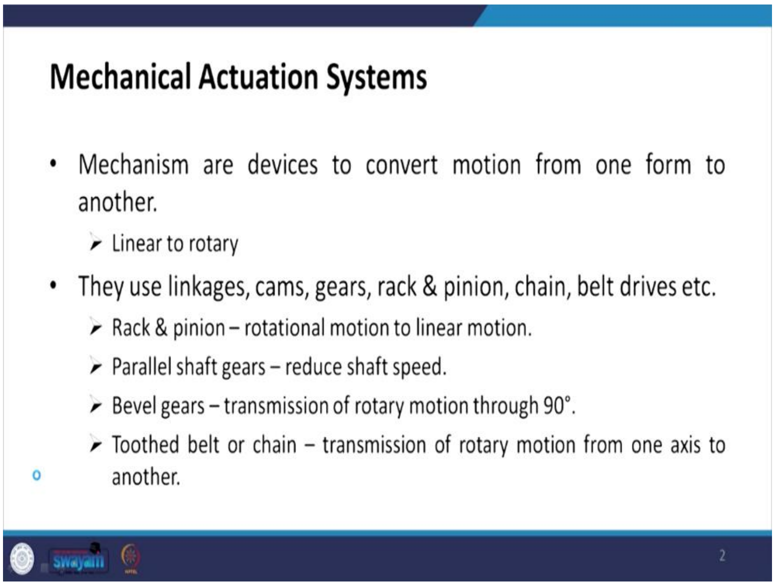
Mechatronics
Prof. Pushparaj Mani Pathak
Department of Mechanical and Industrial Engineering
Indian Institute of Technology, Roorkee

Lecture - 11
Mechanical Actuation Systems

Welcome to this NPTEL online certification course on Mechatronics. Today we are going to study Mechanical Actuation Systems. As we know actuation is one of the important parts of the mechatronics system and we get our control actions implemented by the actuation system.

So, the actuation system is the one that is responsible for imparting the motion whether its translatory or rotary motion to the rest of the system your mechatronic system. So, today I am going to talk about the mechanical actuation system and there are different mechanisms that are used for actuation purposes and these mechanisms are devices to convert motion from one form to another form.

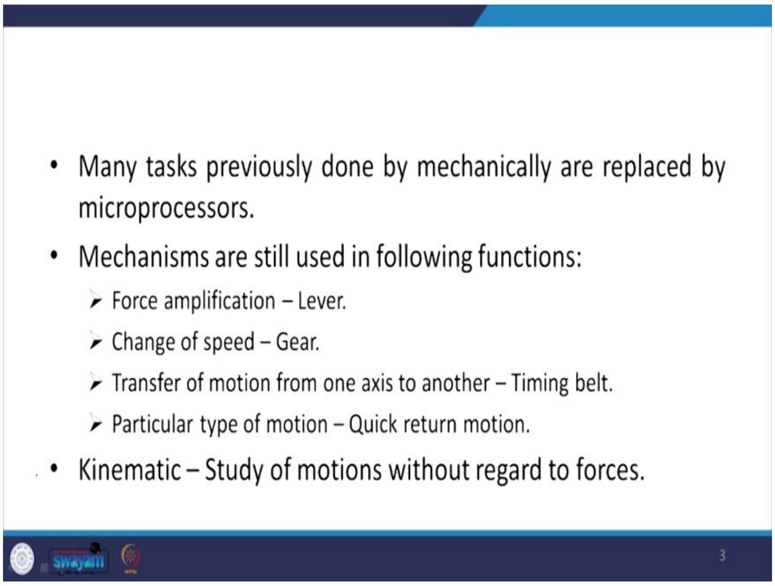
(Refer Slide Time: 01:28)



For example, I want to convert a linear motion to a rotary motion. So, I can use a mechanism to do that. For example, I can use a slider-crank mechanism to convert a linear motion to a rotary motion. They are linkages, cams, gears, racks, and pinion, chain, belt drives etcetera these are some of the examples of mechanical actuation systems.

We use rack and pinion if we have to convert rotational motion into a linear motion. Then there are parallel shaft gears are used in order to reduce the shaft speed or if you want to increase the torque. Again bevel gears are used for the transmission of rotary motion through 90 degrees. There are toothed belts or chains that transmit rotary motion from one axis to another axis. So, these are some of the examples of mechanical actuation systems.

(Refer Slide Time: 02:52)

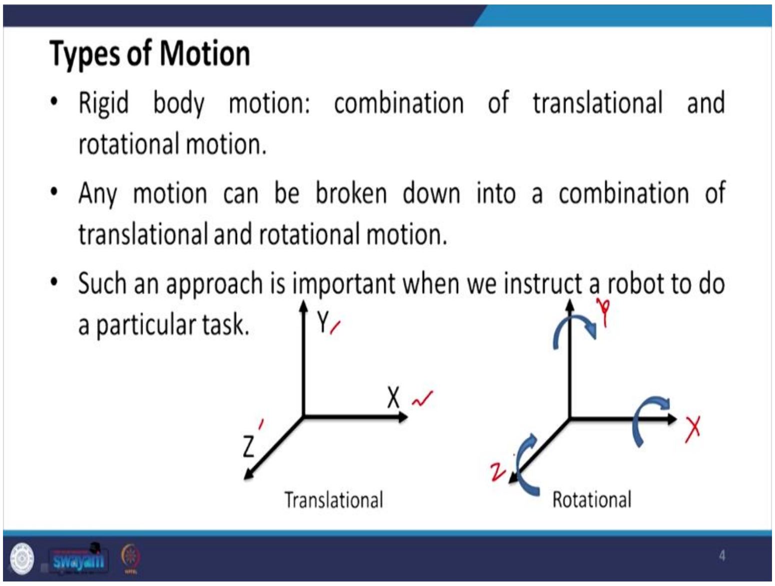


Many tasks previously done by the mechanical system are now being replaced by microprocessors. Mechanisms are still used in the following functions. Although there are many tasks that could be done using microprocessors which were done earlier using mechanical systems, still there are many functions for which we require the mechanisms.

For example, if we have to amplify the forces we need a lever to amplify the force. If we want a change in speed, we need gear. If we want to transfer motion from one axis to another axis we need a timing belt or we need the chain drive. Our requirement may be of a special type. If we want a particular type of motion quick motion, then we may have to use the quick return mechanism which is used in the shapers.

So, many of you who are from the mechanical background know very well the quick return mechanism and in kinematics, we study the motions without regard to forces. So, we study how the motions are being transformed from one form to another form.

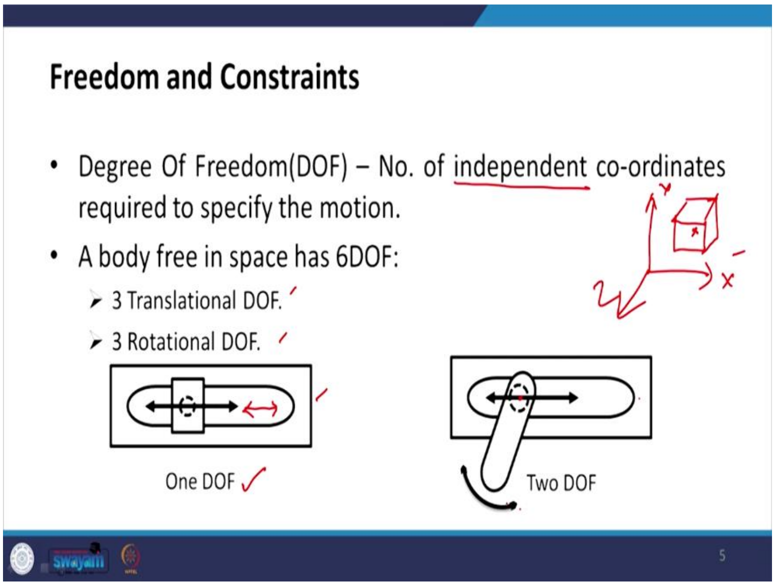
(Refer Slide Time: 04:31)



There are types of motions. Rigid-body motions are a combination of translational and rotational motions and any motion can be broken down into a combination of translational and rotational motion. So, you have any arbitrary motion that motion can be broken down into translational and rotational motion a combination of that such an approach is important when we instruct a robot to do a particular task.

So, what type of motion is there, and what type of task does a robot want the robot to do based on that we plan this breaking down of the motion. So, that translational motion can be we can describe with the help of the X, Y, Z-axis. So, the 3 translational motions are there and similarly, we can have the 3 rotational motions, the rotation about X-axis, rotation about Y-axis, and the rotation about Z-axis.

(Refer Slide Time: 05:44)



In mechanical systems, we often talk about the degrees of freedom and the constraints. These are some of the very important terms especially when we are describing some mechanism. if we are talking about a robot we talk about how many degrees of freedom the robot has. The technical definition of degrees of freedom is that the number of independent coordinates required to specify the motion. Independent coordinates here this independent is the keyword, which we have to see into and see that the coordinates are independent. Then only we can that is those independent coordinates can be called the degrees of freedom.

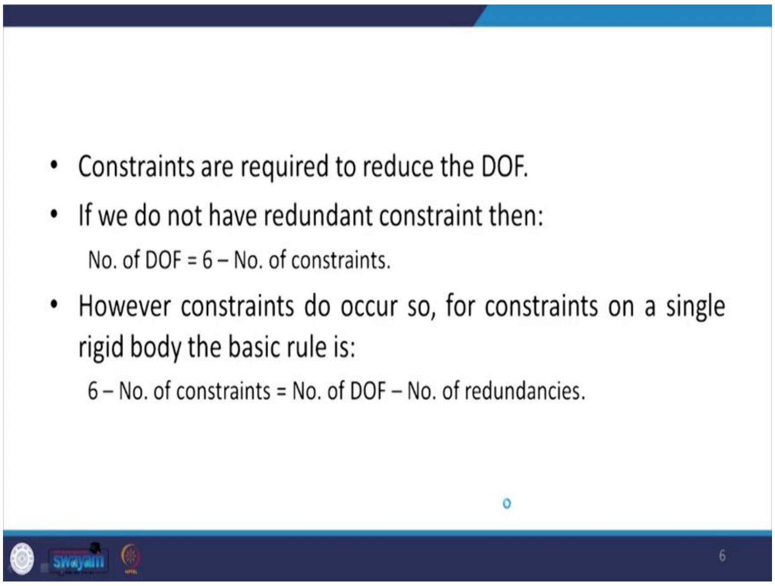
And so, a body in space has got to 6 degrees of freedom, 3 translational degrees of freedom, and 3 rotational degrees of freedom. So, if there is an object in space we can describe it with the help of 6 degrees of freedom that is the 3 translations and 3 rotations.

So, if I have got an object something like this, I can describe the position with the help of these 3 degrees of freedom; X, Y, Z what are the coordinates here and then we can describe the 3 orientations that are the rotation about X, Y, and Z-axis. So, a total of 6 degrees of freedom.

If we talk about an example for one degree of freedom. So, suppose we have a there is an object with a slot cut into and there is a piston. So, this piston is constrained here to move only in this direction. So, this is what we call one degree of freedom that is with the help of one coordinate independent coordinate I can describe the position of the piston at any time. So, that is why we call this one degree of freedom.

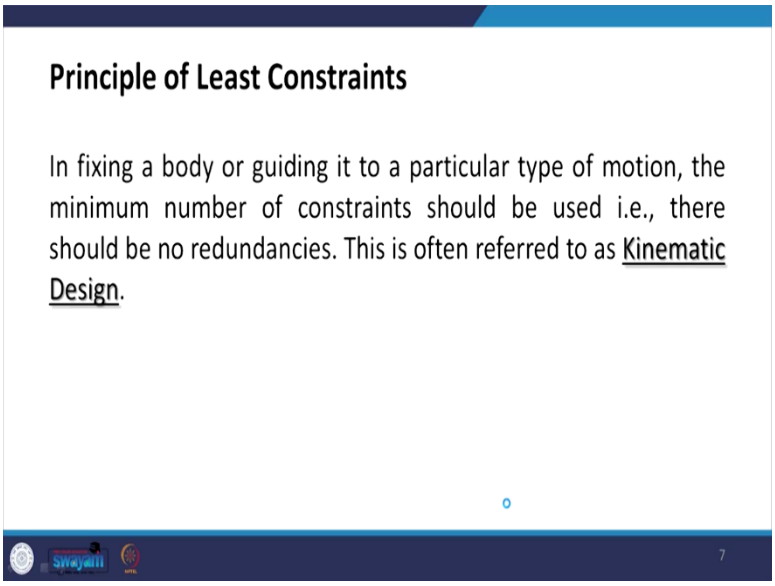
Similarly, if suppose I attach a link with the help of a revolute joint here on the piston and that piston is also moving alright or this link is moving in this direction as well as this link is pure tight here about this axis. So, it has got two degrees of freedom and these degrees of freedom are independent that is one is the translation and the other is the rotation. So, this is how we describe the degrees of freedom.

(Refer Slide Time: 08:33)



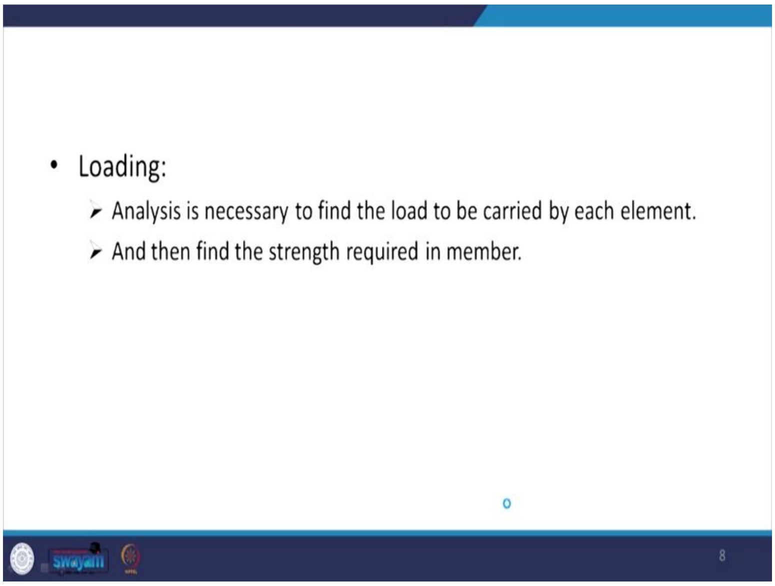
Now, we require constraints to reduce the degrees of freedom, So, if we do not have a redundant constraint then a number of degrees of freedom are (6 – no. of constants). So, Why 6? Because in a space we have the 6 degrees of freedom available that is 3 translations and 3 rotations. However, constraints do occur. So, the constraints on a single rigid body for the constraint on a single rigid body the basic rule is (6 – no. of constraint) has to be equal to the (no. of DOF – no. of redundancies).

(Refer Slide Time: 09:27)



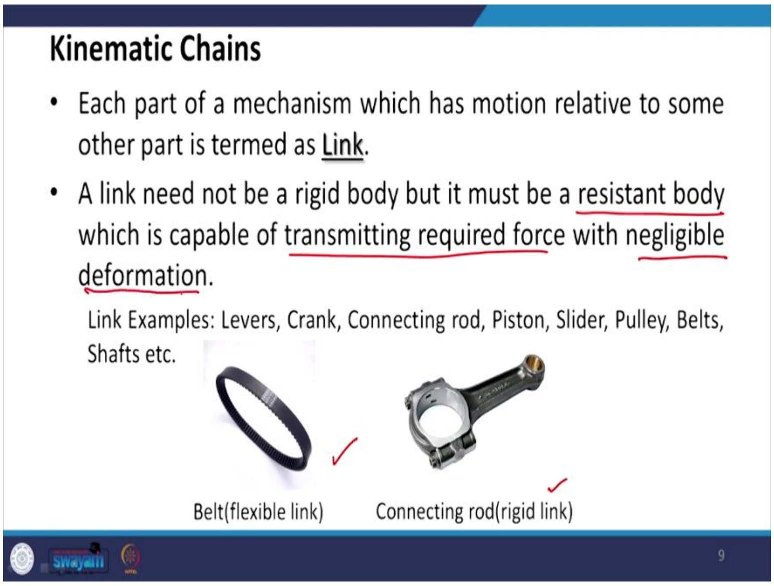
Then there is a principle of least constraints. In fixing a body or guiding it to a particular type of motion the minimum number of constraints should be used. There should be no redundancies and this is often referred to as kinematic design.

(Refer Slide Time: 09:50)



The loading analysis is necessary to find the load to be carried by each element and then based on that we can find the strength required in a particular member.

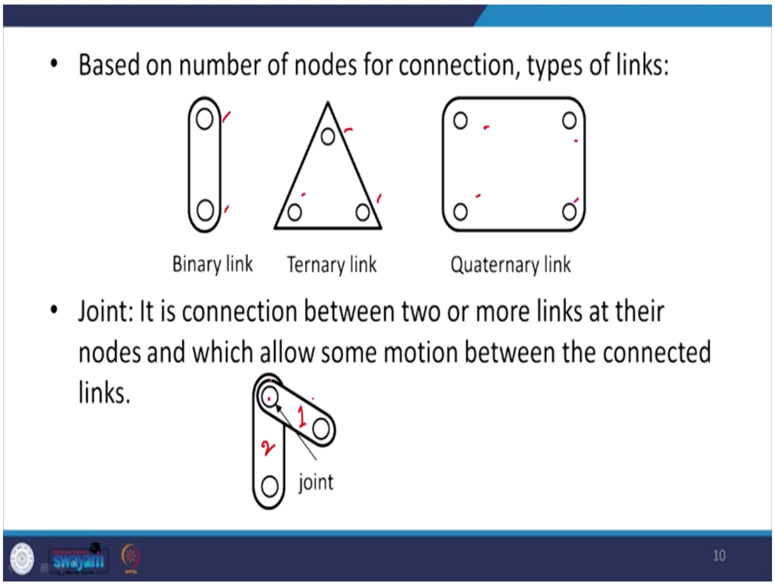
(Refer Slide Time: 10:07)



So, this aspect we have to take care in the mechanical design. Now, let us look at the kinematic chain. Each part of a mechanism that has motion relative to some other part is termed as a link. Now, a link may not be a rigid body, but it must be a resistant body that is which is capable of transmitting the required force with negligible deformation, alright.

The examples could be levers, cranks, connecting rod, piston, slider, pulley, belt, shafts. These are all called a link. They should not deform alright that is the basic definition. So, here a belt can be treated as a flexible link and connecting rod can be treated as a rigid link. Although it is flexible, it is a resistant body that is it is capable of transmitting the required force with negligible deformation. So, this thing we have to keep in mind.

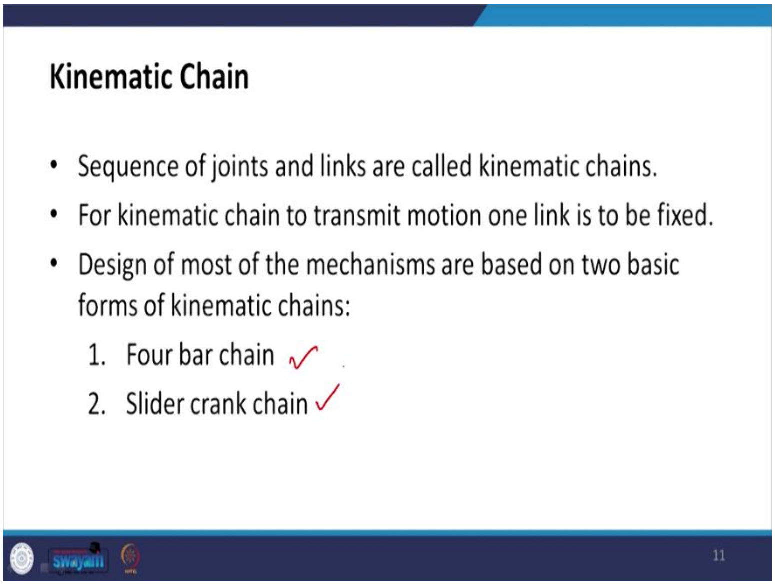
(Refer Slide Time: 11:20)



Now, based on the number of nodes for connection that there could be various types of links. For example, we have a binary link where we can have two connections. There is a ternary link where we can have the three connections possible. And there is a quaternary link where we can have the four connections possible.

A Joint is a connection between two or more links at their nodes and which allows some motion between the connected links. So, here we have link number 1 and there is link number 2 and there is a joint between the tooling.

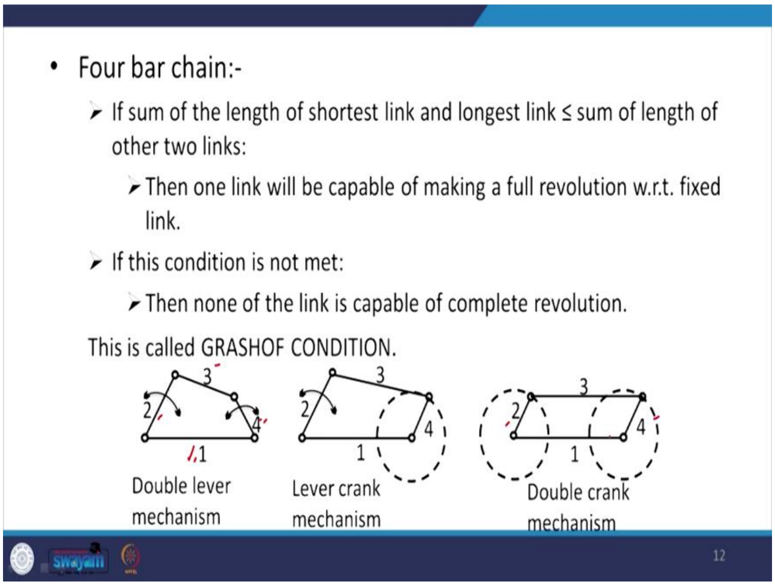
(Refer Slide Time: 12:10)



Now, after the definition of link let us look at what is a kinematic chain. The sequence of joints and links are called the kinematic chains. For the kinematic chain to transmit motion from one link has to be fixed and by fixing the different links of a mechanism we can get the inversions of that.

All these things those of you from the mechanical background they know, must have studied in your kinetics of machine course. The design of most of the mechanisms is based on two basic forms of the kinematic chain. One is the four-bar chain and another is the slider crank chain these are the most popular kinematic chains.

(Refer Slide Time: 13:04)

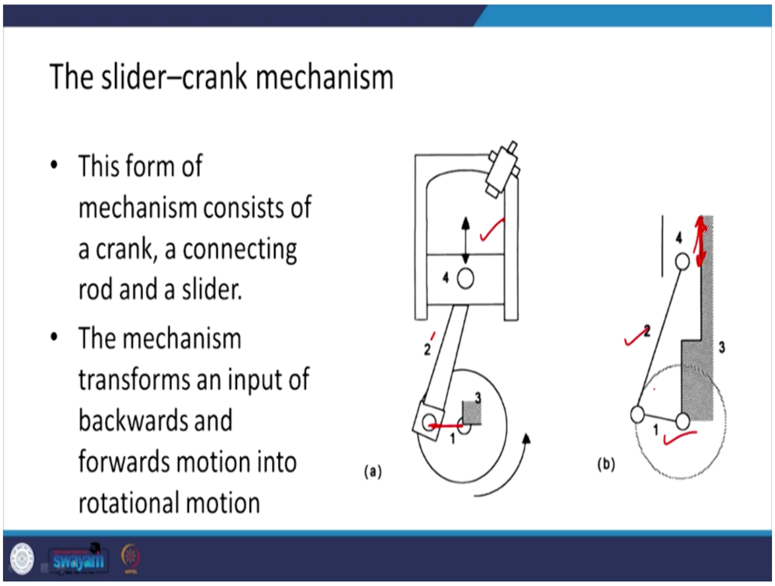


Now, let us look at the first one that is the four-bar chain. In a four-bar chain, there are four links; in case a link 1, 2, 3, and 4 and out of these a one link is fixed. So, in a four-bar chain if the sum of the length of the shortest link and the longest link is less than or equal to the sum of the length of the other two links, then one link will be capable of making a full revolution with respect to the first link.

And if this condition is not met then none of the links is capable of complete revolution and this criterion is what is called the Grashof criteria or Grashof condition. Now, here we can get the different types of motions by adjusting the length of the links fine. So, here we have the double lever mechanism where link 2 has got oscillatory motion and link 4 has also got the oscillatory motion.

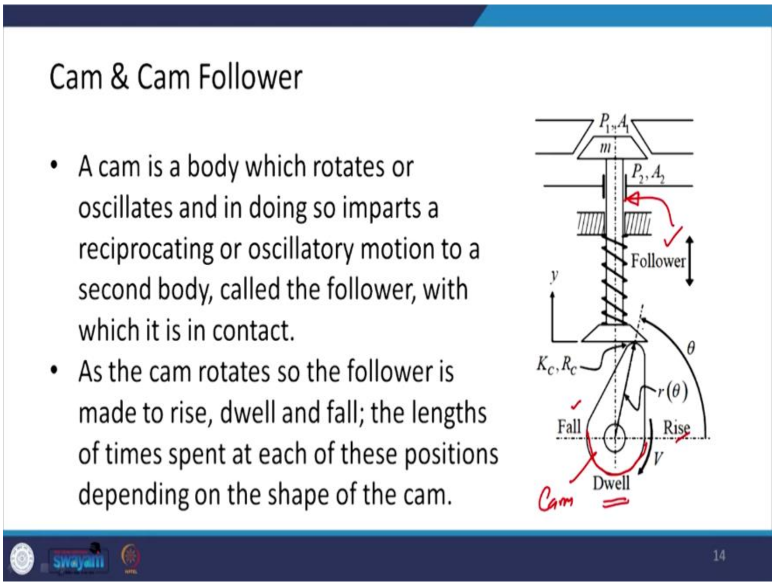
Then we have a lever crank mechanism where the 2 has not got complete rotation whereas, the 4 has got the complete rotation. Link 1 has got a 360-degree rotation we call it a crank and the one which has got not which is not having the 360-degree rotation that we call a lever. Then we have the double crank mechanism also where links 2 and 4 both are having 360-degree revolution possible.

(Refer Slide Time: 15:05)



Here is this picture is about the slider-crank mechanism the other mechanism which I talked about to you. This form of mechanism consists of a crank a connecting rod and a slider. This is the crank, this is the connecting rod and this one is the slider. So, you can see here this one is a slider. This is this forms the crank and 2 is your connecting rod. And the advantage of this mechanism is that it transforms an input of backward and forward motion over here into a rotary motion. So, this is where the slider-crank mechanism can be used.

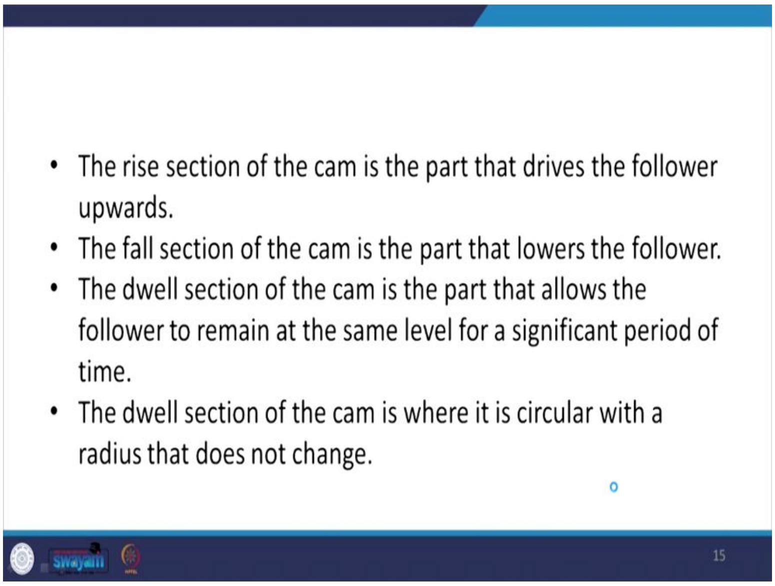
(Refer Slide Time: 15:49)



Then in a mechatronics system, we may require a certain type of motion to be transmitted. So, a cam and cam follower can be used for this purpose. A cam is a body that rotates or oscillates and in doing so, imparts a reciprocating or oscillatory motion to a second body which is called a follower. In this figure, you can see that this is cam and this is the follower. This part is the follower and here in this example there is a wall and by operation of the cam, this wall either opens or it this wall either closes. So, that is there. Now as the cam rotates, the follower is made to either rise, dwell or fall.

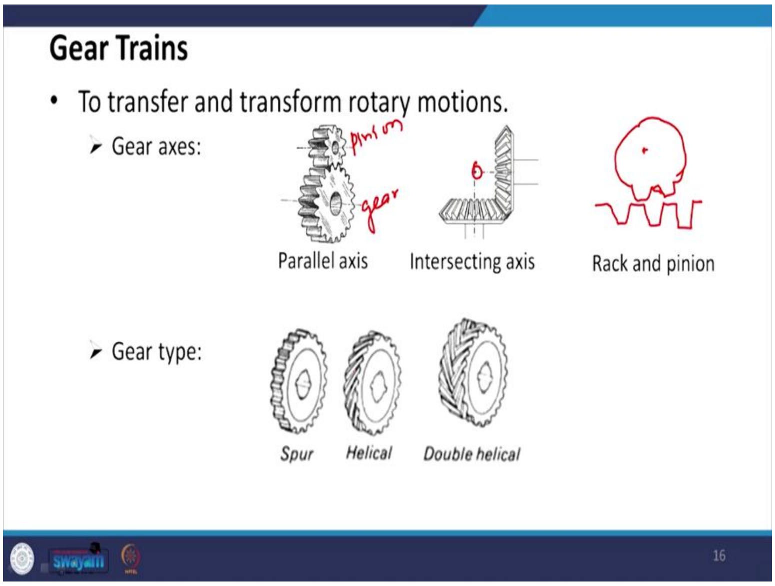
The length of time is spent at each of these positions depends on what shape your cam is having. For example, this portion will be responsible for fall whereas, this portion will be responsible for the rise and this portion will be responsible for the dwell type of motion of the follower.

(Refer Slide Time: 17:13)



The rise section of the cam is the part that drives the follower upward, the fall section of the cam is that part that lowers the follower and the dwell section of the cam is that part that allows the follower to remain at the same level for a significant period of time. That dwell section of the cam is where it is circular with a radius that does not change. So, as I showed you this is the dwell portion, and then we have risen and we have the fall over here.

(Refer Slide Time: 17:49)



Now, let us look at the gears. As I said the gears are used in a mechatronics system to reduce the high speed or to increase that torque. So, we get both effects with the help of gears. If we talk about mechatronic systems such as a robot we our torque requirements are very high, but the conventional motors which we are getting from the market those motors are high-speed motor motors.

So, the gears are used to reduce the speed and increase the torque. So, let us look at some fundamentals of the gears. They transfer and transform the rotary motion and based on the axes of the gear there could be a classification like parallel axis gear where the axes of the two gears are parallel.

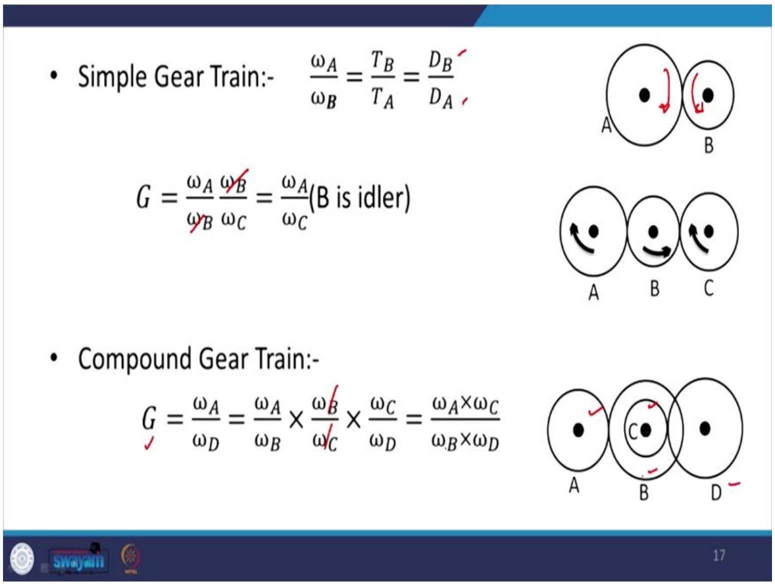
Here the smaller one we call pinion whereas, the bigger one is called as gear. So, this is pinion and this is called gear. Then we have the intersecting axis. If the axes are intersecting at this point, then this type of arrangement of the gear which is used for this purpose is called the bevel gear.

And similarly, we can have the rack and pinion type of arrangement. In the rack and pinion type of arrangement, there is a pinion, something like this with the teeth something like this and we have a gear which is the gear of infinite radius, which one we call the rack.

So, the arrangement is something like this then based on the gear type the classification is spur gear where the teeth of the gear are parallel to the axis of the shaft or there are helical gears where the teeth are inclined or there could be the double-helical gears alright, where there are two inclinations provided to the gear teeth so, that the axial thrust is not there.

So, that combination is what we call the double-helical gear whereas, in the case of helical gear because of the incline teeth in the gear we are going to have the thrust on the axis of the shaft.

(Refer Slide Time: 20:39)



Now, if we have a simple gear train the two gears here are gear A and gear B. We can define the angular velocity ratio,

$$\frac{\omega_A}{\omega_B} = \frac{T_A}{T_B} = \frac{D_A}{D_B}$$

that is the number of teeth in gear B divided by the number of teeth in gear A.

And this is the same as the ratio of the pitch circle diameter of gear B and divided by the pitch circle diameter of gear A.

Now, if we have 3 such gears alright if we have 3 such gears gear A, B, and C and if I find out the gear ratio. So, this will be,

$$G = \frac{\omega_A}{\omega_B}\frac{\omega_B}{\omega_C} = \frac{\omega_A}{\omega_C}$$

or this is what we can that ω_B gets canceled we get ω_A by ω_C.

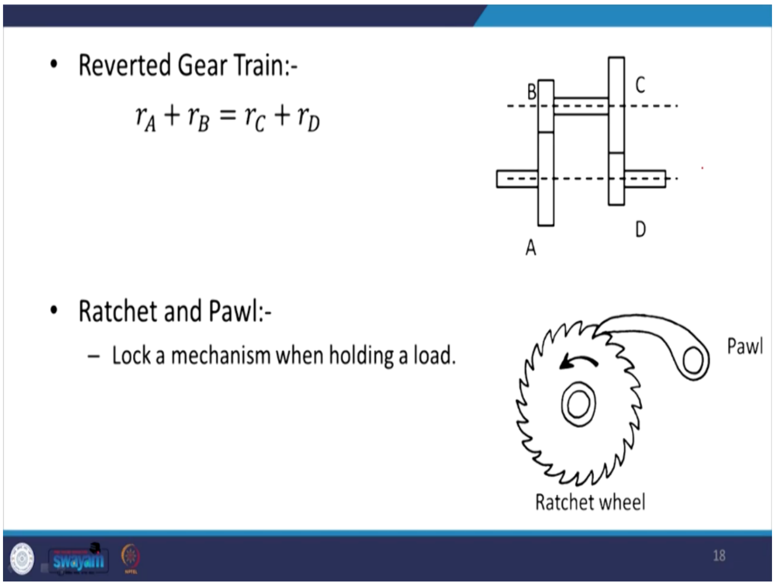
So, here we can see that B is the idler. So, B has got only a role to change the direction. So, here we can see that gear A and gear B; gear A is moving in a clockwise direction whereas, gear B is moving in the counterclockwise direction. But, if we have an arrangement of idlers then we can see that gear A and gear C can be made to move in the same direction.

Now, we may have a combination of gear what we call the compound gear train. Here an example is given. So, here gear A rises gear B, and on the same axis as gear B that is rather on the same shaft you have a gear C and the gear C drives the gear D. So, in this case, gear ratio,

$$G = \frac{\omega_A}{\omega_D} = \frac{\omega_A}{\omega_B} \times \frac{\omega_B}{\omega_C} \times \frac{\omega_C}{\omega_D} = \frac{\omega_A \times \omega_C}{\omega_B \times \omega_D}$$

And so, this is ω_A by ω_B into ω_C by ω_D. Here this ω_B by ω_C gets canceled because they are put on the same shaft. So, this means that it is the product of the angular velocities of the drivers. So, ω_A and ω_C are the drivers here and ω_B divided by the product of angular velocities of the driven. So, here ω_B and ω_D are the driven. Then we have the reverted gear train. The reverted gear trains are the gear train where the input axis is same as that of the output axis.

(Refer Slide Time: 23:36)

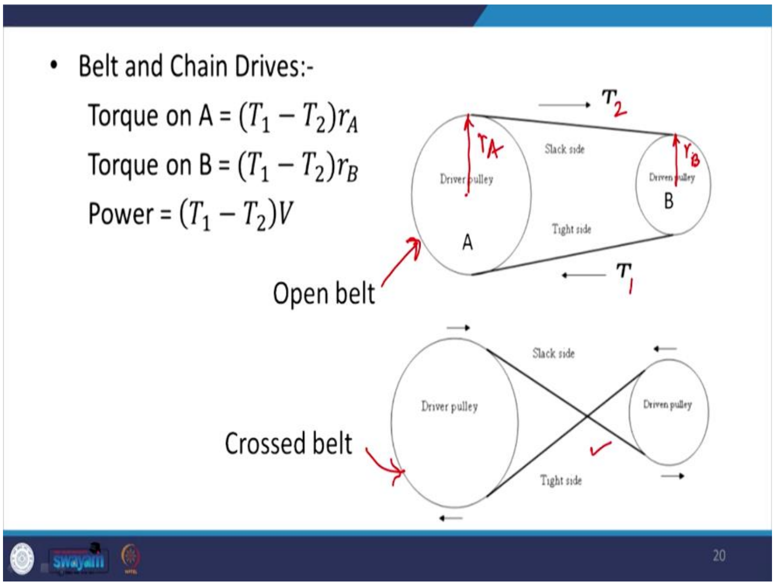


So, here this is the combination, and because of this condition what we can see here is that r_A plus r_B is the same as r_C plus r_D. Then there is Ratchet and Pawl type of mechanism is used in mechatronics system ah. It locks a mechanism when holding a load. So, here we can see that this can move in this direction, but it cannot move in the opposite direction.

(Refer Slide Time: 24:13)

And these are the commercially available gearbox. So, here this one is the spur gearhead. Here you can see that there is an offset in the axis which we usually see in the case of the spur gear head and this is another type of gearhead that I have not talked about the which is the planetary gearhead. When we require a very high gear reduction then we go for the planetary gearhead. When we require a very high reduction in the speed then we go for the planetary gearheads.

(Refer Slide Time: 24:59)



Then next are the belt and chain drives. So, belt and chain drives are used again to transmit power over longer distances; so, here we can see the belt drive there are, open belt configuration is shown and the crossed belt configuration is shown. Here is our open belt configuration this is the crossed belt configuration.

And here tension in the tight size is T_1 and in the slack side it is T_2 then,

$$\text{Torque on A} = (T_1 - T_2)r_A$$

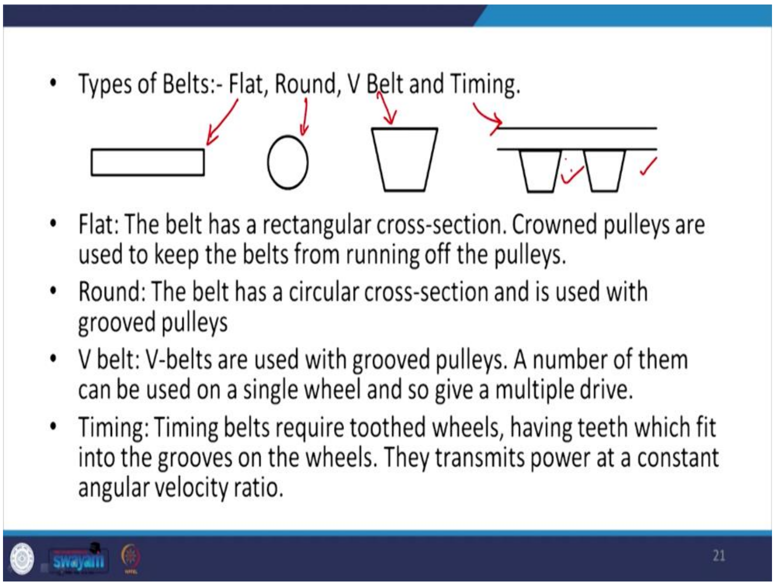
Similarly,

$$\text{Torque on B} = (T_1 - T_2)r_B$$

$$\text{Power } (T_1 - T_2)V$$

Chain drives are similar to the belt drive.

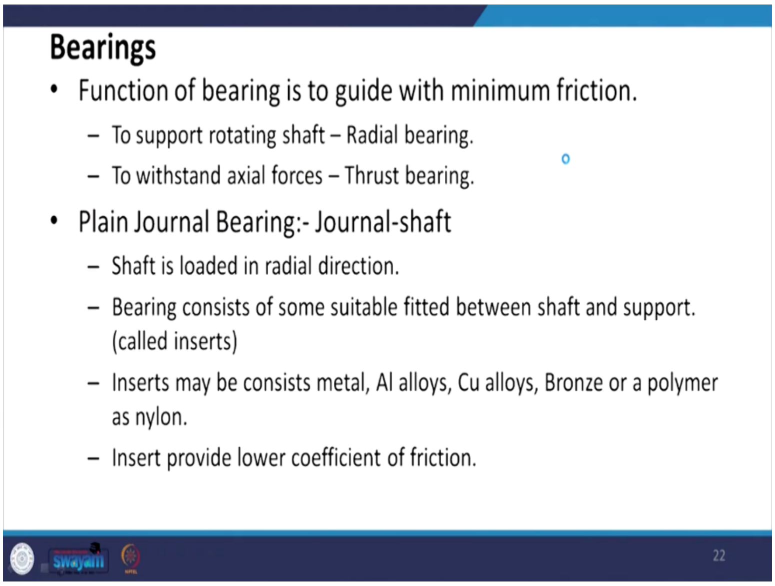
(Refer Slide Time: 26:04)



There are various type of belts. These are the flat type round of flat type then we have the round type belt V belt are there and then the timing belts are there. So, the flat type of belts these as you can see that they have got the rectangular cross-section and crowned pulleys are used to keep the belt from running off the pulley. So, there is a small projection which we call the crown and that crown holds the belt at the surface of the pulley. And then another type the round one the belt has a circular cross-section as we can see and it is used with the grooved pulley. So, the grooves are provided where the round belt is used.

Then similarly we have the V belts these are used again with the grooved pulleys. The beautiful thing about is that a number of them can be used on a single wheel and so, give multiple drives that can be done. And timing belts are required. They have the tooth's here as we can see. They require the tooth wheels to have teeth that fit into the grooves in these wheels and they transmit power at a constant angular velocity ratio. So, that is the beautiful thing about the timing belt. In the mechatronics system when we are using the actuators we need to support the actuators, loads, etc. So, we need to use the bearing. So, the function of the bearing is to guide with the minimum friction alright.

(Refer Slide Time: 27:53)

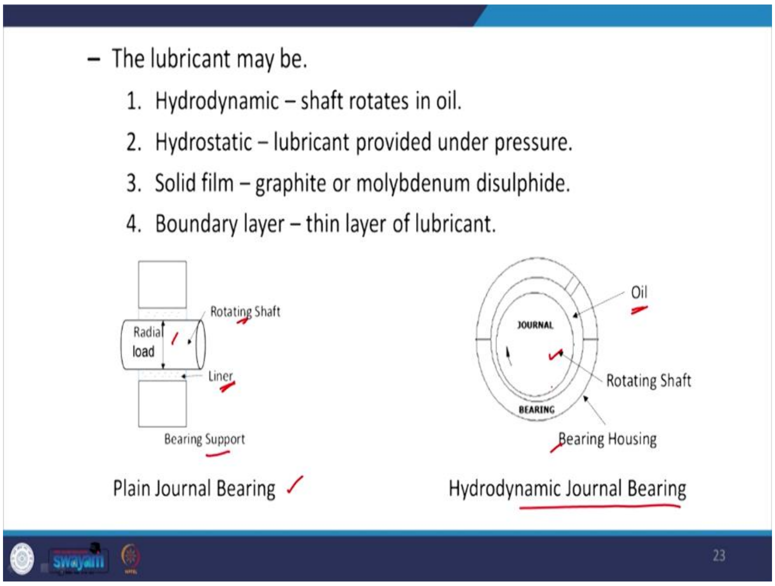


So, to support the rotating shaft we reuse the radial bearing and if we have to withstand or support the axial forces then we have to use the thrust bearing.

The plain journal bearing, let us look at the first one this one. Journal means the shaft which we call the journal in the bearing terminology.

The shaft is loaded in the radial direction in the case of the plain journal bearing and the bearing consists of some suitable fitted between the shaft and the support. This fitting we call the insert and these inserts could be metals or aluminum alloy or copper alloy a bronze or polymer such as nylon and these inserts provide a lower coefficient of friction. So, the lesser amount of (Refer Time: 28:48) loss.

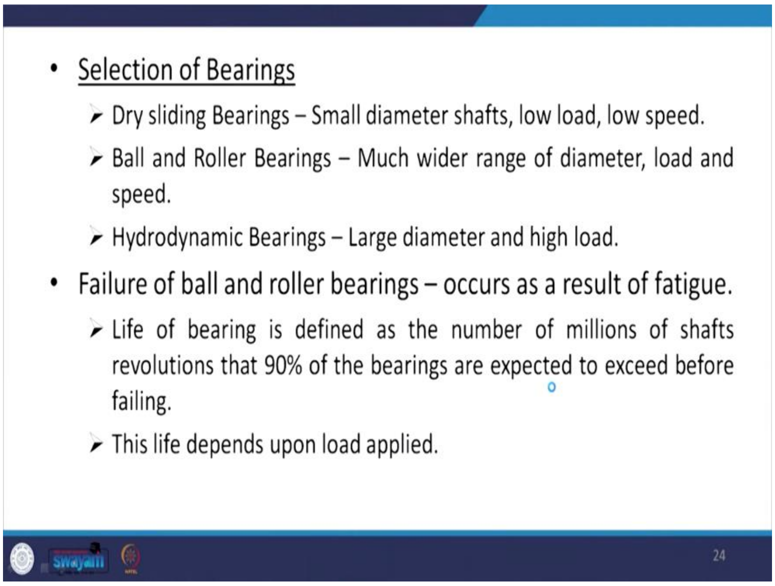
(Refer Slide Time: 28:49)



The lubricant may be either hydrodynamic. The shaft rotate in oil in that in that case or it could be hydrostatic where the lubricant is provided under pressure or it could be a solid film where a graphite or molybdenum disulfide is used or it could be a boundary layer that is a very thin layer of the lubrication could be used.

So, here are the plain journal bearings. This is the liner which I was talking to you about. We have the radial load here and there is a rotating shaft and this bearing supports the shaft. Here is the example of hydrodynamic journal bearing, where we have the bearing housing and on this, the rotating shaft is supported and there is oil which is put in between the bearing and the journal.

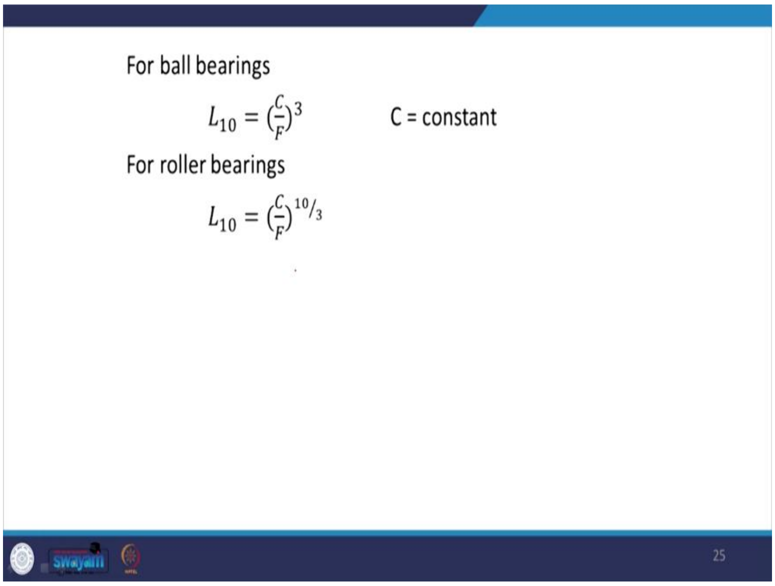
(Refer Slide Time: 29:59)



Now, the selection of bearing has to be done. In the dry sliding bearing the as the name indicates they are dry. They could be used for the small diameter shaft, low load, low speed, and ball roll or roller bearings that have a much wider range of diameter load and speed combinations.

Similarly, hydrodynamic bearings are to be used if you have a large diameter and a high load is there. Now, failure of the ball and roller bearings occurs as a result of fatigue. And we define the life of bearing as the number of millions of shaft millions of shaft revolutions that 90% of the bearing are expected to exceed before the failure occurs. And this life depends upon the load applied.

(Refer Slide Time: 30:40)



So, this life called Elton life can be calculated for ball bearing,

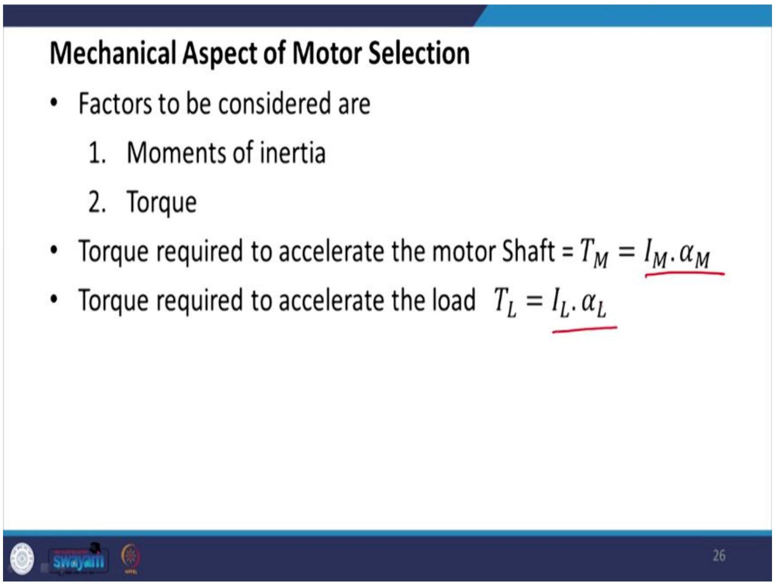
$$L_{10} = (\frac{C}{F})^3$$

where C is a constant and F is a load. And for roller bearing,

this is defined as

$$L_{10} = (\frac{C}{F})^{\frac{10}{3}}$$

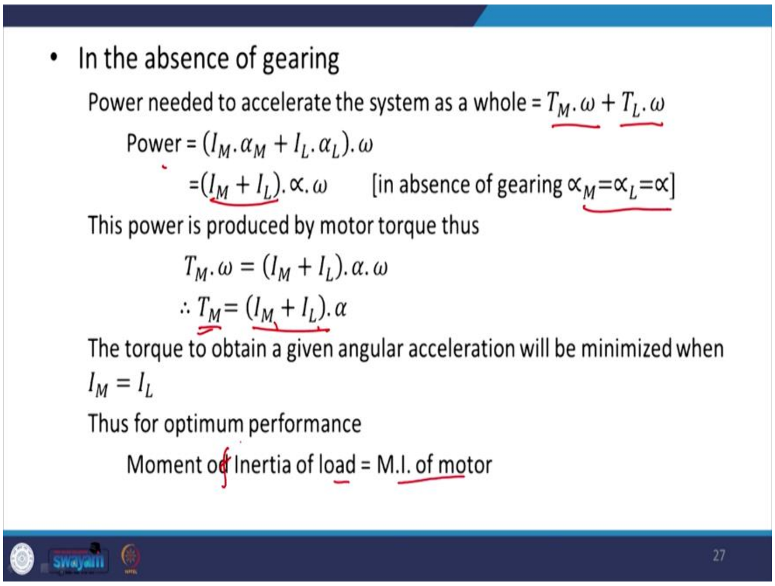
(Refer Slide Time: 30:58)



Then let us look at the mechanical aspect of motor selection. Now, when we are selecting the motor we need to consider the moment of inertia of not only the motor as well as that motor rotor as well as that of the load as well as the torques, torque requirements.

So, the torque required to accelerate the motor shaft is a moment of inertia of the motor into the acceleration of the motor. And the torque required to accelerate the load is the moment of inertia of the load into the acceleration of the load.

(Refer Slide Time: 31:41)



So, if I am not using any gearing then the power needed to accelerate the system as a whole is $T_M\omega$ for the motor and $T_L\omega$ for the load. So, the total power will be,

$$P = T_M\omega + T_L\omega$$

$$P = (I_M.\propto_M + I_L.\propto_L)\omega$$

So, in absence of gearing the motor and load acceleration both are same.

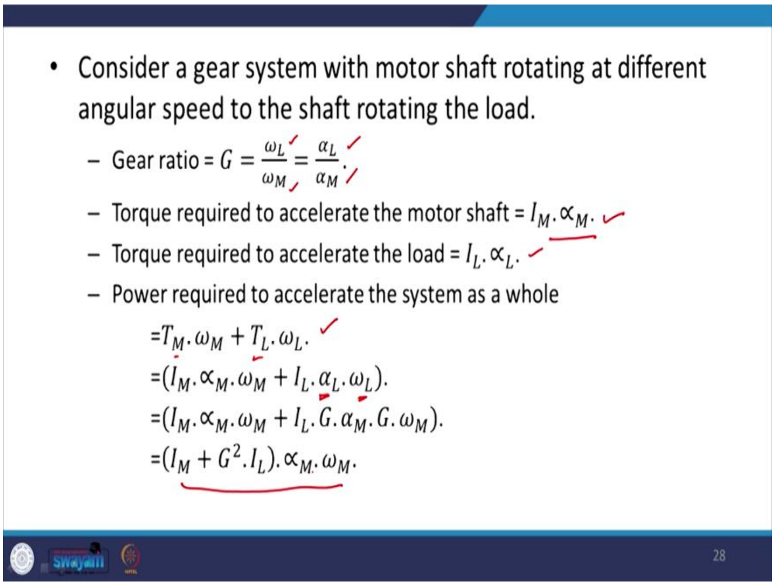
$$P = (I_M + I_L) \propto \omega$$

So, my motor torque requirement is that;

$$T_M\omega = (I_M + I_L) \propto \omega$$

It has to accelerate the inertia of the motor as well as that of the load. And for the optimum performance moment of inertia of the load has to be same as the moment of inertia of the motor (($I_M = I_L$).

(Refer Slide Time: 32:20)

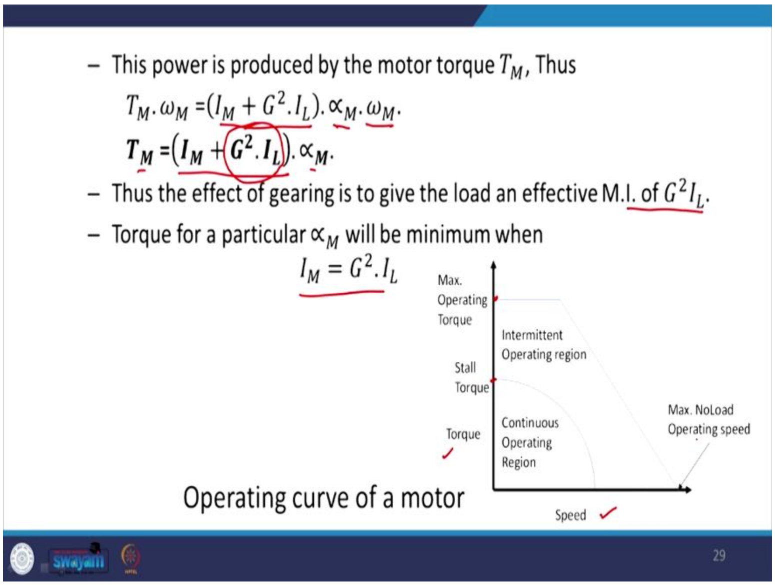


Now, consider a gear system with motor shaft rotating at different angular speed to the shaft rotating the load that is the shaft and load. There is gearing in between the motor shaft and the load. So, we can define the gear ratio,

$$G = \frac{\omega_L}{\omega_M} = \frac{\propto_L}{\propto_M}$$

So, the torque required to accelerate the motor shaft same as we have seen. Similarly, the torque required to accelerate the load same I $\propto$ as we have seen. So, the power required to accelerate the system as a whole is the summation of that. Now, I can substitute here for T_M and T_L, I can substitute over here and then here I substitute for $\propto_L$ and ω_L. So, I get this expression and this is represented in terms of the motor parameters.

(Refer Slide Time: 33:21)



So, power produced by motor is this one.

$$T_M \omega_M = (I_M + G^2.I_L) \propto_M \omega_M$$

So, thus the effect of getting is to give the load and effective moment of inertia $G^2.I_L$. So, this additional inertia will be coming to the motor side because of the gearing.

So, the talk for a particular $\propto_M$ will be minimum when I_M is $G^2.I_L$. And we can look at the operating curve of a motor here. So, there is a plot for speed versus torque. So, the continuous operating reason here we can see that there is a stall torque. So, for the continuous operation, we cannot go more than this and if there are intermediate operating reasons then we can go a little more.

So, we have the maximum operating torque if the intermediate operation is required, and as the speed increases the torque capacity of the motor decreases. So, that is what is clear from this graph and so, here is the maximum no-load operating speed. And you can refer for further reading the Mechatronics book by Bolton as well as you can refer our book on Mechatronics, fine.

Thank you.