Theory & Practice Rotor Dynamics
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Lecture - 1
Introduction

Today, we will be starting a new subject that is rotor dynamics or commonly known as theory and practice of rotors dynamics. As the name implies in this particular subject the theory and the practice actually goes to together, in fact if we see the history of this particular subject, it has been involved through the practice. Based on the experience of the fluid engineers or the practice engineers this particular subject has been involved.

So, based on their experienced, based on their difficulty in the industry they were possessing the problems to the researchers key, we are facing this difficulties and one of the causes are that and the researches they came with some kind of mathematical models. They predicted what the problem is and how it is involving and how it is can be rectified. If we see, let us first see the content of the course and then we will go to the model with the theory of that.

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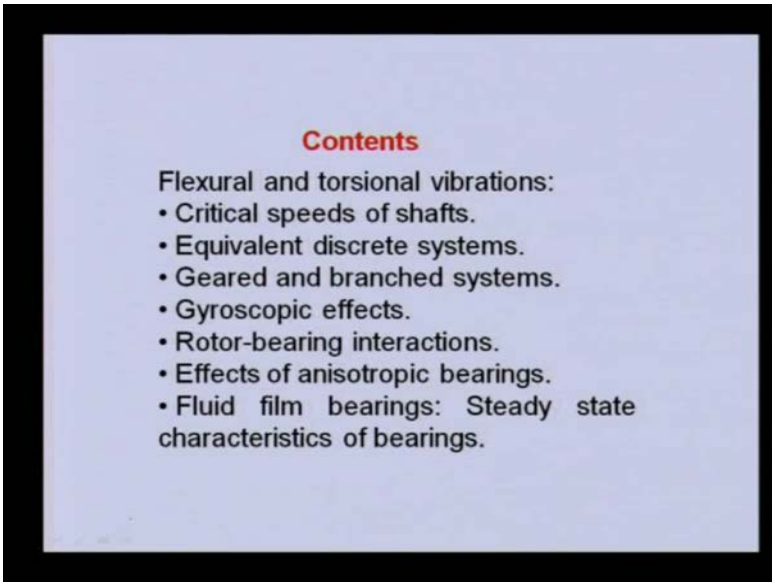

So, this content you can able to see that mainly the flexural vibrations or transfer vibration is the main concern in the rotating machinery. Apart from that, the torsional

vibrations are also a concerned in some of the cases and this will be discussing as will go along the subject. Sometimes, even the flexural vibrations along within the vibrations are also cause of concern in such rotating machinery.

You will be able to see that we have the concept of critical speed in these particular rotating shafts. Even, will be having some kinds of concept of equivalent descript systems in which will be converting the bigger system to its some kind of equivalent discrete systems, geared and branch systems analysis specially for the torsional vibrations. We have will be studying the gyroscopic effect which is very important phenomena in this particular rotating machinery that will be starting. Apart from that, obviously the rotors are mounted on bearing, so how the rotor and bearing interacting that will be study.

Specially, the bearings they have based on the different kind bearings like rolling equivalent bearing and fluid film bearing, they in part varies types of dynamics parameter that mean the stiffness and damping and specially the hydro dynamics bearings. They have some kind of analysis some tropic property that will be studying or even we will be seen how it can be obtain using the equivalent discretions.

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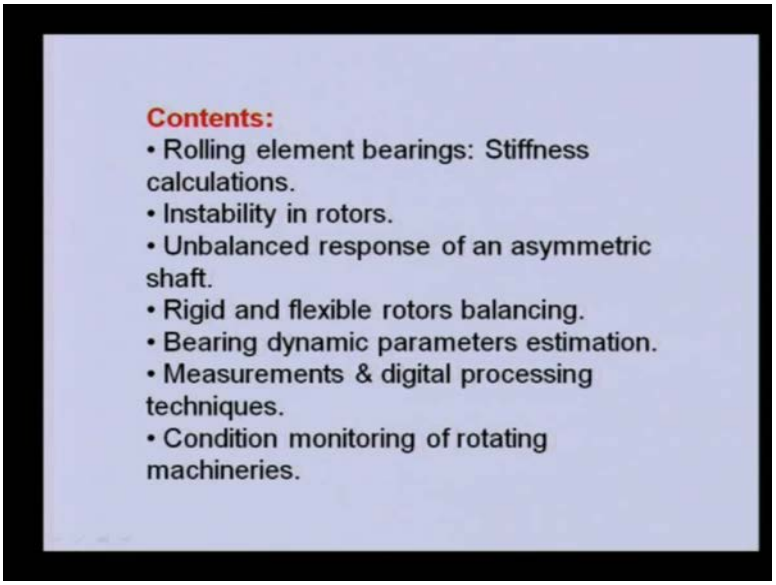

Another important is bearing rolling element bearing will see and how it is impart the stiffness into the rotors systems. Generally, this are called flexures bearing, so the dumping is less in this bearings so the main of the property which this bearing carries

this stiffness apart from that the rotors. They have some kind of instability, they are various this rotor can going to the instability zone we will study this in more detail one of the example is preview varying itself. This gives instability because of in this particular case we have a cross couple stiffness and cross couple damping.

They lead the rotors into the unstable zone and apart from that sometimes the rotors is having asymmetric mass moment energy of two art able directions. That also leads to instability because of the parametric acceptation up the rotor when it is rotates this stiffness changes along with the speed and that give some kinds of the rigid parameter exacted vibrations. As we know that the rotor unbalance is the most common fault and we will see how this unbalance response can be calculated for varies simple and complex rotors. Then, we will be having the concept of the rigid and flexible rotor balancing in which will be studying in more detail how vibration based techniques can be use for balancing the rotors.

Here, will get estimation would the rigid rotor were the flexible rotor and how this is balancing methods are different for this two cases bearing dynamics parameter estimation especially for experimental estimation is very important. We have such models by which we can able to calculate theoretically using Reynolds equations in the stiffness and damping properly of these bearings. But the problem is even we have good theoretical model, but the parameter which it requires like the lubricant property is viscous city.

Other property of the lubricant or actual temperature conditions and how it is varying within the bearing is a problem and because of that, even the theoretical model if it is good we cannot expect good prediction from that. The input which we are giving into that is not correct, so most of the time in industry people do the experimental estimation of this parameters, so we will see that particular methods in more detail. Then, we will see the measurement and the digital processing techniques especially as we know that in rotating machinery.

It gives what over the dynamics are taking place inside the machinery in the form of vibrations and acoustics. So, we will see specially the vibrations how it can be measured and what are the different senses are there, what are the different analysis software were there or what are the varies techniques are there by which we can able to process this

amazed signals. They can be analyzed for the proportion especially for the conditions monitoring and we will look into varies kind of faults which rotating machinery can have, and how they can be monitors through the vibrations measurement.

Now, we are seeing the oral syllabus this are the oral syllabus, but as will go into more detail will be having more idea about the subject. And now let us see every flow how broken this lectures topic wise. So, that we have some kind of idea like this are the module wise lectures and more debit on little bit here and there.

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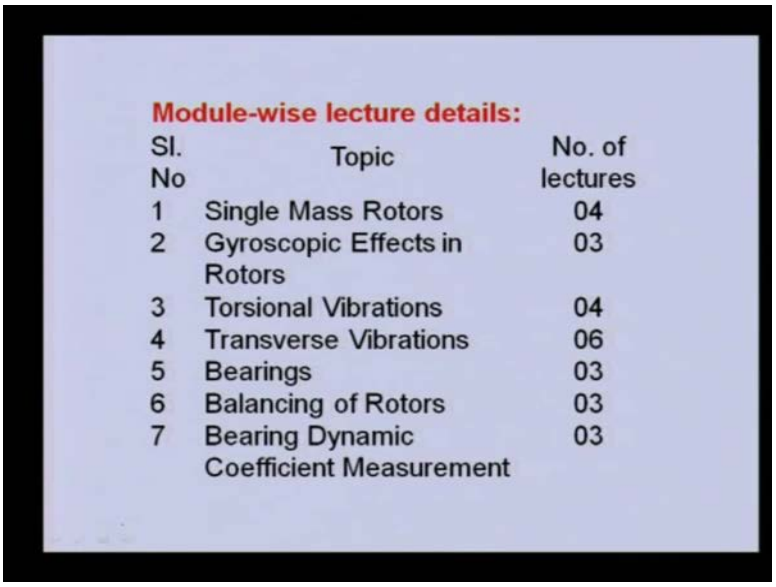

This will be the module distribution of the various lectures like single mass rotors analysis will be around four lectures gyroscopic lectures in rotors from three lectures torsional vibrations four lectures transverse vibration. This is major concerning in the rotating machinery; it will take along six lectures bearing properties estimation that will cover in three lectures balancing of rotor. There is rotor balancing in these lectures, then experimental bearing dynamic parameters estimation that is a three lecture apart from this.

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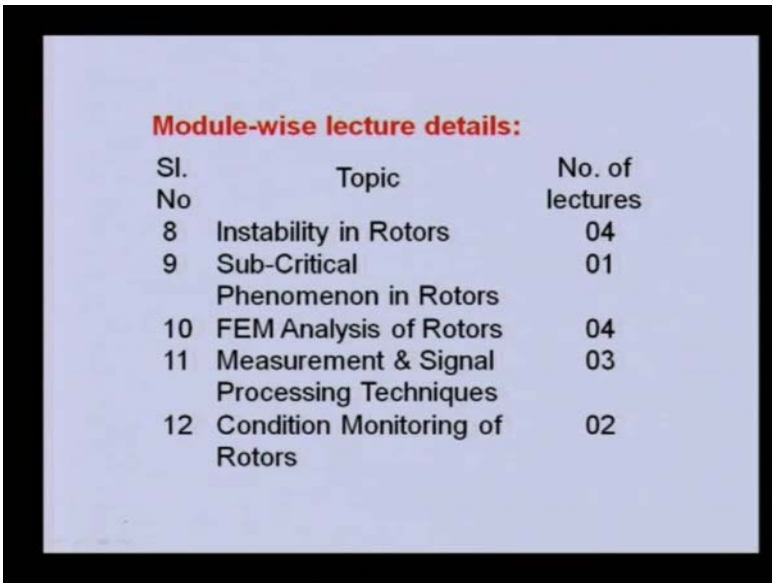

Then, instability which is in major concern in the industry or that will cover four lectures, then there is a phenomena sub critical speed phenomena which will covering one lectures. Then, very important to balance that is fem analysis of rotor will covering four lectures and measurement.

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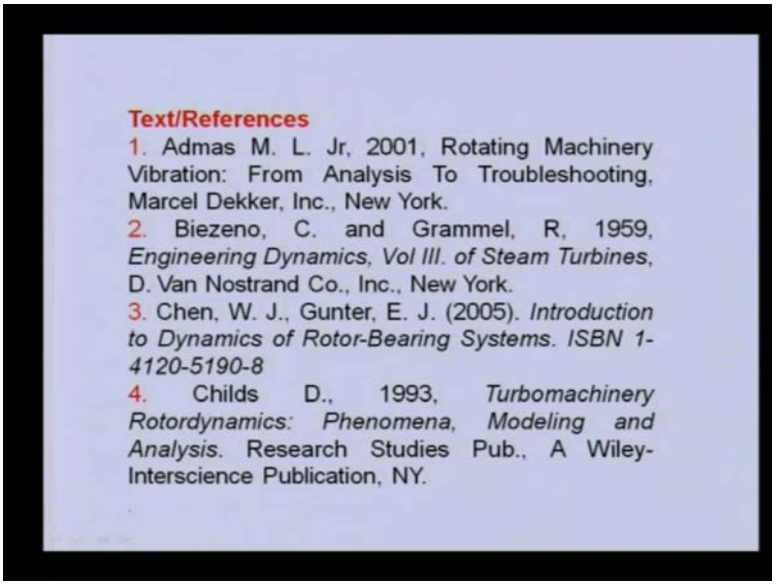

Signal processing in three lectures condition monitoring will covering two lectures these are the various references are there a mostly this references, people have. There are some kind of monographs, they will do the research in there topics, there is on the rotating

machinery. These are something like monograph in which they are put all there research in a book form and we will see as this are not text book like stem.

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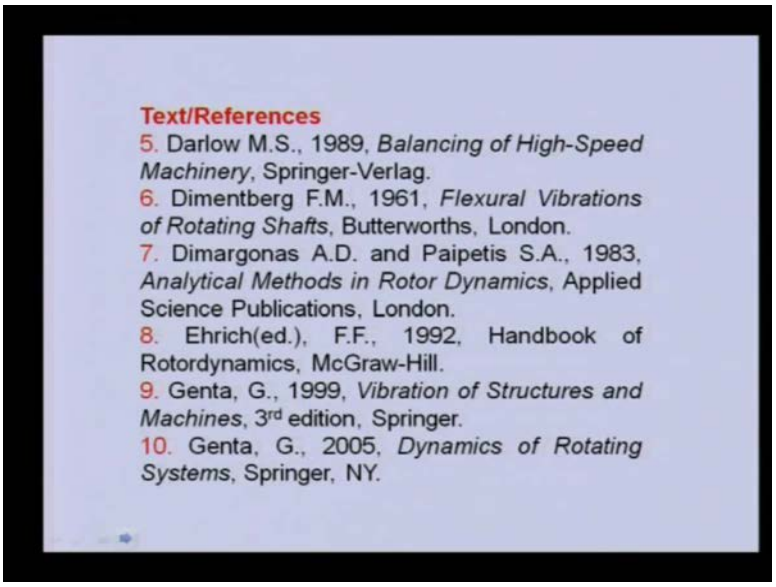

So, many books reference books, I wrote all of them.

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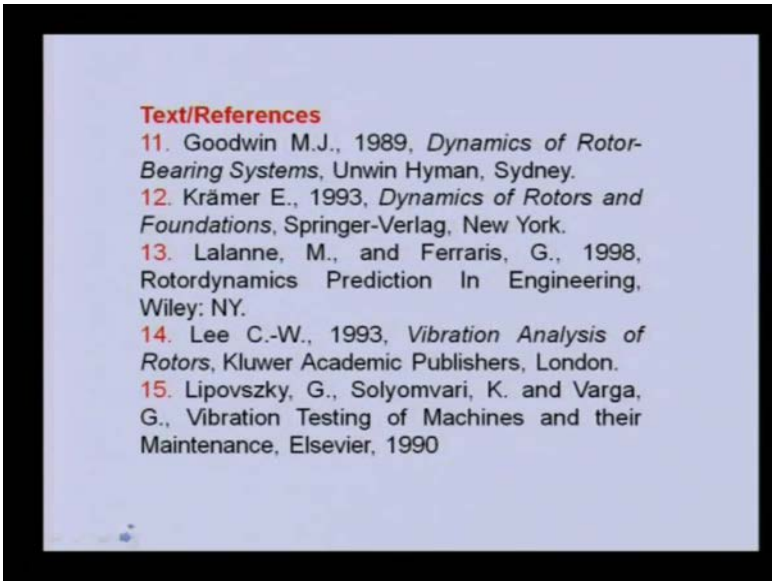

You can just look into that these are all textual reference book.

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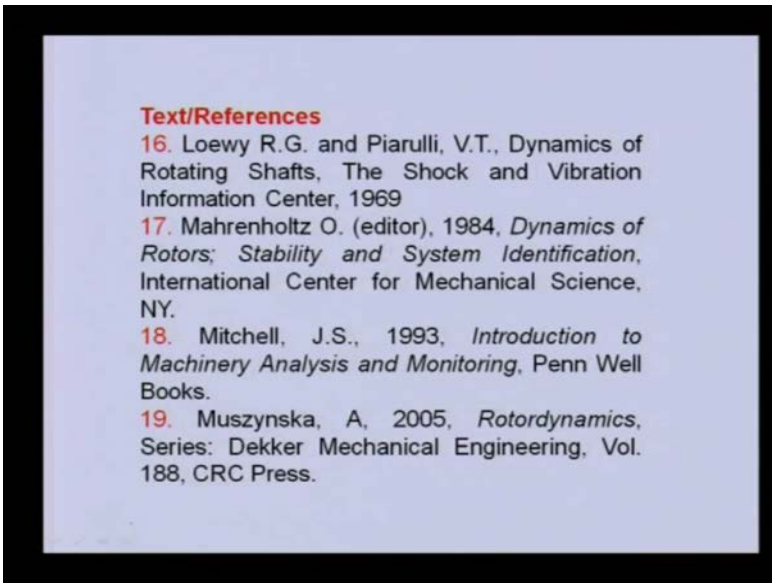

There are so many books in this particular topic, these are all written by evident researchers.

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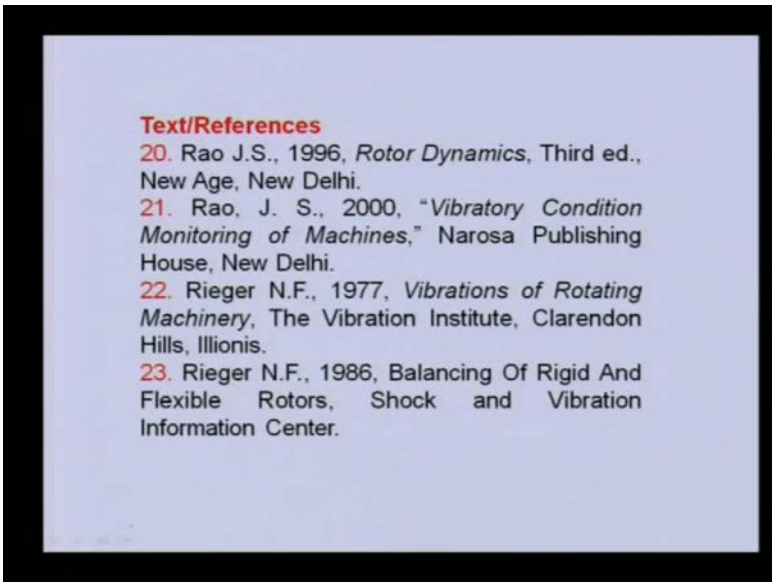

In this particular field, you can able to see it was the seven of books are there, but mostly people there they combine research generics books this are also some more books.

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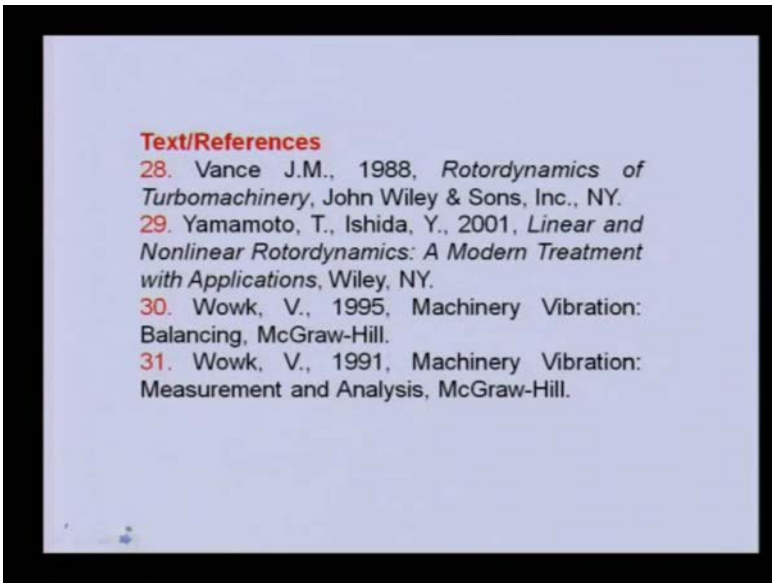

Now, we will see because this particular topic is not only traditional past subject, but still research in this particular field is going on.

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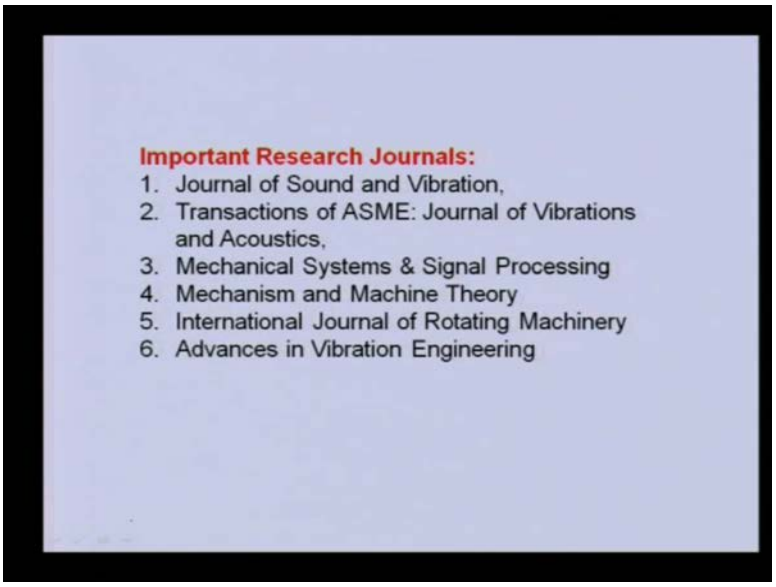

So, this are the some of the journal like sound and vibrations transition of ASME journal of vibrations of acoustics mechanical system and signal processing mechanism and machine theory. In international journal of rotating machinery advances in vibrations engineering, these are the few journal where it is you can find the latest strength on this particular subject.

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Now, let us see some important conferences which generally every 4 years or every 2 years people are conducting it. So, like the first one international federation for the theory of machines and mechanisms that is called, they conduct international conference on rotor dynamics this confluence every 4 year. They conduct institution of mechanical engineers like IMechE, UK they conduct international conference on vibration in rotating machinery. They are also conduct every 4 year international gas turbine institute they conduct one, there is turbo and expo ASME turbo expo, they conduct every year.

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This is very international symposium apart from that the fourth one international symposium on stability controls of rotating machinery or they also conducting regularly this conferences. There is another conferences international symposium on transport phenomena and dynamics of rotating machinery and in India, we have one symposium.

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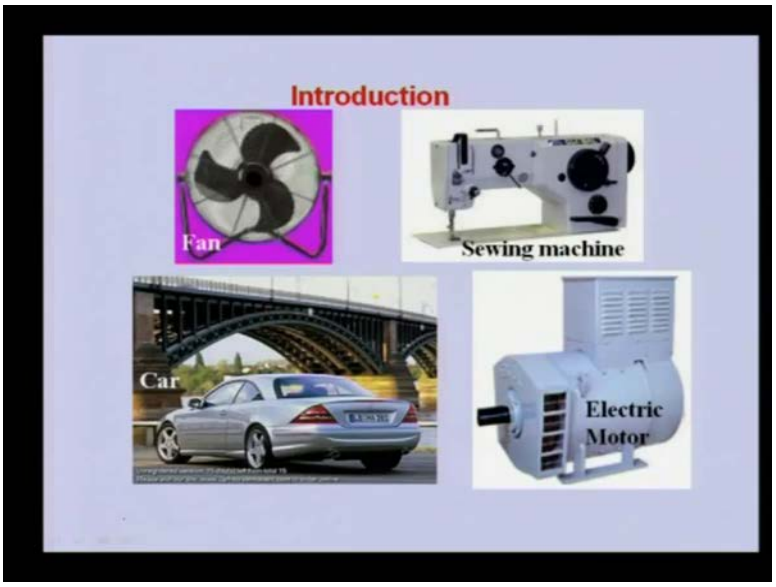

We have seen that two times it has occurred and now every 2 years, it will be conducting national symposium on rotor dynamics NSRD. Now, let us see some of that application of these rotors in that day today life of or industry or in transport everywhere, we will find rotating machineries and the best part with the rotating machineries is that they contain large energy along with that.

So, mainly they are use for transmitting the power, so they have very high density of power and a because of this and associates flexibility in such system there is litter amount of vibration energy is also there. So, you can able to see some of that application here like a fan showing machine or car in this, so many components are there which revolves the electric motor.

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They contain rotating parts or even helicopter, you can able to see turbines amount power is there in the blades, not only the main blades, but also lifted blades. Now, let us see how turbine in actual industry is there, you can able to see huge turbine.

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In this lots of blades are there, and in this tremendous amount of the rotational energy is generated.

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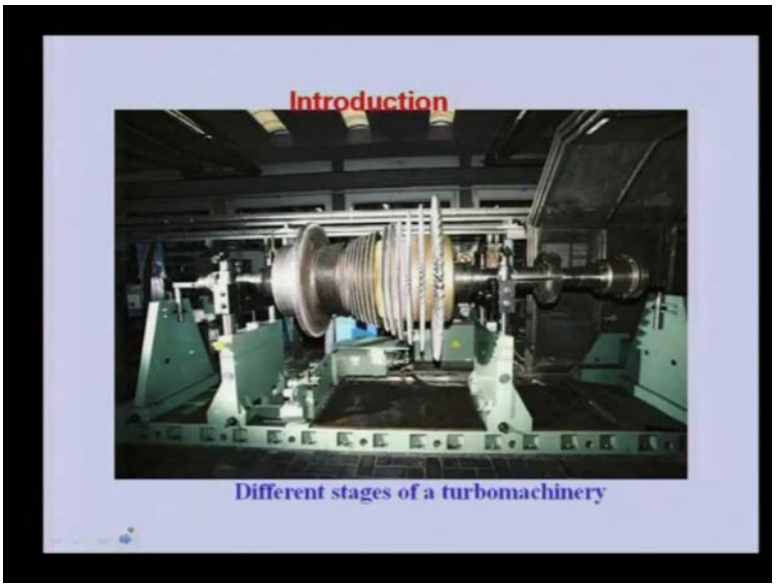

This is another view of the same turbine; you can able to see different stages of the blades.

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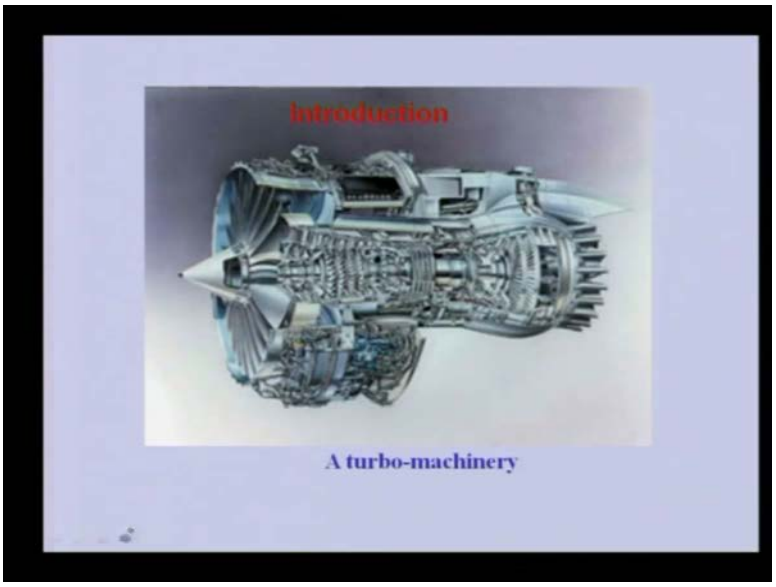

This is a turbine the gas turbine in the air craft engine.

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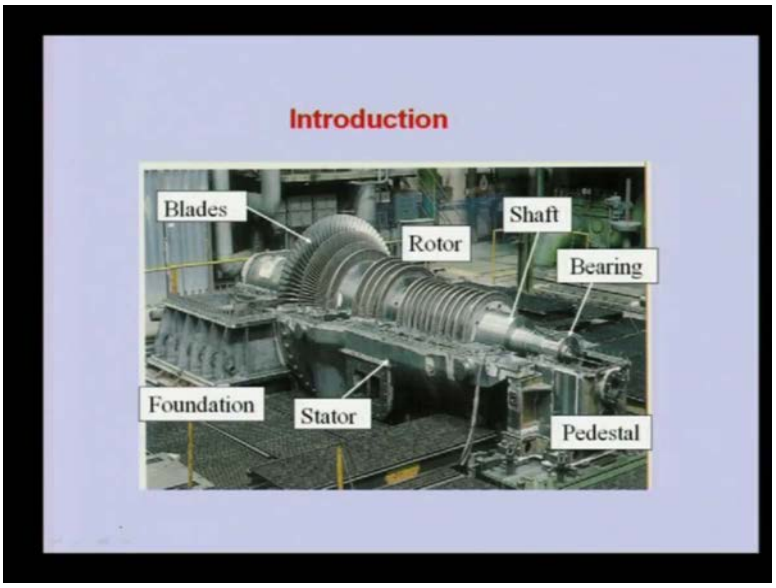

Now, let us see various components of a rotating machinery like the first thing is the shaft on which various revolving apart like blades are bounded. So, this particular you can able to see this shaft containing in this blades everything that is called rotor. So, all the part which is revolving along with the shaft is called rotor, there is in the form of disc or blades or coupling any parts which are bounded on the shaft it is called rotor. Now, apart from that you can able to see the bearing which supports this revolving rotor and it announce the relative motion of the rotor along with the stator is a non rotating component.

This is either the foundation is there is also part of the stator in which this high a rotational energy rotors are kept. You can able to see that these foundations, they observe what over the vibration energy that comes from the rotor. It reduces basically the vibration of the rotors, so here you can able to see the pedestal of the bearings the here is bearing and there is column which is called pedestal of the bearing.

This whole assembly is bounded all rigid base that is called foundation so we have three components mainly in the rotating machinery there is a rotor. Then, bearing and the foundations see as we go along this particular subject bearing turbine which are using in the rotor dynamics. So, first let us see what is a rotor again as I am repeating of already seen in a turbine rotor is nothing but all the components which are bounded on a shaft

including the disc coupling blades fan of component which is rotating along with the shaft called rotor.

There is the stator which is the stationary part which does not rotate and between this two there is a bearing which allows the little motion between the rotor and the base that is the foundation of the stator. Now, these particular rotors as I told they contain very high amount of rotational energy and as a rotor dynamics analyst. The designer of the rotator dynamics has to be very careful that what over the rotational energy dynamics.

There should be maximum and what over the vibrations energy because of the flexibility of the rotor or because of the flexibility of the bearing or the foundations the vibrational energy should be minimum. That is 100 whirls for this kind of machinery, now let us see some of the concept in this particular subject like as I told one is the un balance what is unbalance.

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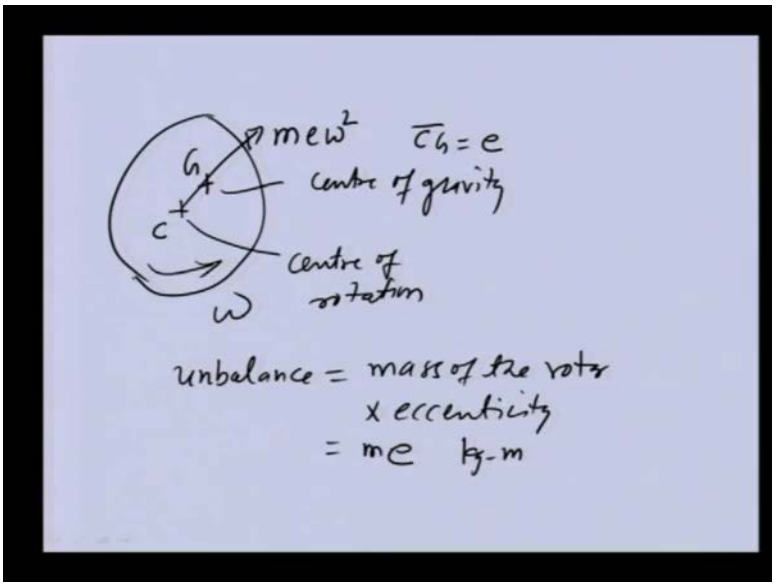

Let us say we have a circular disc this is revolving about its geometrical center, let us say geometrical center of the bearings is revolving about that point at some speed, let us say omega. If this is the geometrical center or revolve center of rotation if the center of gravity is also at the same place, then they will not be any central force, but if center of gravity is upset by some amount from the center of rotation. Let us say G is the center of the gravity, and then you can see that there will be center force which will be m e omega

square and mass of the rotor is the acceleration which is distance between the c n G and omega.

This is the spin speed of the rotor that is having in reduce per second or in rpm here you can use in reduce part circle. Now, you can able to see when the centers of gravities are offset from the center of rotation, we have this unbalance forced. So, in rotor dynamics the unbalance is define as mass of the rotor into the eccentricity, so you can able to see this unbalance and the unbalance unit is kg meter.

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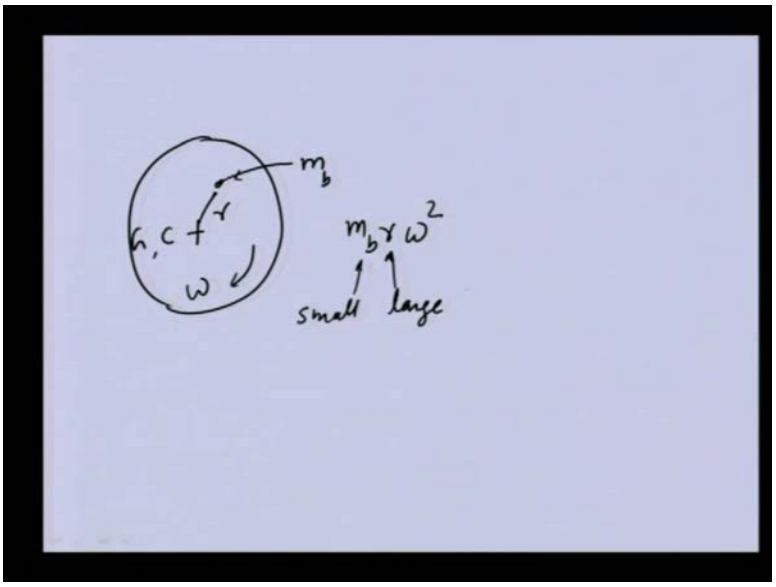

Now, clear unbalance force can come because of some other reason, also like if this the center of rotation and it center of gravity is also at the same place, but if we keep a small mass small mass in the form. Let us say a screw or another, we put here some mass here or cutter it out from the rotor let us say there is small mass m b at the radius r. So, in this particular case when this rotor is rotating, then also we have having centrifugal force and value of that will be m b into r into omega.

You can able to see that this m b is very small mass of a screw, which we are keeping at this radius r here. This particular mass will be small as compare to the mass of the rotor this radius will be large as compare to the extensity of the rotor. If we go back to the previous slide, you can able to see this mass of the rotor is large, but eccentricity is very small.

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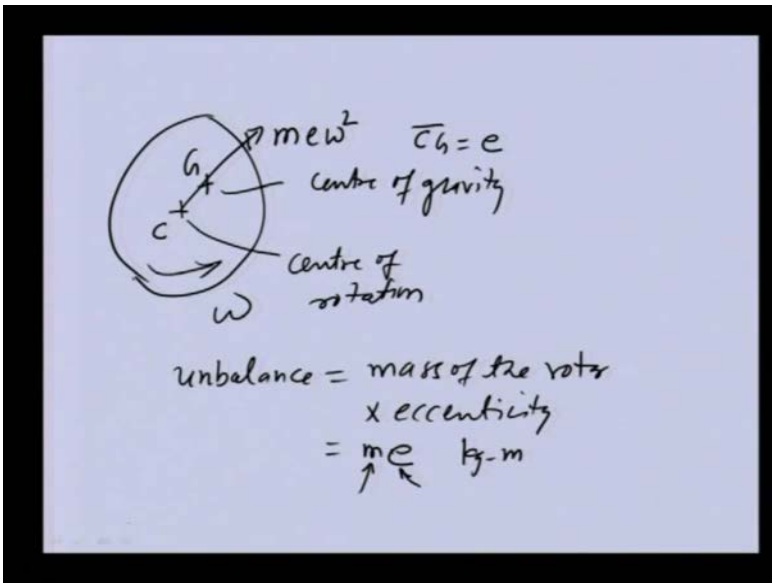

Generally, it will be the order of in grounds and mass of the rotor will in the order of around 100 kg or it depends on the rotor size.

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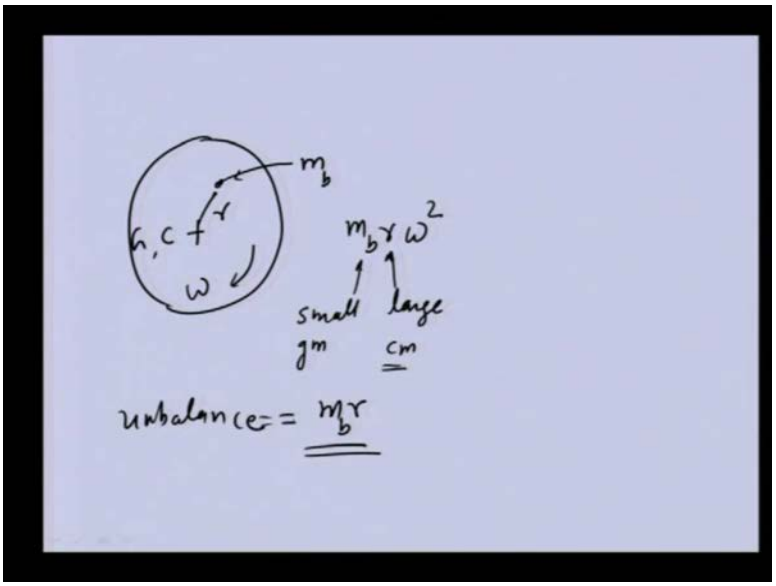

Here, when we talking about keeping small unbalance mass that will be in few grams and this reduce will be in either in centimeter or around the value will be large enough. So, you can able see that the unbalance is coming in this particular case because of some extra mass that we are keeping all to the rotor or we are removing it. So, this is

unbalance if we extend this concept that previous concept was for the rigid disc that is a disc, which is thin.

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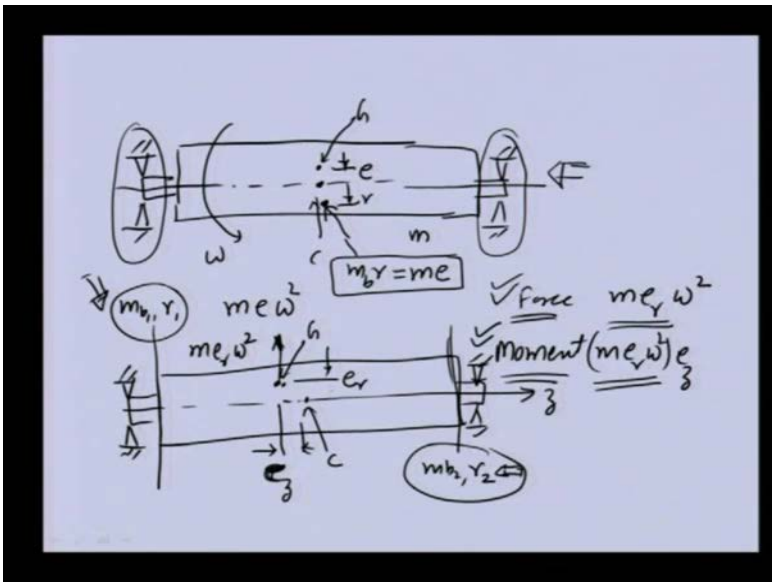

Let us say we have a rotor of this size which is long rotor, then here will having one axis about which this particular rotor, we expect is rotating there will be some supports adorns. Let us say this are some bearing support and this rotors is rotating about its rotational axis, now here let us say this is geometrical center of the rotor and if center of gravity is also at the same place. Then, it will not be having any unbalance force in this particular rotor and it is rotating which center gravities it here exactly at the center of the geometrical center of rotor.

They will not be having unbalance force, but if we have some amount of extensity that means G is here is not along with this then it is distance is e. Then, we have unbalance force if let us say m is the mass of the rotor unbalance force will be again m e omega square. On this particular rotor will be having forces at bearing locations unnecessary force will come onto the bearing because of this unbalance because unbalance is unwanted form.

So, what is the unbalance we are seeing for a rigid disc and for the long rotor case which we will see in more detail about this, but let us see what is why unbalance comes in a rotor unbalance. Actually, we do not want to the rotor because it is giving necessary force to the system, but or it comes may be because of during the manufacturing when

there is some tolerances in the machine components. So, if we want to make perfectly circular disc there will be some defecation or may be to learn it will be other solidly over share or may be some radiations along the redial directions because of that the center of gravity will upset from center of rotations. That will give the eccentricity and that gives the unbalance the mass into the eccentricity apart from this even if we manufacture the rotor perfectly.

There may be problem during the bounding when we bound the let us say disc call to the shaft. So, when we are making a whole out the disc for bounding out to the shaft may be that the whole itself is solidly extremist and because of that we are losing the center of gravity is aware from the center of rotations. Even if we can able to make solely, also perfect what happens during the operation because this also rotors, generally are working in very harsh environment steam high temperature and like gas turbine. There is lot of the fuel and because of that may be here and there take will take place and these rotors which are initially perfectly balanced.

During operation, you may find that you will be having some unbalanced and they gave rise to unbalance forces which are unwanted. So, periodically also we need to balance it if we commission may particular rotor in a industry after commixing we need to balance it, but periodically also because of here and there and another fact the unbalance may come and we need to balance them periodically. So, again coming back to the long rotor case in which I shown one kind of eccentricity you can able to see that eccentricity is in the radial direction, but this particular eccentricity I am showing in solidly more complex situation in which this the geometrical center of the rotor.

In the previous case shown the G in the radial position, but now I am giving the G some upset position in the excel direction also, we have two eccentricity one is radial and another is let us say eccentricity. So, this is the z direction, so e is the eccentricity, now sanctification force will attend at G which is upset in redial as well as in the excel directions this magnitude is mpr omega square.

Now, you can able to see if we translate this force from G at c location will be having one force magnitude will be m e r omega square, but will having moment term also that will be m e r omega square and moment term is z. So, not only the force will come into the rotor, but also the moments will come now you can able to see that in this particular

case situations is more difficult because. Now, we have a moment, also if we were coming back to this particular previous pages rotor in which the eccentricity was the radial direction, you can able to see that this particular rotor if you want to balance it.

So, we need to keep mass opposite to the G location here and let us say if we are keeping small mass md here at radial distance r. So, this should be equal to mass of the rotor and its eccentricity, so with this we can able to balance this particular rotor, but in the second case we have to component one is a force on a moment. So, here the balancing is more difficult and by single mass we cannot have able to balance it, now it can able see the difficulty so we need to have two places two masses component.

We need to keep let us say m b 1 at radial distance r one m b 2 at radial distance r 2 and this two correction masses can be used to balance not only the this particular force also the moment more detail of this. We will go in that particular chapter where we will be talking about balancing of rotors, so I am leaving it you to think how this two masses can be used to balance this particular rotor in which the radial and eccentricity is there and I will be eccentricity this particular concept.

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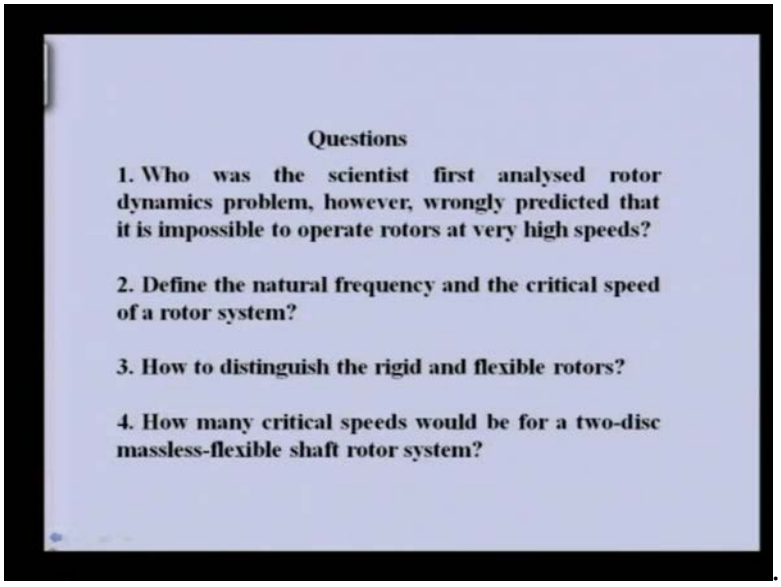

I need some more slides, now we will see this same long rotor how other kind of unbalance may be there in this. So, earlier we do the rotors and they were horizontal in position, but during some assembly.

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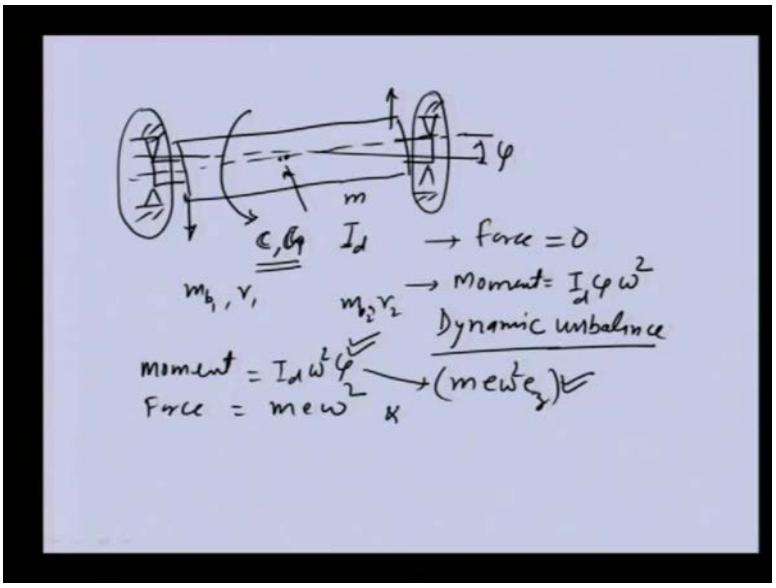

If this is the center of rotation, we may have the center of rotor actual rotor solidly inclined. So, execute this mention the inclination may be will be less than 1 degree in actual case, so rotor is bounded which is solidly inclined. Here, the center of gravity is there at the center of rotations, but rotor is inclined let us say this inclination is at some angle feet mass in this particular case mass of the rotor is I and diameter mass moment of energy of the rotor is I d.

That is perpendicular to this particular rotor not the along the rotor directions, but about the one of the diameter access. So, in this particular case, you can able to see then the rotor is rotating that will not be any certain centrifugal force will be 0 because the center gravity and center of rotation are in the same place, but it will be having moments. It will able to see the cross is inclined, there will be some force and the moment will be having this value.

Now, you can able to see the force is not there, but moment is there and because of this the bearings will take some unnecessary load and to balance this again. We require two masses as we had earlier in two different places to balance this particular kind of unbalance in the rotor. This is generally called dynamics and balance in which we require to place to balance rotors and next situation you can able to see when both the rotor is having inclination as well as the CMG are not at the same place. Then, not only

will be having moment, but also will be having force, so that will be me omega square only radial eccentricity.

If the eccentricity is there, then will be having this particular moment as well as this moment which we already seen in the previous slide. There will be two unbalance moment one this one another this one, just now we have seen that how the unbalance can come in a rotor this unbalance force will give some kind of unwanted force moments into the rotor. When the rotor is having flexibility and either in the on the shaft or at the bearing the unnecessary transfer vibrations will take place. Now, let us see how a particular rotor which is having flexible shaft can have vibrations, so let us sat there is a rotor or this is flexible sharp.

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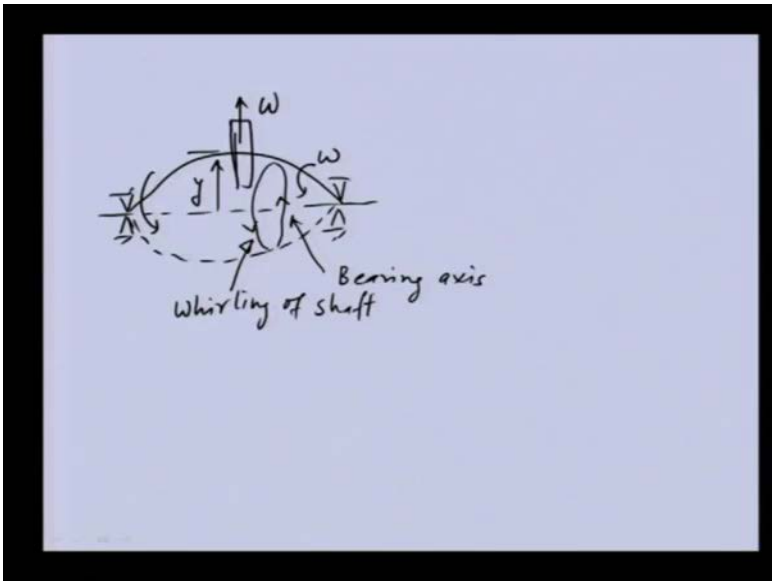

There is the disc and when this particular rotor is at the rest, obviously this will be with the bearing axis with the bearing axis, but it is start rotating give us some unbalance force. It will try to deflect and it will be having some transverse vibration now you can able to see that this particular transverse vibration. When it is rotating, this particular rotor will come this side also, it will bow in a have a circular part or in a to electro part to depending upon the property of the bearings are banned this particular motion. Now, there are two motion of the rotor one is spinning about it own axis and then there is this vibrations transverse vibration that is called whirling of shaft this particular motion.

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Let us see in this particular model, this is simple disc is there and flexible shaft is there in this particular case one is the rotation of this particular disc is revolving about this. Generally, this particular disc will be fixed on to the shaft, so when shaft rotates it will be revolving along with this and where there is unbalance. This particular disc will deform the shaft will deform the shaft will deform like this and it will start the shaft itself will be start revolving about itself vary axis like this.

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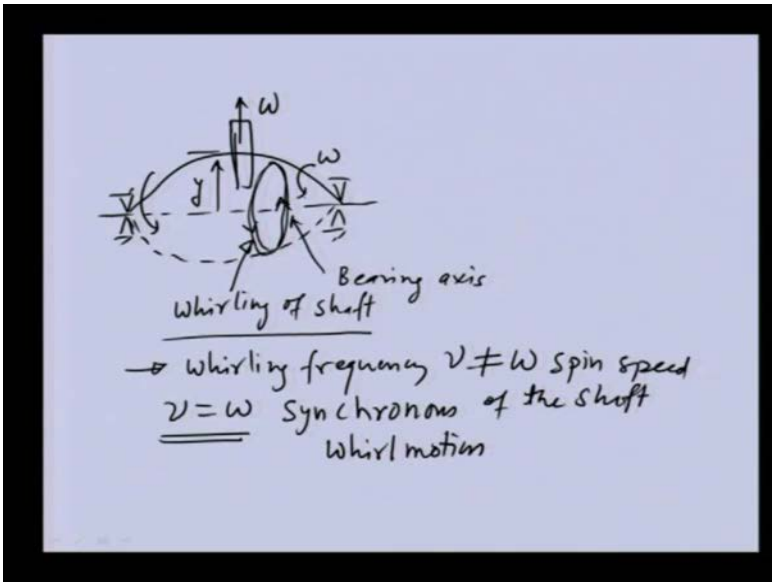

So, not only the disc is revolving about its own axis, but the deflected shaft itself is revolving about the varying axes. There are two motions this particular motion which able to see is called whirling the first one which is revolving of the disc about its own axis called spinning this spinning motion. This is whirling motion, this is whirling motion this here also you can able to see the whirling motion of the shaft this is the particular phenomena which rotor will be having when is having some kind of unbalance.

You can see that the whirling of the shaft because the whirling frequency, generally we represent is a mu in general this will not be equal to the spin speed of the shaft omega is the spin speed of the shaft, but if this whirling is due to the unbalance. We expect mu is equal to omega that is we called as a synchronous whirl in this particular motion in this particular case. We have whirling frequency that means this particular motion frequency same as spin speed, let us see this particular motion in more detail, let us say we have this is the bearing axis bearing whirling.

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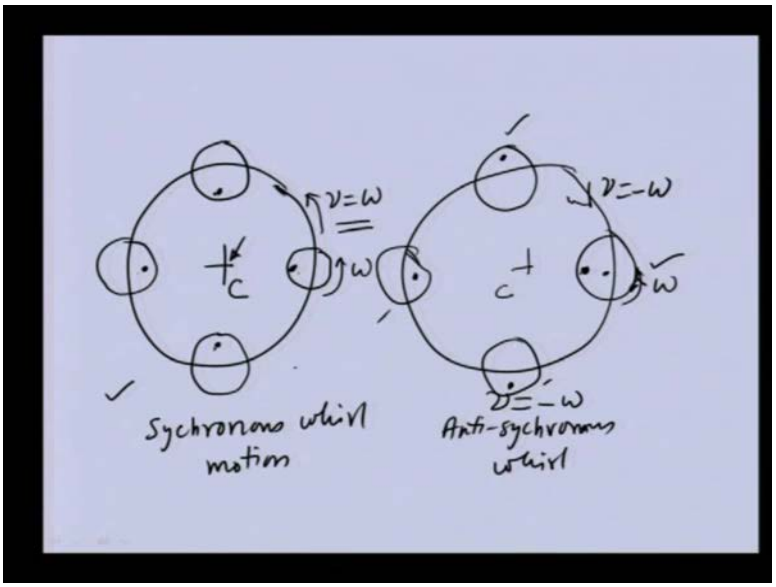

Let us say shaft is revolving in a circular path let us say this the shaft position at one place as let us say this is the direction of the shaft spinning about its own axis. Also, it is spinning whirling with omega, so after sometime it will occupy this position or this position or this position. If we mark a point on to the shaft here, let us say this if this condition is there is whirring frequency will orbital frequency and the spin speed that is

revolving of the shaft about own axis. There is some aspect this particular dot when it is moving we will occupy this position.

So, what is happening in this particular case if we as setting here and looking into the shaft, we will see that same phase of the shaft will see all the time during this motion this motion is called synchronous whirl motion. In real case when in the really the earth and the moon they have this kind of the motions, and because of that we see the same phase of the moon from the earth.

They have synchronous motion the spinning of the moon and the orbital frequency of the moon; they are same because of that we see the same phase of the moon. Here, we have the same situation if we have another kind of motion, let us say when we have this whirl frequency is equal to minus omega. So, this we can cauterize as a anti synchronous whirl and in this particular case let us see, so if we take one point here and we will try to see its location at other places. We will see that when it comes here, it will be outside when it is here it will be inside when it is here it is outside. Now, what is happening you can able to see that when the shaft is having one revolution from this place of and then from here.

It is having the flexural of the shaft is taking place twice in the previous case synchronous case shaft is any no flexural whirl motion. So, if we see in this particular case the shaft bends for synchronous case and its rigid body it revolves about the bearing axis. So, this is synchronous motion in which as such there is no bending and there is tension completion of the shaft is not taking to place like this. It bends and its revolves it is a rigid body more that is it synchronous that is it, but in the anti synchronous whirl, it will be having the bending and the frequency of that flexural motion will be twice per revolution, now let us see more general motion.

We have mu is equal which is not equal to omega, so in this particular case you can aspect that the shaft when it is revolving this, sorry this is omega and this is mu is not equal to omega. So, for this particular case it make take varies position or depending upon over the value relative value of this two, so there be not any fix atom of this, but it will depend upon what is the value of the mu.

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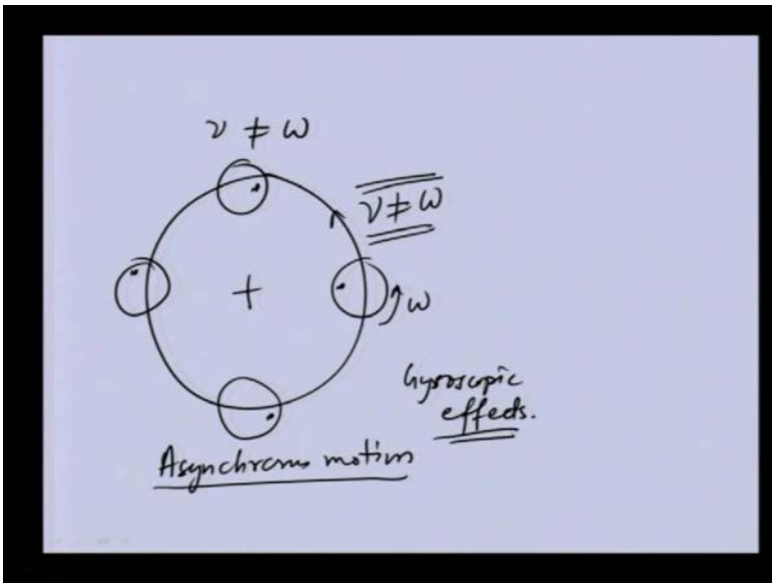

It respects to omega this particular motion is called asynchronous motion and generally this motion will take place and we have gyroscopic effect into the system, this will see in subsequent classes. So, to just to recapitulate what are things learn today, initially we started with the introduction to the subject as I showed you all the content of the subject and how various lectures having divided into various topics. Then, we saw some application of rotating machinery and we found that day today life. Also, even in the planetary motion these kind of rotating motions are taking place and study of this particular type of motion the rotating motion.

The dynamics is very important specially for machineries and after that then I introduce some few concept like one was the unbalanced in the rotor and we have seen that there are two types of unbalance which comes into the rotor. One is the static unbalance which is generally occurs in the thin disc and there is dynamics unbalance and generally in long rotors dynamics balance are there. We have seen that for that dynamics balance we need to plates to corrections masses to balance that.

Then, we have seen the concept of the whirling motion in which the shaft which is flexible when it is spinning not only spins about it own axis for the axis itself rotates about the bearing axis and that is called whirling motion and especially due to the unbalance that whirling motion frequency is same as the spin speed. That particular

motion we called as a synchronous whirl I define the synchronous motion of also generally.

When there is some kind of friction or the contact of the rotor with the stator and that try to rotor in the opposite directions of its whirl and there we can have this anti synchronous whirl. Sometimes, it is also called backward whirl as we go in this particular subject in more deep this phenomena and will able to understand better the synchronous whirl. Also, I introduce and generally these are there when you have like gyroscopic effect or sometimes due to the bearing. The bearing also is having property with changes with speed because of that; also we have this kind of synchronous whirl in the rotating machinery.