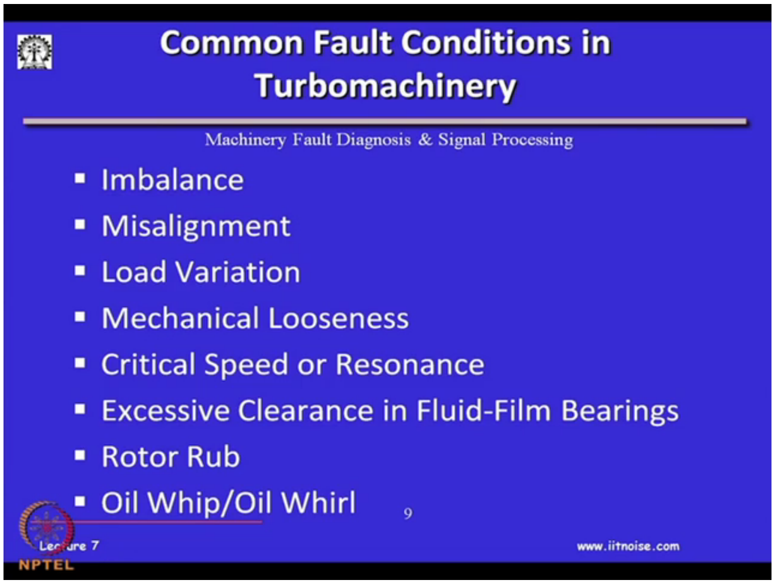


So, this fluid in the wedge is approximately theoretically moving at a frequency of 0.5 Omega or the fluid is churning. So, it is churning or whirling at the speed of 0.5 Omega okay but easily because of the frictional losses. This frequency is around 0.42 to 0.48 of f where f is the rotational speed okay. So, anytime I am having shaft rotating at a frequency of f, I will see predominant frequency somewhere around 0.42 to .48 f.

So, when we do a course up and course down analysis you will be very easily seeing the effect of whirling and this can be removed by changing the damping etcetera okay. In the laboratory do not we have rotor rigs wherein at one end we have a journal bearing wherein we have a particular type of lubricant and then say for example oil and next time we have a kerosene. You we will see the effect of whirling pretty much there okay.

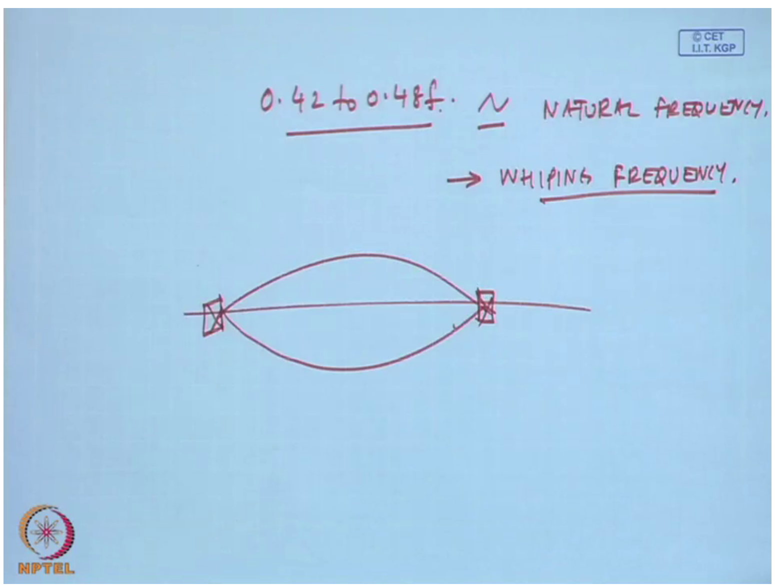
Many times we do lot of constant speed measurements in rotor systems okay and of course the last one is the resonance test which we do on the rotor systems. To find out the natural frequencies of such systems so that we can avoid rotating at the natural frequencies,

(Refer Slide Time: 52:32)



So, some of the common faults which occurs in turbo machinery are the cases of imbalance, misalignment load variations, mechanical looseness, critical speed or resonance, excessive clearance in the fluid film bearings, rotor rub, oil flip and oil whirling another important thing happens as an oil whip for example we are going at a rotating at a particular frequency.

(Refer Slide Time: 53:01)



But this frequency happens to be an oil whirling has occurred all welding occurs at 0.42 to .48 F is this oil whirling occurs what happens it there will be some multiples at which this will be equal to the natural frequency of the system. In such a case the okay; and then this is going to rip around at that frequency. This is going to bow and then it will be latching on to this frequency and that is known as within frequency.

This we will discuss when we talk about the case of unbalanced responses and rotor systems where this whirling occurs okay. So, to summarize in this class we discussed about the requirements and what we do in dynamic analysis. How basically the bearing support stiffness and in particular the damping plays a role in the support forces which come to these supports.

And then how we can select the kind of bearing the rolling element bearings or the hydrodynamic bearings to take care of the loads and then what are the effects which could be there and rotor dynamic systems and then how we have work, thank you.