Dynamics of Machines

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Module No. # 04

Lecture No. # 03

In-Line Engine Balancing

In the last session, you have seen the machine or an engine consisting of a single slider crank mechanism. It produces unbalanced forces in a manner, a part of which can be balanced by the replacing balancing mass as a counter weight to the crank and reciprocating mass produces an unbalanced oscillating force along the system centerline. It can be expressed in terms of an infinite series of harmonic quantity.

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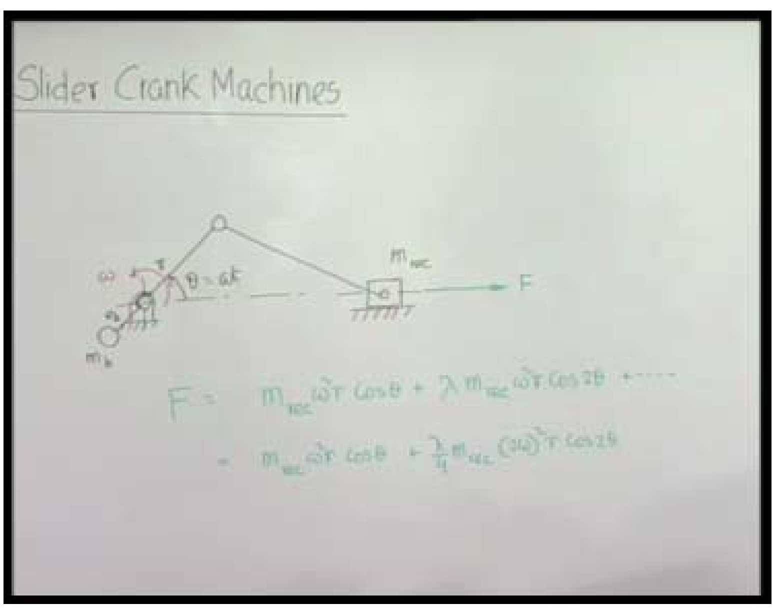

As you know, this theta is nothing but omega t, if you take theta equal to 0 at t is equal to 0. These are nothing but harmonic functions of time of continuously increasing frequency. This is also an approximate situation, because we have replaced the actual connecting rod by two concentrated masses: one at the crank pin and other at the slider pin which is not an exact replacement, but it does not introduce mass. Even then, this situation is like that there is a primary component, the second harmonics, fourth harmonics and so on that we have seen.

It has also been pointed out - in the past that, it will be enough in most cases if we consider only up to the second harmonics. Thus, until and unless mentioned now onwards we will keep our unbalanced forces under consideration only up to this second harmonics or which you called the secondary. Now, you have seen that the primary component of the unbalanced force is something which can be produced by the centrifugal force generated by placing this reciprocating mass at the crank pin. The centrifugal force which will be generated with its component along the engine or the system centerline is nothing but the primary.

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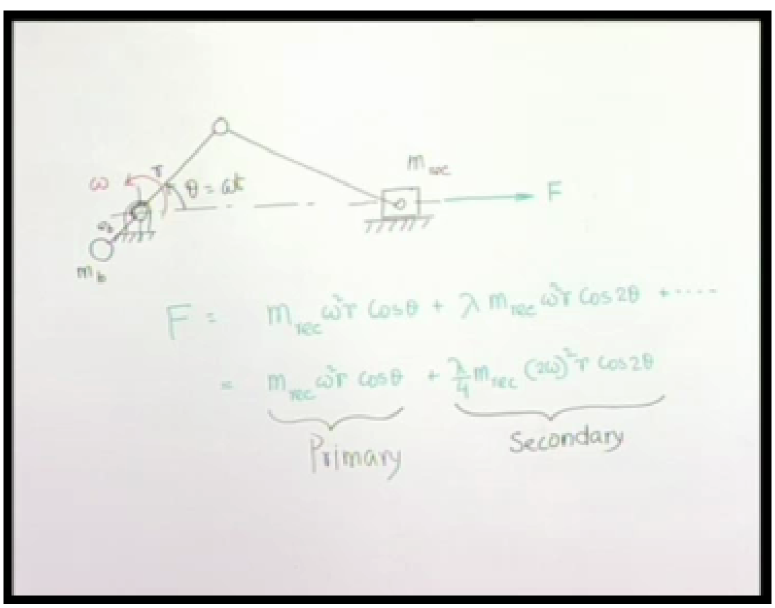

In that remember, if you really place a mass here it will also produce the other component. Thus, if you keep in mind that the real force is only along these, then the primary can be represented by placing this reciprocating mass here. Similarly, the secondary force can be considered as mentioned earlier. As a component along this center line of the centrifugal force produced by placing a mass which is lamda by 4 m, reciprocating at the tip of a hypothetical crank of same radius r, but rotating at double the speed of the primary crank. We have seen that component along this will be same as what real system is or rather equivalent system with a portion connecting rod mass what that produces.

Now, to neutralize these forces it requires an active system by which we can again produce some balancing forces matching exactly magnitude and being opposite in direction and that we have also seen. However, situation is much simpler or rather very convenient in many cases where a system or an engine consists of more than one slider crank. Common examples are the engines. Generally, we find that engines of some considerable power are always multi cylinder.

In such cases, if we design machine or the engine in such a manner that the unbalanced forces of individual cylinder or individual slider crank mechanism they neutralizes other. Then it will be a very nice and convenient situation that the whole engine as a whole will be free from unbalanced forces. Now, what we started discussing precisely is that you consider how to take care of the balancing forces or unbalancing forces in case of multi cylinder system or multi cylinder engine by suitable design.

There are many ways where this multiple slider crank system or multiple cylinders in an engine can be placed. One most common example is in-line engine. In all such cases of multiple cylinders or multiple slider cranks we have to keep in mind that each unit is identical to another one. What I mean to say, that the slider crank mechanism for each and every component of that engine will be identical. In In-line engine the configuration is something like this.

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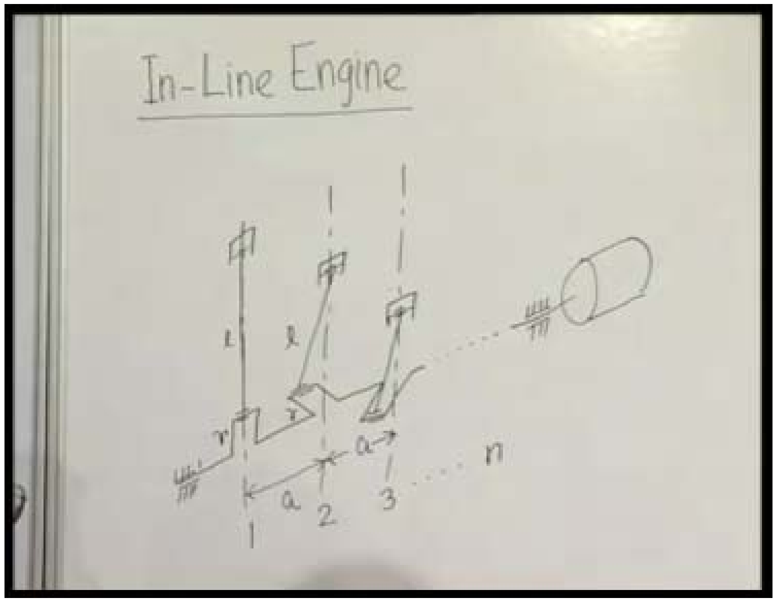

So, in in-line configuration the centerlines of each and every slider crank mechanism or slider crank engine mechanism the centerlines are parallel. Next, the gap between each is something fixed say a, are uniform and I already mentioned that each of this unit are also identical in the dimensions and masses. Let the connecting rod or crank radius for each be r and connecting rod length is l; then all these cylinders are driving their individual cranks. All these cranks are actually driving a common crank shaft, which is actually running or driving the load, whatever it may be. So, this is an isometric view to make our life easier. Generally, we will replace an isometric view by engineering drawing like this.

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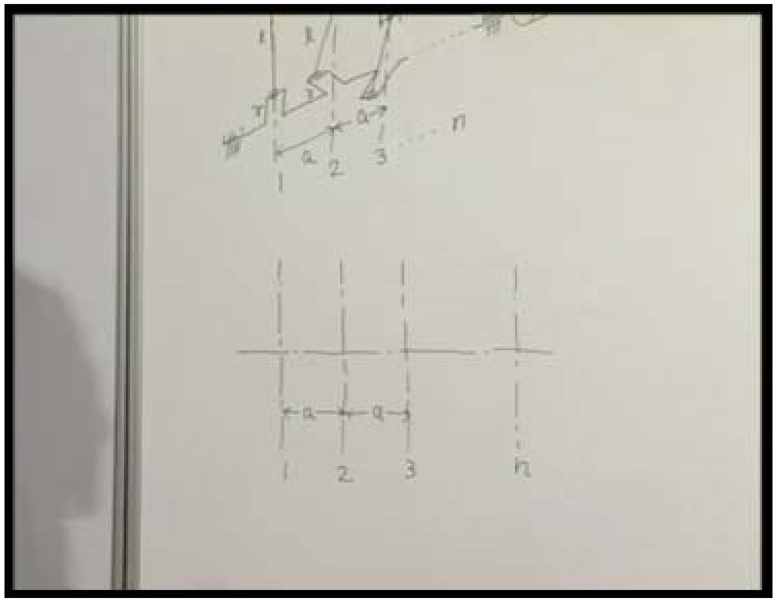

For n cylinder, in-line engine will look like this. This is cylinder number 1, cylinder number 2 and cylinder number 3 and so on. Another condition, we have to keep in mind that when the system is running at one instant, only one cylinder gets fire in case of engine. Therefore, we have to also keep in mind that each firing for individual cylinders is uniformly distributed about time. That means, the whole cycle of the engine when it completes during one complete cycle, it will depend on the number of strokes for the particular cycle the engine is following. It can be either two stroke engine or four stroke engine. In case of two stroke engine, the cycle or total period is given by 2pi that is one rotation; that is, 2 stroke cycles that we know.

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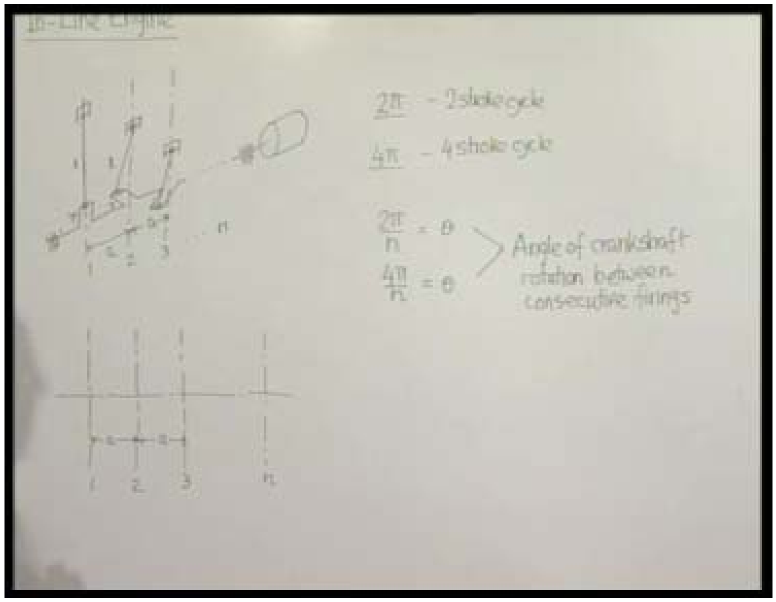

In case of four stroke cycle, the rotation of the crank shaft will be 4pi of the rotation. So, if we have to distribute the firing uniformly over the whole period of the crank rotation either 2pi or 4pi. Therefore, the angle of rotation of the crank shaft between consecutive firing will be either 2pi by n or 4pi by n, this is angle. Thus, we know that the crank has to be so designed or so arranged that the firing takes place at uniform distribution or at uniform interval. If we take side view, the crank will look like this.

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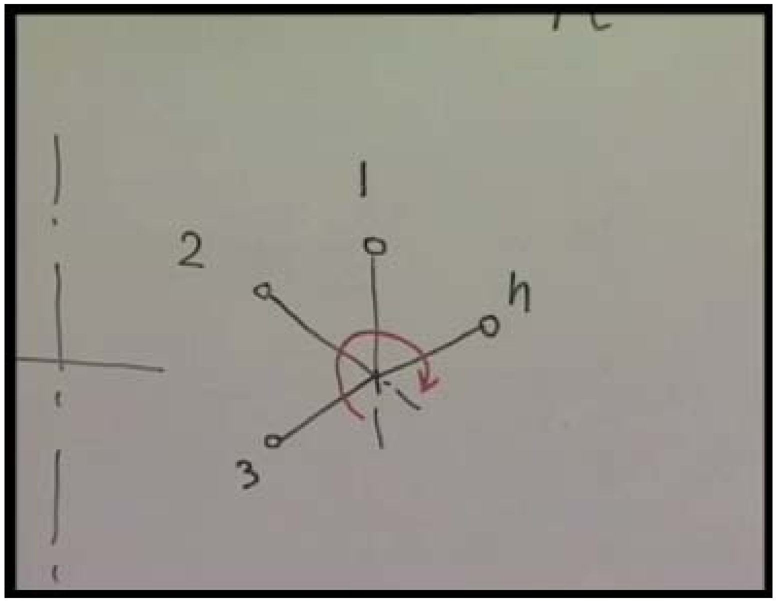

We can have a crank diagram which we call as for cylinder number 1, cylinder number 2 crank, cylinder number 3 crank and so on; so, this is cylinder number n crank. We have to also indicate always in a crank diagram the direction of rotation we know say, the direction of rotation is this. Therefore, we can see from this crank diagram, we can also find out the firing order.

The firing order in this case will be this (Refer Slide Time: 12:55). The way we have kept is 1 next firing is for 2, because when this rotates pi, this angle which is say 2pi or 4pi divided by theta depending on the number of cycles. So, this angle can be 4pi by theta or 2pi by theta. The firing order will be the first one then it rotates by this angle, this come to be top position and firing position then 2, next 3 comes and that gets fire and so on.

We will see, as just now find out that this firing order is very important, because according to that only the crank locations will be arranged. By same engine with different firing order and different crank settings can behave differently, from the point of balancing of its forces and moments.

In case of single slider crank system or single cylinder system there were only a matter of force, but now what we will have? We will also have a moment because forces acting at a different lines. Therefore, if this is the engine centerline, its engine centerline not cylinder centerline; these were the individual cylinder centerline but mid point of this engine is cylinder centerline and we can find out moment of all the forces about the cylinder centerline (Refer Slide Time: 14:24). Now onwards, we will have both unbalanced forces and unbalanced moment. As you have seen, in case of rotary balancing also that system may be balanced from the point of a total force.

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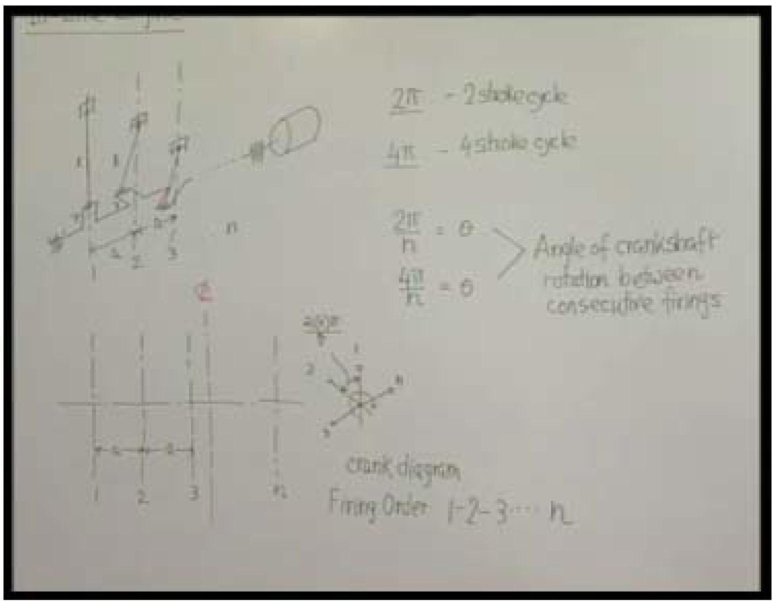

If there are two equal and opposite forces, passing or acting along two different lines of action, then they produce a couple and that can produce unbalanced forces on the supporting bearings. Same thing here, because we have seen that the unbalanced primary force of each one can be represented by placing a mass of the cylinder here and assuming that only the component along this cylinder centerline that is only existing, rest is not existing.

Somehow, we are now converting our reciprocating balancing problem into rotary balancing problem. What we will do now to investigate the condition of balancing? We will place the masses here, at the crank pins and see what state of balancing it produces. If you find that those masses, when reciprocating if you put at the crank pins they balance among themselves. Then obviously, there any component will also get balanced that means the real unbalanced force also get balanced.

If the moments produced by these hypothetical masses at the crank pins, the moment also produced is 0, then the component of the moment which will be actually there could be also 0, that means system will be really balanced. So what we will do, I will explain the whole situation, how to analyze multi cylinder in-line engine with the help of certain examples. So, first example let us take a 4 cylinder engine which is working on 2 stroke cycle.

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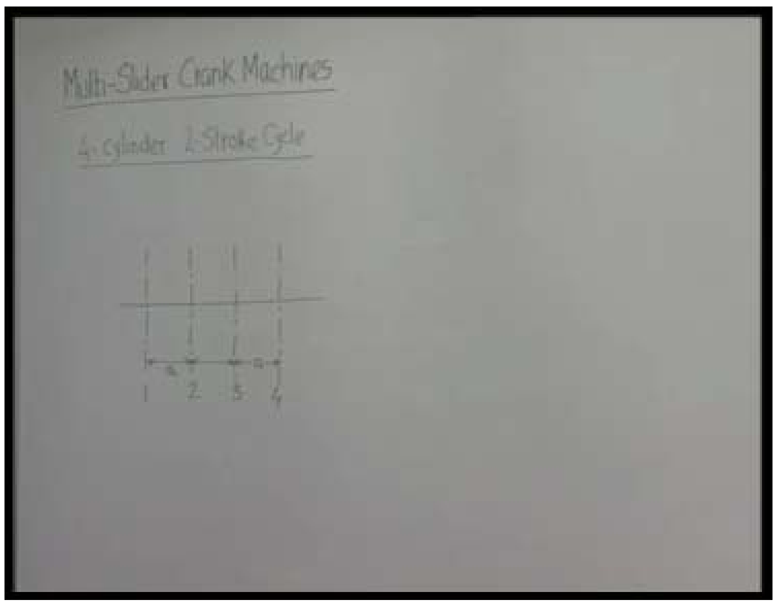

This is the engine cylinder line. Obviously, then this will be a by 2. Next, we take the crank diagram, primary crank. First, we will investigate only the primary force in the moment. Let us keep primary crank 1, if it is 2 stroke cycle then angle between the two consecutive firing cranks will be 2pi by 4 that is, theta will be equal to pi by 2 unless the firing order in this case be 1- 2- 3- 4. This will be firing of crank 1, next firing will takes place at crank 2, next at another 90 degrees is 3 and next another.

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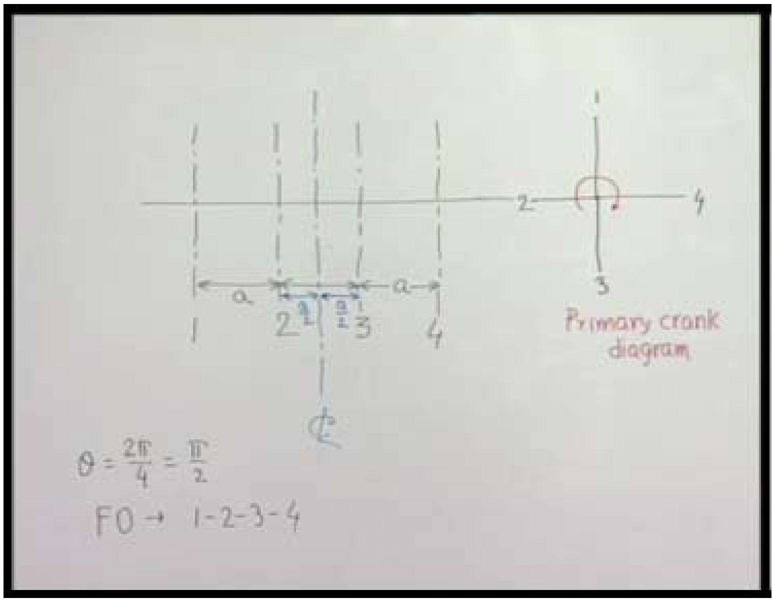

Of course, the primary crank is rotating in this direction. One should never forget to indicate the direction of rotation; otherwise, this firing order has got no meaning. Let us see what happens, if we consider that the reciprocating mass of the cylinder and the portion mass of connecting rod at the cylinder, they are placed here at the tip of the cranks.

While it is rotating, they are producing centrifugal forces and let us see what this primary force diagram is. This primary force produced by cylinder number 1 will be this and this is nothing, but m reciprocating omega squared r (Refer Slide Time: 19:46). The primary force produced by second cylinder which will be nothing but the centrifugal force of this. Of course, we should be remember it is only the component of those forces in this; what we are initially doing is, we are considering only the centrifugal forces produced by the hypothetical mass placed here.

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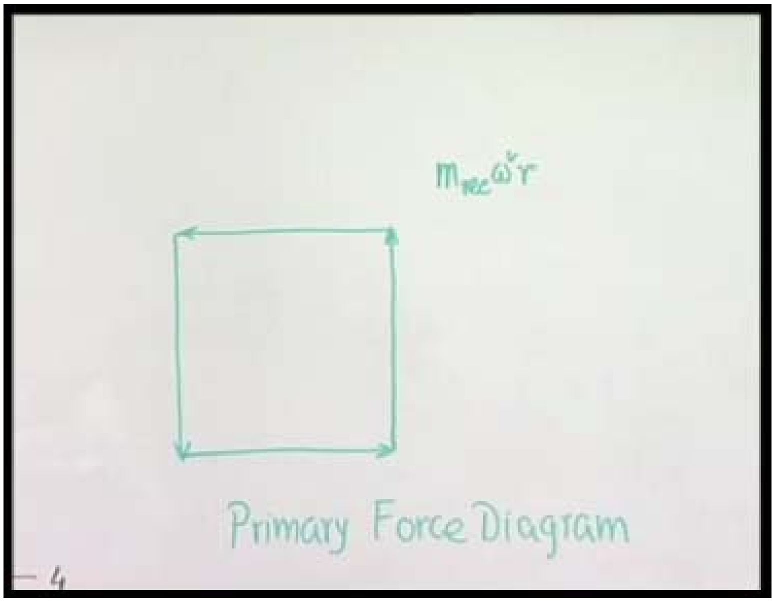

If those centrifugal forces they themselves got balanced then obviously, there components along any direction will be also balanced. For cylinder number 2, the unbalanced force produced is this of same magnitude at 90 degrees. The centrifugal force produced by the third cylinder with that mass here will be this and by fourth cylinder will be this. Therefore, we call it primary force diagram.

As you have seen, in rotary balancing cases here, what it means if there are m reciprocating placed at the crank pins they produce 0 total resultant force in whole engine, because the force vectors they form a closed polygon. Therefore, primary forces are balanced; it means that primary component of force as produced by 4 cylinders they neutralized each other there we no unbalanced effect on the bearings due to the primary forces.

Next, let us see primary moment. Primary moment we always place about the engine centerline, about this point. Again remember that what we have seen we have drawn it from giving in this direction (Refer Slide Time: 22:05). So, moment diagram also we can do and we have seen previously that there are two ways of handling. Suppose, if there is force like this, so it will produce a moment which will be going inside the board when since from this side it will be towards right.

If all the forces are on one side of the point about which we are taking the moment, then you will get the same geometric figure of the moment component or moments. If you rotate the whole diagram by 90 degrees, you have seen that now, without going into such complicated cases, let us directly plot the primary moment diagram looking from this side that what these centrifugal forces will produce about this (Refer Slide Time: 23:04).

The centrifugal force magnitudes are same for each case, which is m reciprocating omega squared r. If this force is acting in this direction, here what will be the moment when you see from this side? The moment will be like this; so it will be going in this direction and moment is m reciprocating omega squared r into 1.5a, the distance from this to this is a plus half a, that is 1.5a. Next, is cylinder number 2; here, when you see from this it has come like this. So, force will be like this (Refer Slide Time: 23:59); as you can see, this is the first cylinder force, the second cylinder force in this direction like this, so this will produce moment in the upward direction.

In upward direction, the magnitude of force is same m reciprocating omega squared r but the distance is only 0.5. Next comes this is cylinder number 1, cylinder number 2, and cylinder number 3; now cylinder number 3 is here, the force is coming in the downward direction, that means this force will produce another moment in this direction and its magnitude will be again same as this m reciprocating omega squared r into 0.5a (Refer Slide Time: 25:05). This cylinder, the force is in this direction and obviously it will produce in the upward direction; its magnitude will be again same as this 1.5a m reciprocating omega squared r.

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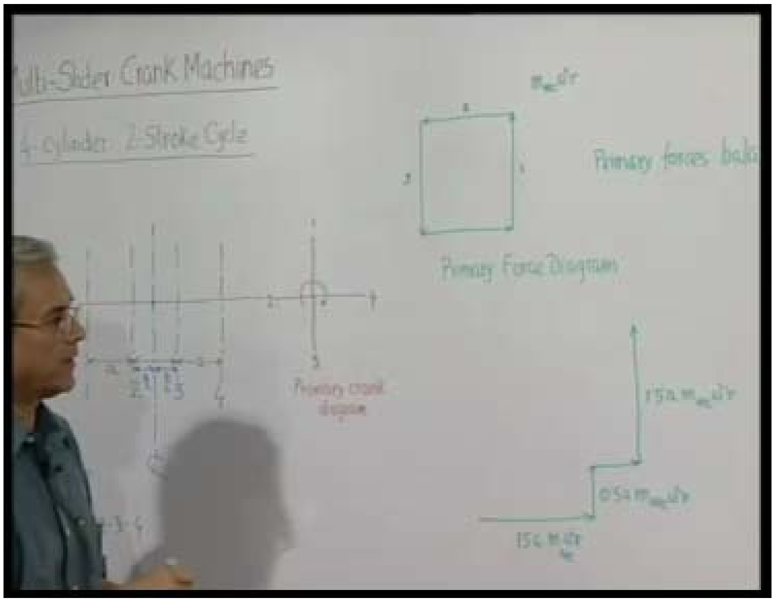

The resultant moment, you can see does not form a closed polygon, so this is the unbalanced moment. This is vector quantity and the whole diagram is rotating. Of course, we have to see that whole thing rotating, with the same speed omega as crank just like a rigid body attached to crank itself whole thing rotates and the resultant being this at certain angles. But remember, the actual moment is not this one, actual moment will be the moment give to the components of this force.

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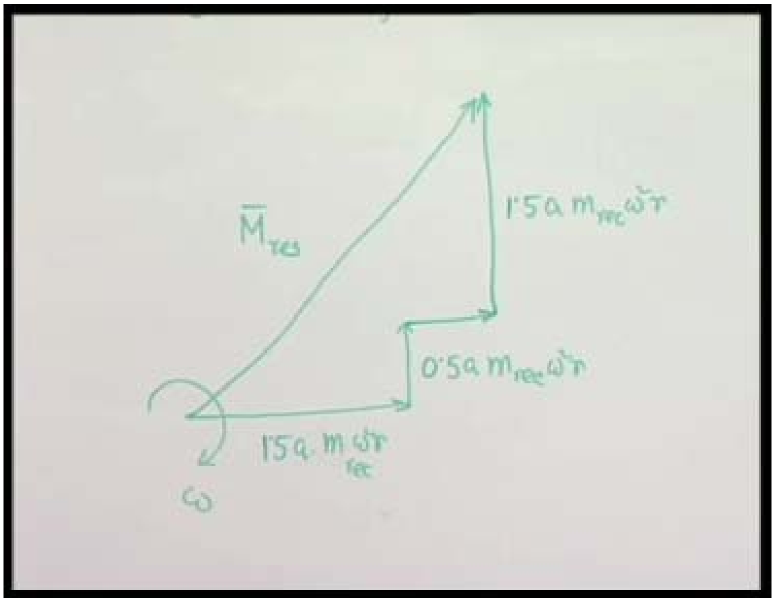

Since, all forces are in vertical direction, in reality. So, the real moment will be always in the horizontal direction. The component, along this is the real moment or actual moment. So, when this is at this position making 90 degree with this direction, then moment is actually instantaneously it is 0. When moment is aligned with this vector, then the total moment it is exactly its magnitude is same as m reciprocating the maximum ((null)).

The magnitude of primary moment unbalanced and since it is unbalanced it will fluctuate maximum. Magnitude is generally indicated by the maximum ((null)) and that is equal to this, which you can easily find out. This is 1.5 0.5, 2.2 so it is 2 root 2a m reciprocating omega squared r, this is the maximum magnitude of the primary moment; this is the primary.

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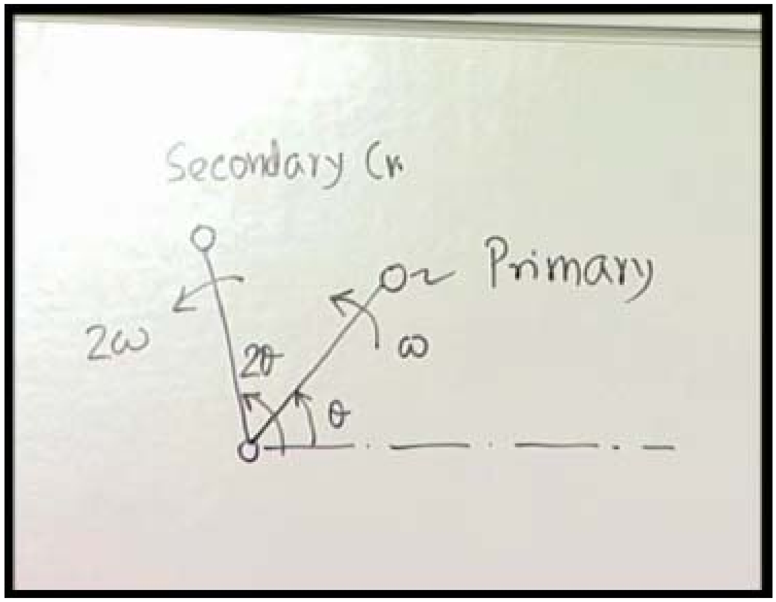

When we have to investigate the secondary unbalanced forces, then first you have to draw the secondary crank diagram. We have seen that in any reciprocating engine or reciprocating slider crank mechanism, what is meant by secondary crank? It means it will rotate at a speed twice that of the primary crank which is nothing but the actual crank. At an instant, it has rotated to double the angle that means if this is the primary crank then the secondary crank will be this, rotating with speed omega. The secondary crank rotates at this speed 2omega and at any instant next angle 2theta.

So, if you have draw and you have seen that secondary forces can also be considered to be produced by the centrifugal force component. The centrifugal force is produced by placing a mass lamda by 8 sorry lamda by 4 m reciprocating at the secondary crank. The angle, what the secondary crank makes is twice the angle made by the corresponding primary crank.

So, for cylinder number 1, what is the angle? This is the centerline direction as you can see; angle made by primary crank about the cylinder centerline is 0; theta is 0, so the secondary crank will be also 2 into 0 is 0. Now, the angle made by crank 2 at this, in the direction of rotation as you do; so, the direction of angle made by crank 2 with this cylinder centerline is how much? It is 3 by 2pi sorry 270degrees that means 3 pi by 2, so double of that will be 3pi.

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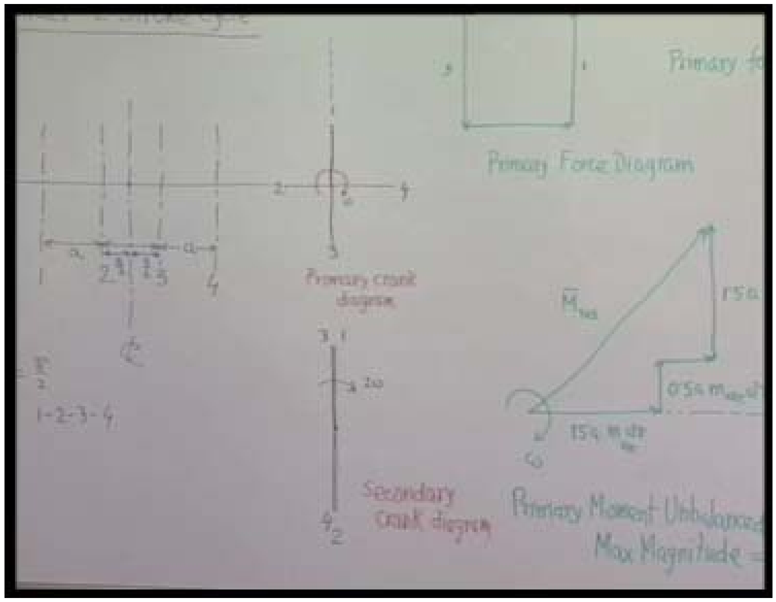

Therefore, it will be 1pi 2pi 3pi. So, in secondary crank they all will be rotating at a speed 2omega. Third crank is making in the direction of rotation from the cylinder centerline is how much 90 degree 180 degree so double of that means 2pi. So, third secondary crank will be here and for cylinder number 4 in the direction of rotation, how much angle it makes with the cylinder centerline is 90 degrees. So, double of that is nothing but 180 degrees, this is the secondary crank diagram for the same engine.

Now, to investigate the secondary forces and secondary moments will proceed in the same way. First, let us consider that we have placed a mass which is lamda m reciprocating by 4, at the tip of each secondary crank and then the centrifugal forces produce.

We consider their component, along the cylinder centerline; but before doing that if we find that their centrifugal forces are balancing among themselves, then obviously components are also balanced or 0. So, secondary force diagram will be in this case: the first cylinder will produce a force lamda by 4 m reciprocating 2omega squared r, in this direction. The second one will produce in the opposite direction the same magnitude. The third one will produce other direction the same magnitude and fourth one will produce and the whole things we have keep in mind we should show it.

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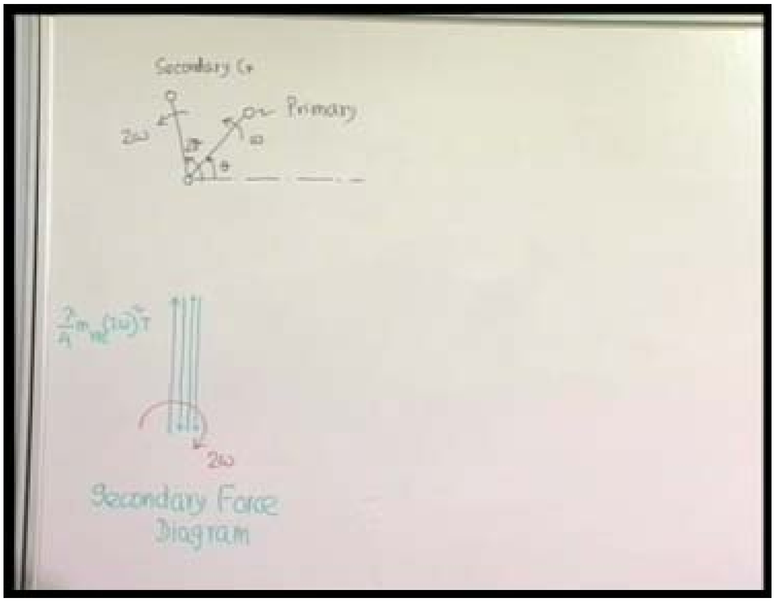

Here, you can see the secondary force diagram is also closed polygon because we have come back to this same point where you start it and from this we find secondary force is balanced.

Let us consider, the secondary moment again in the same way that the force which is produced in this direction. There it will produce a moment in the right hand direction like this and that magnitude will be lamda by 4 m reciprocating 2omega squared r into 1.5 a. Then second cylinder produces this is first, this is second, third, fourth; second produces force in this direction.

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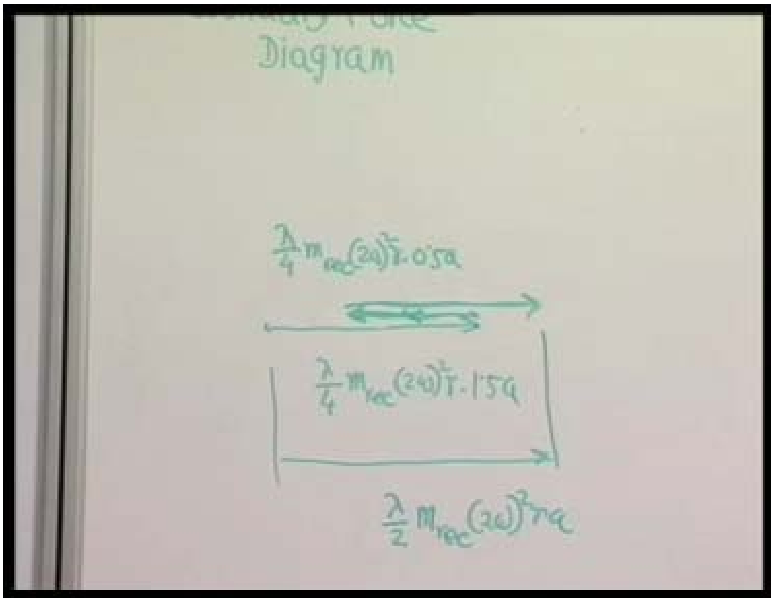

Therefore, it will produce moment in this direction; its magnitude is the lamda by 4 m reciprocating 2omega squared r into 0.5a. Then third one, now you have come to this side of this point and here third one is again, up one is again, produce force in this direction of the same magnitudes m reciprocating lamda by 4 2omega squared r into 0.5a. Then the fourth one, which forces in the upward direction here and obviously here it is down, the downward force should go in the other direction, sorry. This is producing a moment in this direction, this is producing in moment in this direction and now this is in the upward direction (Refer Slide Time: 36:17).

So, that is also producing moment in this direction. I think I was right. Now, this one, fourth one, is producing force this direction that means it should go other direction. It is started here, this is the first - the moment produced by the secondary forces of the first cylinder, this is the moment produce by the secondary force of the second, this is moment produced by the secondary force of the third and this is the moment produced by the secondary force of the fourth one.

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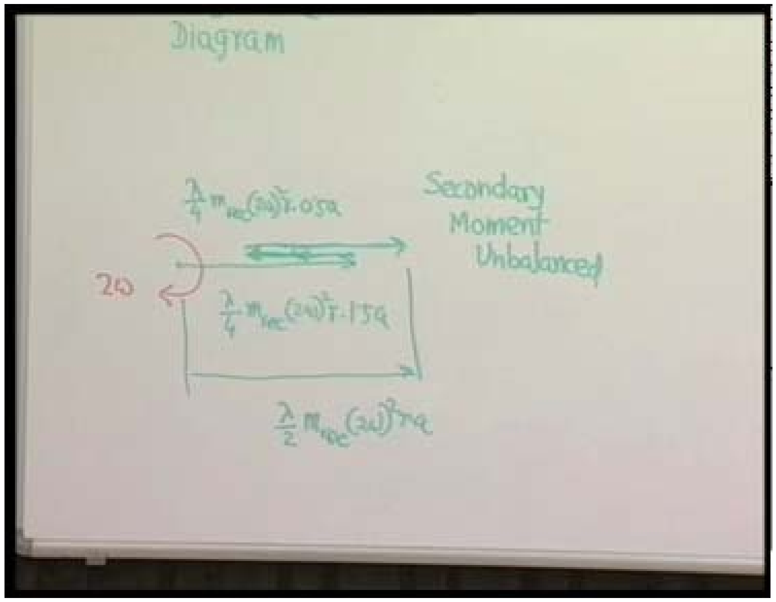

So, this is the resultant, magnitude of the left over how much is that, this is last obviously this is 0.5. Therefore, it will be lamda by 2 m reciprocating 2omega squared r and whole thing is rotating as before. We find here, secondary moments are also unbalanced and how much is the maximum possible value or what you call magnitude is this. At any instant, what is the value of the magnitude? It is since forces of all in vertical direction, so their actual moment vector will be also horizontal, so this component is the real instant. Since, it is rotating at this particular instant we get the full value some other instant it will be client and we have to take only component, but magnitude is given by maximum value as it was done here.

If I find in a 4 cylinder in-line engine, operating on two stroke cycle the primary forces are balanced, secondary forces are balanced; but both primary and secondary moment are unbalanced. Next, what we going to do more realistic case, when we take up 4 cylinder in-line engine operating on 4 stroke cycle. Here, the angle between consecutive firing cranks is 4pi by 4 that is equal to pi.

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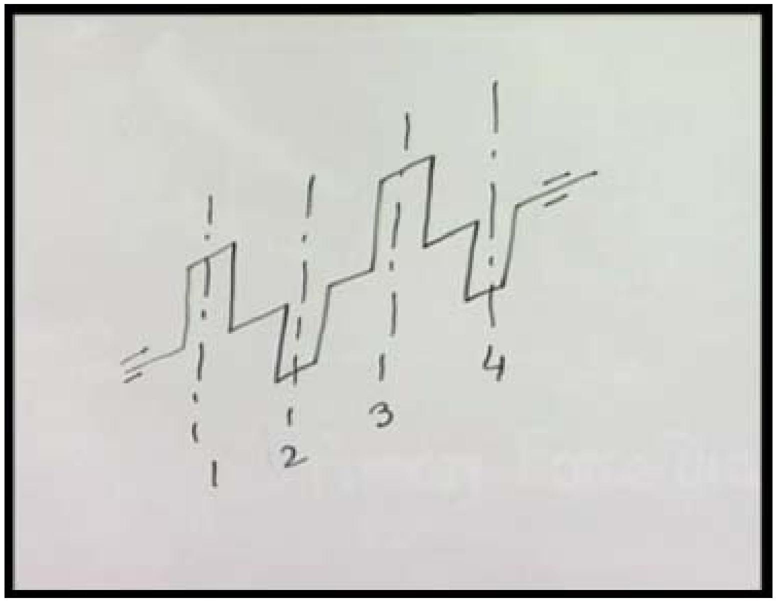

In case of 4 cylinders 4 stroke cycle engine, the angle between the consecutive firing cranks will be 4pi by 4 that is equal to pi and say, this is the system. The primary crank diagram will look like this, suppose we start with firing of 1 and if the firing order we keep as 1- 2- 3- 4.

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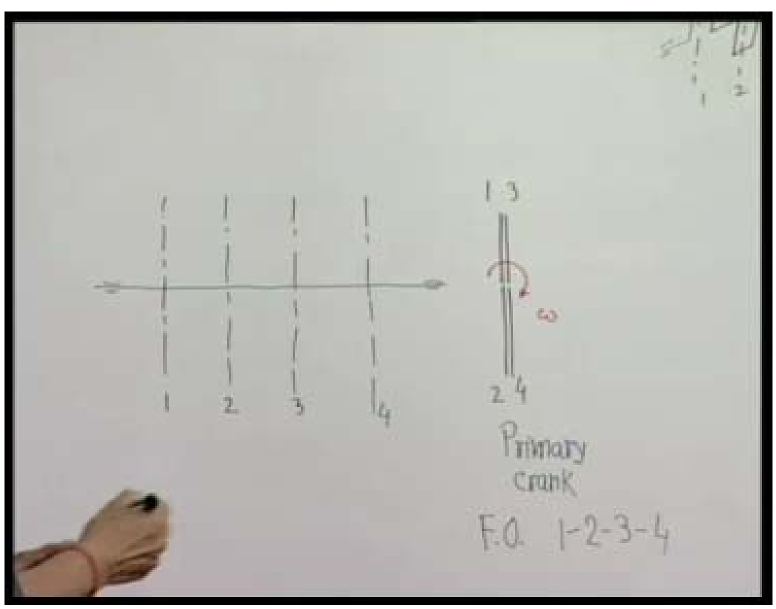

Then, first number 1 which is here, then next 2 comes up 180 degree rotation of the crankshaft; then number 2 expires; then number 3 comes up after total of 2pi that means after 2 it will be again another pi; when 3 comes up, then that fires and then finally, another 180 rotation and crank 4 cylinder number 4pi. So, this will be the isometric view of the common crankshaft.

In this case again, we will now quickly take care of the vector diagram, the primary force diagram. It will be 1 and magnitude is m reciprocating omega squared r, this will be number 1; number 2 will be just opposite to this direction, number 3 will be same magnitude in this direction and number 4 will be in this direction and the whole things as you know is rotating with a speed omega.

So, it is very clear that the force diagram produced by the centrifugal force of hypothetical masses placed that the crank pins they balance themselves, if those balance themselves, then obviously there components along any direction will be also balanced; so the primary force are balanced.

Now, primary moment, for this we can draw the diagram. So, for the number 1, it is in this direction. Since, this is cylinder in engine centerline and this is point, it should take the moment. So, this will produce moment in the right hand direction, whose magnitude is known; this into 1.5a. Then, this one in the downward direction; so it produces in this direction and magnitude is this into 0.5a. Then, this one is in this direction it produces again a force a moment in this direction whose magnitude is again this into 0.5a and then finally 4 produces such a moment this direction by right hand side rule and comes here.

The resultant moment and the whole things of course are rotating; so primary moment is unbalanced very clear. At any instant, since the forces are vertical the moment will be horizontal direction; the direction is perpendicular board, so this will be direction of the actual balance. So, competently you have to take this instant of course you are getting the full one and magnitude is simply this last 0.5. So, 2 m reciprocating omega squared r that is magnitude of the unbalanced primary moment, the maximum value.

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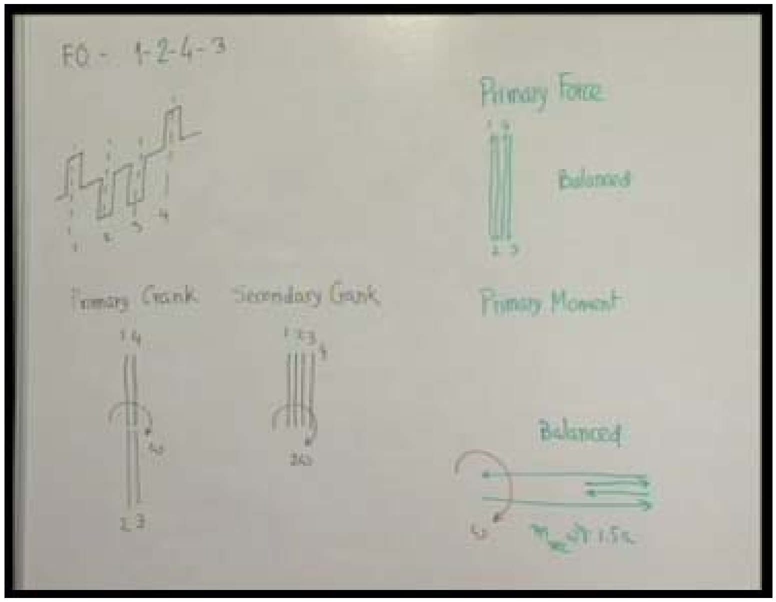

Whatever the secondary, when you draw the secondary crank 2 into 0; that is for cylinder number 1 or crank number 1 it will be 0. Then 2 it is at angle 180 degrees or pi; so, two of that will be 180 degrees it will be like this. Then, 3 is also again 0 so two of 0, 2 into 0 will be again 0 and 4 is again 90, 180 degrees two of that will be again.

Now, you find secondary cranks are aligned and they are rotating at a speed 2omega. So, the forces will be as shown in slide (Refer Slide Time: 45:10). This is by the first cylinder which will be lamda by 4 m reciprocating 2 omega squared r, for the second cylinder in this direction, third cylinder in this direction, fourth cylinder in this direction.

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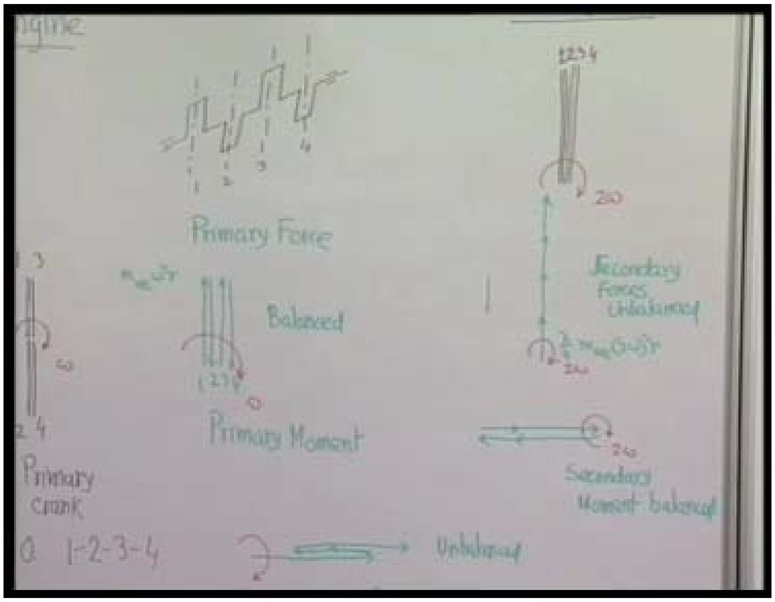

Primary forces or secondary forces are unbalanced; now secondary moments we will find will be balance because this will produce four moments in this direction. Then this will produce again a moment in this direction, then this will produce again a moment in the opposite direction and this center four will produce a moment in this direction and whole thing is rotating; both these also rotating and it is started here. So, you come back therefore resultant is 0.

So, secondary moments are balanced. The important thing now, we should know that in this kind of situation where you are taken a 4 stroke cycle - 4 cylinder engine with the firing order 1- 2 - 3- 4 the primary forces are balanced; primary moments are unbalanced. You should try to balance the primary as much as possible; because the magnitude is maximum, secondary forces are unbalanced for secondary moments are unbalanced.

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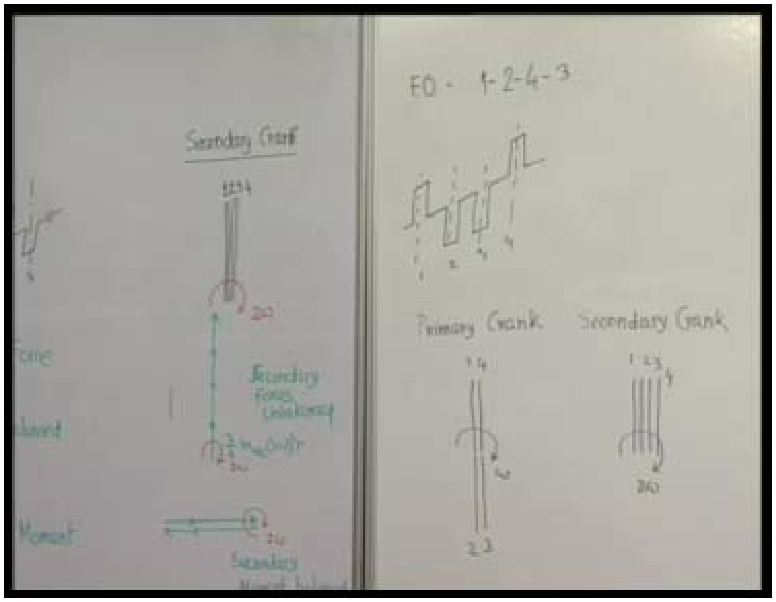

You will see; what actually you want to tell now, which is very important that just by changing the firing order it is possible to include balancing situation. Suppose, the same engine we take the firing order as 1- 2- 4- 3 that means first cylinder fires, then second cylinder fires, then fourth cylinder fires and finally third cylinder fires. This will be the isometric view of the common crankshaft 1 2 3 4 and crank diagram will be as shown in slide for primary crank.

1 2 3 and whole thing is rotating and secondary crank 1 will be here itself, 2 will be also here, 3 will be also here, 4 will be also here and whole thing is rotating at 2omega is the secondary crank. The interesting thing will be now, if you draw the force and moment diagrams.

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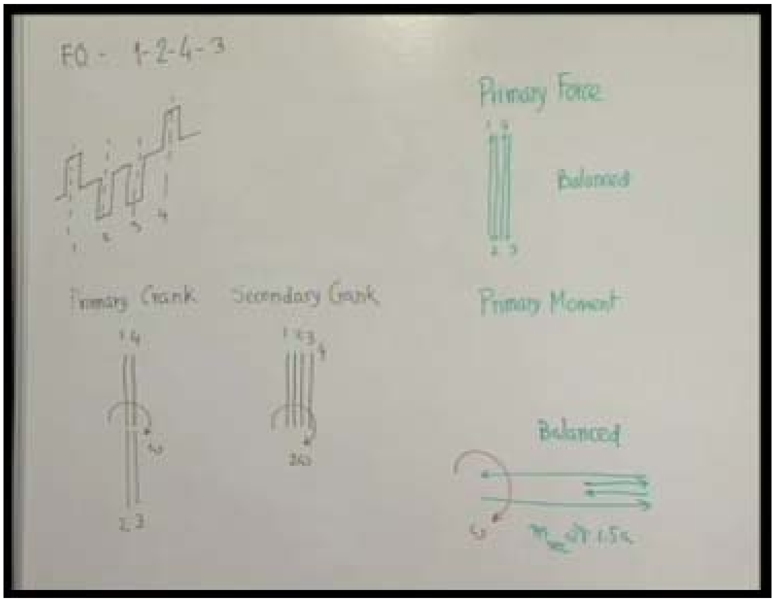

Primary force diagram if you want to draw here, obviously you can see primary force 1 then 2, then 4 and then 3. So, 1 2 4 3 primary force balanced; on here also, it was balanced primary moment. Primary moment the force 1 will produce moment in this direction and that is m reciprocating omega squared r into 1.5a. Second one is in this direction; so that produces a force in this moment in this direction, this is one third of this, and then 3 is again in the downward direction (Refer Slide Time: 50:22).

So, it will produce if moment in the opposite direction to that and same magnitude. Finally, the fourth one which is in the upward direction that will produce a moment in this direction and whole thing is rotating; this primary moment diagram and as you have seen that where we have started, we have come back here. Therefore, it is balanced so we started here and come back here, therefore it is balanced.

This is different that will be earlier, our primary moment was unbalanced, now you have got primary moment balanced, just by changing the firing order from 1- 2- 3- 4 to 1- 2- 4 -3 and crankshaft being this. Secondary if you can find out, since secondary crank is like indistinguishable from the secondary crank of the previous one.

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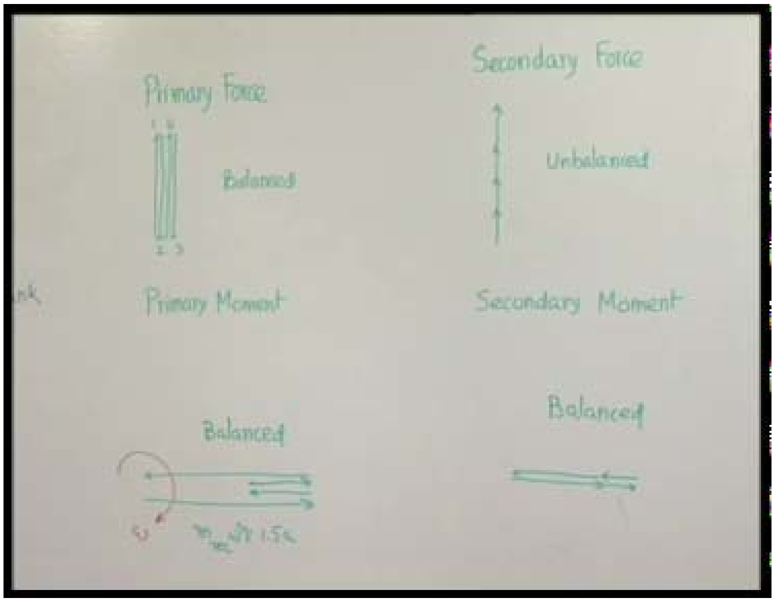

We will find that, the forces will be obviously unbalanced and moment you can check what it is. We will find it will be first cylinder will produce in this direction, second cylinder also produce same force, third also same and fourth also same; so unbalanced. In secondary moment, we will find first one is producing in this direction, second one also producing in same direction, third one is producing again in the same direction; third one is down like second; so, it will produce something sorry and fourth one is at the end it will also produce same.

Here, again you find the secondary moments are balanced. So, over all there is an improvement, because earlier the secondary forces are unbalanced and primary moment was unbalanced just by changing the firing order. We have achieved total primary balance and only the secondary force unbalanced.

Now, I think this ((sense message)) that firing order is very important and one can take up in case of 6 cylinder engines with 4 stroke cycle and crank arrangement if you take, it will be found that where ever it is symmetric about the midpoint like say, if I take the six cylinder engine four stock cycle, say if I keep a firing order like 1- 2- 3- 4- 5- 6 it is rotating like this.

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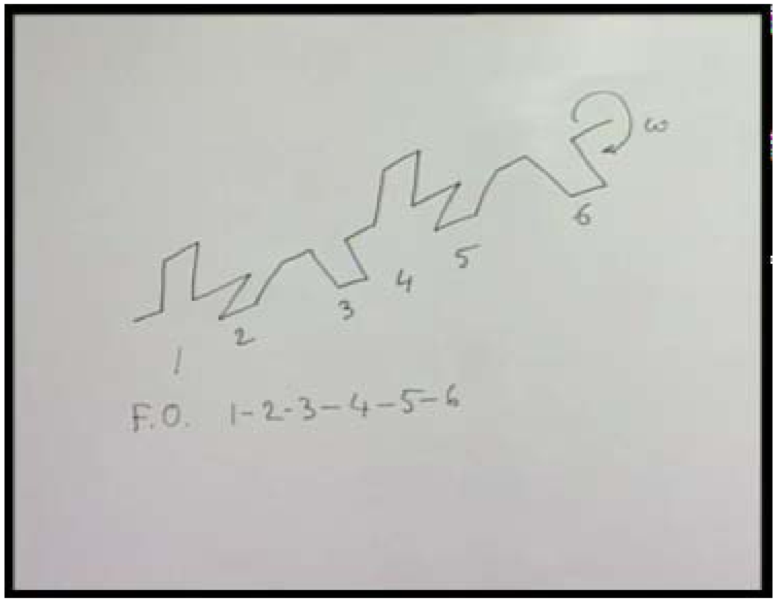

First this fire, because it is top, next comes 2, next comes 3 and next comes 4 so on. After every 120 degrees rotation of 1 firing takes place and total three, 720 degrees will be taken is 4pi to make all the cylinder fire once. If you keep on going, the same kind of analysis, we will find primary forces will be balanced, secondary forces will be balanced and one should be very careful drawing primary and secondary cranks.

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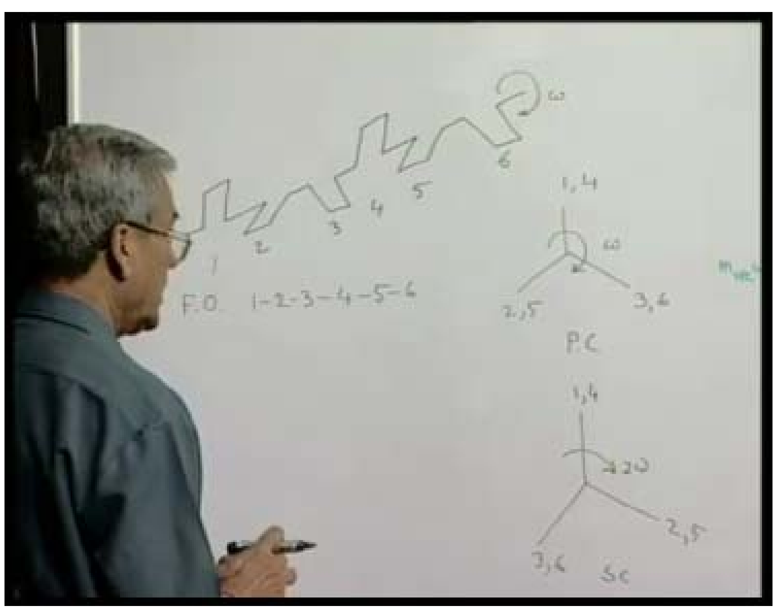

This is the primary crank, so 1 2 3 4 5 6 this is primary crank; secondary crank, one will be same because 0 into 0 is 0, 2 the angle is 240 degree, double of that is 480 that means 360 plus 120, 2 will be here, then 3 is 120 double of that is 240, it will go it in the direction, 3 will be here, 4 will be again here, then 5 will be here and 6 will be here, this will be secondary.

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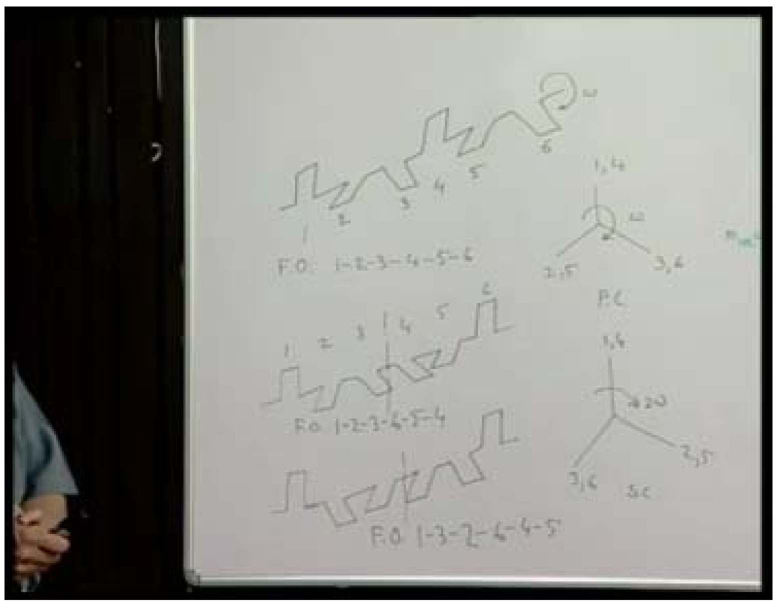

You can see that replace mass at the crank pins; primary force will all balanced because there are symmetrically placed, secondary force will all balanced as there also symmetrically placed, but primary moments and secondary moments not be balanced. To achieve, both primary and secondary force balance, and to achieve primary and secondary moment balance that is complete balance up to secondary, we have to take crankshaft which are symmetrical like this or its 1- 2- 3- 4- 5- 6.

So, firing order in this case will be 1- 2- 3 after 3 of course, 6 will be fired, then 5 will be fired, then 4 will be fired, then again 1. In this case, firing order will be 1, then 3, then it may be 2, then it may be 6, then it may be 4 and 5 like that; whatever we distribute the arrangement of the cranks, in the crankshaft should be symmetric about engine centerline.

You can see this is symmetric about this, this is symmetric about this (Refer Slide Time: 58:53). So, in all these cases if you draw the primary force and secondary force; primary moment and secondary moment it can be easily shown that it will completely balance after the secondary. Thus, the arrangement at this same engine is properly design can be completely balanced, without techniques trouble of attaching active measure like putting separate balance mass, the unbalance forces themselves in neutralizing with each other.

In the next session, what we will do? We will take up some other kinds of arrangements of various cylinders or engine or slider crank mechanism; so that we get also proper running without unbalancing and two such cases are popular, one is b engine another one is radial engine. We take up this in the next session.