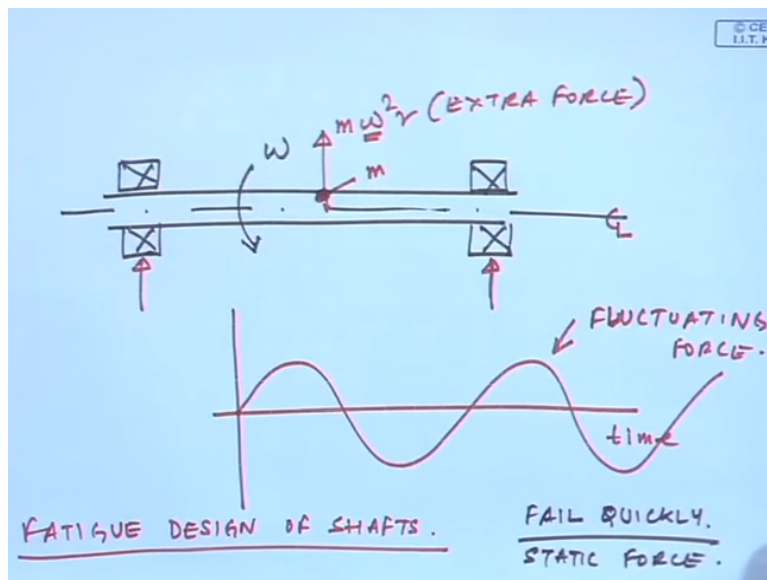


Machinery fault diagnosis and signal processing
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Module No # 05
Lecture No # 23
Unbalance Detection

Well this is a lecture on unbalance deduction in fact this is the first of the series in this module where in after having understood the rudiments of signal processing and of course the elements of machinery maintenance and condition monitoring. We are now specifically coming to do we detect different kinds of faults in rotating machines. And to begin with and going to start with unbalance and most common form of mechanical defect in many rotation machinery.

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Well in before we begin with this lecture let me tell you what we mean by unbalance okay. As you all know in these machines of ours we are always going to have shafts which will be rotating and the shafts are supported on bearings and these shafts will be rotating at very high speed, low speeds whatever. Now in some reason there is an unequal distribution of the mass which is rotating around this center line geometrical center line of the body and there is a small mass M .

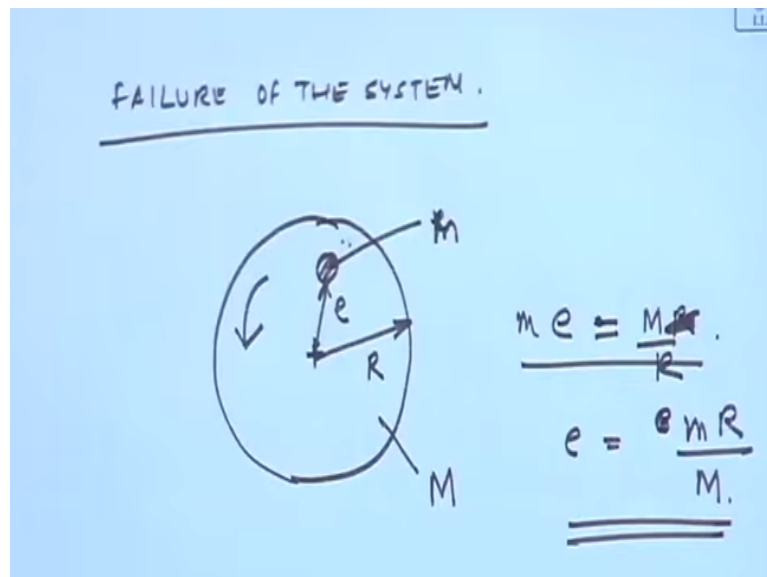
This mass because it is not uniformly distributed is going to give a force $M\omega^2 R$ okay and this force is going to be a radial in nature going to be a function of speed, function of the distance of the unbalance location from the center of the axis and because of this extra force

which is coming on to the system the rotor or the shaft in this case there will be extra reaction forces and in an effect the bearing or subjected to forces much more or beyond what the where initially designed in selected form.

When a designer select the bearing they know the radial loads coming to that bearing and then the design and select the select on design the bearing but on top of it if I have this extra force they are going to add to it and another problem you see is this force is not a constant force as a function of time since it is rotating this force is also fluctuating. So this compounds the problem fluctuating force.

So if you recall your name fatigue design of shafts because of such enforces the materials of shaft is going to fail quickly in comparison to in case of this static force. So presence of an unbalance force leads to force such excessive if we take force and then that leads to a failure system okay.

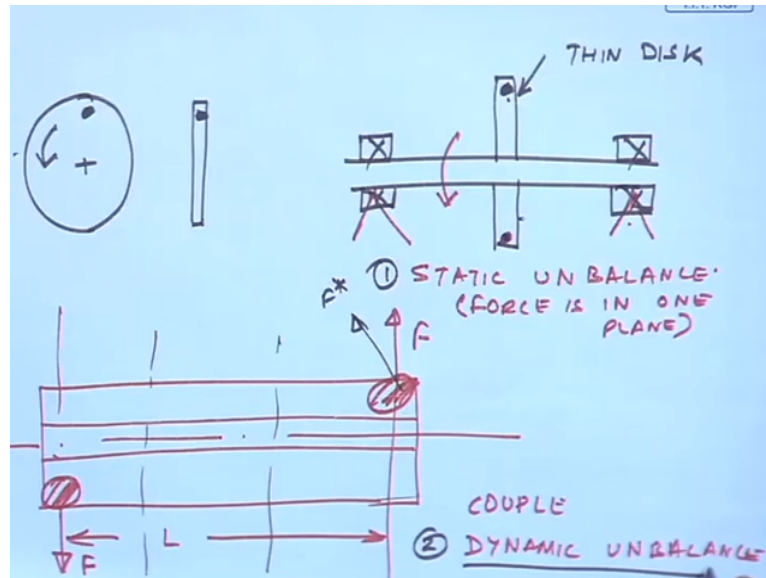
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So not let us look at it from a different prospective let us look at it disk with is rotating this as a initial mass I have a mass M rotating. So this has a radius R at some location E I have a small mass sorry small mass m at a location of E okay. So the amount of unbalance it can be unbalance force can be written as given by this expression okay. So we can define for a particular okay.

I will define the unbalance welcome to this of course I later on okay wherein we can define the out of unbalance first we define it and then come back to slide.

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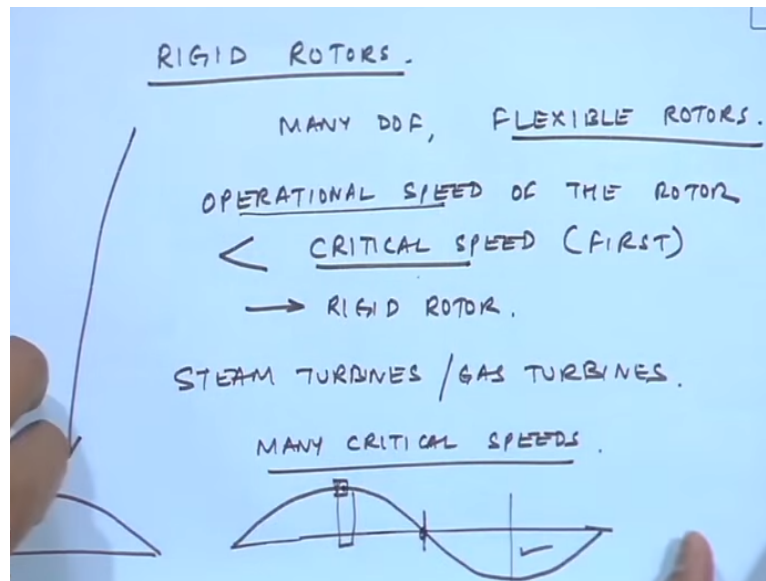


Now this disk could be thin which is rotating about the shaft this is a thin disk which is normal as mass. So in this case if I support this disk on of (()) (06:26) like this okay and this is going to always come down because of this location and this is the case of a static unbalance where the forces are in only one plane unbalance force is in one plane. Now imagine instead of this disk I have a long router like the role of this paper.

If I have a unbalance mass at this location and if I have a unbalance mass at this location so this is the giving to be unbalance force at this direction. So from force point of view this is unbalance okay but you say this because they are in different planes they give us to a couple okay and this is what is termed as dynamic unbalance and in some book or some literature the say this is a couple term of unbalance and then they have a dynamic unbalance where this forces are actually inclined to some access okay.

But in our class we are going to treat one as the static unbalance and other as a dynamic unbalance. So in the case of static unbalance at a very easy to balance by estimating what is the amount of unbalance I can put an mass opposing to it and then balance it. In the case of dynamic unbalance just balance in this does not happen we have to balance put some more weight and another planes.

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So at the couples there also reduced of couples have balanced on dynamic balance later on and of course one of the fundamental assumptions we are doing in this balancing is or unbalances these are rigid or routers but you know from our class of for route dynamics that the routers have many degrees of freedom and then they have they have need to treated as flexible routers.

But as long as the operational speed of the router is less than the critical speed of course to being with the first critical speed I can consider it to be rigid router and unbalancing at one location or putting a weight at one location balances the shaft but when I talk about the steam turbine or gas turbines where there are it is a long shaft having sets of compressors or veins and turbine veins.

This are long shafts and as you know there will many critical speeds okay so balancing may not be possible in one plane because if I if I think of more shifts and the shafts and many speeds this could be the more speeds and this could be most speeds and could be first most speeds okay. Sometimes because of more locations this may have no motion and then if I balance and here we reduce it okay but then I am not doing anything here okay.

In case of here flexible balancing we have to be balance an different planes okay and of course you know we always sure not run at the critical speed away from the critical speed so that we do not have condition of resonances but in this class our attention is focus to this rigid routers and

we are looking at operational speeds less than the first critical speed okay. So balancing can be very very complex phenomena when we are talking about a long router, large routers.

Again there are sets of disk could be compressors could be turbines could be you know some sort of blow of handsets. When it is a long routers flexible router there will be many critical speeds and its difficult task to balance those multiple unbalancing okay though people do that there are software which we can do that but in this course we will focus or relation to very simple may be just router with a shaft which is a rotating below the critical speed it has a disk which as an unbalance mask how do we balance it and what are the effects of it.

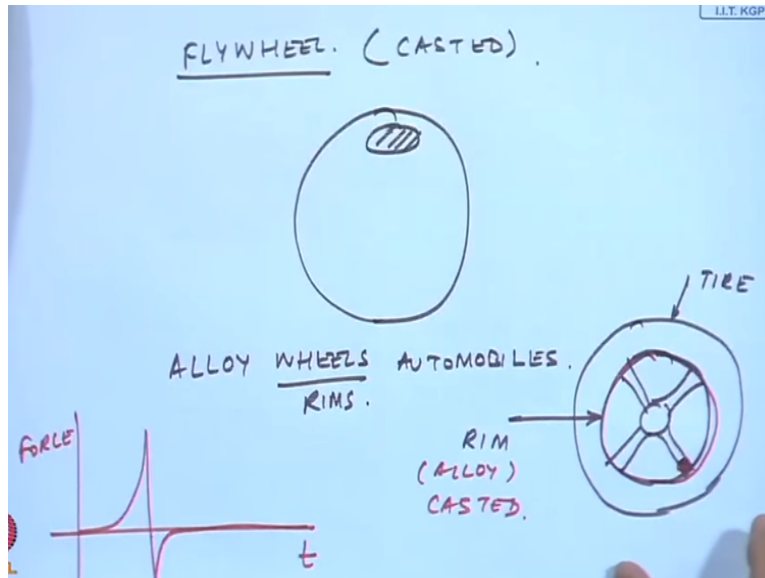
And how would you how do we detect such an unbalance and that is the first part which we need to look into it. Well before I go into how we detect the unbalance.

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What are the possible source of unbalance one of course if the component for example many components in a rotating systems are casted.

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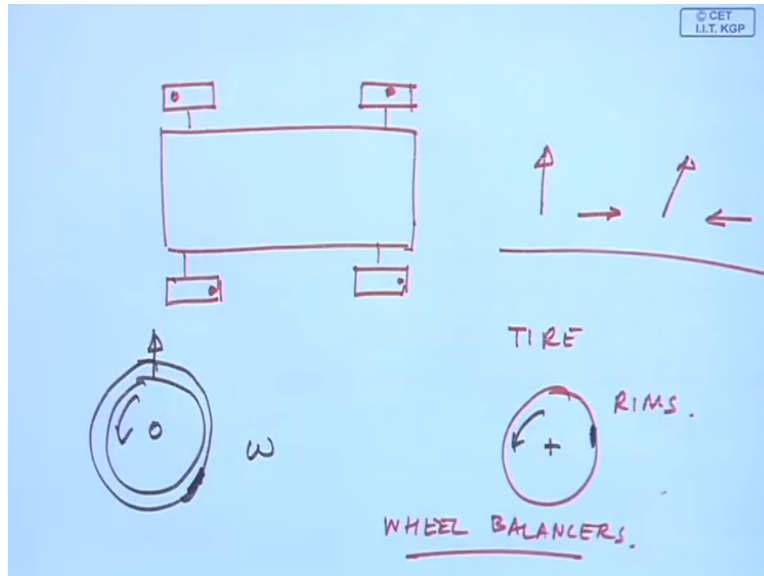


For example in automobile flywheel is a very very important component in a could be a particularly in the single cylinder or two stroke engines couple of cylinder of course in a we have more number of cylinder. The cycles are balanced and then fly will of lesser size but I am talking about of four cylinder and cylinder engine wherein the flywheel is mounted after the clutch ok sorry after the (()) (13:17).

So that we reduce the cyclic engine variations and imagine such a fly wheel has a mount of unbalance mass so this is going to give an unbalance force on to the shaft this is not a desirable and usually flywheels are casted there are many engineering applications are I will tell you for example you could have seen the alloy wheels in a automobiles or wheels on particularly other rims okay and which we have the this is the tyre this is the rim and this could be an analog wheel rim okay.

And which is actually casted you can understand if this casting as the defect or there is some sort of unbalance mass every rotation of the wheel you are going to get a force like this. Okay and imagine a scenario it can be complicated.

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If you have a vehicle which four wheel drive of four wheels and everyone is giving a force there may not been face then one is giving an force in this direction or it is giving it in this direction or it is giving in this direction other it is giving in this direction. So imagine if you have a erratic motion of the vehicle okay and this are undesirable okay bumpy ride forces coming from because of unbalance.

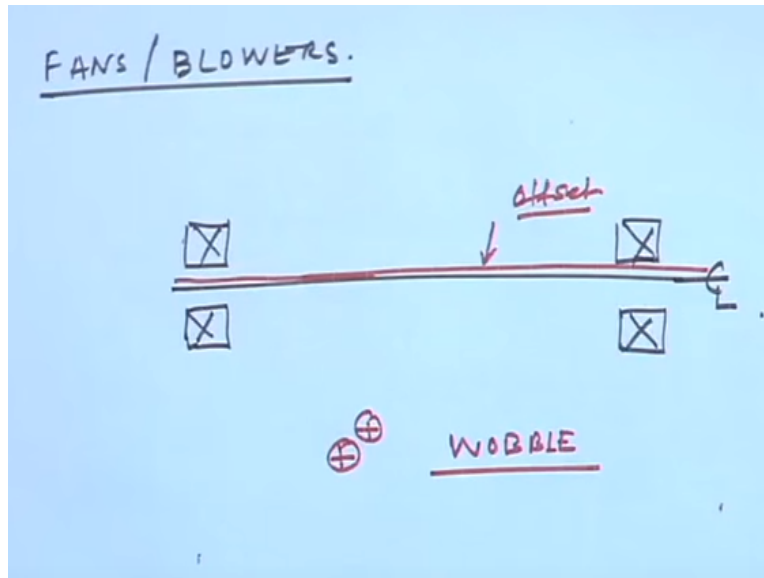
So am sure all of you must have realize it or witness when you buy a tire and we mounted on the rims or rims okay they have in you go to automobile garage they have wheel balancers because and then if you note this particular not in the alloy wheels from the front you cannot see but if you go to the casted steel wheels which a small amount of weight given here depending on of the balance they would have attached a balancing weight to it okay.

And those of you who are riding bicycle must have experienced if you have a bad tire ok so we always do that when we are students okay. If the tire was weak when have a money to change the tire we go to the cycle guy then you put the layer of cut tire in between okay and then you would have patch work and then if you roll that kind of a cycle you will get periodic heads on a seat of a bumps.

So this is because of the unbalance okay and imagine is this kind of things rotate at very high speed so sources will be very high and this sources are finally taken up at the supports. So therein so in subjected to fitting damage and then they will fail much quickly okay first as a

unpleasant right quality in vehicles and then bearings will break a things subject to fitting this will be not good for the machine or the cycle or automobile in this case.

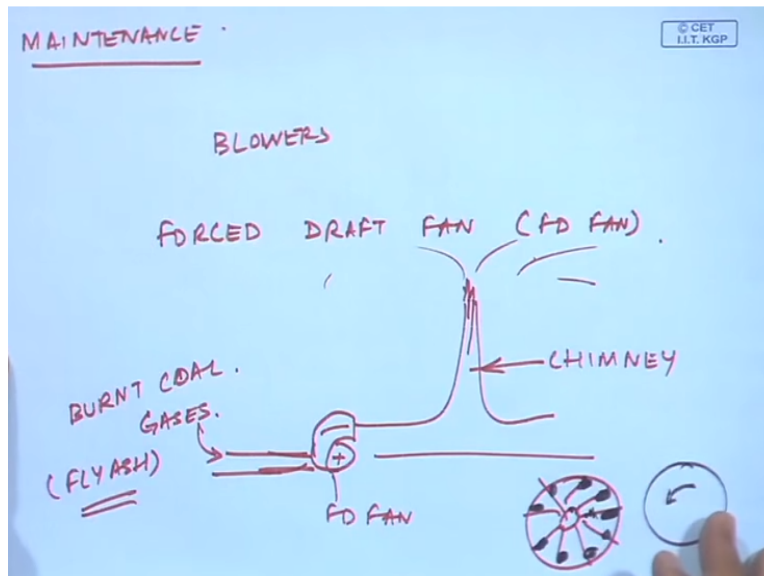
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This is too far in the case of fan and blowers particularly in industries I will come to that is just an while little bit so one possible source of unbalance is whenever we have casted components there could be casting defects blowers which leads to uneven distribution of the mass and then we have a case of unbalance. One is another one next one is the case of a certain installation issues.

Imagine we have a large system okay and which has to be put in place perfectly between the bearings okay and they have to be in the geometric center lines in the system okay. Now imagine if this was a not in the center and there was a slight offset okay. So this is going give rise to unbalance in the geometric center does not match with the line which connect the center of the mass then there will be column and then things will wobble.

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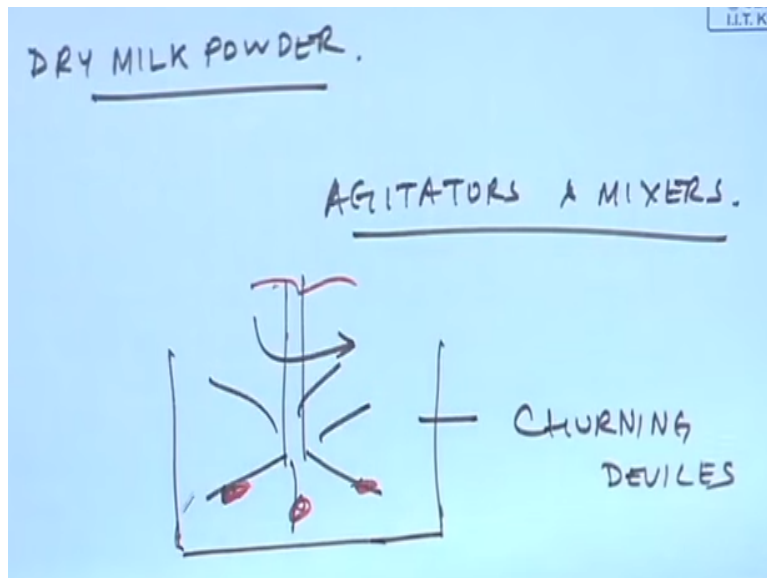


So wobbling will lead to the case of unbalance as well okay while installation we have to take care of this issues also another case which happens is the case of maintenance particularly in a plants where in we have lot of blowers may be a FD Fan force draft fan FD fan FD fan basically what happens when we have this is chimney okay and then we put an FD fan here and these are the gases okay which are after burning the coal actually then fly ash in this gases.

Okay what happen so because to give an extra draft to the fan we put a fan and this fan basically pushes out the gases out of the chimney because the chimney is of certain height we do not want to release the gases all round us we send it high up and send it so that disperse (()) (21:13). Okay the problem is with fly ash fly ash on top of it if it is wet and moist they will become like sludge and then they will another fans a blades am just.

So with time whatever this fly ashes get deposited they stick to the fan blades okay and then want the stick they may not stick uniformly in some location they may get stuck okay and then this gives rise to a fan which is unbalance and then we have seen cases where in this fans are filled blades here off and the bearings get damaged because of this excessive a fatigue force which went unnoticed because things got deposited in the blades.

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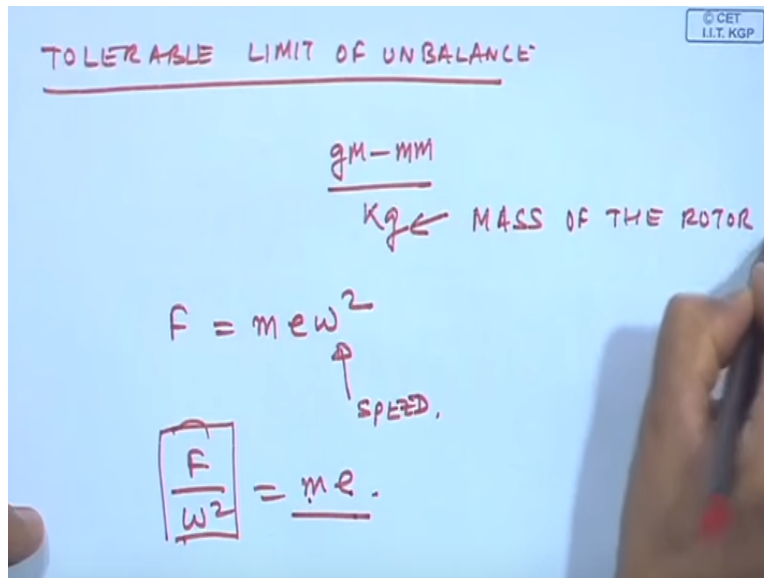


This happens in lot of chemical plants and food processing plants also when we are talking about dry milk product okay we have seen how dry milk powder becomes sticky how gets contact with moisture with the water imagine when you have a in the milk processing plant there are lot of agitates and mixers. Agitates and mixers are nothing but again some high speed churning devices in a tank churning devices.

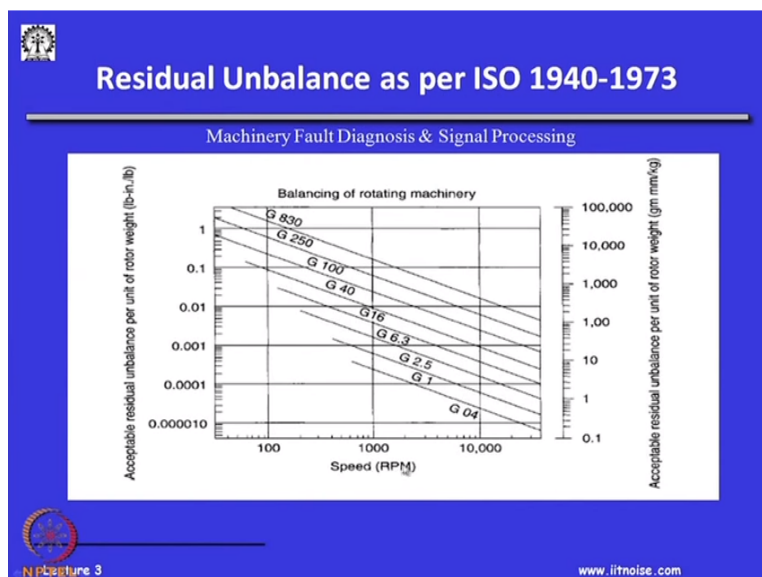
Again the same thing if I feed in certain material which is susceptible to moisture and then it gives sticky they will stick to the blades and then because it is rotating. Then unbalance and finally find these things as failed okay because of excessive fit in loading again. So periodically in many of this plants beat the FD Fan in a power plant beat an agitator in food processing plant.

Periodically in regular maintenance the scrap of and there are a long levels also suddenly to see that the weight in uses etc. They know that some is getting deposited we are talking about iron ore centering plant okay. A lot of things happen lot of places where things can stuck they will get unbalance and then the things will get break off okay. So the sources of unbalance are manufacturing defects, installation issues, maintenance issues and so on. And then the question is what is the tolerable limit of unbalance? okay.

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See everything can be balanced okay but how less should this force be reduced to and how much should be acceptable this is the function given by this curvier one its says the speed of the machine and other is the acceptable residual unbalance per unit of rotor weight if given is gram per millimeter per KG the denominator is the so acceptable unbalance mass.

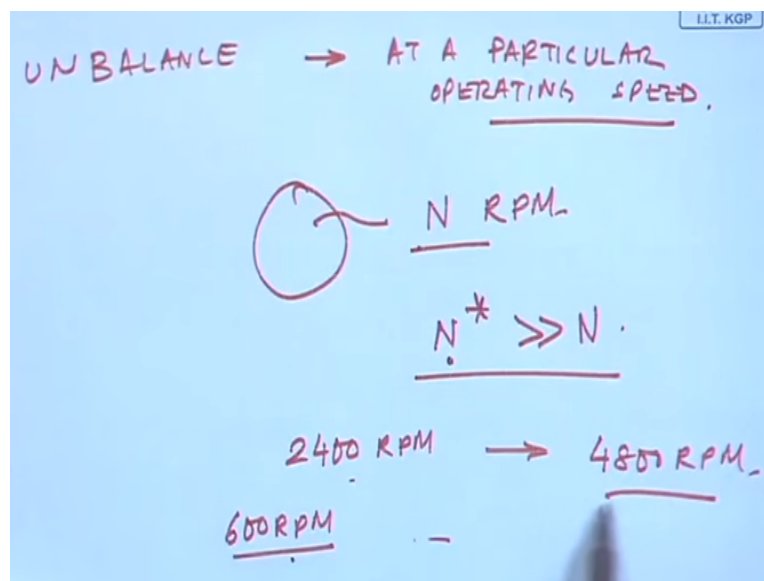
Because if I unbalance force is $ME \omega^2$ if I remove the speed out $F / \omega^2 = ME$ so either it can says gram per millimeter okay. And then if it is a particular speed I know what is residual and the mass this is the mass of the rotor in KG okay. So for large levels G830 means very well very high mass rotor and if you see this is G .04 and with speed okay the

amount of unbalance which we can tolerate obviously will reduce because with speed anyhow we have a very high force ω^2 .

So obviously at the same grade will have hard levels of unbalance acceptable unbalance at lower speeds that is obvious intuitive okay? And this is the case of precision unbalancing now imagine in a watches etc., if there was in this was not precision balanced okay and we have lot of problems but when I am talking about know may be a steam engine or a big drum big cement drum rotating at very lower speed. I can this numerator can be very high okay.

So depending on the grades of unbalance this chart is given as per the ISO 1940 standard they have classified the grades on unbalance as to how much acceptable quantities unbalance how much is not balance when we should go for unbalancing and so on. So this is a grade which reference to that we never known we have got a residual unbalance of 100 sorry of 1 gram rather than .1 gram is it okay is it 1 gram okay .1 gram okay .01 okay or 1 KG okay we do not know then we have to follow this standard accordingly we have to specify that.

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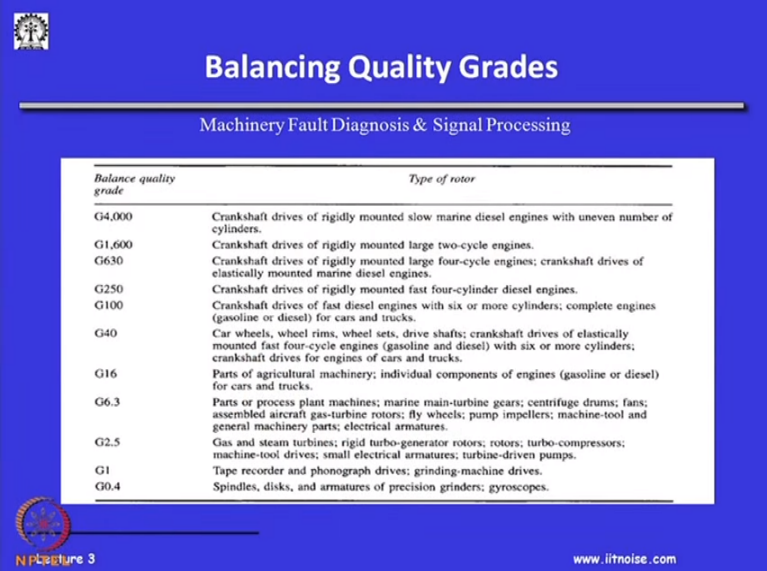


And very important thing we have to keep in mind is of course we will talk about this in the next class balancing or unbalance is defined or specified at a particular operating speed okay. If I have balanced a particular RPM N / N RPM okay obviously an amount of unbalance will get magnify if I operate it at N^* which is much higher than N because of the ω^2 term.

The residual unbalance which was there will get magnified if I get increase the speed so it is always safe to balance a system at its operation speed okay. Otherwise if I operate because if I operate at 2400 RPM and then try to operate it at 4800 RPM and magnifying the amount of residual unbalance is there. So usually as the rule of thumb is in a suppose it is operating at a 600 RPM you also balance it at 600 RPM okay.

But usually there is a problem in that we do not have high speed balancing machines so usually people try to do it at a lesser reduction at RPM and then try to operate it at higher RPM but the word which careful that we do not want it at a too much of a higher speed then it was maintained at to balance for.

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Balance quality grade	Type of rotor
G4,000	Crankshaft drives of rigidly mounted slow marine diesel engines with uneven number of cylinders.
G1,600	Crankshaft drives of rigidly mounted large two-cycle engines.
G630	Crankshaft drives of rigidly mounted large four-cycle engines; crankshaft drives of elastically mounted marine diesel engines.
G250	Crankshaft drives of rigidly mounted fast four-cylinder diesel engines.
G100	Crankshaft drives of fast diesel engines with six or more cylinders; complete engines (gasoline or diesel) for cars and trucks.
G40	Car wheels, wheel rims, wheel sets, drive shafts; crankshaft drives of elastically mounted fast four-cycle engines (gasoline and diesel) with six or more cylinders; crankshaft drives for engines of cars and trucks.
G16	Parts of agricultural machinery; individual components of engines (gasoline or diesel) for cars and trucks.
G6.3	Parts or process plant machines; marine main-turbine gears; centrifuge drums; fans; assembled aircraft gas-turbine rotors; fly wheels; pump impellers; machine-tool and general machinery parts; electrical armatures.
G2.5	Gas and steam turbines; rigid turbo-generator rotors; rotors; turbo-compressors; machine-tool drives; small electrical armatures; turbine-driven pumps.
G1	Tape recorder and phonograph drives; grinding-machine drives.
G0.4	Spindles, disks, and armatures of precision grinders; gyroscopes.

Now this is a typical balance quality grades this is from the same standard of ISO 1940 now you say this balance quality grade it is a G0.4 this is basically for spindles and disc, armatures of precision grinders, gyroscopes. I will just come to G100 this is the crankshaft drives of fast diesel engines with 6 or more cylinders with complete engines for cars and trucks G 100 grade okay.

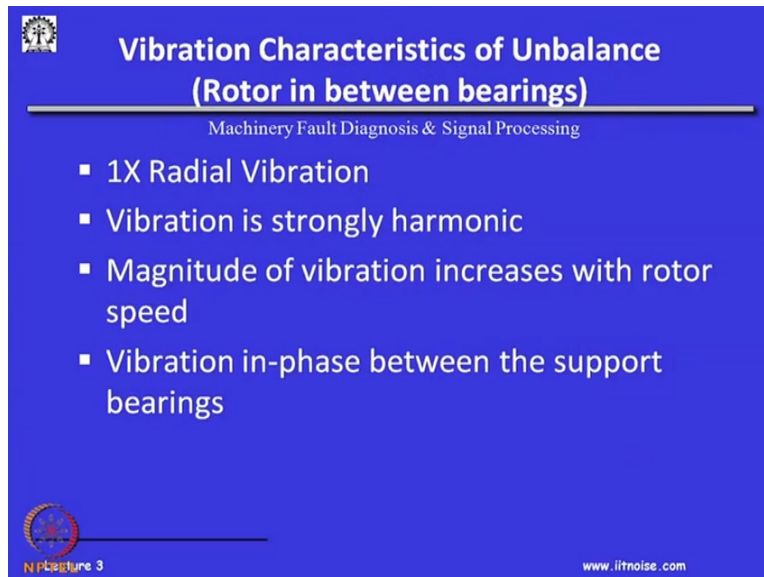
When we have say G 1600 crankshaft drives of rigidly mounted large two cycle engines and marine engines etc. So for small gas turbines, steam turbines, Rigid turbo generator G2.5 so balance quality grades which are we have to balance is actually specified by such standards okay. Now question is with this brief understanding of unbalance what are the effects it have on

systems. Because many machinery components actually start failing because of balance unbalance.

Because see what happens unbalance gives rise to say see forces at a supports so suppose the bearings will get damaged so we may be alarmed because of a bearing failure but the initial problem could be something else could not be bearing failure and to say that again. Unbalance if it goes undetected unbalance will give rise to forces of the bearings the bearings are subjected to high forces the bearings are going to fail and then we will be may be if the bearings are making noise etc bearings fail shafts are going to fail.

So eventually we will be drawn to a fail bearing or a fail shaft but the initial culprit could have been unbalance which was undetected just for that examples I told you something is getting deposited on the veins and blades which you went unnoticed okay. But there are many ways to find out unbalance and a vibration again is a helpful tool to us deduct vibration.

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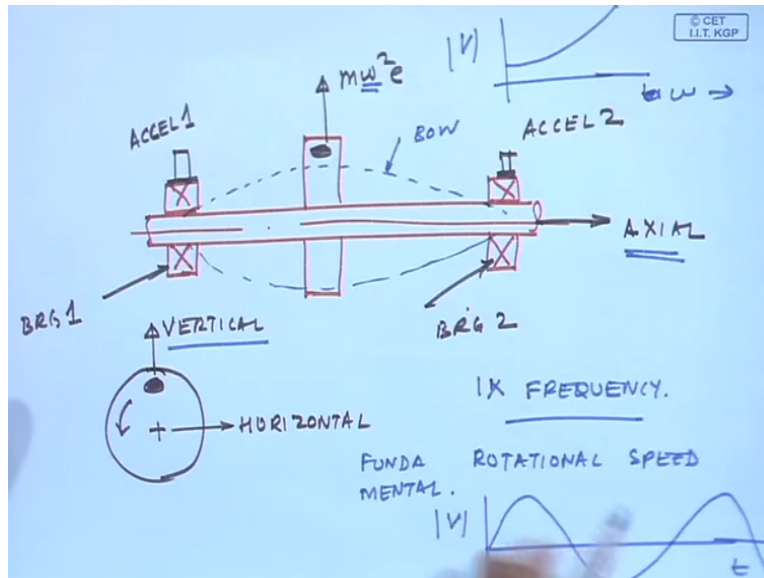
Vibration Characteristics of Unbalance
(Rotor in between bearings)

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- 1X Radial Vibration
- Vibration is strongly harmonic
- Magnitude of vibration increases with rotor speed
- Vibration in-phase between the support bearings

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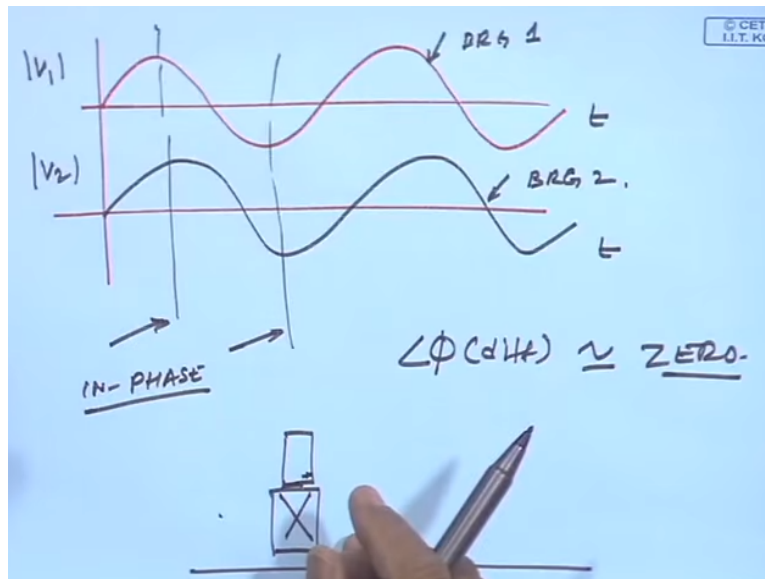
I will give you two specific examples with how the vibration helps us to deducting unbalance in couple of cases in one case we have a rotor may be on the rotor we have a disc which as a unbalance and then we have this rotor supported on this bearings and what I do here is I put a accelerometer say accel 1, accel 2 and there is an unbalance. So am getting a $M \omega^2 E$ unbalance force now of course we look into the from the side the rotor will look something like this.

So this is my vertical direction this is my horizontal and of course this is my axial direction okay. In this example am measuring the vibration of this two location this is bearings 1 bearings 2 because I can obviously only put the accelerometer fix to this location and necessarily bearings 1 and bearing 2. So imagine what is going to happen because of this unbalance the shaft is going to bow okay.

So because of this bowing because of this unbalance force am going to have very high vibrations okay they will be this vertical or horizontal this acceleration will be much higher than the axial. And they will be at the 1X frequency / 1X frequency I mean it is at the rotational speed fundamental rotational speed okay. And this is strongly harmonic and because you can you can understand is the rotating unbalance with every time so it is going to change okay it is going to be a $(\sin)$ (35:22) okay.

So because of this $(\omega)^2$ (35:25) term it is going to have a harmonic and obviously with speed because of the omega square term. The vibration amplitude is going to increase like a parabola with time sorry this with omega okay this is the square term and another very important thing which we have to note is in deducing of such unbalances this is in fact between the support the bearings that means by in fact I mean whenever there is an acceleration at location one is at maximum the vibration at location 2 is also a maximum.

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So that means the phase relationship between them is 0 degree or close to 0 degree that means they are in phase. Whereas to plot in an oscilloscope if I draw 2 lines here this is for a V_1 , V_2 time okay this is bearing 1 and this is for bearing 2 by in fact whenever this guy is maximum this guy is maximum this guy is minimum this is minimum they are in phase or the phase difference between them this is 0 okay.

But this is very ideally speaking this is nice to tell it in notes at once you go to the field to measure because no system is perfect when I drive if I show you an unbalance time of the signal this is now where close to it because in a machine everything is mixed up now this sensor which you put on the bearing okay. This lets us have a lot of things this measures the bearing vibrations on top of the unbalance okay.

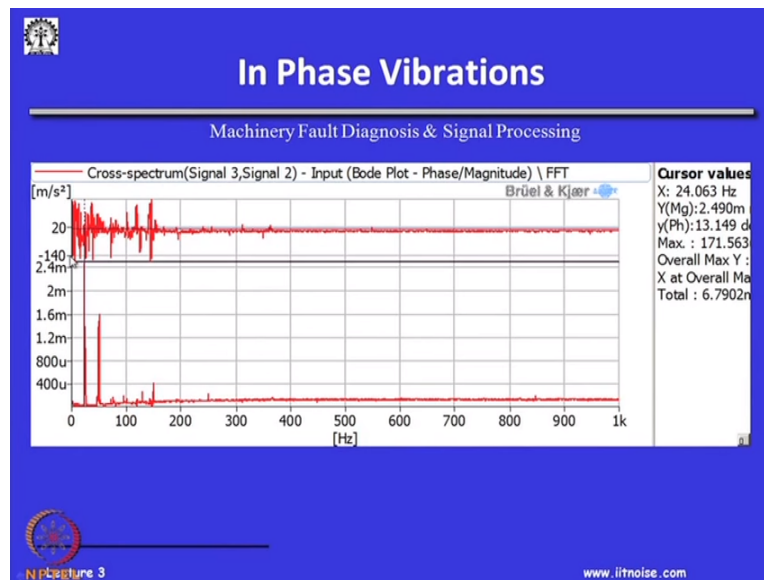
This measure suppose the shaft had some other problem like a loose thing or a loose shaft at the crack shaft where misaligned so all these signal vibration or going to come into this

accelerometer here. So these are the diagnostic techniques or routines which we have follow to ensure that it is unbalance or not looseness or misalignment or grant shaft.

So this are the processes by which we can know or we can be sure that yes there is an unbalance because am having an high radial force or high radial vibration compared to the vibration and then axial direction and then of course the vibration between the two bearings are in phase or they are at 0 degree. You may not quite get 0 degree you may get 10 degree, 20 degree but you know while this is this is not zero because of other reasons but then we are going to get sure test that this is the case of unbalance okay.

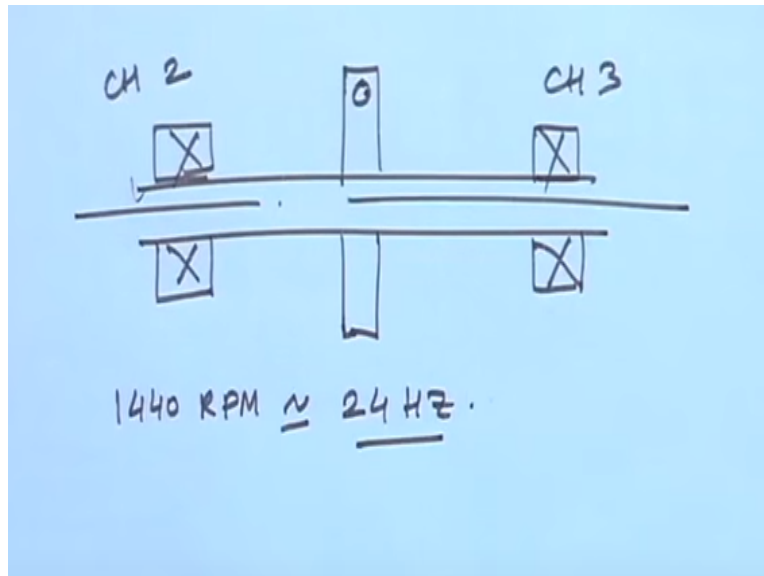
And this configuration is true when the rotor in between bearings and as I told you right from the beginning that we are talking about the balancing of rigid rotors in a where the rotational speed is less than the critical speed but there could be another configuration am sorry yeah.

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There could be or before I go here I just want to show this and this what we have measured here. Now you see we measured signal 3 is 1 accelerometer, signal 2 is 1 accelerometer which we have monitored on.

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Okay this is by channel 2, channel 3 wherein we have a disc I will show you the picture of this setup in the next class okay. And if I look here and this is the in phase vibration and this is the top plot is the cross spectrum okay. Cross spectrum establishes the delay between each other in this case we have the phase and the magnitude most important is the phase here and this was rotating at 24.06 that was it is closed to about 1440 RPM.

This corresponds to about 24 Hertz okay and you can see this is about 24.016 because you know in this what we find in the shaft was rotating at 1440 RPM and then if you see this dotted line here if you can see it here the cursor has been imported 24.063 hertz and the Y in phase is about 13.149 degrees and if you cross spectrum of course you cannot see here actually it should have been in magnitude in you will see a very strong component in the cross spectrum of course you have seen auto spectrum as well.

And this indicates that there is a high level of vibration have not shown you the axial vibrations then that was too low less in this case and this was actually simulated in experimental wherein we introduce an mass of unbalance and rotated it and measure the phase between two and three I did not report here the acceleration because it was too less but you have I wanted to show you regarding the in phase vibrations and their in phase okay.

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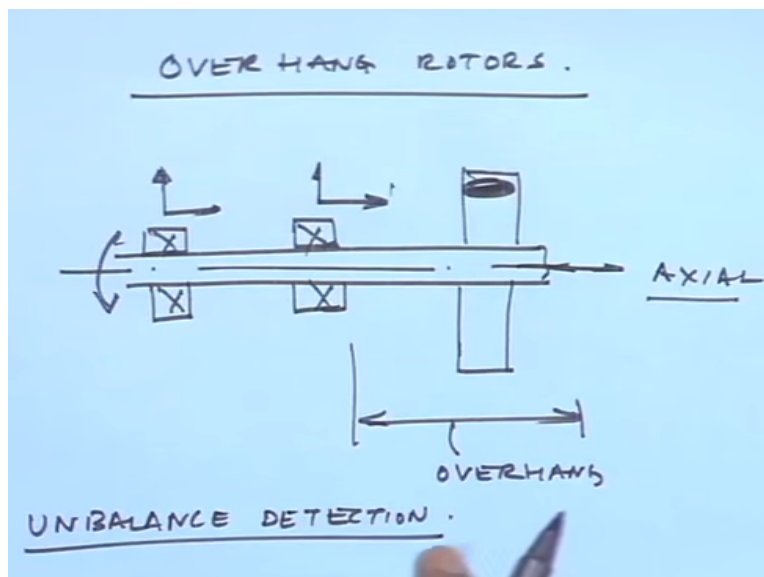


Vibration Characteristics of Unbalance (Overhang Rotors)

Machinery Fault Diagnosis & Signal Processing

- 1X Radial and Axial Vibration
- Axial Vibration may be unsteady
- Axial Phase may be unsteady

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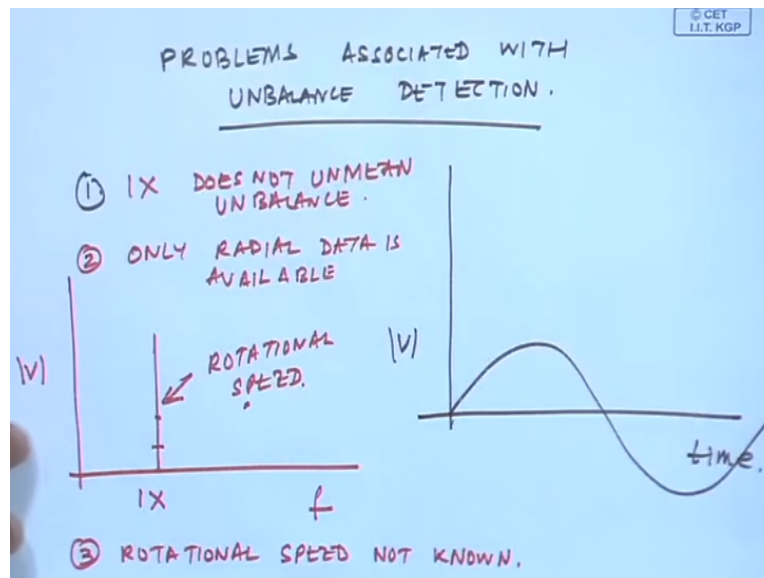


Another case is when we have a case of overhang rotors in case of a overhang a configuration will be like this have a shaft on to which I put a disc and they are supported on two bearings and this is the overhang part okay. Now in the previous example when the shaft was supported in between two bearings I have told you that there will strong radial vibrations.

Hence in overhang vibrations unbalances there may be also a string axial vibrations this is direction as well as this direction okay. And though the axial vibration may be unsteady and axial phase between these two may be little unstable they may not be stable okay and this is again a

case of an example where in on the overall rotor unbalance it can be deducted. But the problem was unbalance deduction is many.

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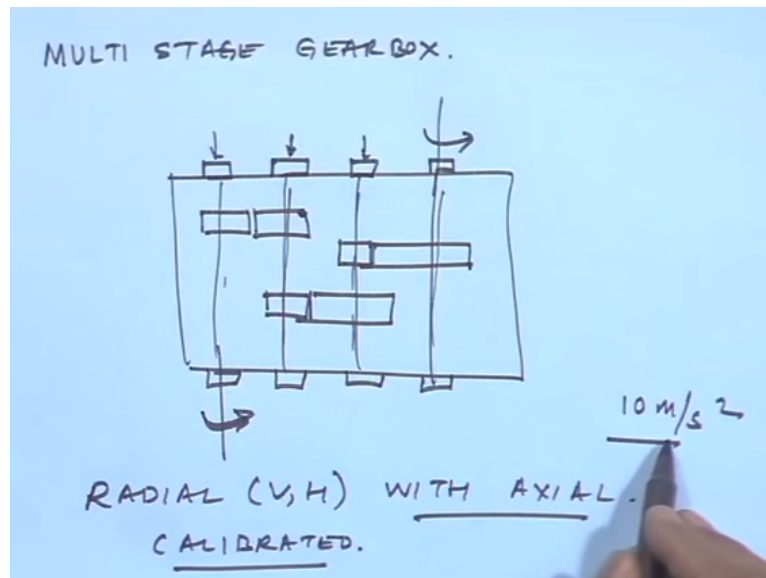
So what are the problems associated with unbalance deduction one problem is whenever we have an unbalance or we have a machine rotating at a particular speed I will get a harmonic vibration because it is periodic vibration. If I look it look at it in the frequency spectrum I will always get a 1X component and this is because of a rotational speed but think of it any machine.

It has to rotate at its rotational speed and so in any vibration I am bound to get this rotational speed in this spectrum. So this may be misleading I have seen many times people when they see a rotational speed this it is unbalance that is not true. Because this rotational speed is fundamentally because of the physics of the problem it is there. Of course this can be less this can be more but think of it if it this was misaligned this was bearing.

I am still going to have rotational speed it coming up so just seeing in the spectrum you can see at 1X you should be bias to deduct unbalance. So 1X does not mean unbalance this is very important. Because the reasons of 1X are many it is a fundamental rotational speed it is there could be looseness there could be misalignment there could be crafts there could be bearing defects.

So how do you say for sure that this unbalance and that is when you look into the phase relationship between few transmissions. That is when we look into the relative amplitude between the radial and the axial okay. So because many times another problem is only radial deduct is available okay. Number 3 which is common to nay machine rotational speed not known for a system simple notice system wherein we can measure the rotational speed is not a problem.

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But think of a multistage gearbox wherein have an input shaft and of course there are lot of inlet shaft and then okay I have bearing at this location okay these are all that so this speeds are shaft sometimes are not unknown as I do not know the gear ratios okay. And then there could be a problem of unbalance here because of one to broke it fall it may get unbalance.

But I am I can put a accelerometer here and measure so if I do not know as a rotational speed are not able to pinpoint what is which shaft is having an unbalance. So these are problems associated with a unbalance another thing is very careful is we have to compare the radial that is the vertical and horizontal with axial we have to be sure that they have been calibrated the accelerator are calibrated and when I say I mean 10 meters per second square in a particular direction.

I also mean that this has been calibrated for that level okay otherwise you know when I am getting a value of 10 meters per second square each and this was not calibrated am not getting a value of 8 meter per second square. There is no way I should be able to compare and will be

comparing this two so people are by mistake are miss this distances when they do the unbalance deduction okay. We have to be careful that this kind of problems are taking care of.

So to summarize this class we looked into the causes of unbalance in fact first we define what is static unbalance and what is dynamic unbalance? How we define the grades of balancing? And then most important in is to know what is the source of unbalance in the system and then how do we deduct unbalance? So this source deduction is very important now once we have a deducted unbalance as suppose other mechanical system falls like looseness, misalignment, cracks through signal processing not through the single processing on the measured vibration.

We can pinpoint this shows the unbalance as occurred in the system and in the next class we will see that how this balancing can be reduced and then we can balance the system is which is rotating okay. Thank you