Computer Numerical Control of Machine Tools and Processes
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Lecture 08
Tachogenerators Printer Circuit Motors Encoders

Welcome viewers to the 8th lecture in the open online course "Computer numerical control of machine tools and processes". So today we are going to discuss about some devices which are used in CNC systems for example, tachogenerators, printed circuit motors, encoder, et cetera. What is the focus of our discussion is? These devices are required for the proper execution of control action in CNC machine tools, it can be feedback, it can be the requirement of accuracy of profile geometry of the part which is produced by CNC machining, et cetera, so let's start right away.

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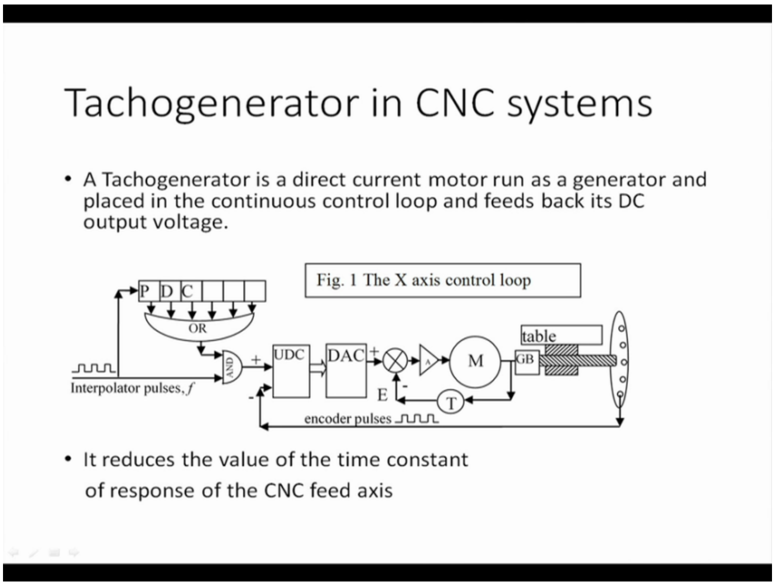

Up till now we have had a look at this particular control loop for CNC systems in continuous control. Just to remind you, in case of continuous control the control of velocity and the ratio of the axis velocity is done by the interpolator and in this case as you can see from the left-hand side of the figure, pulses are coming from the interpolator at a controlled rate to the first to the position down counter to keep account on the movement, which is going to take place, so a definite number of pulses are going to be passed through and it is then going into the control loop continues control.

Now continuous control 1st of all is taking care of the fact that particular velocity to be attained is achieved and maintained say in case of linear interpolation and also this control loop ensures that, the steady-state velocity say in the linear interpolation is attained within a very short time. This thing can be achieved by making the time constant of the system of this particular axis that means all the rotary devices taken together. Time constant that means the response of this particular system to say a step input like a step voltage to the motor, this response has to be very fast.

In order to make this response very fast, a tachogenerator which is nothing but a DC motor run as a generator so that faster it rotates proportionately higher voltage is emitted at its output. This is the output side; it is emitting a voltage proportional to its angular velocity. Since it is going to be mounted on the shaft of the prime mover motor therefore, its angular velocity is equal to the angular velocity of the shaft of the prime mover motor in this case this is the say permanent magnet DC motor. So it is emitting a voltage is equal to a constant say K_T multiplied by angular velocity ω. So its main advantages I mean the main reason for incorporation of this inner velocity control loop is to reduce the time constant or quicken the response time of this particular axis of motion okay.

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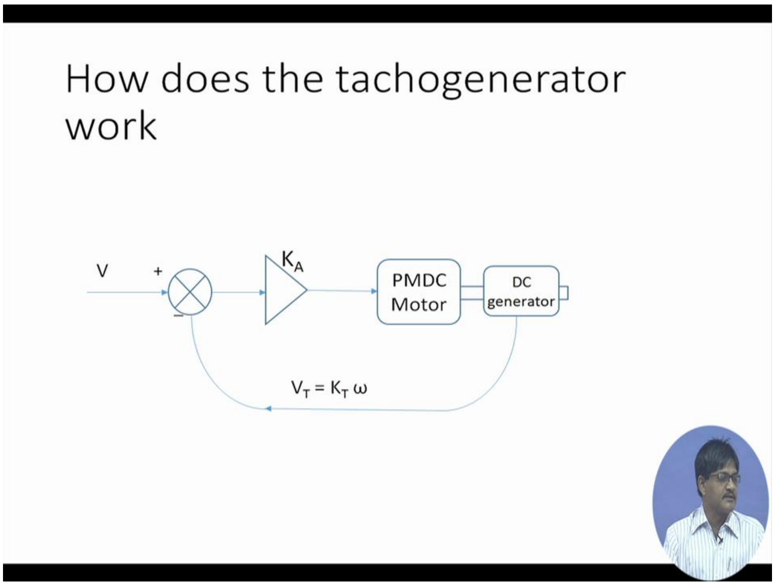

So this is how the tachogenerator is expected to work. 1st of all the input voltage is sent and is compared by an analog comparator with the feedback voltage which is coming from the tachogenerator which is basically a DC generator in the in this case and is therefore is fed in negative feedback that means voltage V is coming in from that voltage V_T is subtracted and the result is amplified since it is going to be a very small value as it is subtracted okay, so this result is amplified through an amplifier which has a multiplying constant of K_A, so we will basically have $(V - V_T)$ multiplied by K_A and this is fed into the permanent magnet DC motor.

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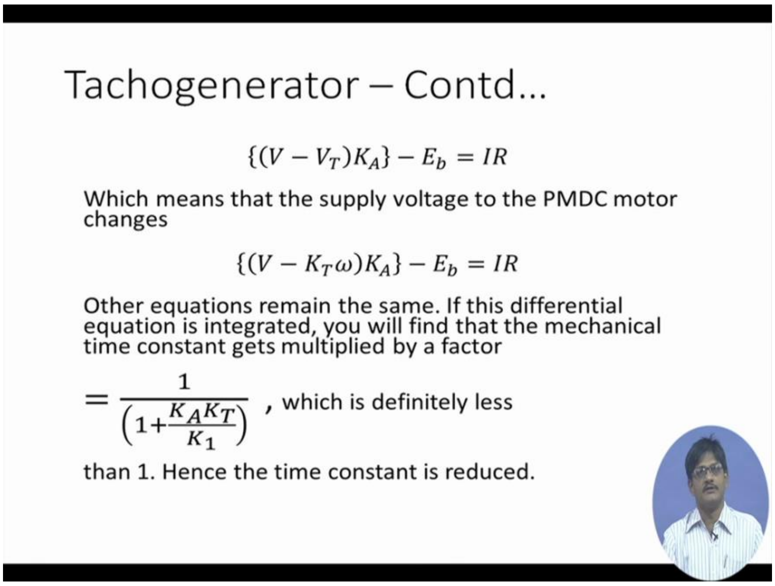

Now if you refer to the lecture on permanent magnet DC motors, you will notice that in that case we had a particular voltage input to the permanent magnet DC motor which was V, this V value now gets modified to $(V - V_T)$ multiplied by K_A and this is given in this next equation, $(V - V_T)$ multiplied by K_A - back EMF = IR, so just the input voltage term is modified and therefore, we can process this particular equation in the same way as that equation so this particular algebra I am sure that you can follow once you have the notes of that previous lecture in front of you and it will ultimately be found that the τ or time constant which was calculated last time to be $R \times J / K_1^2$ e gets modified by a multiplying factor of $\frac{1}{1+\frac{K_A K_T}{K_1}}$ which is definitely less than 1.

Why, because it is having something added to 1 in the denominator which is nonnegative okay, it is a positive term. So $K_A K_T / K_1$ is positive and therefore, τ when multiplied by this particular factor will definitely become less. This way, it is shown mathematically that the incorporation of a tachogenerator tends to reduce the time constant and make the response of the system faster to any external stimulus like a step voltage. However, this is not the only way in which we can address this particular issue, there is another way of looking at it let's have a look.

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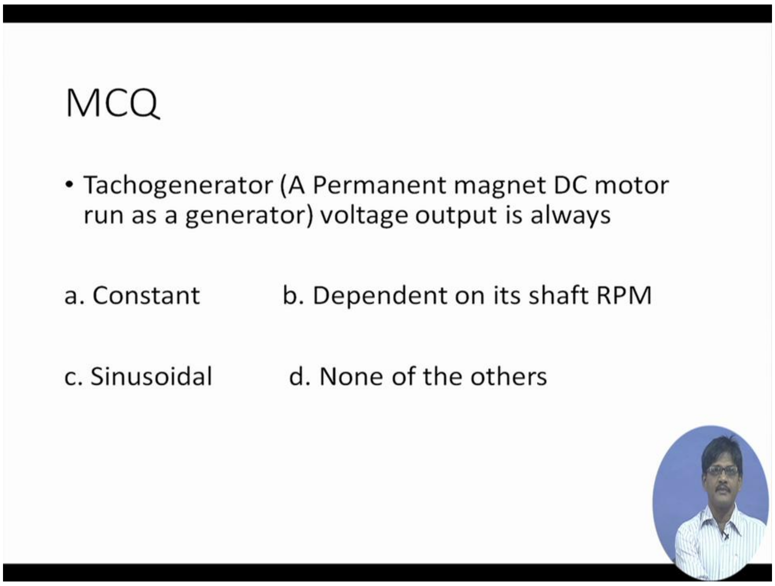

So oh we just have one multiple-choice question here. A tachogenerator which is a permanent magnet DC motor run as a generator, its output voltage is always; constant, dependent on its shaft RPM, sinusoidal, none of the others. So let's take the 1st option constant, tachogenerator voltage output is it constant? No, as we discussed it depends upon its angular velocity of its shaft, so the 1st option is definitely not correct. Dependent on its shaft RPM, now what is RPM, rotations per minute. Rotations per minute is related to angular velocity by the relation 2πN, N being the RPM 2 pie multiplied by RPM by 60 = ω, ω is the angular velocity let me write down here.

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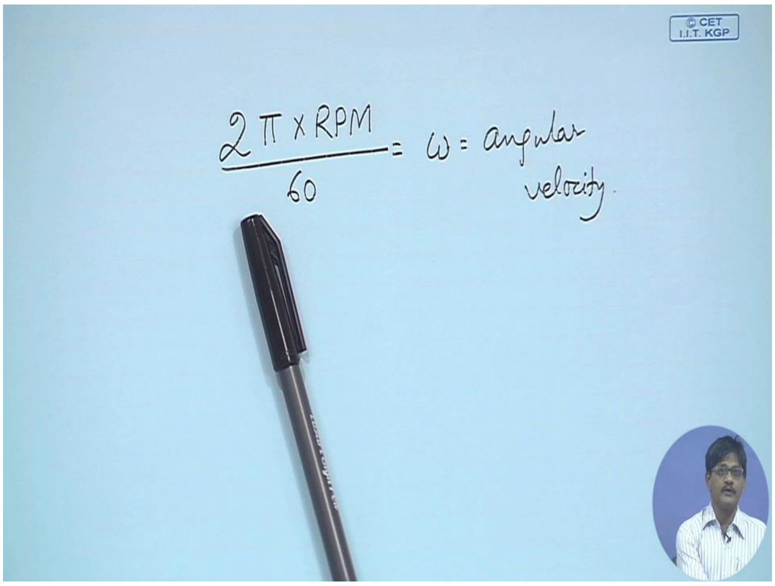

So if you look at this one, 2 Pie RPM / 60 is equal to ω equal to angular velocity, it is the measure of the rate at which you are rotating your shaft. So if it is proportional to ω, it must be proportional to RPM as well because all that other terms concerned, they are constant; 2, Pie and 60. So definitely B seems to be correct, but let's also look at the other options in order to make the final decision. The tachogenerator voltage output is sinusoidal always, definitely not because it depends upon the angular velocity and angular velocity does not have any reason to always be sinusoidal, so C is also not correct. None of the others, this is also not correct because we have found that B is definitely correct, so the answer to this is B. Let us now investigate another aspect by another way in which we can address the issue of quick response.

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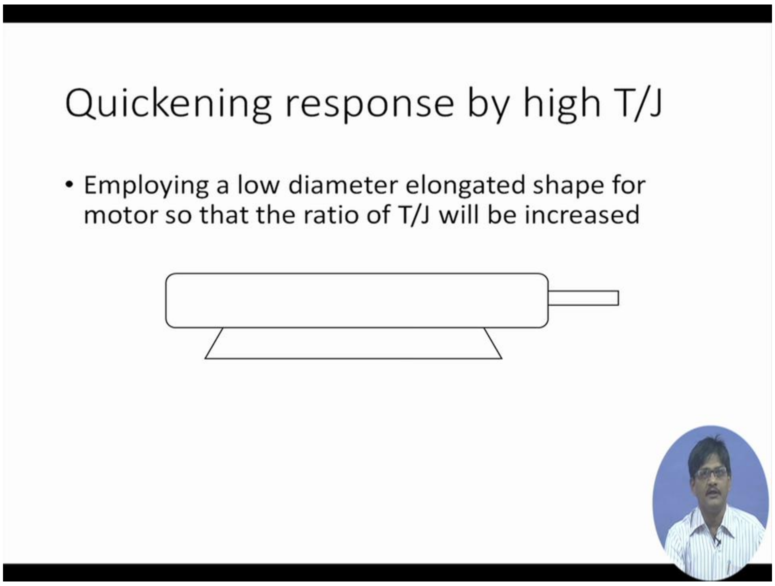

If we interrogate this particular term torque divided by polar moment of inertia, it is similar to the term force divided by mass. Force by mass from Newton's 2nd law we know is equal to acceleration, so here this must be torque divided by, polar moment must be angular acceleration. So if we can make this particular term high, it essentially means that we are making the angular acceleration of the system very high that means you can catch up with a particular predetermined value of velocity very fast. However, there is a danger that it might overshoot but let us not concern ourselves with the other side, let us concern ourselves with acceleration at this moment. And therefore, we understand that if T /J can be made high for a particular motor, it is going to have very high acceleration, very fast response.

So the answer to this might be the design of a motor, which has very small diameter which means that the armature radius is going to be extremely small. And in order to increase its power capacity suppose we make it elongated just like long cylinder with high L / D ratio, now why are we doing this? Because we want to have a high T / J, now how does it help? Torque is proportional to the 1^{st} power of radius okay, it is equal to force × it is a couple so this torque is proportional to the radius okay. Force into radius, or if you consider force × diameter. Now if torque is proportional to the 1^{st} power, what about the denominator? We have not looked at the denominator up till now.

Denominator is J, if we consider M mass it is going to be proportional to the 2^{nd} power of radius and if we consider geometrical moment of inertia it is going to be proportional to 4^{th} power of radius. So if we increase radius then we will expect that this term will become smaller and smaller, so in the same way if we decrease the radius as we have done now, we will expect that T / J will definitely increase. So we should have the basic idea will be to make smaller and smaller diameter what you call it, motor. Surprisingly, when we investigate the market for such motors where time constant is low due to high acceleration, you will find this sort of motor also existing and these are called sometimes Printed circuit motors or even Pancake motors.

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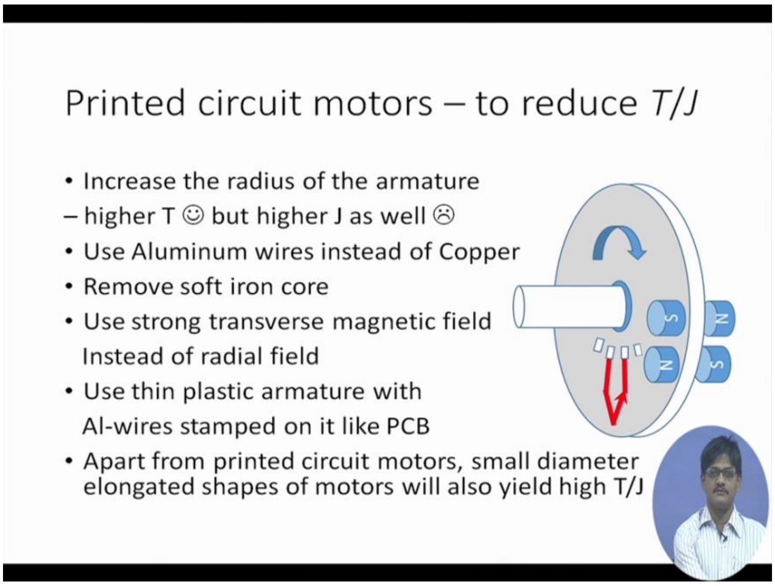

What is the basic idea in this Printed circuit motors? It is 1^{st} of all accepted that increase of radius of the armature will bring in higher T because torque is proportional to the 1^{st} power of radius, but unfortunately it will bring a higher value of J that means the denominator will also become higher so that ultimately this term will become very low because it is proportional to the 2nd power of radius if you consider mass okay MR^2 so that means we do not gain, but we are doing it, it is it is actually available, this kind of motor, why do we do that? The term is actually modified from another point of view, it is argued this way since force into a distance which is the radius here, since force into distance is defining T.

We are increasing the radius and at the same time let us increase the force so that it gets a fair contribution from both the terms present in the numerator. And for the denominator J, let's investigate the other multiplying factors like mass and reduce it sufficiently so that the combined effect of mass and radius square that will ultimately be reduced, so in this particular type of motor, all the terms are modified. Let's see how it is done for example force, force can be increased instead of radial field by magnets in the stator. We are going to have transverse field with very strong ceramic magnets, as you can see some magnets are kept very close to the armature on both sides of it.

The armature has become thin almost paper thin okay and these magnets are creating the field for ultimate motion of the armature. How is the current flowing? The current is flowing this way out and this way in and the direction is changing due to these commutators. So how is the motion being obtained? By, if you apply the left-hand rule you can find that ultimately motion will take place this way because the field direction is in this direction and the current in this arm is this way and in that arm is that way and that is why the field is becoming opposite in successive pole pair positions, but what about the force getting increase?

So the force gets increased as the field is stronger that is very good, but what about reduction of mass how are we reducing the mass of the armature and the rotor system. First of all instead of having a bulky armature with huge number of copper coils which are very heavy, copper is used for its low conductivity I mean high conductivity. So instead of using copper we go for a compromise, we go for aluminium which is much lighter okay. So aluminium wires are stamped on the armature as if the armature wire of printed circuit boards paper thin, not paper thin but extremely thin plastic armature is used just like a printed circuit board.

And just like we have stamped circuit on it, we are going to have the armature wires on it made of aluminium so that sufficiently reduces the weight of the armature, so mass comes down in the denominator. Add to it the fact that we have a soft iron core at the centre of the armature to make the field perfectly radial, but now there is no radial field to start with so there is no question of keeping that soft iron core in the middle and it is done away with and therefore, this armature becomes extremely light for all these considerations so that ultimately what we have is very high forces multiplied by very large radius multiplied by okay a large radius square multiplied by an extremely small value of mass, this combination ultimately gives us very high T by J ratio, so that we get a sufficiently low time constant from this type of configuration.

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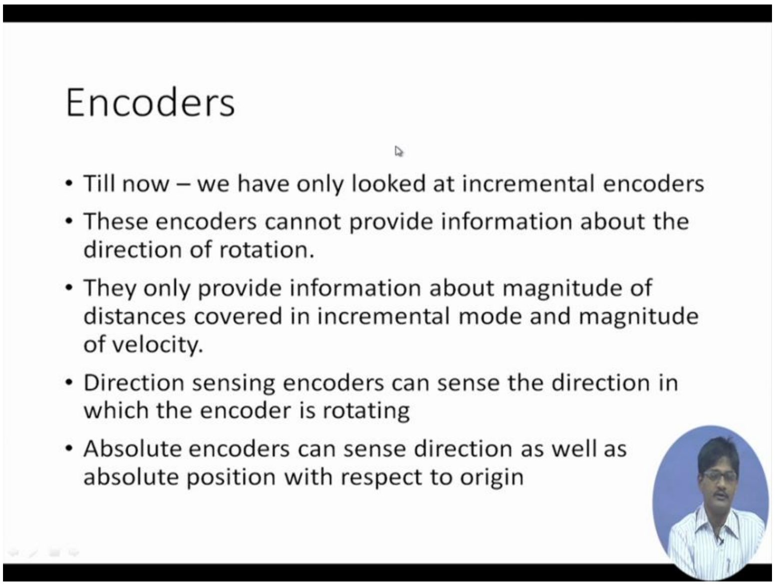

Now, let us have a look at encoders. Ultimately up till now we have had looked at encoders, but they were incremental encoders with a single row of holes and through these holes light was passing that is we restricted our discussion to optical encoders and the principle is same for other encoders as well. So basically the incremental encoder that we have had a look up till now, they have one problem. The problem is, this cannot provide information about the direction of rotation and they can only provide information about the magnitude of distances covered in incremental mode.

That means just this distance has been covered whether it is in the clockwise direction or anticlockwise direction, no information is available in that way and also whether the velocity is once again clockwise or counterclockwise, we have no way to check. So in order to solve this problem, there are encoders available called Direction sensing encoders. They can sense direction, but of course the way in which this is done, it is slightly differs from incremental encoders, we will have a look at that. And there are absolute encoders as well which can sense direction as well as absolute position with respect to some origin, so let’s have a quick look at these devices.

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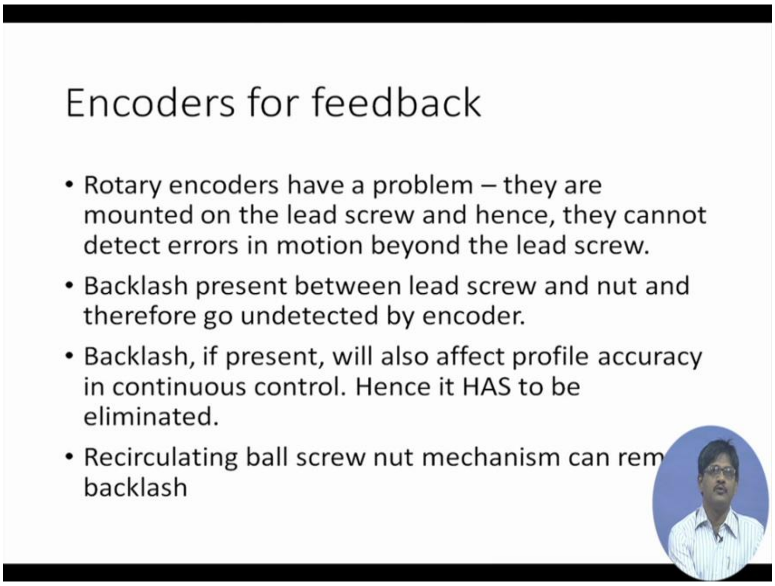

So when we are having a look at rotary encoders, we need to mention one more thing that a rotary encoder is essentially mounted on the lead screw and they cannot detect any errors in motion beyond the lead screw. That means say the job is mounted on the table and the job is deflecting sufficiently, there are sufficient defections on the job when machining is being done, there is no way the encoder can access this information that is it can get this information and send it to the machine control unit, no we do not have any way of checking it. So there is also a question of backlash which is present between the lead screw and the nut and this is also not received by the rotary encoder mounted on the lead screw.

There can be other types of encoders, linear encoder, but the rotary encoder is the most popular one. So if backlash is present, we may be able to avoid the problem of backlash interfering with the part geometry accuracy in point-to-point machining, but in continues control we simply cannot do with backlash present in the machine feed screws. If there is backlash, the geometry of the part will get affected so it has to be eliminated. So, one way to eliminate this backlash is by providing recirculating ball screw nut mechanism, it looks somewhat like this.

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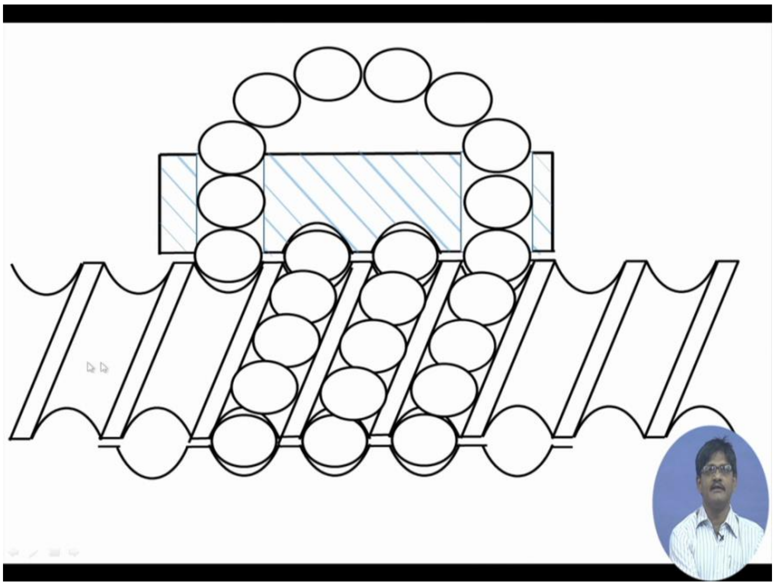

The depiction is not very good, this is the screw inside. Instead of directly coupling with the nut, we have balls which are circulating okay and rolling in between the screw and the nut and they ultimately get recirculated to enter the helix once again this way, on the other side they move up, role in between, go this way, role, come out and again they get recirculated like this so that sliding friction is replaced by rolling friction and if these balls are little oversized and with preloading okay. One such nut preloaded against another nut with some axial loading; in that case backlash can be eliminated to a large extent.

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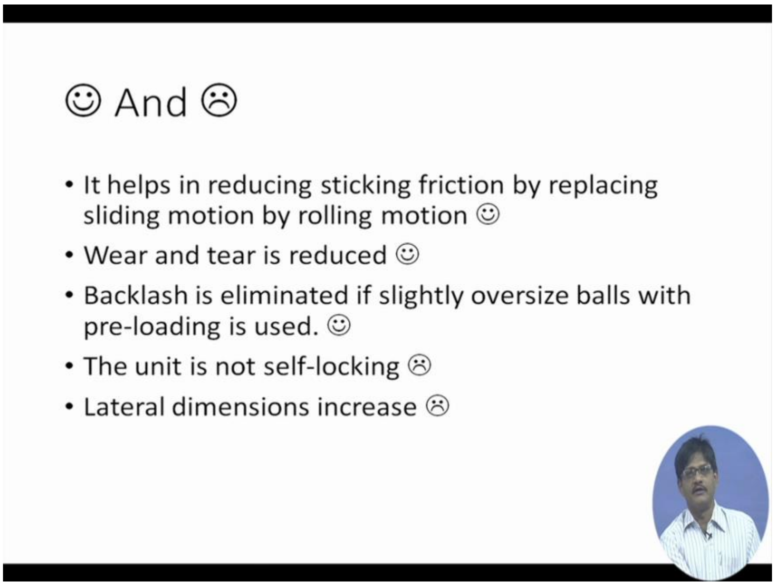

And it has some other advantages and some disadvantages also. If we use a recirculating ball screw nut mechanism, it helps in reducing sticking friction by replacing sliding friction by rolling friction. What is sticking friction? When we are in a region where there is just in between metal to metal contact and fluid film lubrication, in that region the motion of member against another engineering part becomes uncertain that means it might be sticking at some time with the other body and it might be slipping against the other body as sometime, so that jarring what you call it, jarring motion takes place with a lot of vibration and it it is supposed to be avoided at all costs.

This generally takes place at very low speeds and if sliding friction can be completely avoided by rolling friction, we can do away with sticking friction so the recycling ball screw can avoid sticking friction by bringing in rolling motion instead of sliding. Further, wear and tear is reduced as there is rolling instead of sliding and backlash is eliminated as we discussed. But the problem is this system is not self locking, if you push the nut you will get motion, in ordinary screw nut mechanism if you push the nut, no matter how much you push the nut, you cannot set it into motion or you cannot make the screw rotate, so some other device has to be there to make sure that it is self locking. And lateral dimensions, the nut become larger in dimensions okay, taking up more space and as space is also expensive nowadays.

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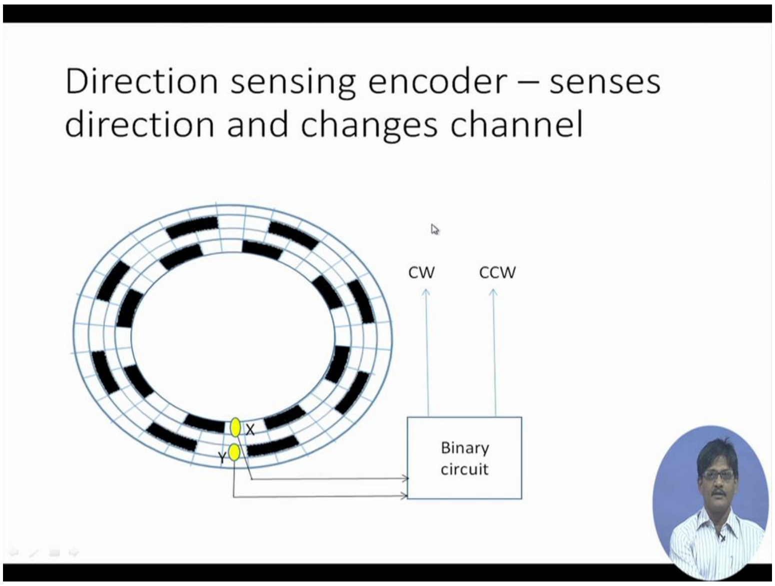

So, let’s have a quick look at the direction sensing encoder. We have 2 rows of holes and they have a stagger that means there is a difference in phase so that, these black portions are the transparent places and these white portions are opaque, so that if we have 2 light emitting devices with receptors on the other side, we will have pulses coming out with a phase difference from these two. So if you notice, we have written here X and Y, so if this encoder direction sensing encoder rotates in a clockwise direction, X pulses will lead the Y pulses by half a wave.

In the counterclockwise direction, X pulses will lead the Y pulses. Now what do we get out of it, there is a very simple binary circuit with the help of which we can completely separate the pulses depending upon whether it is rotating in clockwise direction on whether it is rotating in counterclockwise direction.

That means if it is rotating clockwise, I can make the pulses come out this way and this line will be dead. And on the other hand, if it is rotating in the counterclockwise direction the pulses will be coming out here this line will be dead in that case. And we can connect these 2 up to the 2 sides of the Up-down counter okay; we will come to that when we discussed at length the continuous control loop with respect to interpolators. So this is how the direction sensing encoder can sense the direction and change the channel along which the output is to be produced.

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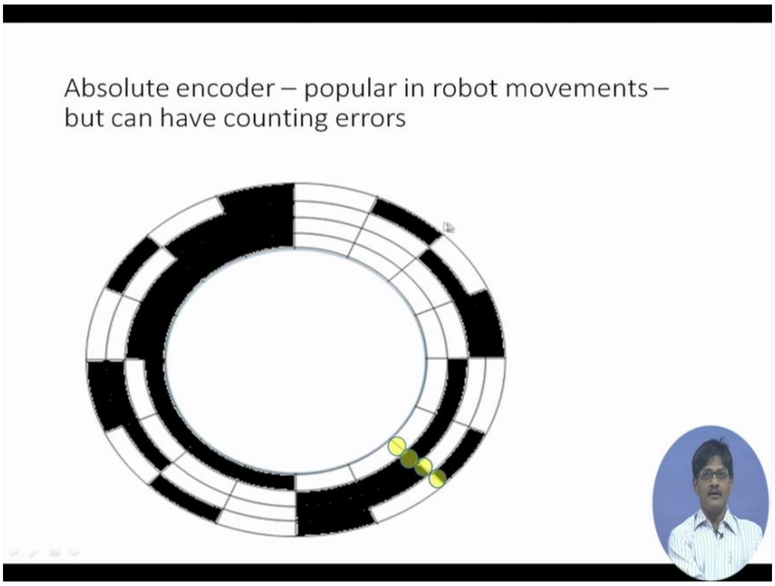

Absolute encoders they are generally used where we want to be very sure about the particular position with a particular reference point and they can also sense direction. They are popular in robot movements, robot joints where generally the movement is restricted within one rotation, so how does it work? These black portions are transparent, while white portions are opaque. So when we have sensors corresponding to 4 of these channels, there are 4 channels here. The outermost channel is the least significant bit and the innermost channel is the most significant bit, so when it is rotating the outermost channel goes 101010 like that.

So 1st it reads 0, all of them are 0, so 1st it reads 0000 then 0001, 0010 which is 2 then 0011 which is 3, et cetera, 4, 101 5, 110 6 that is good, so that means ultimately the problem of the encoder is solved, not really because whenever you are having these sensors placed at a particular place, if there is more than one change taking place, there might well be a case where there is simultaneous change is taking place more than one change, there might well be a case where there will be some reading error, which means that while changes taking place in the 1st channel say in 2nd channel there is a slight phase difference so that the change has not yet taken place so that it might read 0 .

It might read at this particular position 1011 because the 1st channel has not yet changed for say a several nanoseconds it might read 1011 because change has taken place here, change has not taken place here just because these are physical devices and they have their limitations, so these changes takes place a little late and therefore it reads 1011 and that is a gross error because it tells the machine that I have reached actually this position of the encoder at this particular angular line. So these changes if they are coming in pairs or more than that, they are going to they might result in reading errors, counting errors.

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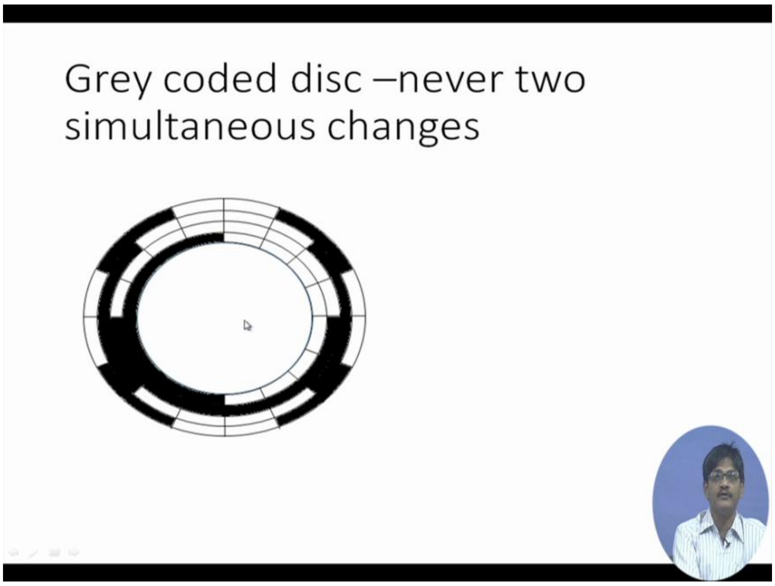

And therefore we have a system of grey code where we ensure that from one reading to other there is only one change so that counting errors as such will be completely eliminated. But what do we have here? If we start from here and call this 0, you will never get to understand that this is 0 because suppose a person does not know that we have done this change in order to avoid counting errors, what does it do? So he has to either therefore refer to a lookup table or the machine control unit inside has to have some sort of decoding arrangement so that it knows that okay this really means 0, this really means 1 so on and so forth, so grey coded disc solves the problem of counting errors by not allowing more than one change at a particular point in time, thank you very much.