Mechanical Vibrations
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Module - 12
Signature analysis and preventive maintenance
Lecture - 3

Field balancing of rotors

Today we will be studying balancing of rotor. In practical rotors we will find always there will be some unbalance in the rotors and these unbalance are the major faults in rotating machineries. They give rise to forces: centrifugal forces and generally the bearings fails due to these forces, because after all whatever the unbalance force is there in the rotor it comes to the bearings and bearing get failed and these unbalance which is inherent in the rotor always may come from variety reasons of like, may be due to the manufacturing defect or when we are machining a particular rotor may be we want to make a rotor is circular but because of tool vibration may be it becomes elliptical in shape or other shape because of that the center of gravity of the rotor deviates from the center of rotation of the rotor and because of that this unbalance comes.

Apart from this manufacturing defect there may be thermal bow in the rotor which may leads to the unbalance force in the rotor. And apart from that like material non-homogeneous material may leads to non uniform distribution of the mass and because of that we can have the deviation of the center of gravity from its center of rotation. Another cause of unbalance could be from the residual unbalance or other cause of vibration could be due to the residual stresses in the material of the shaft.

So, first we will see basic principles of the unbalance how it comes and how it can be balanced, because if we can balance these unbalances, then unnecessary load which are coming to the bearings can be reduced. There are 2 type of unbalance in the rotor; one is called static unbalance and another is called dynamic balance. Let us see these unbalances.

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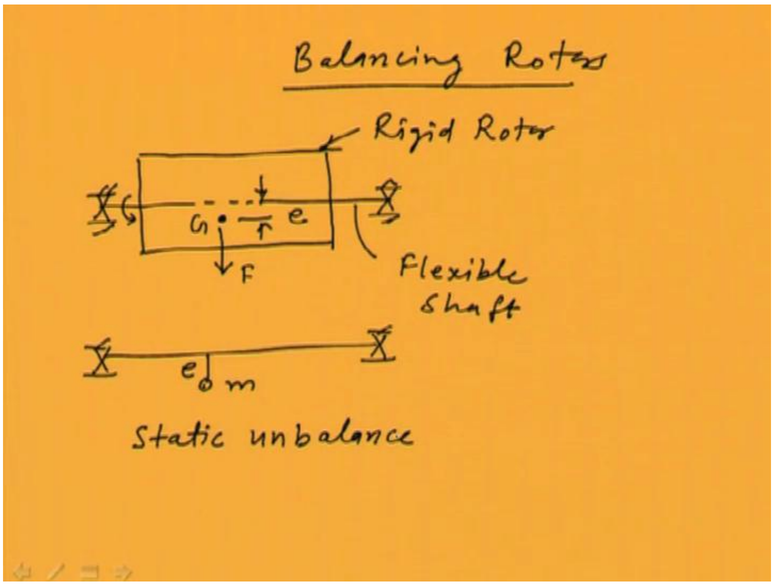

So, balancing of rotors; so let us say there is a rotor like this and it is rotating about a axis and bearings are provided at the ends. So, a something like rigid rotor. So, it is a rigid rotor and this is a flexible shaft. Now if center of gravity of the rotor is somewhere here, this is offset by e. Then, when this shaft rotates will bearing centrifugal force which will be acting outward to this and this can be represented in a simple line diagram like this. Mass of the rotor is concentrated here at the center of gravity and it is at the radius e. So, here this particular kind of unbalance is called static unbalance in which we can able to balance this using single plane. That we will see later.

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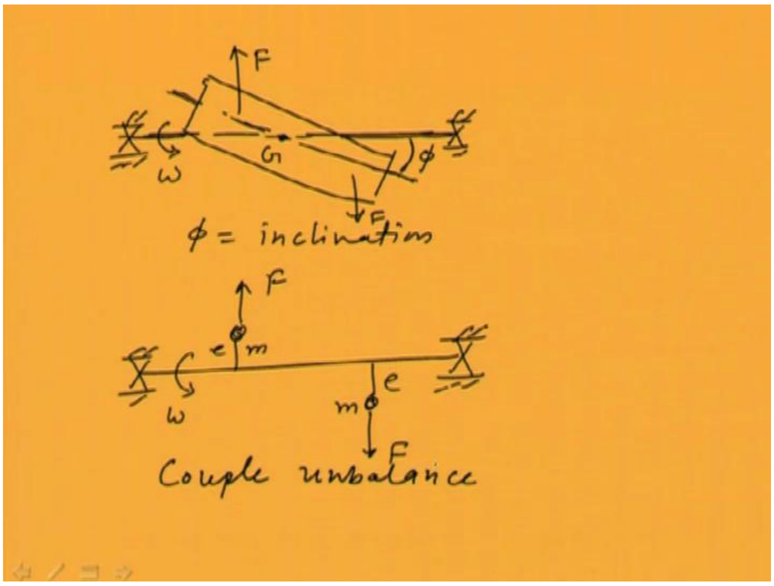

Another kind of unbalance which is called dynamic unbalance, this is the rotation of the shaft. Let us say the shaft this particular rotor is inclined by some angle. This angle is phi this particular rotor is rotating. I have exaggerated the inclination just to show the, so this is the particular shaft here and this rotor is rotating about this particular axis with omega and phi is the inclination of the shaft. So, principle axis of the shaft is along this direction, but rotation of the shaft is not coinciding with that, so we are having this much angle and because of that you can see that there will be some force, which will be acting on this rotor which we can able to here for time being let us, consider the center of gravity is coinciding with the center of rotation of the shaft. So, there is no eccentricity as such, but inclination is there now.

So, this particular rotor can be represented like this in which we have m e here m e. So, forces are acting here when this shaft is rotating. Because we have considered the center of gravity on the center of the rotation of the shaft, so there is no centrifugal force coming from there, but because of the inclination we are getting a couple. So, this particular unbalances sometime called couple unbalance. This is 1 form of the dynamic unbalance.

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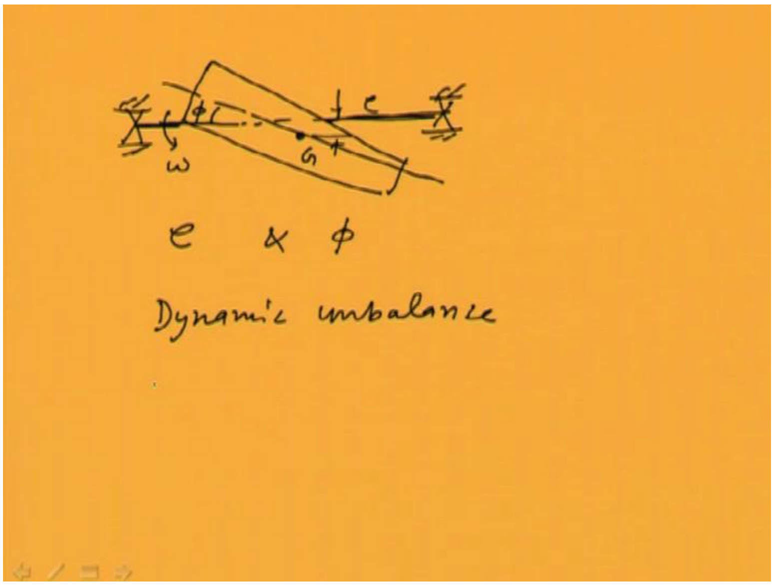

Next let us consider more general case, when the shaft is inclined also the center of gravity is away from the axis of rotation. This is the axis of rotation. So, now have eccentricity, also the inclination phi. So, we have eccentricity and phi both and this particular case is called dynamic unbalance, which is superposition of the previous 2 cases.

So, from this description we can able to see that the static balance static unbalance can be balanced by a single plane. Whereas, the couple or the dynamic unbalance has to be balanced by, 2 planes and there are other kind of rotors which are flexible. Flexible rotors are those rotors which are rotating above their critical speeds or near their critical speeds. And when they rotate around its critical speed they bent also and because of that, we have apart from the inherent eccentricity in the rotor because of the deflection also, the distribution of the centrifugal force changes along the length. So, let us see how the eccentricity of a flexible rotor changes. So, in general we have this is a continuous rotor.

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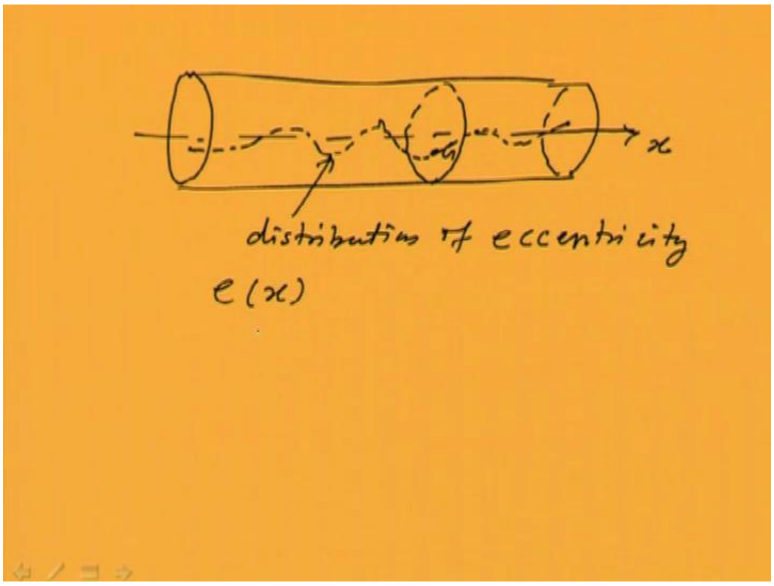

let us say. And if we take a particular segment plane, this is the axis of rotation of the shaft. Here center of gravity is offset by some amount and if we see this center of gravity as we will move in the axial direction, then it change because of the material non-homogeneity or other reasons. So, this is the distribution of eccentricity. Now, this is function of the axial position. This kind of rotor are very difficult to balance, they come under the category of flexible rotor balancing. And we will be focusing our attention toward the rigid rotor balancing only. Now, we will see the principles of balancing for rigid rotor case that is: for static balancing and unbalance there is dynamic balancing.

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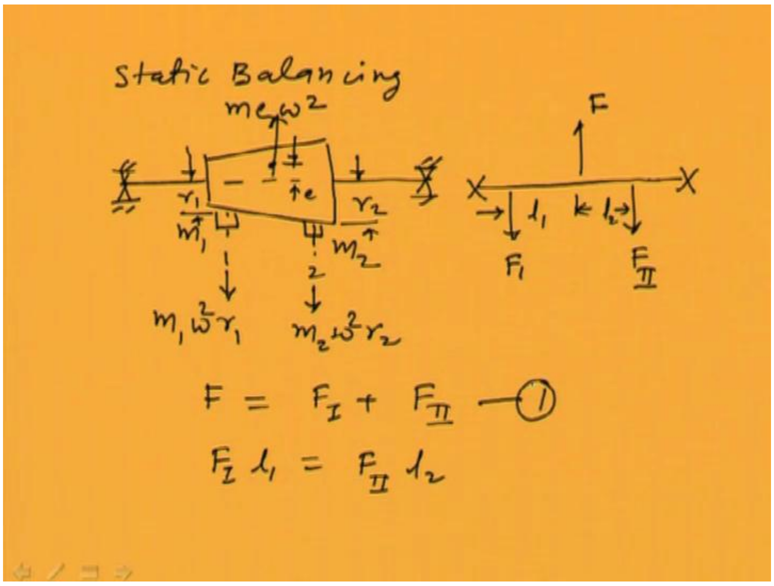

So, let us start with the static balancing. So, we have a rotor like this, which is mounted on bearings at the ends. Now, the eccentricity of this rotor is e because of that, we are having centrifugal force. Now, let us say we have 2 planes; plane 1 and plane 2 where we can put the correction masses m1 and m2. So, these correction masses will give rise to, forces m1 omega square their position is let us say: r1 and r2. So, this position is r2 radial position and this position is r1. Now, this system can be expressed shown like this: where, this is the centrifugal force for balancing plane 1 and balancing plane 2.

So, we need to consider these relations when we want to balance the rotor. First is this another is let us say, this is l1 this is l2. So, F1l1 should be equal to F2l2. So, first equation is ensuring that, the unbalance is getting balance by the correction masses. The second equation is ensuring that, we are not getting any moment from the correction masses and these equations 1 and 2 can be solved for F1 and F2. So, they will take this form.

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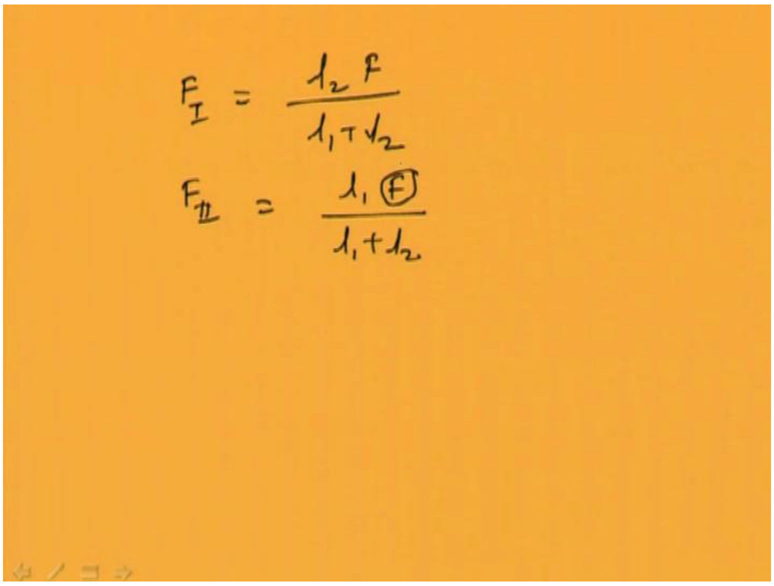

F1 will be l2F by l1 plus l2 and F2 will be l1F by l1 plus l2. F is the unbalance force which is there in the rotor.

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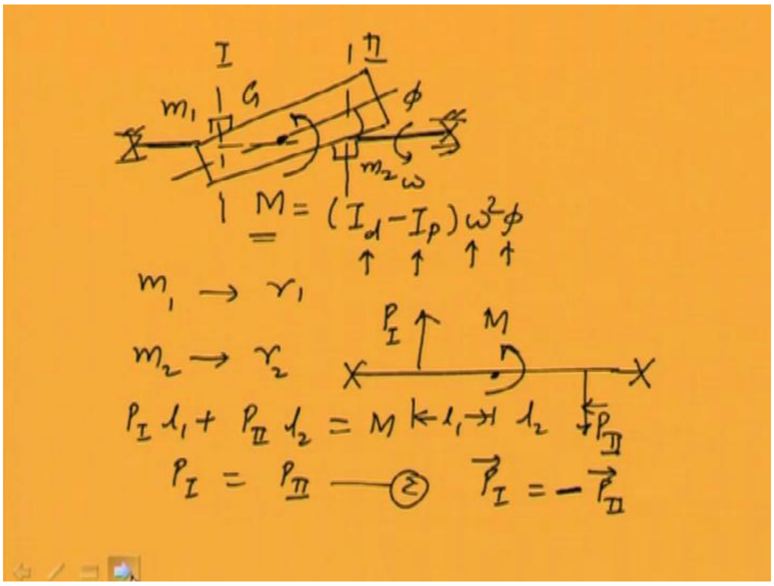

Now, consider the couple unbalance case. In this particular case we have, a rotor which is inclined like this; which is rotating about this axis, this is the axis of rotation, this is the inclination center of gravity we are assuming there on the line of rotation. So, because of this inclination we will get a moment onto the rotor and is given by, this expression in which this is the diametric mass moment of inertia and this is the polar mass moment of inertia of the rotor; omega is the speed of the speed of the rotor, phi is the inclination.

Now, to balance this moment we need to put correction masses in 2 planes: plane 1 and plane 2 in the rotor. And let us say we are keeping m1 mass here and m2 mass here and there radial position for mass m1 is r1 and for M2 it is r2 radial positions are these. So, the this particular system can be, again we can able to represent like this: let us say this is P1, this is P2 their distance are l1 and l2. So, we need to satisfy P1l1 plus P2l2 should be equal to the moment which is coming from the inclination and also, this P1 should be equal to P2, because they should not give any unbalance force, they should balance the couple only and they should not introduce any other centrifugal force. So, whatever the correction masses we are putting that should be equal. So, that is given by the second equation. This second equation in vectorial form should be a like this; that means vectorially they should be equal, but opposite. These can be solved for P1 and P2.

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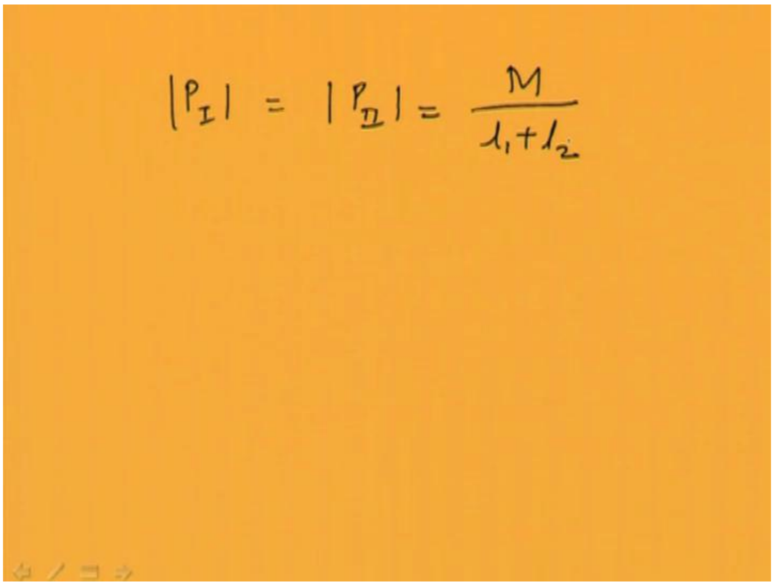

So, we will get P1 magnitude P2 magnitude is equal to the moment divided by l1 plus l2. In this particular case when we considered the couple unbalance we assumed that, the plane of the couple we know. Now, we will consider a combine case when we have static unbalance also the couple unbalance that is that, comes under the dynamic unbalance case.

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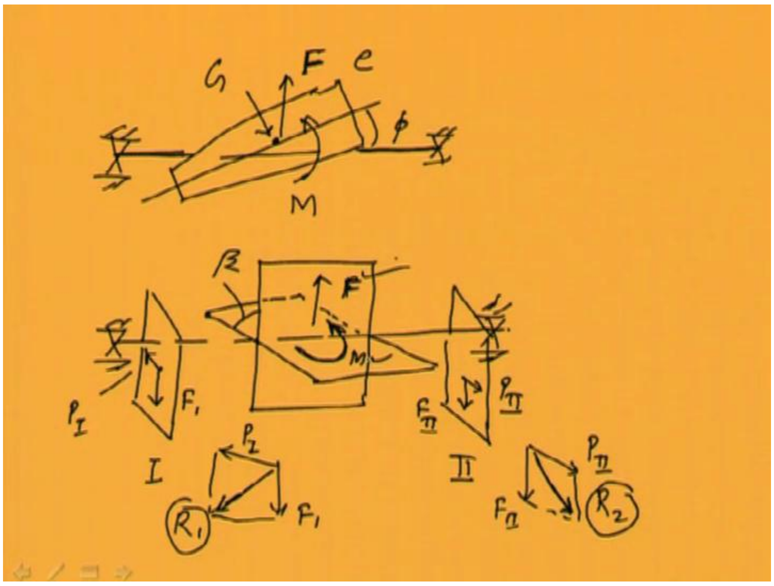

So, in this dynamic unbalance case let us say, a rotor is inclined like this. This is the axis of rotation of the rotor; it has upset in the eccentricity. So, G is here and is having inclination. So, it is getting force; also the moment. Moment is coming from the inclination F, this centrifugal force is coming from the eccentricity e. So, for this particular case, the centrifugal force which is acting and the couple which is acting they may not be in the same plane.

So, we need to consider the correction masses when, we need to consider these correction masses, because these forces at moments are in the different plane. Because this particular rotor can have moment let us say, in 1 plane this is a plane in which let us say, force is acting and there is a another inclined plane which not necessary horizontal like this. So, this can have angle not necessary 90 degree. So, on this plane the moment is acting and the bearing is somewhere here. So, we need to have correction mass planes like this. This is a plane 1 and this side there is another plane.

So, we need to consider the balancing in plane 1 and plane 2 because of the force F and moment. So, we already obtained what are the correction required for F. So, that we can able to use here that is, F1 and F2. These are corresponding to the force; centrifugal force which is coming from the eccentricity of, due to the couple M we can have correction mass in this direction that is P1 and this direction P2, because P1 and P 2 should form like couple and it should be equal and it should be opposite to the direction of the moment.

Moment is if we see from the top is having counterclockwise direction. So, the couple due to the P1 and P2 should make direction of the clockwise. So, you can see that in plane 1 we have 2 forces that is, F1 is acting downward and P1 is acting is some other angle. So, the resultant of this can be obtained and similarly, for second plane P1 and P 2 and F2 are there. So, we can able to obtain the resultant on that: R2. So, R1 and R2 are now correction masses, you can see their directions are different now. Even the magnitude will be different, but they will be balancing both the force and the moment.

So, this is the basic principle of the dynamic balancing using 2 planes plane 1 and plane 2. So, in equation form we can able to write R1 is vector R1 is P1 plus F1 and R2 is P2 plus F2. Static balance balancing we have balance using 2 plane balancing, but if we know the plane of the balancing of this static unbalance; we can able to use single plane also for balancing it or if, the rotor is very thin or then it is very easy to find out the plane of the balancing. So, we can able to balance using single plane.

When disc is thin then we know the plane of balancing of the rotor. So, we can able to balance the rotor using single plane. So, once we now are familiar with the principles of the balancing procedure. Now, we will try to see how we can able to apply these methods to the practical rotors. So, we will start with the simple balancing procedure of single plane balancing, in the case when the rotor is very thin. We can mount the rotor on some flexible support, we can mount the rotor on some frictionless support and we can mark some position on the rotor by a chock. And we will allow the rotor to rotate by hand and maybe we will stop after sometime and we will we will see the position of the marking position. What we will do? We will repeat this rotation several time and always we will see the position of the marking where it is stopping. If we find that that marking position is always at the same position; that means, there is heavy unbalance in the rotor and that unbalance is trying to stop the rotor at the same position. Let us see this by a figure.

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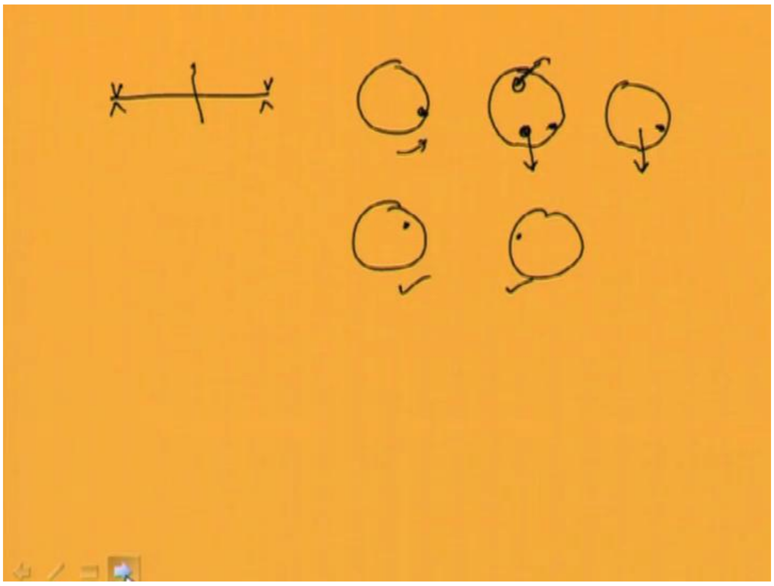

So, this is rotor which is mounted on flexible support. If we see from the side may be mark some position here on the rotor. And we will rotate this rotor by hand and another to stop at some position. So, if it is stopping somewhere here, in the next position also if it is stopping in the same position that means, unbalance is there somewhere here which is trying to stop the rotor at the same position.

If, this position is different all the time sometime here, sometime here, that means, rotor is balanced. But, if it is stopping at the same position then we can able to find out where is the unbalance. So, here by sum means we can able to put some correction masses opposite to that either by, welding we can put or may be, we can able to remove some material back as cutting or we can put some treaded screw this side. And then again the same procedure will be repeating, till we get indifferent position of the marking. That means we have achieved the static unbalance.

But most of the rotors in the practice are not in the single plane. And we need to go for the dynamic balancing of such rotors and when we need to go for dynamic balancing of rotor, we should have provision for rotating, we have we should have provision for rotation of the shaft, so that the dynamic effects are predominant and we can able to find out their effect. So, now I will be describing 1 machine: balancing machine by which we can able to balance the rotor.

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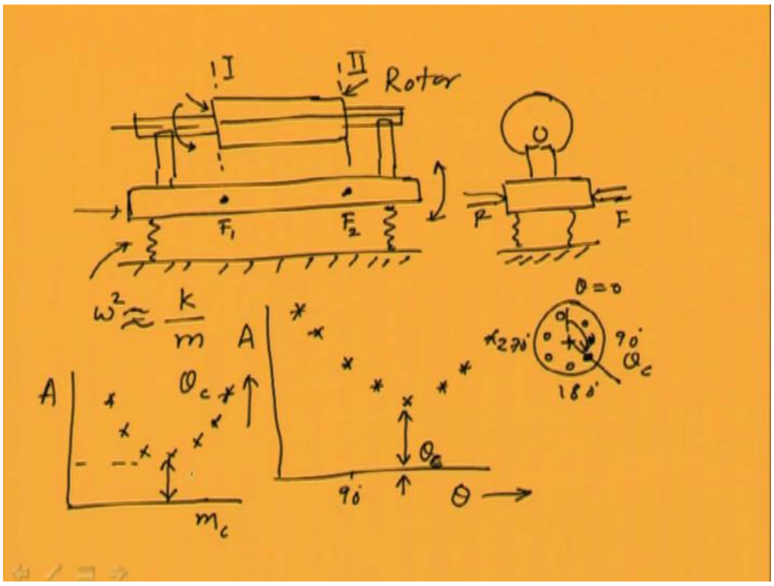

So, this particular machine; it mounts the rotor on flexible support and the support is also frictionless. This is the foundation. This is the rotor and this support itself is mounted on some flexible spring like structure. And we can have balancing; generally we can able to apply some balance correction masses on these planes. So, let us say these are the 2 balancing planes plane 1 and plane 2. And corresponding to this we have provision for fulcrum this base: F1 and F2. This will be more clear if we will see from the side. The fulcrum is something like this and spring loaded spring supported and rotor is mounted here like this.

Now, when we are rotating the rotor by a some external means; by belt and pulley arrangement. What we can do, we can fix the this particular foundation either, at F1 or F2 so that, if we are fixing at F1, this whole structure can oscillate about F1 or when we are fulcruming about F2, the whole structure will oscillate about the F2. So, let us first case we have fulcrum at F1. So, that the when we are rotating the rotor it, oscillate about F1.

Generally the speed of the rotor is kept near the resonance of the foundation structure. So, the speed of the rotor will be, if it is stiffness of the support is k and total mass support is m. So, it should be nearly k by m. So, that square of that so that, we have large oscillations which we can able to measure. So, when we fulcrum the rotor at F1, we will measure the vibration which is taking place and we will note down those amplitude of vibration. And next, we will be putting some trail unbalance on the plane 2.

So, 1 plane rotor this is the end of the rotor. So, may be you can have some marking on this. Various angles are given theta 0 to may be 90, 180, 270 like this. And we can put unbalance at various position let us say, at 90 or initially, we will measure the amplitude of vibration. Let us say it comes this much: corresponding to 90 then we can change the position of the rotor unbalance somewhere else. And we will measure the unbalance response; let us say it comes here.

So, we will change that same correction mass at various location and amplitude of vibrations. And you can see from this, this is the angular position of the trial mass and this is the amplitude of the vibration. The minimum amplitude is taking place corresponding to some angle this 1. Let us say this is theta c. So, this is a angle at which we need to put the correction mass let us say this is the theta c. So, at this place we need to put the correction mass may be in the next trial what we will do, we will measure the amplitude. Now, we will change the correction mass and we will be keeping correction mass all the time at theta c. So, again we will get some variation of the amplitude and we will see at 1 location we will be getting the minimum amplitude and that is the actual correction mass required, because corresponding to that we are getting the lowest amplitude of vibration.

So, this will give us the correction mass on plane 2 and the same procedure we have to repeat by fulcruming the rotor at F2. So, by that way we will be getting the correct mass for plane 1. So, the method which we have described is called cradle balancing machine and this method is very tedious because all the time we have to do that trial unbalance, not only the position also the magnitude of that we have to keep trying for various values. So, it is very time consuming. There another method by which we can able to find out the unbalance magnitude and its angle by measuring only four measurements.

So, in this procedure we need to first, the same cradle balancing machine can be used in this. And first we will be running the machine without any trial unbalance. We will be fulcruming let us say, at F1 and we will be measuring the vibration amplitude. And then we will be keeping 1 trial mass at some 0 angular positions and again we will be measuring the amplitude of vibration. Then the same correction mass we will put at the 90 degree and then again we will be measuring the vibration through this will be the third reading, and then we will be keeping the unbalance at 180 degree and that will be our fourth measurement and these four measurements will be used to obtain the correction mass magnitude in position. Let us see by drawing how we can able to do it.

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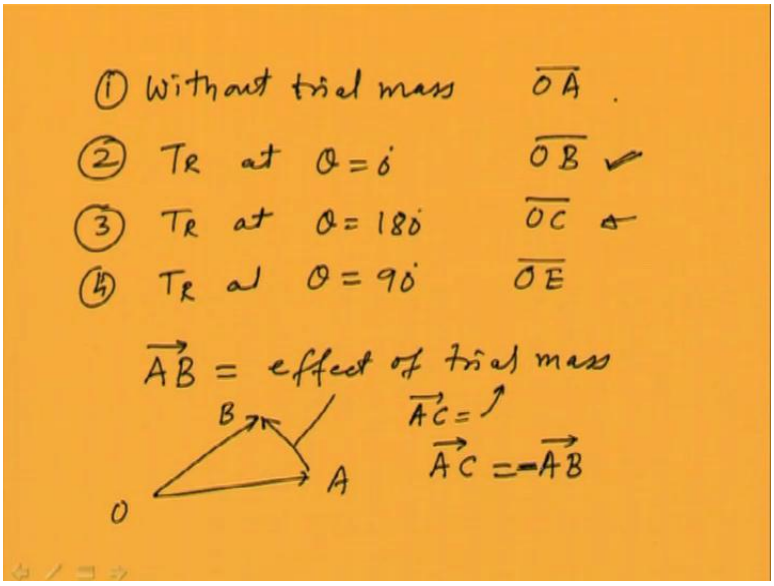

Without trial mass let us say, this is OA; second is trail mass at theta is equal to 0, let us say this is OB; third is trial mass at theta is equal to 180 degree, let us say it is OC and fourth is trial mass at theta is equal to 90 degree this is OE. Now, let us analyze these measurements. When we put the trial mass we got the measurement OB. So, because we do not know the angular position of OA and OB, but we have showed that AB will represent the effect of trail mass. Because, let us say O is here, A is this direction, B is this direction. So, AB is the effect of trial mass. Now the same trial mass we are keeping at 180 degree and we are getting the response OC. So, AC is again is the effect of trail mass, and because we are keeping the unbalance at 180 degree as compare to the previous 1. So we should get AC is equal to AB only thing is, if we see vectorially they will be in opposite direction because of 180 degree phase. So, with these information that the AC is equal to minus of AB we will try to obtain the position of the actual unbalance.

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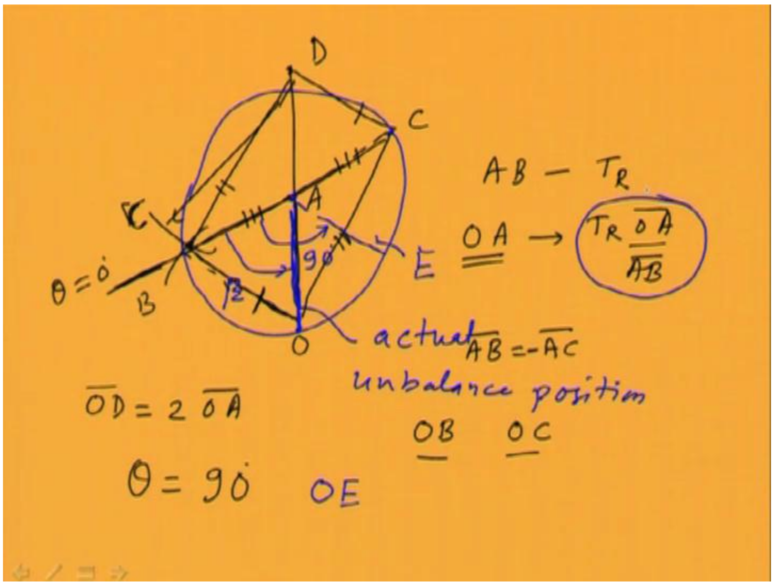

Let us draw a line in any direction and magnitude of OD is twice of OA, the measurement which we have taken. The inclination of OD can be any direction. Now with the help of OB and OC measurement we will cut arcs like, from OB we will cut arc this direction and with OC we cut arc this is the OB, this is the OB arc. And then we will, D is the center we will make another arc with OD OC. So, we will get intersection here. So, this can be joined with O and D. On the same lines we can able to make this. This is actually parallelogram with, this side is equal to this and this side is equal to this. And let us say this is OC. So, OC is this much, OB is this which we have taken the measurement.

So, basically we have drawn parallelogram. Now because it is a parallelogram, so we can see that this particular line here: AB is equal to AC. There is a condition we require, because this AB is the effect of trail unbalance and it should be equal to AC and therein the opposite direction, so negative. So, you can see that now, AB is the theta 0 direction because AB is corresponding to the trial mass when we kept at the 0 location. So, and the magnitude of the unbalance will be OA, because AB we know corresponding to the trail mass, so A OA we can able to measure and that will give us the magnitude of the unbalance.

Now, we need to find out the location of the trial unbalance with respect to the reference axis, theta is equal to zero. For that we need the third measurement that is corresponding to trail mass at 90 degree. So for that let us first, draw a circle with center at as A and diameter as B C like this. Now, we will use the third measurement that is fourth measurement that is, OE and we will cut that from center, we will cut on the circle; let us say it cuts here. So, that means this is the 90 degree. So, the and OA is representing the actual unbalance. This is the actual unbalance position. That means this particular angle let us say, beta is the actual location of the unbalance.

So, we got the magnitude of the unbalance using this and the position as beta. Now, once we have obtained the position of the unbalance and the magnitude of that; that is corresponding to the plane 2, because we fix the fulcrum 1. Now, the same procedure can be repeated by fulcruming in F2. And then whatever the correction masses, magnitude and angle we will be getting that will be corresponding to plane 1. So, we have to repeat this 2 times.

Till now whatever the procedure we discussed, in that we used amplitude of vibration for finding the location and magnitude of the unbalance. Now, because of the various development in the measurement especially, the phase measurement of the vibration there are now various new techniques available by which we can able to do the dynamic balancing a very quickly also very precisely and 1 of the method which I will be explaining now, is called influenced coefficient method in which, we will be using not only the vibration amplitude information also the phase with respect to the some reference point on the shaft. And for that this is for the dynamic balancing. So, obviously here we will be having 2 planes of the balancing and we will be having 2 planes for measurements. And these 2 planes can be different, not necessary they should be same, and so let us see this procedure through a figure.

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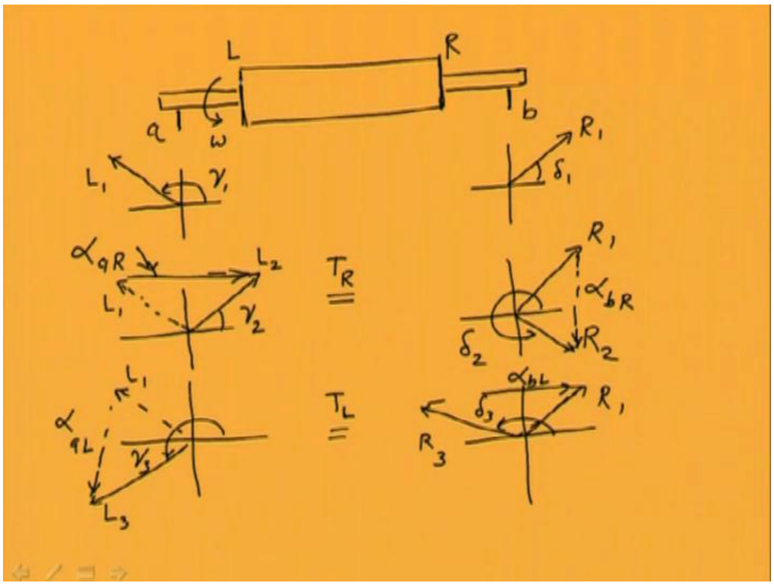

Let us take a rotor and it is rigid rotor. We have 2 planes let us say: left plane and right plane, these are the balancing planes where correction masses will be keeping. There are 2 another plane a and b, these are measuring planes where generally, these are the bearing locations from where we will be measuring the vibration. Either, amplitude we will be measuring displacement, velocity or acceleration.

And in this particular case, we will be measuring the amplitude and the phase of that with respect to some reference point onto the shaft. So, let us say we are rotating this particular rotor at certain rpm and a because of this, there will be some vibration which will be measured at a and b locations. And this particular vibration will be because of the residual unbalance which is present in the system, which is which we want to balance it.

So, let us say for this particular case, we got in the left of the bearing L1 as the vibration response and its phase is gamma1 because displacement or velocity and acceleration their vector quantity, they will be having magnitude and phase. So, I have represented the vibration measurement as a vector. And in the right plane we have this measurement and angle is let us say delta 1.

Now, we will put 1 trail mass that is, TR of known magnitude in the right plane here, we will put this. So and again, we will rotate the rotor at the same speed and let us say, we got the measurement on the left bearing L2 and in the phase of that is gamma2. Similarly, in the right plane on the bearing we got the measurement let us say, r2 and phase of that is delta2. Now, if we draw the response due to the residual unbalance here itself; and this vector it is the difference between the present point and the previous 1. This particular vector is the effect of the trial mass, which we are keeping in the right hand side on the left bearing. So, it is indicating something like influence coefficient AR, because this is the effect of trial mass in right plane at bearing A, what is the change in the response. And if we do the same thing at the right plane, this particular vector is the effect of the trial mass TR on b plane

So, it indicates the influence coefficient br. On same lines now, we will remove the trial mass from right plane; we will put another trial mass in the left plane L1. And let us say we have measurements corresponding to this as L3 with, this is the phase let us say gamma3 and in the b plane we have measurement R3 with angle delta3.

Now, we are again taking the plane of the first response. So, this will be the effect of the left plane balance, left plane whatever the unbalance we have, trail unbalance we have kept. So, this will be alpha aL similarly in the right side if we take the R1 here, this will be the effect of the trial mass which is there in the left plane. How much vibration is affecting on the b plane. So, it is indicating the alpha bL.

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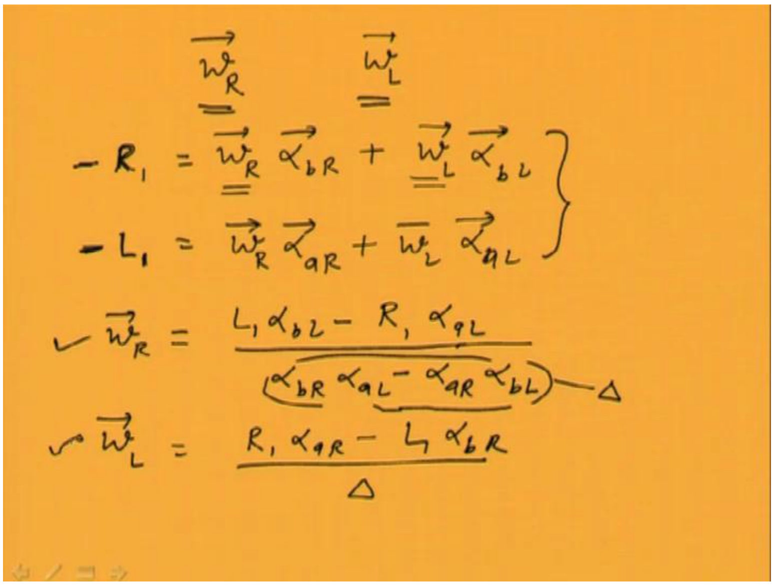

Let us say we have correction masses in the right plane. This is the, to balance the rotor these are the correction masses in the right and left plane which is required. Now, if we multiply this unbalance correction mass with influence coefficient plus for the other unbalance correction mass; this quantity is nothing but because these are the correction masses. So, they should produce equal and opposite response corresponding to the without trial mass; that means, minus of R1.

Similarly and the second equation is corresponding to minus of L1. So, that means, if we will go back to the previous, so after putting the correction mass we should get minus of this or as a response and minus of this so that, we get the total balancing of the rotor; that means, there is no vibration of the rotor when we are having no trail mass. So, with this correction masses we expect that rotor is totally balanced. Because of that we are getting these responses which is negative of the without balancing.

Now, you can see that this can be solved for these 2 correction masses and the expression for that will be in denominator is they contain influence coefficients. Advantage of this particular vector quantity, that we can able to write them in a complex form. So, this is a WR and WL will be and denominator remains the same as this. So, these are the correction masses required which can be obtained, because we already obtained the influence coefficients also the other measurements. So, once we have explained the procedure of influence coefficient method, let us see the what are the instrumentations is required for this purpose and I will be drawing the line diagram of this and I will explain also how to measure the phase.

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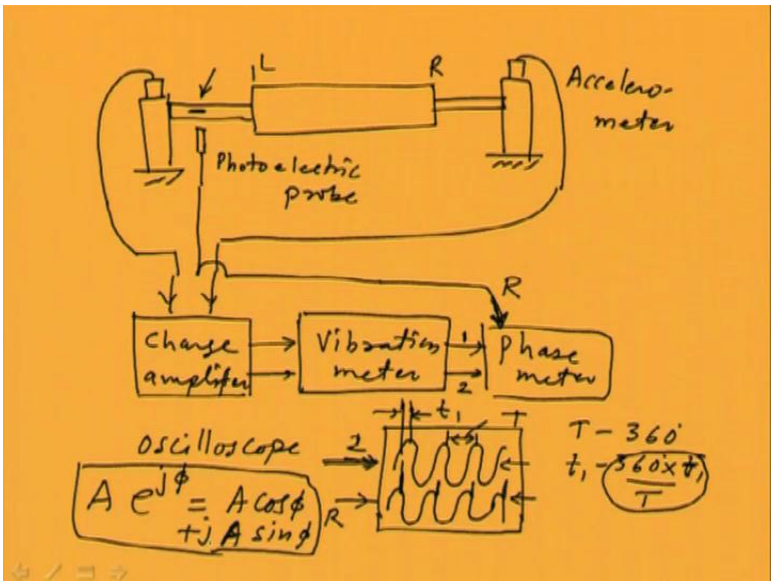

We have a rotor like this, in which we have left and right plane, these are the correction mass plane and this is the bearing which is supporting the rotor. We can have some instrument that is called accelerometer, which measure the acceleration and which can be integrated to get the velocity or displacement, so these can be used. Then, on the shaft we can have 1 photoelectric probe with sense a tape which is attached to the shaft and that is a reference position through which we will be measuring the phase all the time. So, this measurement also is here. So, basically we are having 3 sensing devices: 2 accelerometer and 1 photo sensitive probe as a reference signal.

Now, let us see how what are the instrument we can use to measure the phase and amplitude. So, we can have charge amplifier which will not only condition the signal, even we can able to integrate the signal and this charge amplifier can be the signal can be given to the vibration meter, which gives the acceleration or velocity or displacement magnitude and their phase measurements also, phase meter So, phase meter 2 signals and this reference signal should go to the phase meter. So, this phase meter will give phase of reference signal with signal 1 and signal 2. So, all the phase measurement will be with respect to the reference signal. This also can be done on the oscilloscope

Oscilloscope is something like this. So, let us say signal 1 we are giving and we are giving the reference signal: this is the reference signal. So, this is the response the reference signal will be something like this, and because of the phase marker which we have kept here, it will be having some distorted position in all the signals. So, this particular mark is corresponding to the tape. So, the phase measurement can be like this and maximum of the signal; this time derivation can be noted. And know the time period of the signal T also.

So, T is corresponding to the 360 degree. So, t1 can be calculated corresponding to what angle. So, this will be the phase of this signal corresponding to the reference signal. So, likewise we can change the, this particular signal or to 2 and then we can get the phase. 1 minute is left. So, now, we have seen that we can able to measure the vibration amplitude using vibration meter and phase either with the phase meter or using oscilloscope with the help of reference signal. And once we get this data, the previous procedure which I explained of the influence coefficient can be used in this;, because we have vibration magnitude in phase.

So, we can able to express the quantity in a vector form like this like, if we have amplitude and phase. So, this will be A cos phi plus j A sine phi. So, like this we can able to express the quantity in a complex form. So, in this particular lectures we have explained the, what is the unbalance and what is the basic principle of balancing and how we can able to balance a practical rotor. So, different method we have described, 1 was the using the cradle balancing machine in which we have to do lot of trial and in the influence coefficient method which is more sophisticated in which, we can use modern measuring instrument like: phase meter and vibration meter and instruments like accelerometer and photoelectric probes has we have described. So, with this I think you can able to do a dynamic balancing of rigid rotors.