ME 407 – MECHATRONICS

MODULE IV

- Mechatronics in Computer Numerical Control (CNC) machines: Design of modern CNC machines.
- Mechatronics elements - Machine structure: guide ways, drives. Bearings: anti-friction bearings, hydrostatic bearing and hydrodynamic bearing. Re-circulating ball screws, pre-loading methods. Re-circulating roller screws.
- Typical elements of open and closed loop control systems. Adaptive controllers for machine tools.
- Programmable Logic Controllers (PLC) –Basic structure, input/ output processing.
- Programming: Timers, Internal Relays, Counters and Shift registers. Development of simple ladder programs for specific purposes.

MECHATRONICS IN COMPUTER NUMERICAL CONTROL MACHINES

- CNC machine is the best and basic example of application of Mechatronics in manufacturing automation.
- Efficient operation of conventional machine tools such as Lathes, milling machines, drilling machine is dependent on operator skill and training. Also a lot of time is consumed in work piece setting, tool setting and controlling the process parameters viz. feed, speed, depth of cut. Thus conventional machining is slow and expensive to meet the challenges of frequently changing product/part shape and size.
- Computer numerical control (CNC) machines are now widely used in small to large scale industries.
- CNC machine tools are integral part of Computer Aided Manufacturing (CAM) or Computer Integrated Manufacturing (CIM) system.
- CNC means operating a machine tool by a series of coded instructions consisting of numbers, letters of the alphabets, and symbols which the machine control unit (MCU) can understand. These instructions are converted into electrical pulses of current which the machine's motors and controls follow to carry out machining operations on a workpiece.
- CNC automatically guides the axial movements of machine tools with the help of computers.
- Manual operation of table and spindle movements is automated by using a CNC controllers and servo motors. The spindle speed and work feed can precisely be controlled and maintained at programmed level by the controller.
- Modern machine tools are now equipped with friction-less drives such as re-circulating ball screw drives, Linear motors etc.
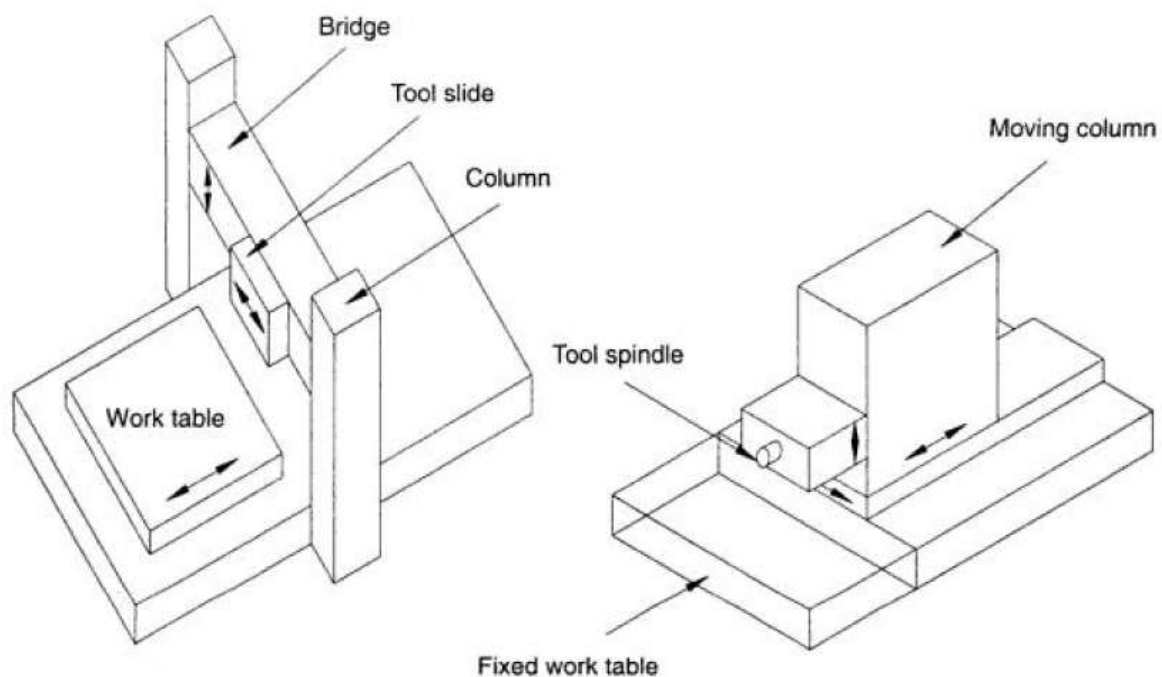
MACHINE STRUCTURE

- The machine structure is the load carrying and supporting member of the machine tool.
- All motors, drive mechanisms and other functional assemblies of the machine tools are aligned to each other and rigidly fixed to the machine structure.

- The machine structure is subjected to static and dynamic forces and it should not deform or vibrate beyond the permissible limits under the action of these forces.
- All components of the machine must remain in correct relative positions to maintain the geometric accuracy, regardless of the magnitude and direction of these forces.
- The machine structure configuration is also influenced by the considerations of manufacture, assembly and operation.

Static Load:

- It results from the weights of slides and the workpiece, and the forces due to cutting.
- The structure should have adequate stiffness and a proper structural configuration to keep the deformation under static loading within the permissible limits.
- Generally there are two basic configurations of machine tools as shown in figure 4.1

Fig 4.1 Commonly Used Configurations of Machine Tools

Dynamic Load:

- It is a term used for the constantly changing forces acting on the structure while movement is taking place. These forces cause the machine system to vibrate.
- The origin of such vibration is;
  - Unbalanced rotating parts
  - Improper meshing of gears
  - Bearing irregularities
  - Interrupted cuts while machining
  - The effect of these vibrations can be reduced by;
  - Reducing the mass of the structure
  - Increasing the stiffness of the structure
  - Improving the damping properties

Thermal Load:

- Some of the local heat sources which set up thermal gradient in machine tools are;
  - Electric motor
  - Friction in mechanical drives and gear boxes
  - Friction in bearings and guideways
  - Machining process
  - Temperature of surrounding objects
- These heat sources may cause localised deformation, resulting in considerable inaccuracies in machine performance.
- The following steps are generally followed to reduce thermal deformation;
  - External mounting of drives, i.e. motors and gear boxes
  - Removing frictional heat from bearings and guideways by a proper lubricating system.
  - Efficient cooling and swarf removal system for the dissipation of heat generated from the machining process
  - Thermo – symmetric designing of the structure.
  - Reducing ambient temperature by installing air conditioning units.

GUIDEWAYS

- Guideways (slide ways) are linear bearings for translatory motion between two members of a machine tool such as carriage and bed in lathe.
- Guideways are used in machine tools to;
  - Control the direction or line of action of the carriage or the table on which a tool or a workpiece is held.
  - To absorb all the static and dynamic forces.
- The shape and size of the work produced depends on the accuracy of the movement and on the geometric and kinematic accuracy of the guideway.
- The geometric relationship of the slide (moving part) and the guideway (stationary part) to the machine base determines the geometric accuracy of the machine.
- Kinematic accuracy depends up on the straightness, flatness and parallelism errors in guideways.
- Factors considered while designing guideways;
  - Rigidity
  - Damping capability
  - Geometric and kinematic accuracy
  - Velocity of slide
  - Friction characteristics
  - Wear resistance
  - Provision for adjustment of play
  - Position in relation to work area
  - Protection against swarf and damage.
- Guideways are primarily of two types;
  - Friction guideways
 - Antifriction linear motion (LM) guideways

FRICTION GUIDEWAYS

- Friction guideways are most widely used because of their low manufacturing cost and good damping properties.
- These guideways operate under conditions of sliding friction and do not have a constant coefficient of friction.
- The coefficient of friction is very high when the movement commences and as the speed of the slide increases, it rapidly falls and beyond a certain critical velocity it remains almost constant.
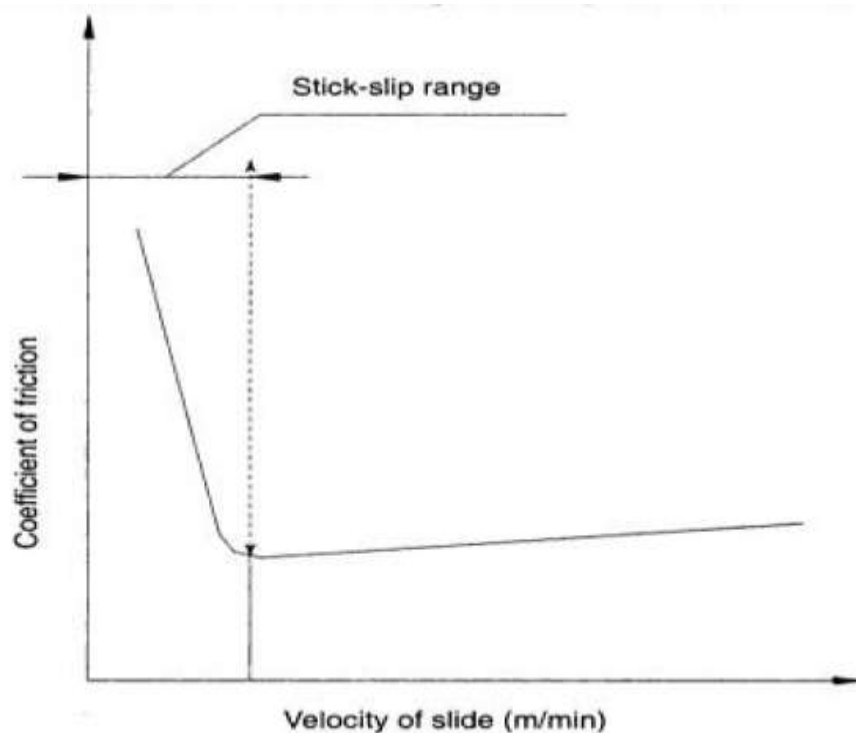
Fig 4.2 Coefficient of Friction vs Slide Velocity

- *Stick – slip phenomenon* – To start the movement, the force to overcome friction has to be correspondingly high. This force results in the drive mechanism, such as a screw, being elastically deformed. The energy thus stored in the screw, together with the applied force, causes the carriage to slip and move at a faster rate.
- As the speed increases the friction decreases and a greater amount of movement than that intended for the slide takes place. There is a possibility of this cycle of events repeating itself and resulting in errors in positioning and consequently in jerky motion. This phenomenon is known as stick – slip phenomenon.
- There should be a minimum but constant friction between the surfaces in contact to avoid this phenomeneon. It is achieved by using strips of materials such as Poly Tetra Fluoro Ethylene (PTFE) or Turcite lining at the guideway interface.
- Different types of friction guideways are;
  - Vee Guideways
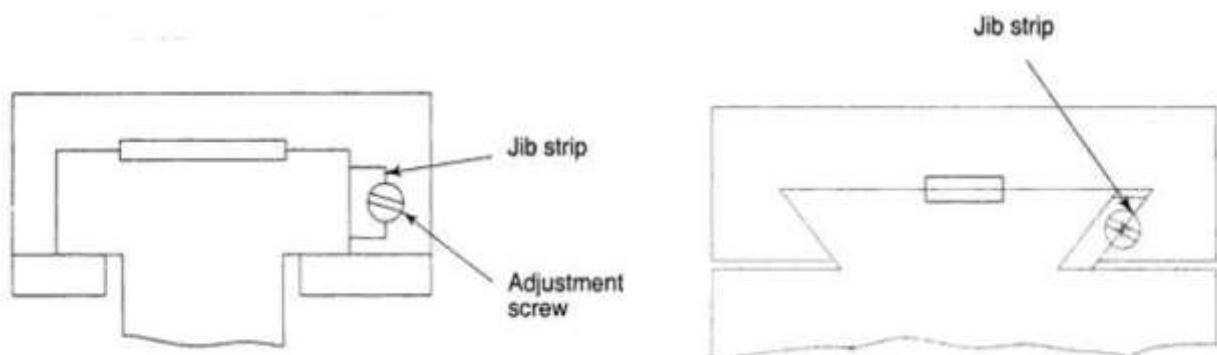 - Flat and Dovetail Guideways
  - Cylindrical Guideways

Vee Guideways
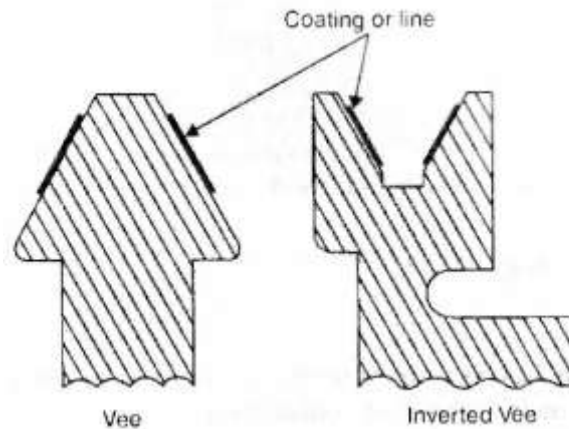
Fig 4.3 Vee Guideway

- The vee or inverted vee is widely used on machine tools, especially on lathe beds.
- One of the advantages of vee or inverted vee is that the parallel alignment of the guideway with the spindle axis is not affected by wear.
- There is a closing action as the upper member settles on the lower member, and this automatically maintains the alignment. Jibs are, therefore, not required with the vee guideway to take up the clearance caused by wear.
- On some machines, the angles of the vee are different so as to reduce the possibility of uneven wearing of vee sides.
- The majority of lathes have a combination of vee and flat guideways to prevent the carriage from lifting of the guideway.

Flat and Dovetail Guideways

Fig 4.4 Flat and Dovetail Guideway

- Flat or dovetail forms are commonly used in CNC machine tools. The flat guideways have better load – bearing capabilities than the other guideways.
- Jibs are used to ensure accurate fitting of the slide to both the flat and dovetail guideways. The jibs are tapered and can be adjusted to reduce excessive clearance caused by wear.
- The metal to metal contact on the vee, flat and dovetail types of guideway is normally cast iron to cast iron. The cast iron may be heat treated to increase its hardness and the surfaces ground to obtain the required accuracy.

Cylindrical Guideways

Cylindrical guidance
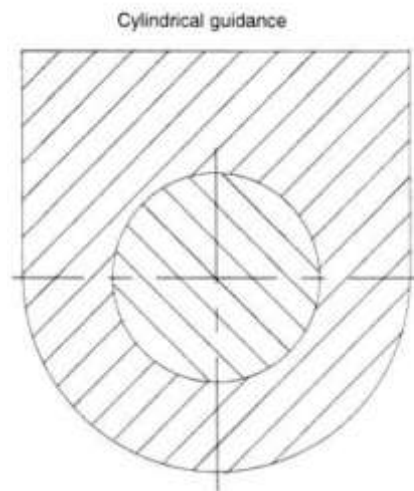
Fig 4.5 Cylindrical Guideway

- In cylindrical guideways, the bore in the carriage housing provides support all around the guideway.
- For relatively short traverse and light loads, cylindrical guideways are very efficient.
- A limitation on the use of these guideways for long traverse is that if the guide bar is supported only at each end, it may sag or bend in the centre of the span under a load.

ANTIFRICTION LINEAR MOTION (LM) GUIDEWAYS

- These are used on CNC machine tools to;
    - Reduce the amount of wear
    - Improve the smoothness of the movement
    - Reduce friction
    - Reduce heat generation
- Antifriction guideways are used to overcome the relatively high coefficient of friction in metal to metal contacts and the resulting limitations addressed in the above list.
- They use rolling elements in between the moving and stationary elements of the machine.

TYPES OF ANTIFRICTION GUIDEWAYS

- Linear bearing with balls.
- Linear bearing with rollers

Linear bearing with balls:
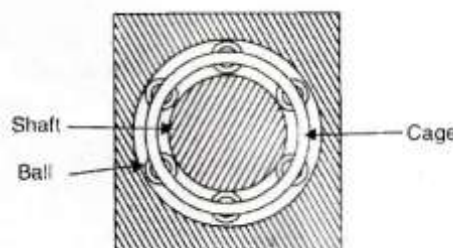
Shaft ——
Ball ——
—— Cage

Fig 4.6 Linear Bearing with Balls

- A linear ball bush uses recirculating balls within a bush type of bearing.
- These are designed to run along precision ground shafts and offer frictionless movement over varying strokes of length with high linear precision.

Linear bearing with rollers:
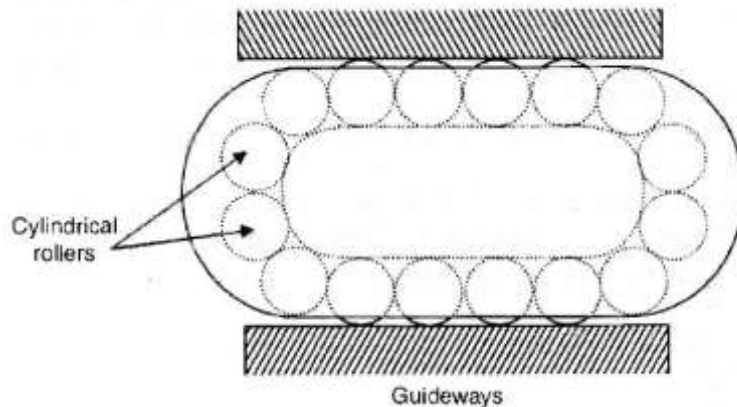
Fig 4.7 Linear Bearings with Rollers

- The recirculating linear roller bearings are used for movement along a flat plane.
- Their main characteristic feature is that there is continuous roller circulation which allows unlimited linear movement.
- It consists of hardened and precision ground supporting elements and a number of cylindrical rollers. As in the case of roller bearings, the rollers are guided between shoulders of the supporting elements with very close tolerances.
- The grinding element prevents the rollers from falling out and sliding against each other. Also the guiding element assists in smooth return of the rollers to the loading zone.
- The rollers are in constact with guideway machined on the bed of the machine. This arrangement provides smooth and easy movement but the machine bed has to be machined to an accurate form. Also the machine bed surfaces coming in contact with the rollers have to be hardened.
- These bearings can be mounted horizontally for load carrying applications such as machine tool table or they can be mounted vertically to provide support, guidance and motion for the vertical elements of the machine tool.

<u>**Advantages:**</u>

- Low frictional resistance
- No stick – slip
- Ease of assembly
- Commercially available in ready to fit condition
- High load carrying capacity
- Heavier preloading possibility high traverse speed

<u>**Disadvantages:**</u>

- Lower damping capacity

OTHER TYPES OF GUIDE WAYS

Hydrostatic Guideways

- The surface of the slide is separated from the guideway by a very thin film of fluid supplied at pressures as high as 300bar.
- Frictional wear and stick slip are entirely eliminated.
- A high degree of dynamic stiffness and damping is obtained with these guideways.
- Their application is limited due to high cost and difficulty in assembly.

Aerostatic Guideways

- The slide is raised on a cushion of compressed air which entirely separates the slide and the guideway surfaces.
- The major limitation is the lower stiffness, which limits their application to positioning only (Eg. Coordinate Measuring Machine)

DRIVES

- Basic function of a CNC machine is to provide automatic and precise motion control to its elements such work table, tool spindle etc. Drives are used to provide such kinds of controlled motion to the elements of a CNC machine tool.
- A drive system consists of drive motors and ball lead-screws.
- The control unit sends the amplified control signals to actuate drive motors which in turn rotate the ball lead-screws to position the machine table or cause rotation of the spindle.
- Drives used in an automated system or in CNC system are of different types such as electrical, hydraulic or pneumatic.

Electrical drives:

- These are direct current (DC) or alternating current (AC) servo motors. They are small in size and are easy to control.

Hydraulic drives:

- These drives have large power to size ratio and provide step less motion with great accuracy. But these are difficult to maintain and are bulky.
- Generally they employ petroleum based hydraulic oil which may have fire hazards at upper level of working temperatures.
- Also hydraulic elements need special treatment to protect them against corrosion.

Pneumatic drives:

- This drives use air as working medium which is available in abundant and is fire proof.
- They are simple in construction and are cheaper.
- However these drives generate low power, have less positioning accuracy and are noisy.

The various drives used in CNC machines can be classified as:

- Spindle drives to provide the main spindle power for cutting action
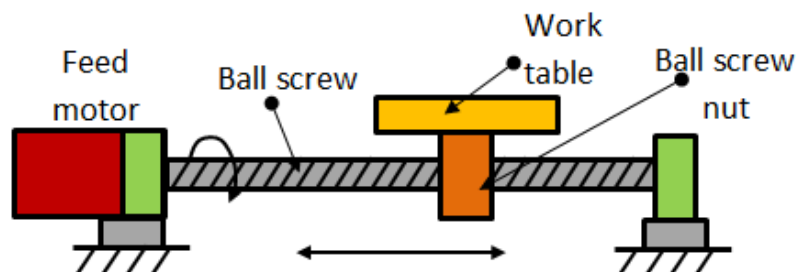- Feed drives to drive the axis

SPINDLE DRIVES
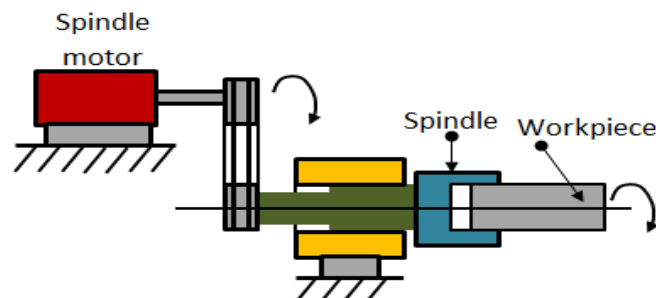
Fig 4.8 Schematic of Spindle Drive

- The spindle drives are used to provide angular motion to the workpiece or a cutting tool.
- These drives are essentially required to maintain the speed accurately within a power band which will enable machining of a variety of materials with variations in material hardness.
- The speed ranges can be from 10 to 20,000 rpm.
- The machine tools mostly employ DC spindle drives. But as of late, the AC drives are preferred to DC drives due to the advent of microprocessor-based AC frequency inverter.
- High overload capacity is also needed for unintended overloads on the spindle due to an inappropriate feed. It is desirous to have a compact drive with highly smooth operation.

FEED DRIVES

Fig 4.9 Schematic of Feed Drive

- These are used to drive the slide or a table.
- The requirements of an ideal feed drive are as follows.
  - The feed motor needs to operate with constant torque characteristics to overcome friction and working forces.
  - The drive speed should be extremely variable with a speed range of about 1: 20000, which means it should have a maximum speed of around 2000 rpm and at a minimum speed of 0.1 rpm.
  - The feed motor must run smoothly.
  - The drive should have extremely small positioning resolution.
  - Other requirements include high torque to weight ratio, low rotor inertia and quick response in case of contouring operation where several feed drives have to work simultaneously.

- Variable speed DC drives are used as feed drives in CNC machine tools. However now-a-days AC feed drives are being used.

ELECTRICAL DRIVES *(Refer Module V Notes)*
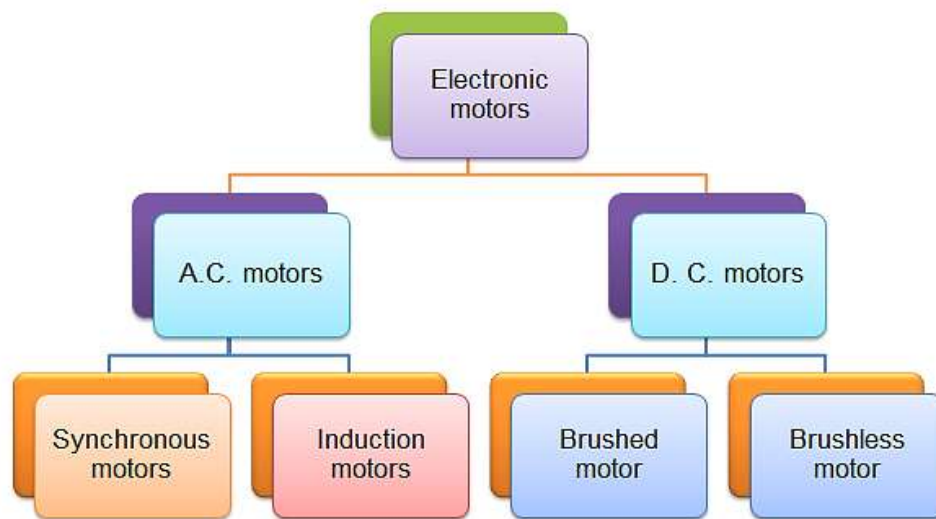
Fig 4.10 Classification of Electrical Drives

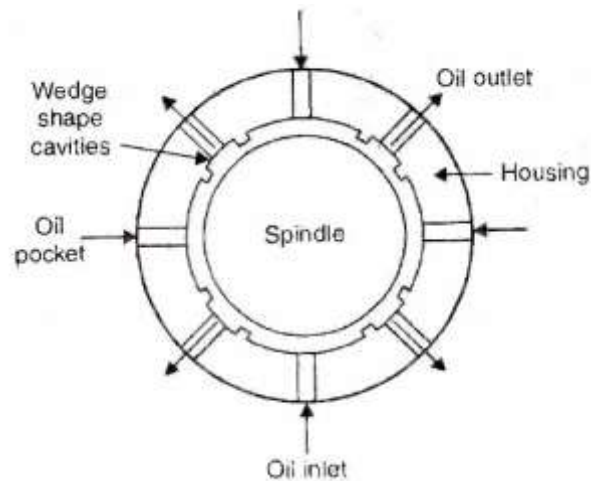## SPINDLE BEARINGS

- The rotational accuracy of the spindle is dependent on the quality and design of the bearings used and the preloading.
- The bearings should support the spindle radially and axially.
- The accuracy and the quality of the work produced depends directly on the geometrical accuracy, running accuracy and stiffness of the spindle assembly.
- Various types of spindle bearings used in the design of a spindle for machine tools are;
    - Hydrodynamic bearings
    - Hydrostatic bearings
    - Antifriction bearings

HYDRODYNAMIC BEARINGS

- Hydrodynamic bearings are journal bearings with a thin film of oil between the spindle and journal.
- These are used where the load carrying capacities are low and frequent starting and stopping of the spindle is not required.
- The essential features are;
    - Simplicity
    - Good damping properties
    - Good running accuracy.
- The pressure of the oil is created within the bearings by the rotation of the spindle. As the spindle rotates, the oil in contact with the spindle is carried into wedge shaped cavities

between the spindle and the bearing . the oil pressure is increased as the oil is forced through the small clearances between the bearing and the spindle.

Fig 4.11 Principle of Hydrodynamic bearing

- The main limitation of hydrodynamic bearing is that a definite clearance (50μm to 200μm) must be provided for the oil flim to be maintained between the spindle and the bearing. This clearance may result in the centre of a spindle in the bearing to change its position owing to variation in the applied force.

HYDROSTATIC BEARINGS
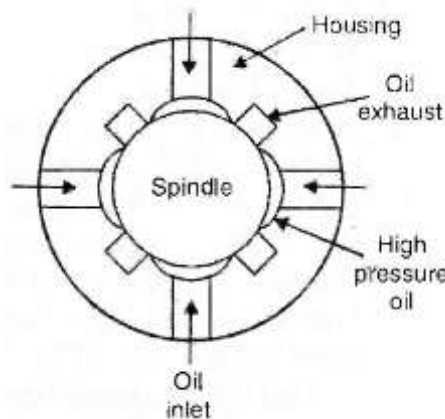
Fig 4.12 Principle of Hydrostatic Bearings

- The spindle is supported by a relatively thick film of oil supplied under pressure.
- The oil is pressurized by a pump external to the bearing.
- The load carrying capacity of this type of bearing is independent of the rotational speed.
- These are used only where temperature effects cause problems in the part accuracy as in the case of grinding machines and fine boring machines.
- They are very expensive.
- Advantages are;
  - High damping properties
  - High running accuracy
  - High wear resistance

ANTIFRICTION BEARINGS

- These are suitable for high speeds and high loads.
- For efficient service, it is essential that all the components of the ball and roller bearings, particularly the rolling elements, and the inner and outer bearing tracks are of the highest accuracy. An error in one component can affect the quality of the work produced.
- The selection of a particular type of bearing for the spindle depends on the requirements of the particular machines like speed of operation, accuracy of the spindle and stiffness of the spindle.
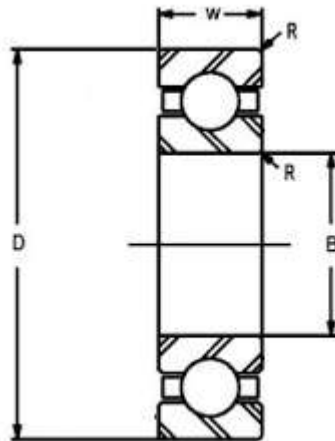
Fig 4.13 Deep Groove Ball Bearings

- Different types of ball and roller bearings used in CNC machines are;
  - Ball bearings
  - Deep groove ball bearings
  - Angular contact ball bearings
  - Roller bearings
  - Cylindrical roller bearings
  - Cylindrical roller bearings (double row) with taperd bore
  - Tapered roller bearings

Advantages:

- Low friction
- Moderate dimensions
- Lesser liability to suffer from wear or incorrect adjustment
- Ease of replacement
- High reliability.

RECIRCULATING ROLLER SCREWS

- They provide backlash free movement and their efficiency is of the same order as of ball screws.
- Generally two types of roller screws are used:
  - Planetary
  - Recirculating

- They will provide more accurate positional control.
- Roller screws are much costlier than the ball screws

PLANETARY ROLLER SCREW

- In planetary roller screw the rollers are threaded and gear teeth are cut on each end of the rollers. The gear teeth mesh with an internally toothed ring on the nut which drives the roller to provide a rolling motion between the nut and the screw.
- Rollers are equally spaced and positioned using spigots which engage themselves in the locating rings at each end of the nut.
- There is no axial movement of the rollers relative to the nut.
- They are capable of transmitting high loads at fast speeds.
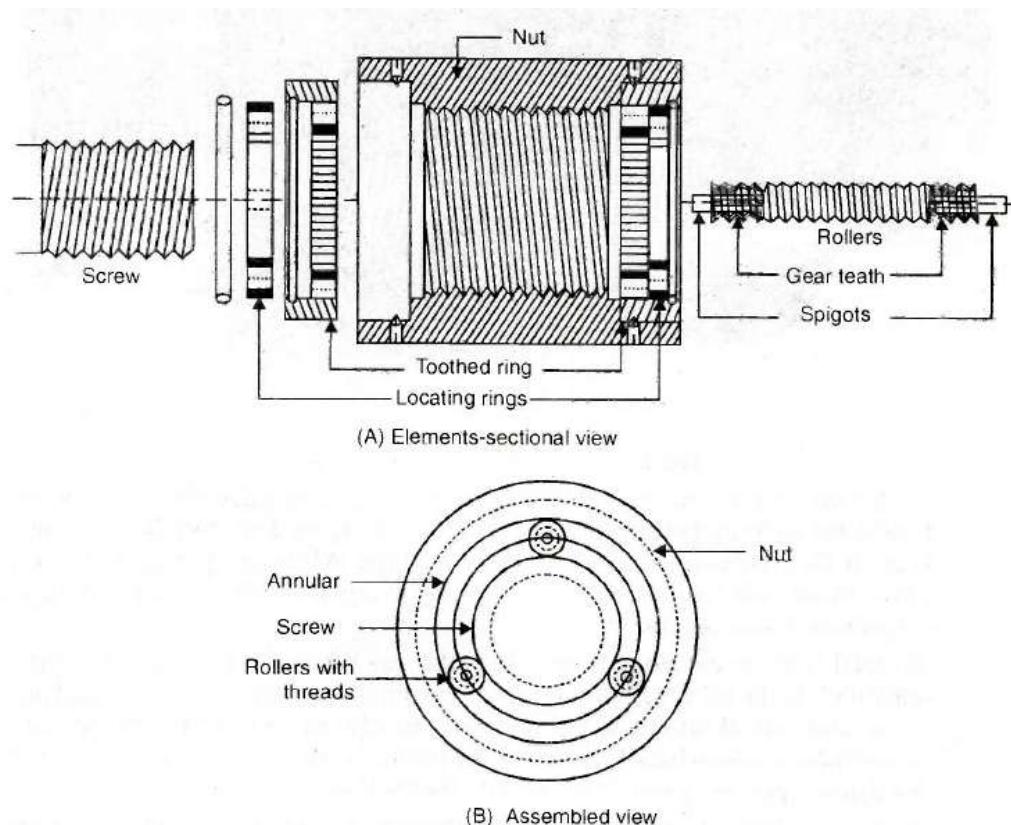
Fig 4.14 Planetary Roller Screw

RECIRCULATING ROLLER SCREW

- In recircuating type the rollers are not threaded but have circular grooves of thread form along their length. The rollers are equally spaced around the shaft and are kept in their circumferential position by a cage. The rollers move axially relative to the nut at a distance equal to the pitch of the screw for each rotation of the screw or nut.
- There is an axial recess cut along the inside of the nut. After one rotation of the drive screw, the rollers pass into this recess and disengage from the thread on the screw and the nut. While they are in the recess, the edge cam on a ring inside the nut causes them to move back to their starting positions. While one roller is disengaged, other rollers provide the driving power.

- They are slower in operation than the planetary type, but are capable of taking high loads with greater accuracy.
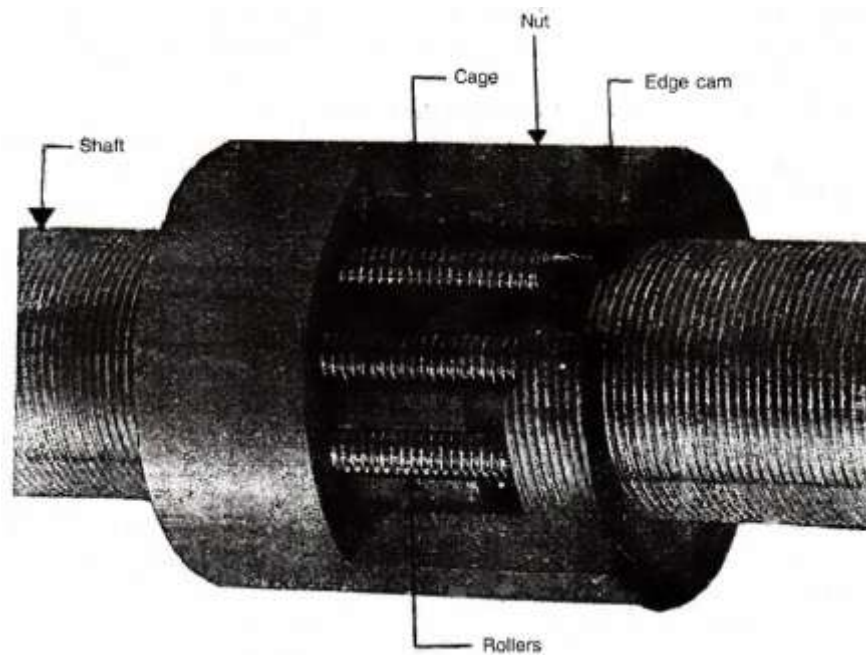

Fig 4.15 Recirculating Roller Screw

RECIRCULATING BALL SCREWS

- In ball screws, the sliding friction encountered in conventional screws and nuts is replaced by rolling friction in a manner analogous to the replacement of simple journal bearings by ball bearings.
- Two types of thread forms are used on these screws. They are gothic arc and circular arc.
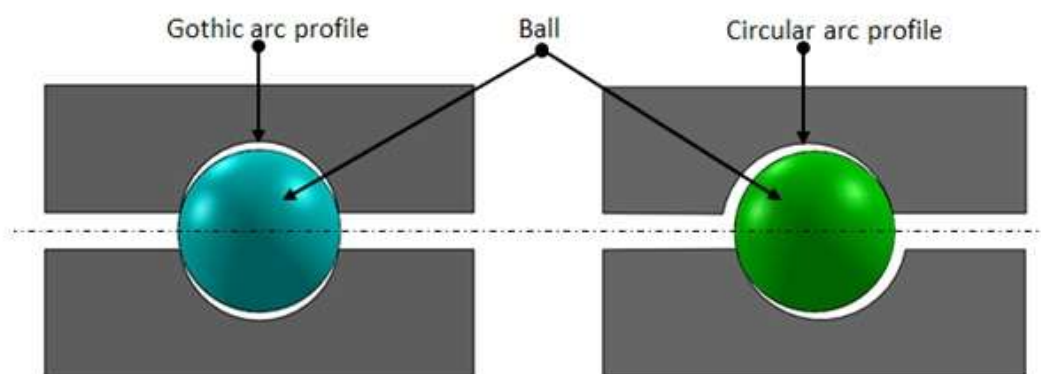
Fig 4.16 Thread Forms Used in Recirculating Ball Screws

- The efficiency of the recirculating ball screw is of the order of 90% and is obtained by the balls providing rolling motion between the screw and the nut.
- The mounting arrangement of ball screw depends on its required speed, length and size.
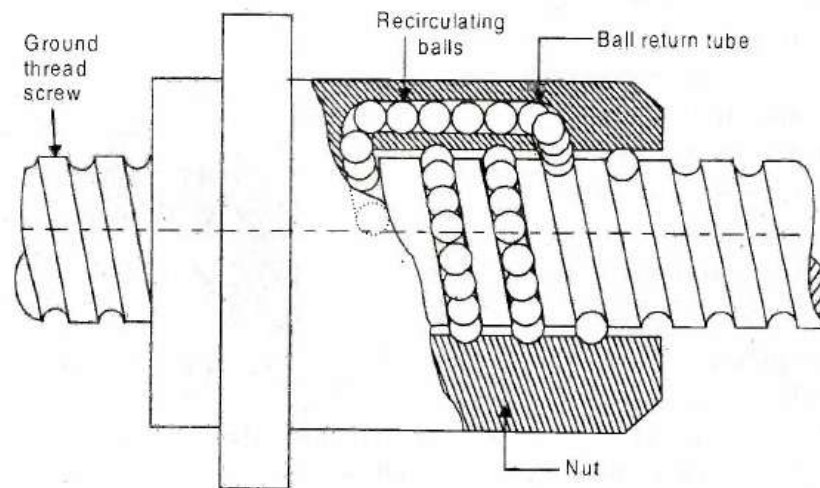
Fig 4.17 Recirculating Ball Screw

Recirculating arrangements:

- The balls rotate between the screw and the nut, and at some point are returned to the start of the thread in the nut. Two types of arrangements are there;
- **Recirculation through an external tube** – the balls at the end of the thread will be picked up by a return tube which recirculates the balls to the beginning of the load zone by providing continuous rolling motion
- **Recirculation through an insert channel** – the balls are returned to the start through a channel inside the nut.

<u>**Advantages:**</u>

- o Low frictional resistance
- o Low drive power requirement
- o Little temperature rise
- o Less wear and longer life
- o No stick – slip effect
- o High traverse speed
- o High efficiency

<u>**PRELOADING**</u>

- Pre loading is an axial or thrust load applied to a bearing that removes excess backlash.
- Preloading is the process of applying initial load to the nut which will cause elastic deformation of the screw threads in the axial direction, thereby increasing the axial rigidity of the ball screw nut.
- Preloading of ball screws may be classified as follows;
    - o Constant pressure preload ballscrews
        - ▪ Belleville spring
        - ▪ Coil spring
    - o Constant position preload ballscrews
        - ▪ Double nut type preload
            - • Tension preload type

- Compression preload type
  - Single nut type preload
    - Integral preload type
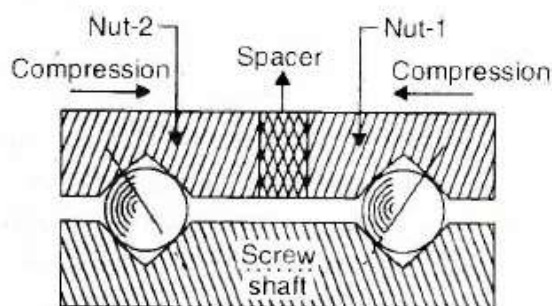   - Oversize ball preload type

Tension preload
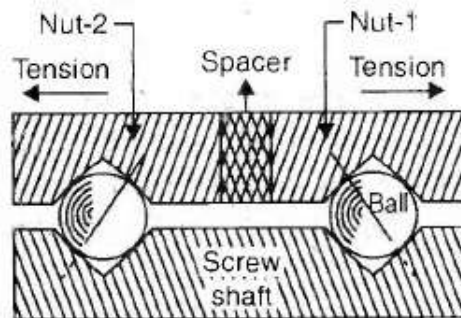
Fig 4.18 Tension Preload

- Tension preload provides the required amount of preload by the insertion of a spacer of specified width between the two nuts.
- Each nut exerts pressure on its perspective ball, thus forcing the balls away from each other.

Compression preload

Fig 4.19 Compression Preload

- In this case also the preload is achieved through the insertion of a spacer between the nuts but the pressure is applied in the opposite direction, squeezing them together and forcing the balls against threads of the screw shaft.
- The spacer thickness depends on the amount of preload

Oversize Preload

- For single nit ball screws, one type of preload is accomplished by using balls which are just slightly larger than the space provided between the nut and screw shaft.
- This method is best suited to provide comparatively light preload to the extent of eliminating axial clearance.
- In oversize ball preload, the balls have 4 point contact, thereby increasing the operational efficiency.
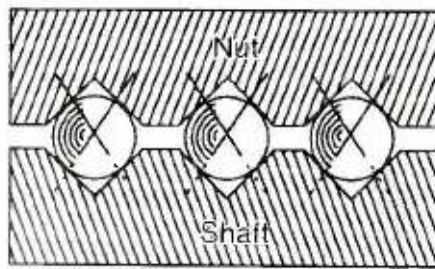
Fig 4.20 Oversize Preload
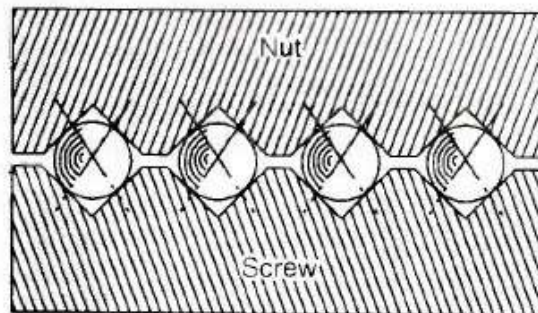
Integral Preload

Fig 4.21 Integral Preload

- The integral preload ball screws, in outward appearance, appear the same as single nut oversize ball or non – preloaded ball screws, however there is a dimensional allowance in the nut internal rotating element which provides the proper amount of preload.
- The nut dimensions can be made shorter compared with the double nut type.
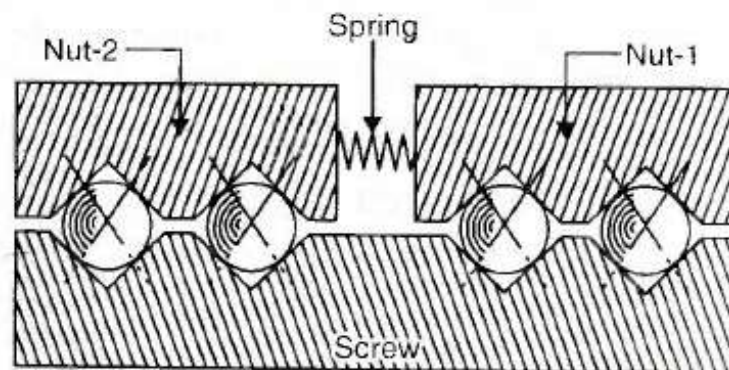
Constant pressure preload

Fig 4.22 Constant Pressure Preload

- In this method of preloading a coil spring or Belleville spring is inserted between the two nuts to provide a constant pressure preload.
- Overloading should be avoided otherwise the balls may get jammed resulting in stoppage of the motion
- By this method transmission efficiency as high as 90% can be achieved.

CONTROL SYSTEMS

- A control system is an arrangement of physical components connected or related in such a manner as to command, direct or regulate itself or another system.

Elements of a control system:

The elements of a control system are enumerated and defined below:

- *Controlled Variable* – The quantity or condition of the controlled system which can be directly measured and controlled is called controlled variable.
- *Indirectly controlled variable* – The quantity or condition related to controlled variable, but cannot be measured directly is called indirectly controlled variable.
- *Command* – The input which can be independently varied is called command.
- *Reference input* – A standard signal used for comparison in the close – loop system.
- *Actuating signal* – The difference between the feedback signal and reference signal is called actuating signal.
- *Disturbance* – Any signal other than the reference which affects the system performance is called disturbance.
- *System error* – The difference between the actual value and ideal value is called system error.

CLASSIFICATION OF CONTROL SYSTEMS

Control systems are classified into the following two basic types :

- Open-loop control systems (Unmonitored or non-feedback control systems)
- Closed-loop control systems (Monitored or feedback control systems)

OPEN-LOOP CONTROL SYSTEMS (Non-feedback Systems)

- An Open-loop control system is one in which the control action is independent of the desired output. The actuating signal depends only on the input command and output has no control over it.
- The elements of an open-loop control system can usually be divided into the following two parts:
- Controller
- Controlled Process
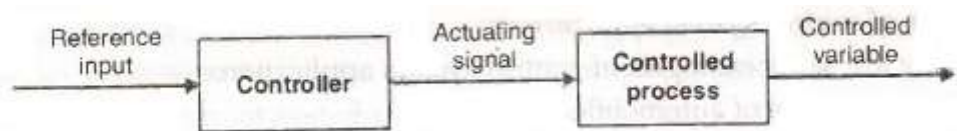
Fig 4.23 Elements of Open Loop Control System

- An input signal or command is applied to the controller, whose output acts as the actuating signal; the actuating signal then controls the controlled process so that the controlled variable will perform according to prescribed standards.

- In simple cases, the controller can be an amplifier, mechanical linkage, filter, or other control element, depending on the nature of the system. In more sophisticated cases, the controller can be a computer such as a microprocessor.

Advantages:

- Simple construction.
- Easy maintenance.
- Less costly than a closed-loop system.
- No stability problem
- Convenient when output is difficult to measure or measuring the output precisely is economically not feasible.

Disadvantages:

- Since the system is affected by internal and external disturbances, the output may differ from the desired value.
- For getting accurate results, this system needs frequent and careful calibrations.
- Any change in system component cannot be taken care of automatically.
- Presence of non-linearities causes malfunctioning.

CLOSED-LOOP CONTROL SYSTEMS (Feedback control systems)

- A closed-loop system is one in which control action is somehow dependent on the output.In this case the controlled output is fed back through a feedback element and compared with the reference input.
- Thus the actuating signal is the difference of desired output and reference input.
- Feedback is that property of a closed-loop system which permits the output or some other controlled variable of the system, to be compared with the input to the system, so that the appropriate control action may be formed as some function of the output and input.
- A feedback is said to exist in system when a closed sequence of cause and effect relations exists between system vaariables.
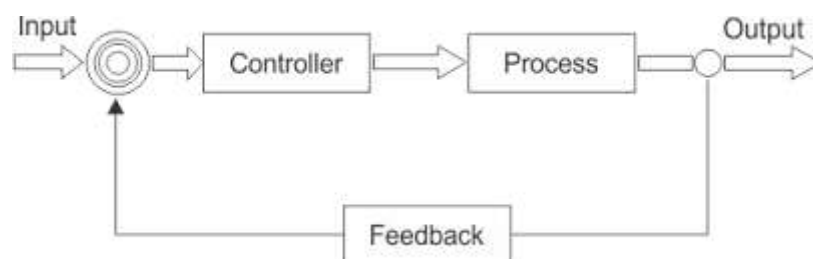

Fig 4.24 Elements of Closed Loop Control System

- . The Characteristics of feedback are as follows:
  - Increased bandwidth
  - Increased accuracy.
  - Tendency towards oscillation or instability.
  - Reduced effects or non-linearities and distortion.
  - Reduced sensitivity of the ratio of output to input to variations in system characteristics

FEEDBACK DEVICES

- Position feedback devices are used to measure the displacement of position of slide or table and send signals to the comparator to correct the position.
- Different types of position feedback devices are;
  - Linear transducers
    - Ferranti System (Moire Fringe Digitizer)
    - Inductosyn
  - Rotary transducers
    - Rotary encoder
      - Absolute encoder
      - Incremental encoder
      - Gray coded encoder
    - Resolver

FERRANTI SYSTEM
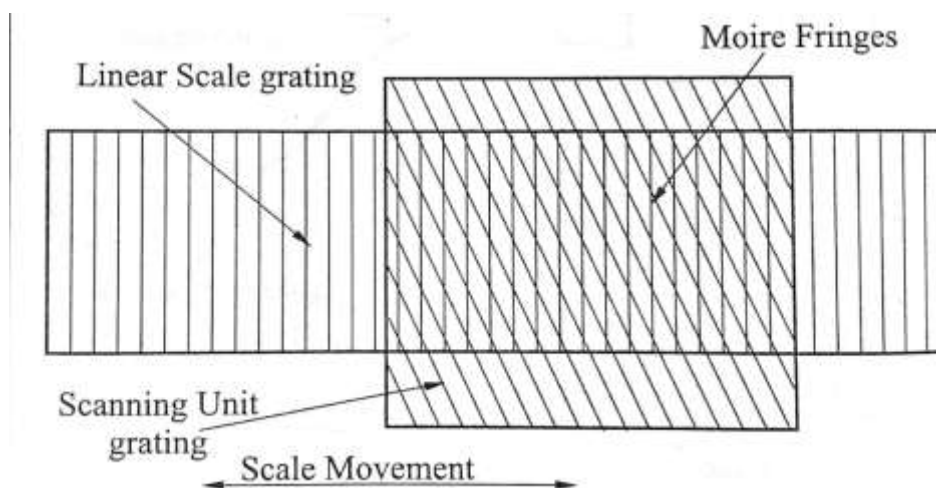
Fig 4.25 Ferranti System

- A similar device as incremental encoder, but in operation principle its slightly different.
- It makes use of Moire fringe detection in order to permit easier detection of position.
- In linear transducer, the optical gratings are used. When the two grating overlap each other, a 'Moire fringe' pattern is formed depending on the displacement.
- The moire fringe pattern is formed when the linear grating is slightly tilted with respect to scanner unit grating.
- The actual distance moved by the fringe pattern can be calculated since it depends on the grating spacing, the angle of grating and the distance moved.
- Scale grating is available for both linear and rotary forms.

INDUCTOSYN

- The principle of operation is similar to a resolver with very large number of stator poles rather than 2 and with only one rotor.
- The linear system has two parts namely scale and slider. The scale is similar to stator and the slider is similar to rotor winding.

- They have coils in the form of hair pin turns etched on to glass, steel or aluminium plates. The coils are bonded to the scale over an insulating layer. The slider is sliding over the scale.
- When two different voltages are applied with these two sliding coils, a corresponding emf is induced. This emf is directly proportional to the position of the slider with respect to scale.
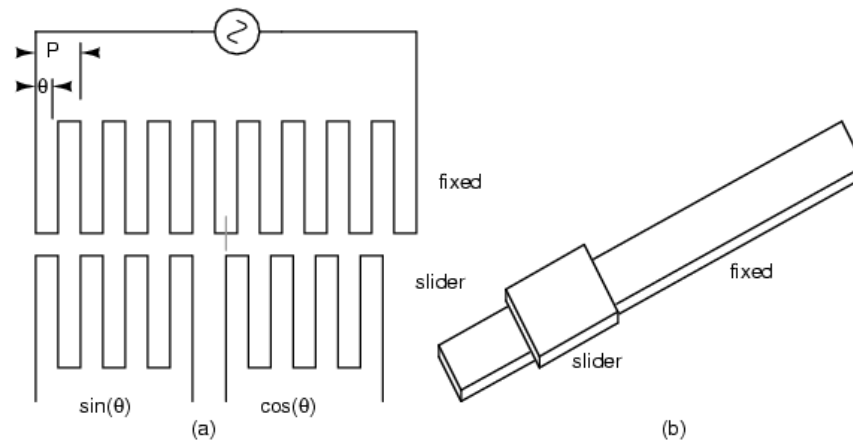

Fig 4.26 Inductosyn

ADAPTIVE CONTROLLERS (AC) FOR MACHINE TOOLS

- Adaptive control system is a logical extension of the CNC- mechanism.
- In CNC mechanism the cutting speed and feed rates are prescribed by the part programmer. The determination of these operating parameters depends on the Knowledge and experience of programmer regarding the work piece, tool materials, coolant conditions and other factors.
- By contrast in adaptive control machining, there is improvement in the production rate and reduction in the machining cost as a result of calculating and setting of optimal parameters during machining.
- Adaptive control (AC) machining originated out of research in early 1970's sponsored by U.S Air Force.
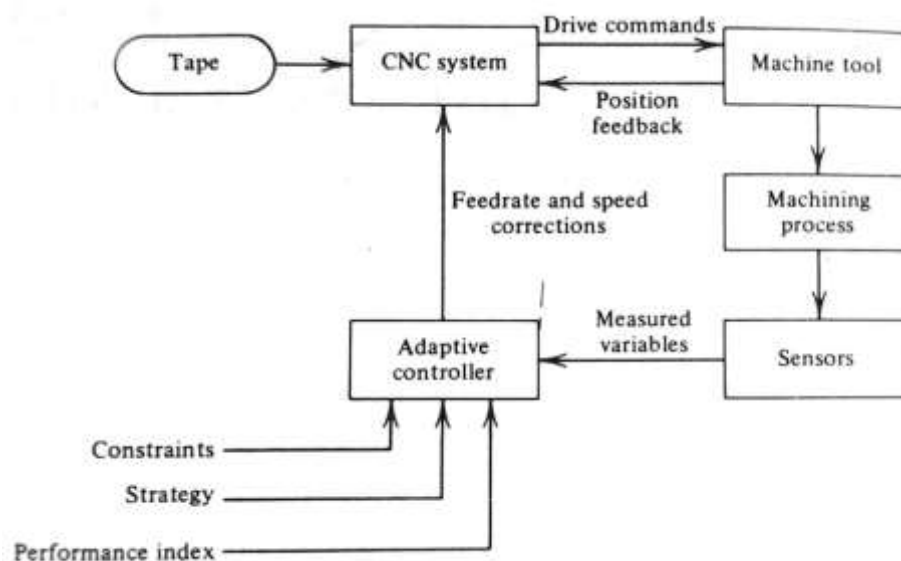

Fig 4.27 Adaptive Control for Machine Tools

- For a machining operation the term AC denotes control systems that measures certain output variables and uses to control speed or feed. Some of the process variables that have been used in AC machining systems include spindle deflection or force, torque, cutting temperature and horse power.
- The adaptive control is basically a feedback system that treats the CNC as an internal unit and in which the machining variables automatically adapt themselves to the actual conditions of the machining process.
- ***IP (Performance Index) -*** is usually an economic function such as max production rate or minimum machining cost.
- Adaptive control is not suitable for every machining situation. In general, the following characteristics can be used to identify situations where adaptive control can be beneficially applied.
    - The in-process time consumes a significant portion of the machining cycle time.
    - There are significant sources of variability in the job for which AC can compensate.
    - The cost of operating the machine tool is high.
    - The typical jobs involve steels, titanium and high strength alloys.

FUNCTIONS OF ADAPTIVE CONTROL

- The three functions of adaptive control are:
    - Identification function
    - Decision function
    - Modification function
- The main idea of AC is the improvement of the cutting process by automatic on line determination of speed and/or cutting.
- The AC is basically a feedback system in which cutting speed and feed automatically adapt themselves to the actual condition of the process and are varied accordingly to the changes in the work conditions as work progresses.

Identification Function:

- This involves determining the current performance of the process or system.
- The identification function is concerned with determining the current value of this performance measure by making use of the feedback data from the process.

Decision Function:

- Once the system performance is determined, the next function is to decide how the control mechanism should be adjusted to improve process performance.
- The decision procedure is carried out by means of a pre-programmed logic provided by the designer

Modification Function

- The third AC function is to implement the decision.
- While the decision function is a logic function, modification is concerned with a physical or mechanical change in the system.

- The modification involves changing the system parameters or variables so as to drive the process towards a more optimal state

CLASSIFICATION OF AC SYSTEMS

- In practice the AC system of machine tools can be classified into two types:
    - o AC with optimization (ACO)
    - o AC with constrains (ACC)
    - o Geometric Adaptive Control (GAC)

ADAPTIVE CONTROL WITH CONSTRAINTS (ACC)
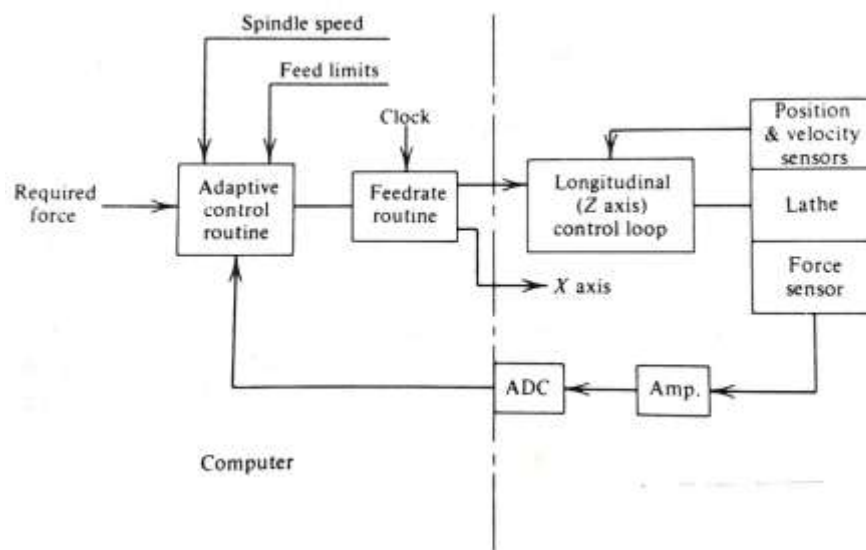
Fig 4.28 Basic Structure of ACC for a Lathe

- ACC are systems in which machining conditions such as spindle speed or feed rate are maximized within the prescribed limits of machines and tool constrains such as maximum torque, force or horse power.
- In AC system the correct feed and speed are automatically found and it is not necessary to spend efforts on calculations of optimum feeds and speeds.
- ACC systems do not utilize a performance index and are based on maximizing a machining variable (e.g., feed rate) subject to process and machine constraints (e.g., allowable cutting force on the tool, or maximum power of the machine).
- The objective of most ACC types of systems is to increase the MRR during rough cutting operations.

ADAPTIVE CONTROL WITH OPTIMIZATION (ACO)

- The ACO Systems for N/C machine tools is a control system that optimizes performance index subjects to various constraints.
- It is basically a sophisticated closed loop control system, which automatically works in optimum conditions, even in the presences of work piece and tools materials variations.
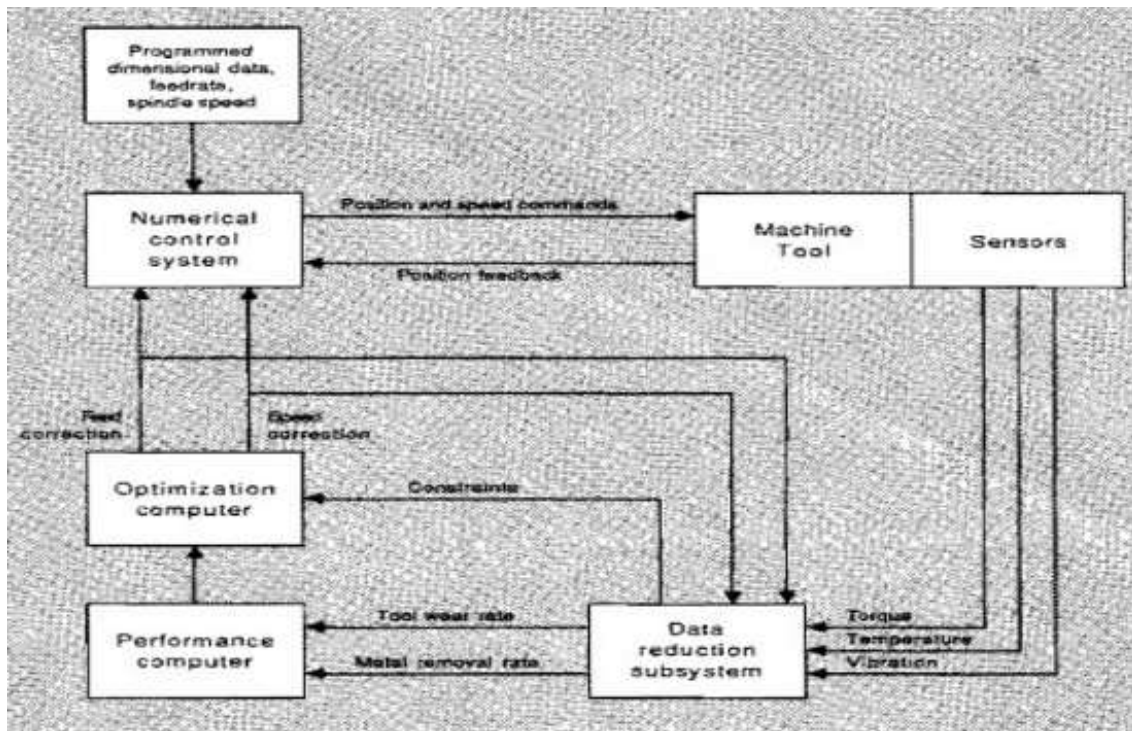
Fig 4.29 Basic Structure of ACO

Drawbacks of ACO

- The main problem is that this require on-line measurement of tool wear.
- So far there have been no industrially acceptable methods developed for the direct measurement of tool wear.
- Indirect measurement assumes that tool wear is proportional to other measurable variables such as cutting forces and temperatures.
- The drawback of using these indirect measurements is that variations in their values can be caused by process variations other than tool wear, such as workpiece hardness or cutting conditions.
- Thus making it difficult to identify the tool wear effect from the effect of the other parameter variations on the measurements.

GEOMETRIC ADAPTIVE CONTROL (GAC)

- GAC are typically used in finish machining operations.
- In GACs the part quality is maintained in real time by compensating for the deflection and wear of cutting tools.
- The objective of GAC is to achieve:-
- the required dimensional accuracy and
- a consistency of surface finish of machined parts despite tool wear or tool deflection

Drawback of GAC

- Both the dimensional accuracy and the surface finish are affected by the flank wear and the crater wear of the tools which deteriorate during cutting.
- These variables cannot be measured in real time; neither can they be accurately predicted from off-line tool testing.

BENEFITS OF ADAPTIVE CONTROL

- Increased production rates.
- Increased tool life.
- Greater part protection.
- Less operator intervention.

LIMITATIONS OF ADAPTIVE CONTROL

- A major drawback is the unavailability of suitable sensors that have a reliable operation in a manufacturing environment . (Tool wear sensor).
- Another problem is the interface of an AC system with CNC units. As yet, manufacturers have not standardized interfaces.

PROGRAMMABLE LOGIC CONTROLLERS (PLC)

- PLC is a microcomputer-based controller that uses stored instructions in programmable memory to implement logic, sequencing, timing, counting and arithmetic functions through digital or analogue input/output modules for controlling machines and processes.
- A programmable controller operates by examining the input signals from a process and carrying out logic instructions (which have been programmed into its memory) on these input signals, producing output signals to drive process equipment or machinery.

STRUCTURE AND COMPONENTS OF PLC

- The basic components of PLC are :-
  - o Processor
  - o Memory Unit
  - o Power Supply
  - o I/O Module
  - o Programming Device

- All these components are housed in a suitable cabinet designed for the industrial environment.
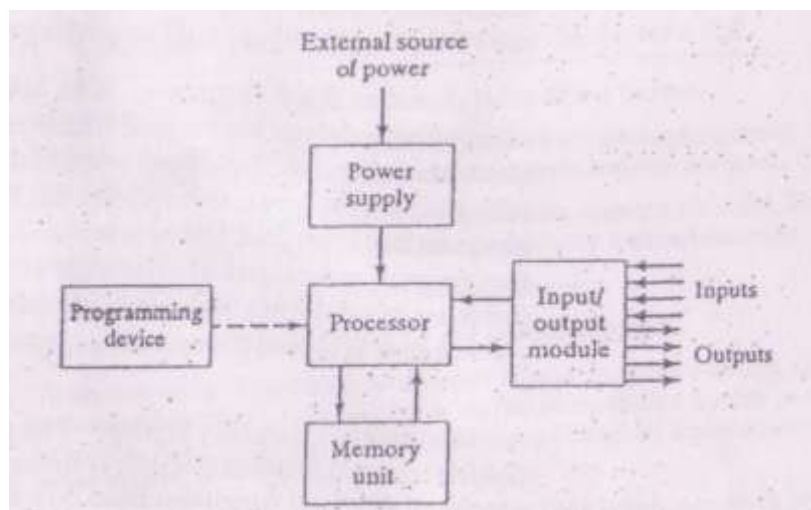
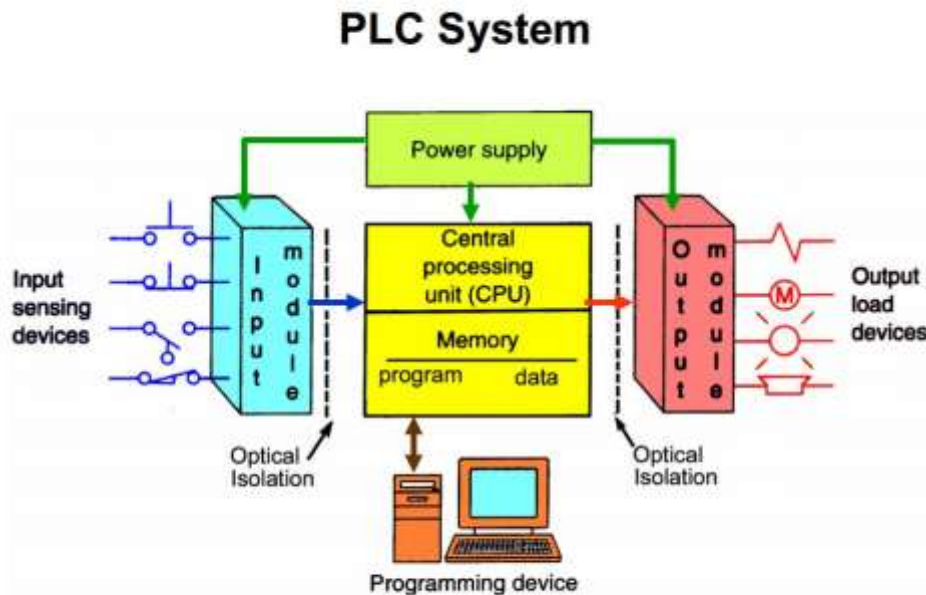
Fig 4.30 Basic Components of PLC

PLC System

Fig 4.31 Structure of PLC

Processor

- Central Processing Unit (CPU) of programmable controller.
- Operates on PLC inputs to determine appropriate output signals.
- Executes various logic and sequencing functions.
- CPU consists of one or more microprocessors that are designed to facilitate I/O transactions.
- PLC microprocessors include a range of bit sizes and clock speeds

Memory Unit

- Contains programs and data files of logic, sequencing and I/O operations.
- Also called user or application memory as its contents are entered by user.
- In addition, the processor also has a system memory that directs execution of control program and coordinates I/O operations.

Power Supply

- 120V AC typically used.
- Converts 120V AC into DC
- Contains battery backup.

Input/Output Module

- Provides connections to the equipment or process that is to be controlled.
- Input signals are from limit switches, push-buttons, sensors and other ON/OFF devices.
- Outputs from the controller are ON/OFF signals to operate motors, valves and other devices.
- The size of a PLC is usually rated in terms of number of its I/O terminals.

PLC Size	I/O Count
Large PLC	≥ 1024
Medium PLC	< 1024
Small PLC	< 256
Micro PLC	≤ 32
Nano PLC	≤ 16

Fig 4.32 Size Rating of PLC

Programming Device

- PLC is programmed by means of a programming device.
- It is detachable from the PLC cabinet so that it can be shared among different controllers.
- Personal Computers are also used to program PLCs.

PLC OPERATING CYCLE

- As far as the PLC user is concerned, the steps in the control program are executed simultaneously and continuously.
- In truth, a certain amount of time is required for the PLC processor to execute the user program during one cycle of operation.
- The typical operating cycle of PLC is called a *scan* and it consists of three parts :
    - o Input Scan
    - o Program Scan
    - o Output Scan

During *Input Scan* :-

- Inputs to the PLC are read by the processor
- Status of these inputs is stored in memory.

During *Program Scan* :-

- Control program is executed.
- Input values stored in memory are used in the control logic calculations to determine the output values.

During *Output Scan* :-

- Outputs are updated to agree with the calculated values.
- The time to perform the scan is called Scan Time, and it depends on :-
    - – Number of inputs that must be read.
    - – Complexity of control functions to be performed.
    - – Number of outputs that must be changed.
    - – Clock speed of the processor.

ADVANTAGES OF PLC

- Reliability
- Flexibility in programming and reprogramming.
- Cost effective for controlling complex systems.
- Small physical size, shorter project time.
- High speed of operation.
- Ability to communicate with computer systems in the plant.
- Ease of maintenance /troubleshooting.
- Reduced space.
- Energy saving.

DISADVANTAGES OF PLC

- PLC devices are proprietary it means that part or software of one manufacturer can't be used in combination with parts of another manufacturer.
- Limited design and cost option
- Fixed Circuit Operations.
- PLCs manufacturers offer only closed architectures.

TIMERS

- There are four fundamental types of timers shown in Figure.

	on-delay	off-delay
retentive	RTO	RTF
nonretentive	TON	TOF

TON - Timer ON
TOF - Timer OFf
RTO - Retentive Timer On
RTF - Retentive Timer oFf

Fig 4.33 The Four Basic Types of Timers

- An on-delay timer will wait for a set time after a line of ladder logic has been true before turning on, but it will turn off immediately.
- An off-delay timer will turn on immediately when a line of ladder logic is true, but it will delay before turning off.
- Consider the example of an old car. If you turn the key in the ignition and the car does not start immediately, that is an on-delay. If you turn the key to stop the engine but the engine doesn't stop for a few seconds, that is an off delay.
- An on-delay timer can be used to allow an oven to reach temperature before starting production. An off delay timer can keep cooling fans on for a set time after the oven has been turned off.

- A retentive timer will sum all of the on or off time for a timer, even if the timer never finished.
- A nonretentive timer will start timing the delay from zero each time.
- Typical applications for retentive timers include tracking the time before maintenance is needed.
- A non retentive timer can be used for a start button to give a short delay before a conveyor begins moving.

COUNTERS

- There are two basic counter types:
    - o count-up
    - o count-down.
- When the input to a count-up counter goes true the accumulator value will increase by 1 (no matter how long the input is true.) If the accumulator value reaches the preset value the counter DN bit will be set.
- A count-down counter will decrease the accumulator value until the preset value is reached.
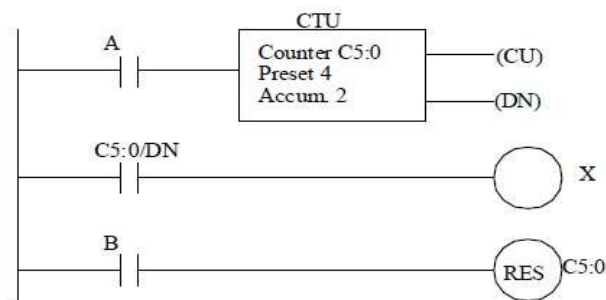
Fig 4.34 An Allen Bradley Counter

- An Allen Bradley count-up (CTU) instruction is shown in Figure above. The instruction requires memory in the PLC to store values and status, in this case is *C5:0*.
- The *C5:* indicates that it is counter memory, and the *0* indicates that it is the first location. The preset value is 4 and the value in the accumulator is 2.
- If the input *A* were to go from false to true the value in the accumulator would increase to 3. If *A* were to go off, then on again the accumulator value would increase to 4, and the *DN* bit would go on. The count can continue above the preset value.
- If input *B* goes true the value in the counter accumulator will become zero.
- Count-down counters are very similar to count-up counters. And, they can actually both be used on the same counter memory location.

INTERNAL RELAYS

- Inputs are used to set outputs in simple programs. More complex programs also use internal memory locations that are not inputs or outputs. These are sometimes referred to as 'internal relays' or 'control relays'.
- Knowledgeable programmers will often refer to these as 'bit memory'. In the Allen Bradley PLCs these addresses begin with 'B3' by default.

- The first bit in memory is 'B3:0/0', where the first zero represents the first 16 bit word, and the second zero represents the first bit in the word.
- The sequence of bits is shown in Figure. The programmer is free to use these memory locations however they see fit.

bit number	memory location	bit number	memory location
0	B3:0/0	18	B3:1/2
1	B3:0/1	19	B3:1/3
2	B3:0/2	20	B3:1/4
3	B3:0/3	21	B3:1/5
4	B3:0/4	22	B3:1/6
5	B3:0/5	23	B3:1/7
6	B3:0/6	24	B3:1/8
7	B3:0/7	25	B3:1/9
8	B3:0/8	26	B3:1/10
9	B3:0/9	27	B3:1/11
10	B3:0/10	28	B3:1/12
11	B3:0/11	29	B3:1/13
12	B3:0/12	30	B3:1/14
13	B3:0/13	31	B3:1/15
14	B3:0/14	32	B3:2/0
15	B3:0/15	33	B3:2/1
16	B3:1/0	34	B3:2/2
17	B3:1/1	etc...	etc...

Fig 4.35 Bit Memory

SHIFT REGISTERS

- A shift register is a digital memory circuit found in calculators, computers, and data-processing systems. Bits (binary digits) enter the shift register at one end and emerge from the other end. The two ends are called left and right.
- In its most basic form, the shift register is a bidirectional FIFO (first-in first-out) circuit. When a bit is input on the left, all the bits in the register move one place to the right, and the rightmost bit disappears. When a bit is input on the right, all the bits move one place to the left, and the leftmost bit disappears.
- Shift register instructions are PLC output instructions that are used to load data into a bit array, one bit at a time.
- The data is shifted through the bit array, and then unloaded from the bit array one bit at a time. Shift register instructions are useful in conveyor applications and product evaluation (pass/fail) control.
- The PLC on your trainer includes the following shift register instructions: the bit shift left (BSL) instruction and the bit shift right (BSR) instruction.
- To enter a BSL or BSR instruction, the following parameters must be programmed:
  - **File:** address of the bit array through which the bits are shifted. The array must start at the first bit position of a 16-bit element (element 1, 2, 3, etc.) in a binary (B) data file.
  - **Control:** 3-word register (R data file) that stores the status bits of the BSL or BSR instruction and the length of the bit array.

Word	B₁₅	B₁₄	B₁₃	B₁₂	B₁₁	B₁₀	B₉	B₈	B₇	B₆	B₅	B₄	B₃	B₂	B₁	B₀
0	EN		DN		ER	UL										
1	Length (size) of the bit array															
2	Reserved															

Fig 4.36 R Data File Structure

- **Bit Address:** location of the source bit that is inserted into the array. With a BSL instruction, this bit is inserted into the first (lowest) bit position of the array. With a BSR instruction, this bit is inserted into the last (highest) bit position of the array.
- **Length:** total number of bits to be shifted within the bit array

PLC LADDER PROGRAMMING

- A very commonly used method of programming PLCs is based on the use of ladder diagrams. Writing a program is then equivalent to drawing a switching circuit.
- The ladder diagram consists of two vertical lines representing the power rails. Circuits are connected as horizontal lines, i.e., the rungs of the ladder, between these two verticals.

In drawing a ladder diagram, certain conventions are adopted:

- The vertical lines of the diagram represent the power rails between which circuits are connected. The power flow is taken to be from the left-hand vertical across a rung.
- Each rung on the ladder defines one operation in the control process.
- A ladder diagram is read from left to right and from top to bottom. The top rung is read from left to right. Then the second rung down is read from left to right and so on.
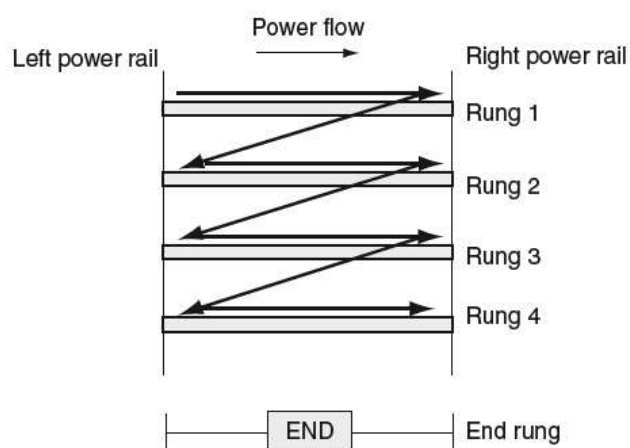

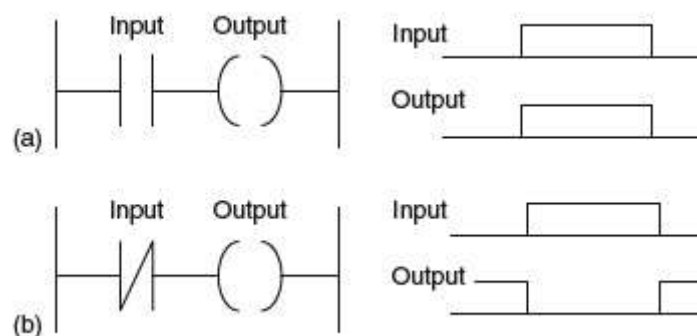**Fig 4.37 Scanning the Ladder Program**

- When the PLC is in its run mode, it goes through the entire ladder program to the end, the end rung of the program being clearly denoted, and then promptly resumes at the start. This procedure of going through all the rungs of the program is termed a cycle. The end rung might be indicated by a block with the word END or RET for return, since the program promptly returns to its beginning.

- Each rung must start with an input or inputs and must end with at least one output. The term input is used for a control action, such as closing the contacts of a switch, used as an input to the PLC. The term output is used for a device connected to the output of a PLC, e.g., a motor.
- Electrical devices are shown in their normal condition. Thus a switch, which is normally open until some object closes it, is shown as open on the ladder diagram. A switch that is normally closed is shown closed.
- A particular device can appear in more than one rung of a ladder. For example, we might have a relay that switches on one or more devices. The same letters and/or numbers are used to label the device in each situation.
- The inputs and outputs are all identified by their addresses, the notation used depending on the PLC manufacturer. This is the address of the input or output in the memory of the PLC.
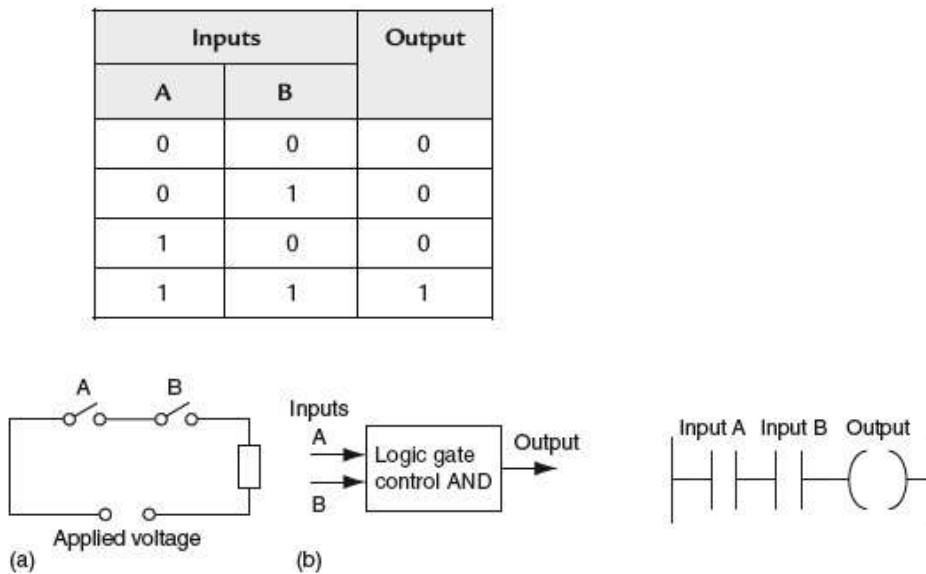
Basic Symbols

**Fig 4.38 Basic Symbols**

Fig 4.39 A Ladder Rung

LOGIC FUNCTIONS

AND

- It is a situation where an output is not energized unless two, normally open, switches are both closed. Switch A and switch B have both to be closed, which thus gives an AND logic situation.
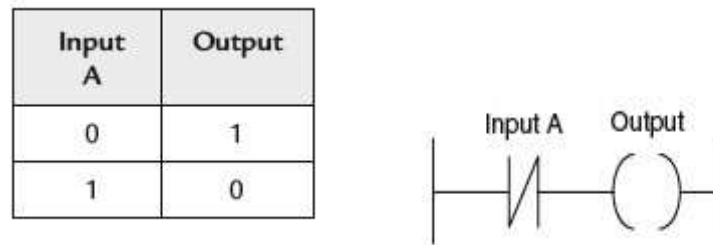
Inputs		Output
A	B	
0	0	0
0	1	0
1	0	0
1	1	1

Fig 4.40 (a) AND Circuit (b) AND Logic Gate (c) AND Ladder Diagram Rung

OR

- Figure below shows an electrical circuit where an output is energized when switch A or B, both normally open, are closed. This describes an OR logic gate in that input A or input B must be on for there to be an output.

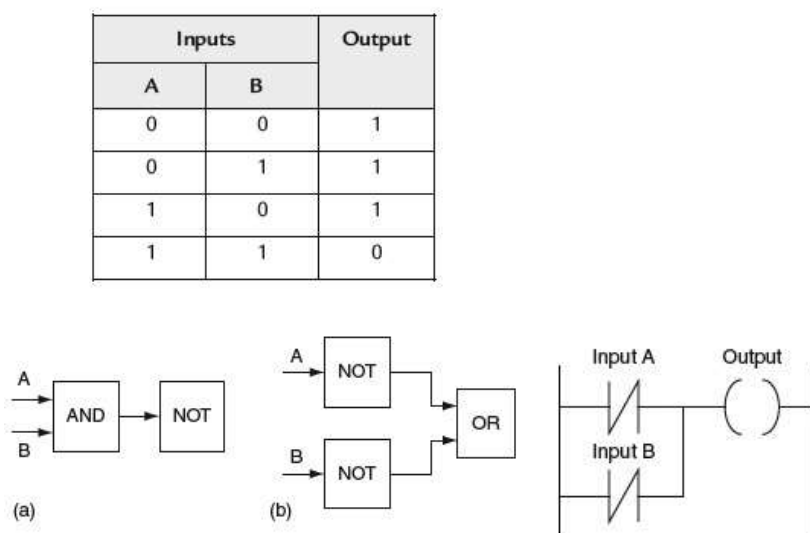| Inputs		Output
A	B	
0	0	0
0	1	1
1	0	1
1	1	1
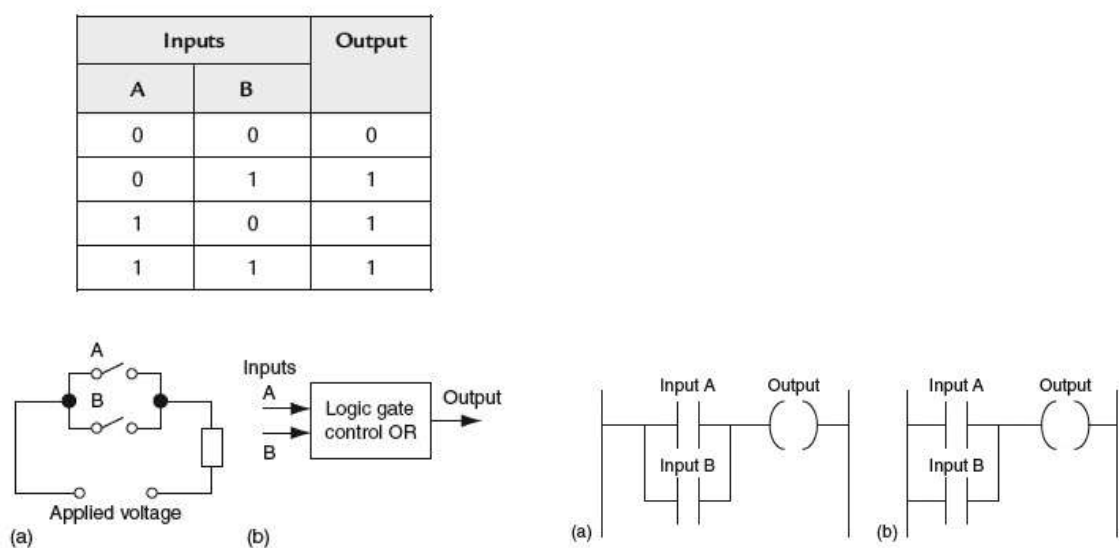
Fig 4.41 (a) OR Circuit (b) OR Logic Gate (c) OR Ladder Diagram Rung

NOT

- Figure below shows an electrical circuit controlled by a switch that is normally closed. When there is an input to the switch, it opens and there is then no current in the circuit.
- This illustrates a NOT gate in that there is an output when there is no input and no output when there is an input. The gate is sometimes referred to as an inverter.

Input A	Output
0	1
1	0

Fig 4.42 NOT Gate

NAND

- Suppose we follow an AND gate with a NOT gate. The consequence of having the NOT gate is to invert all the outputs from the AND gate.
- An alternative, which gives exactly the same results, is to put a NOT gate on each input and then follow that with OR.
- Both the inputs A and B have to be 0 for there to be a 1 output. There is an output when input A and input B are not 1. The combination of these gates is termed a NAND gate

Inputs		Output
A	B	
0	0	1
0	1	1
1	0	1
1	1	0

Fig 4.43 NAND Gate

NOR

- Suppose we follow an OR gate by a NOT gate. The consequence of having the NOT gate is to invert the outputs of the OR gate. An alternative, which gives exactly the same results, is to put a NOT gate on each input and then an AND gate for the resulting inverted inputs.
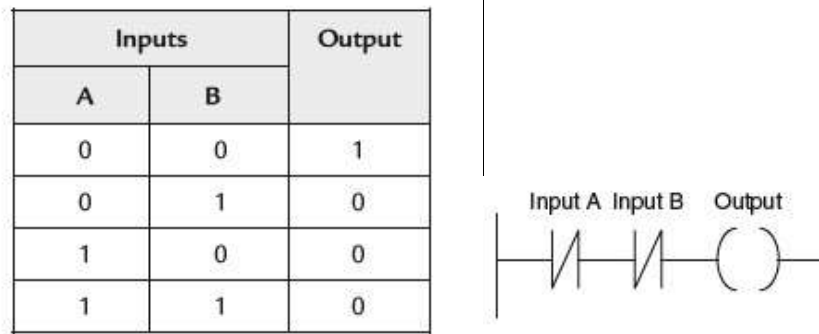- The combination of OR and NOT gates is termed a NOR gate. There is an output when neither input A or input B is 1.

Inputs		Output
A	B	
0	0	1
0	1	0
1	0	0
1	1	0

Fig 4.44 NOR Gate

EXCLUSIVE OR (XOR)

- The OR gate gives an output when either or both of the inputs are 1. Sometimes there is, however, a need for a gate that gives an output when either of the inputs is 1 but not when both are 1.
- Such a gate is called an Exclusive OR or XOR gate. One way of obtaining such a gate is by using NOT, AND and OR gates.
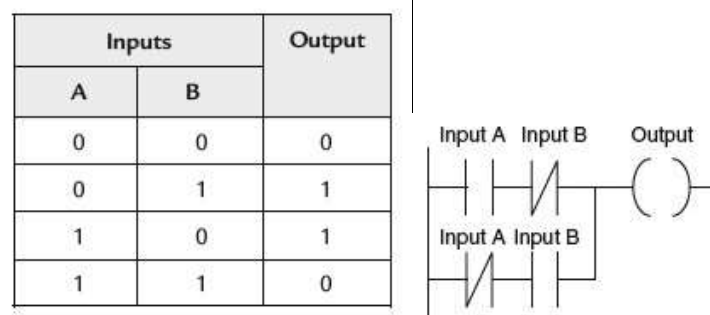
Inputs		Output
A	B	
0	0	0
0	1	1
1	0	1
1	1	0

Fig 4.45 XOR Gate

LATCHING

- There are often situations where it is necessary to hold an output energized, even when the input ceases.
- A simple example of such a situation is a motor, which is started by pressing a push button switch. Though the switch contacts do not remain closed, the motor is required to continue running until a stop push button switch is pressed.
- The term latch circuit is used for the circuit used to carry out such an operation. It is a self-maintaining circuit in that, after being energized, it maintains that state until another input is received.
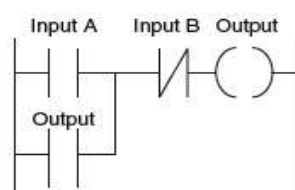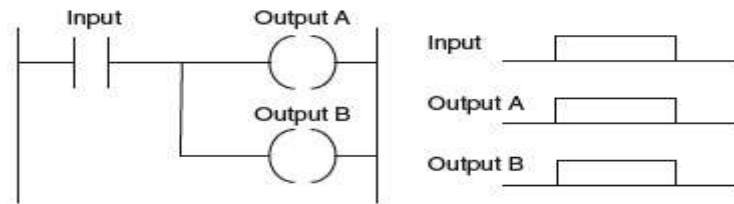
Fig 4.46 Latched Circuit

MULTIPLE OUTPUT

- With ladder diagrams, there can be more than one output connected to a contact. Figure shows a ladder program with two output coils. When the input contacts close, both the coils give outputs.

Fig 4.47 Ladder Rung with Two Outputs

- For the ladder rung shown in Figure below, output A occurs when input A occurs. Output B only occurs when both input A and input B occur.
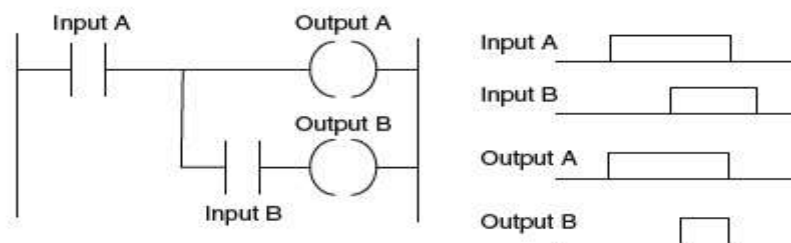
Fig 4.48 Ladder Rung with Two Inputs and Two Outputs

LADDER SYMBOLS

To enter a pair of contact

To enter an output

To indicate the start of a junction

**To indicate the end of a junction path**
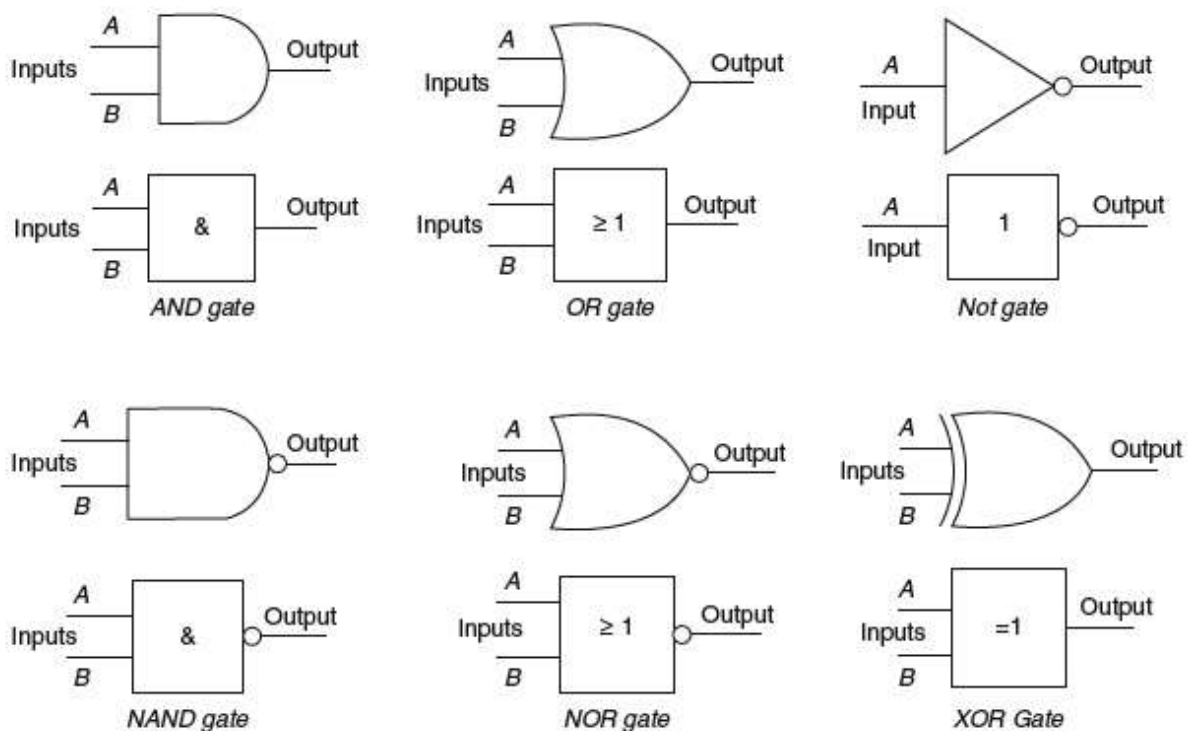
To indicate horizontal circuit links

FUNCTION BLOCKS

- The term function block diagram (FBD) is used for PLC programs described in terms of graphical blocks. It is described as being a graphical language for depicting signal and data flows through blocks, these being reusable software elements.
- A function block is a program instruction unit which, when executed, yields one or more output values. Thus, a block is represented in the manner shown in figure below with the function name written in the box.
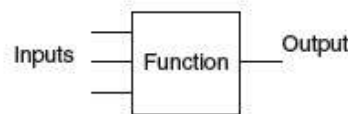
Fig 4.49 Function Block

LOGIC GATES

Fig 4.50 Logic Gate Symbols