LECTURE NOTE

SUB: MECHATRONICS(TH-4)

BRANCH:- MECHANICAL ENGG.

SEMESTER:5TH

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Mechatronics and Manufacturing Automation

Module 1 Introduction

Lecture 1
Introduction

Objectives of this course:

1. To study the definition and elements of mechatronics system.
2. To learn how to apply the principles of mechatronics and automation for the development of productive and efficient manufacturing systems.
3. To study the hydraulic and pneumatic systems employed in manufacturing industry.
4. To learn the CNC technology and industrial robotics as applications of Mechatronics in manufacturing automation.

1. What is "Mechatronics"?

Mechatronics is a concept of *Japanese* origin (1970's) and can be defined as the application of electronics and computer technology to control the motions of mechanical systems (figure 1.1.1).

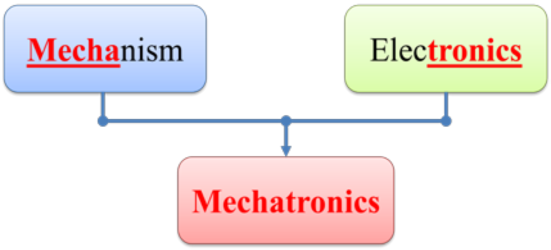

Figure 1.1.1 Definition of Mechatronics

It is a multidisciplinary approach to product and manufacturing system design (Figure 1.1.2). It involves application of electrical, mechanical, control and computer engineering to develop products, processes and systems with greater flexibility, ease in redesign and ability of reprogramming. It concurrently includes all these disciplines.

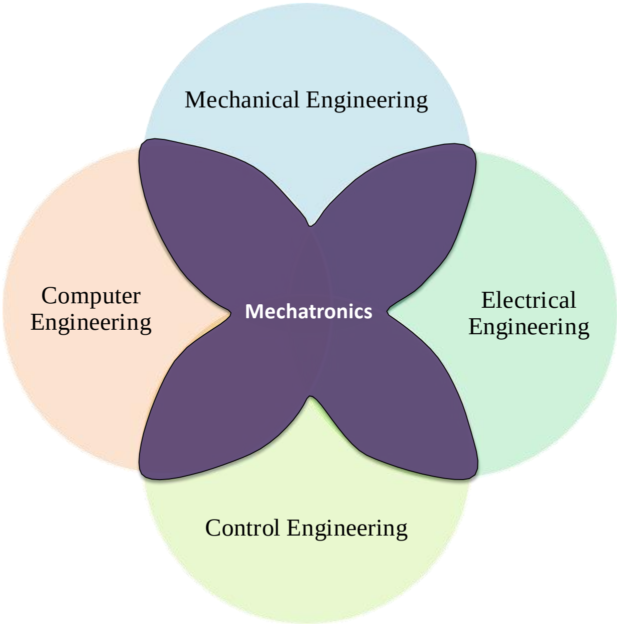

Figure 1.1.2 Mechatronics: a multi-disciplinary approach

Mechatronics can also be termed as replacement of mechanics with electronics or enhance mechanics with electronics. For example, in modern automobiles, mechanical fuel injection systems are now replaced with electronic fuel injection systems. This replacement made the automobiles more efficient and less pollutant.

With the help of microelectronics and sensor technology, mechatronics systems are providing high levels of precision and reliability. It is now possible to move (in x – y plane) the work table of a modern production machine tool in a step of 0.0001 mm.

By employment of reprogrammable microcontrollers/microcomputers, it is now easy to add new functions and capabilities to a product or a system. Today's domestic washing machines are "intelligent" and four-wheel passenger automobiles are equipped with safety installations such as air-bags, parking (proximity) sensors, anti-theft electronic keys etc.

2. *Importance of Mechatronics in automation*

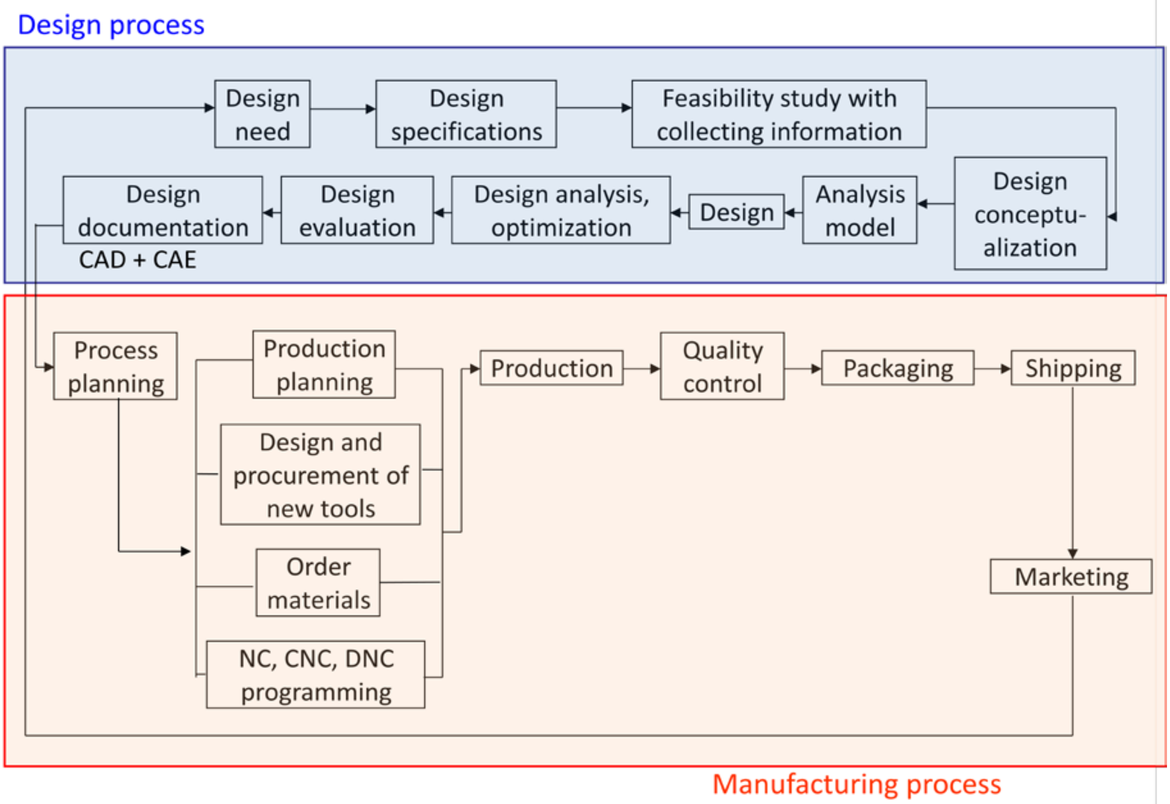

Figure 1.1.3 Operations involved in design and manufacturing of a product

Today's customers are demanding more variety and higher levels of flexibility in the products. Due to these demands and competition in the market, manufacturers are thriving to launch new/modified products to survive. It is reducing the product life as well as lead-time to manufacture a product. It is therefore essential to automate the manufacturing and assembly operations of a product. There are various activities involved in the product manufacturing process. These are shown in figure 1.1.3. These activities can be classified into two groups viz. design and manufacturing activities.

Mechatronics concurrently employs the disciplines of mechanical, electrical, control and computer engineering at the stage of design itself. Mechanical discipline is employed in terms of various machines and mechanisms, where as electrical engineering as various electric prime movers viz. AC/DC, servo motors and other systems is used. Control engineering helps in the development of various electronics-based control systems to enhance or replace the mechanics of the mechanical systems. Computers are widely used to write various softwares to control the control systems; product design and development activities; materials and manufacturing resource planning, record keeping, market survey, and other sales related activities.

Using computer aided design (CAD) / computer aided analysis (CAE) tools, three-dimensional models of products can easily be developed. These models can then be analyzed and can be simulated to study their performances using numerical tools. These numerical tools are being continuously updated or enriched with the real-life performances of the similar kind of products. These exercises provide an approximate idea about performance of the product/system to the design team at the early stage of the product development. Based on the simulation studies, the designs can be modified to achieve better performances. During the conventional design-manufacturing process, the design assessment is generally carried out after the production of first lot of the products. This consumes a lot of time, which leads to longer (in months/years) product development lead-time. Use of CAD–CAE tools saves significant time in comparison with that required in the conventional sequential design process.

CAD-CAE generated final designs are then sent to the production and process planning section. Mechatronics based systems such as computer aided manufacturing (CAM): automatic process planning, automatic part programming, manufacturing resource planning, etc. uses the design data provided by the design team. Based these inputs, various activities will then be planned to achieve the manufacturing targets in terms of quality and quantity with in a stipulated time frame.

Mechatronics based automated systems such as automatic inspection and quality assurance, automatic packaging, record making, and automatic dispatch help to expedite the entire manufacturing operation. These systems certainly ensure a supply better quality, well packed and reliable products in the market. Automation in the machine tools has reduced the human intervention in the machining operation and improved the process efficiency and product quality. Therefore it is important to study the principles of mechatronics and to learn how to apply them in the automation of a manufacturing system.

3. Mechatronics system

A system can be thought of as a box or a bounded whole which has input and output elements, and a set of relationships between these elements. Figure 1.1.4 shows a typical spring system. It has 'force' as an input which produces an 'extension'. The input and output of this system follows the Hooke's law $F = -kx$, where F is force in N, x is distance in m and k is stiffness of the spring.

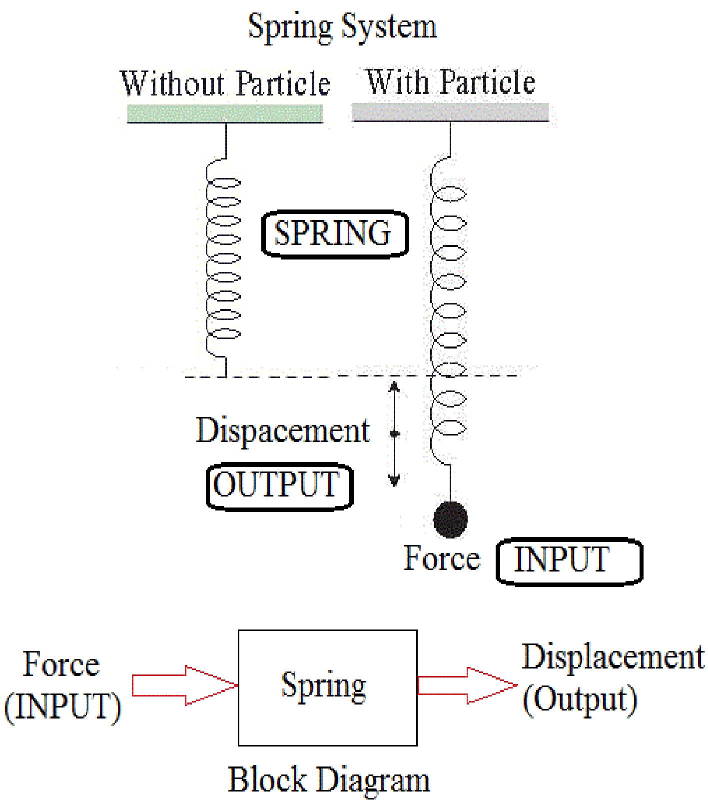

Figure 1.1.4 A spring-force system

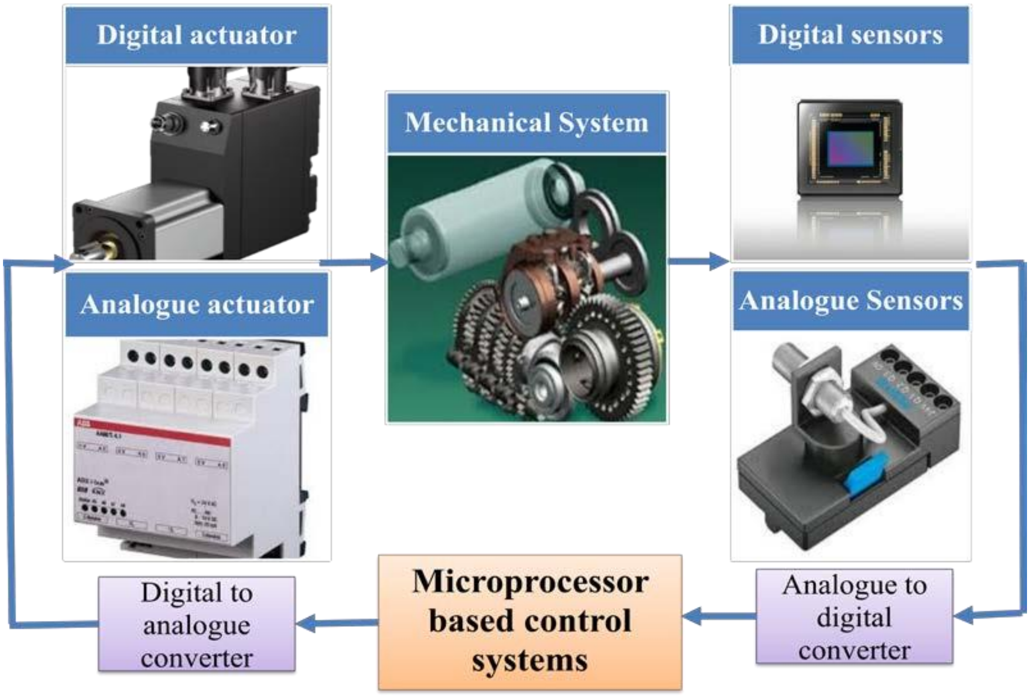

Figure 1.1.5 Constituents of a mechatronics system

A Mechatronics system integrates various technologies involving sensors, measurement systems, drives, actuation systems, microprocessor systems and software engineering. Figure 1.1.5 shows the basic elements of a mechatronics system. Consider the example of a simple spring-mass system as shown in figure 1.1.4. To replace the mechanics of this mechanical system with an equivalent mechatronics based system, we need to have the basic controlling element, a *microprocessor*. Microprocessor processes or utilizes the information gathered from the sensor system and generates the signals of appropriate level and suitable kind (current or voltage) which will be used to actuate the required actuator viz. a hydraulic piston-cylinder device for extension of piston rod in this case. The microprocessor is programmed on the basis of the principle of Hooks' Law. The schematic of microprocessor based equivalent spring mass system is shown in figure 1.1.6.

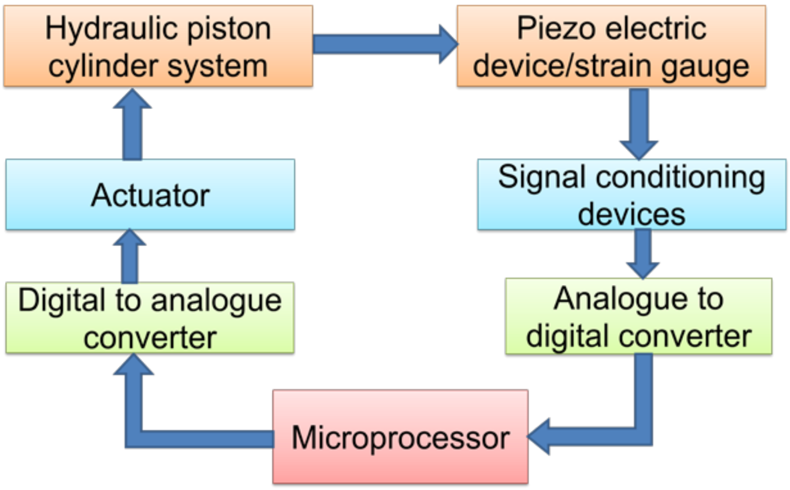

Figure 1.1.6 Microprocessor based equivalent spring mass system

The input to the system is a force which can be sensed by suitable electro-mechanical sensors viz. piezo-electric device or strain gauges. These sensors generate either digital signals (0 or 1) or analogue signals (milli-volts or milli-amperes). These signals are then converted into right form and are attenuated to a right level which can properly be used by the microprocessor to take generate the actuation signals. Various electronics based auxiliary devices viz. Analogue-to-Digital Converter (ADC), Digital-to-Analogue Converter (DAC), Op-amps, Modulators, Linearization circuits, etc. are used to condition the signals which are either received by the microprocessor from the sensors or are sent to the actuators from the microprocessor. This mechatronics based spring-mass system has the input signals in the digital form which are received from the ADC and Piezo-electric sensor. The digital actuation signals generated by the microprocessors are converted into appropriate analogues signals. These analogue signals operate the hydraulic pump and control valves to achieve the desired displacement of the piston-rod.

In this course we will be studying in detail the various elements of a Mechtronics system (shown in figure 1.1.5) and their applications to manufacturing automation.

In the next lecture we will study the applications of Mechatronics in manufacturing engineering and in the subsequent lectures; above-mentioned elements will be discussed in detail.

Assignment 1: Study the product life cycle diagram and elaborate the various design and manufacturing activities for a product: four-wheel automobile (a passenger car) or a mobile cell phone.

Assignment 2: Identify a mechatronics system being used by you in your daily routine. Analyze its elements and state its importance in the functioning of that system.

References:

1. HMT Ltd. Mechatronics, Tata McGraw-Hill, New Delhi, 1988.

2. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.

Module 1 Introduction

Lecture 2
Mechatronics: products and systems in manufacturing

Mechatronics has a variety of applications as products and systems in the area of 'manufacturing automation'. Some of these applications are as follows:

1. Computer numerical control (CNC) machines
2. Tool monitoring systems
3. Advanced manufacturing systems
   a. Flexible manufacturing system (FMS)
   b. Computer integrated manufacturing (CIM)
4. Industrial robots
5. Automatic inspection systems: machine vision systems
6. Automatic packaging systems

Now, let us know in brief about these applications one by one.

1. *Computer numerical control (CNC) 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 workpart 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.

Conventional Milling Machine CNC Machine Tool

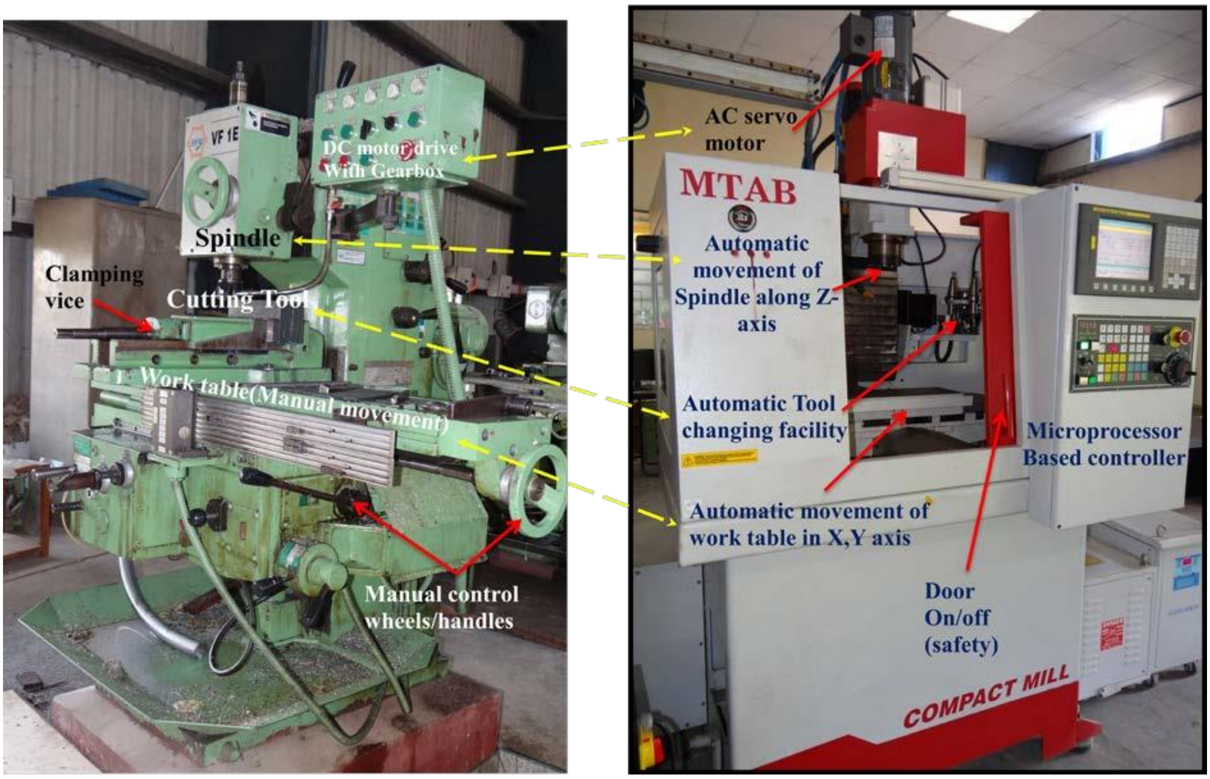

Figure 1.2.1 Comparison between a conventional machine tool and a CNC machine tool

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. Numbers, letters, and symbols are the coded instructions which refer to specific distances, positions, functions or motions which the machine tool can understand.

CNC automatically guides the axial movements of machine tools with the help of computers. The auxiliary operations such as coolant on-off, tool change, door open-close are automated with the help of micro-controllers. Figure 1.2.1 shows the fundamental differences between a conventional and a CNC machine tool. 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. The controller has self diagnostics facility which regularly alarms the operator in case of any safety norm violation viz. door open during machining, tool wear/breakage etc. Modern machine tools are now equipped with friction-less drives such as re-circulating ball screw drives, Linear motors etc. The detail study of various elements of such a Mechatronics based system is the primary aim of this course and these are described at length in the next modules.

2. *Tool monitoring systems*

Uninterrupted machining is one of the challenges in front manufacturers to meet the production goals and customer satisfaction in terms of product quality. Tool wear is a critical factor which affects the productivity of a machining operation. Complete automation of a machining process realizes when there is a successful prediction of tool (wear) state during the course of machining operation. Mechatronics based cutting tool-wear condition monitoring system is an integral part of automated tool rooms and unmanned factories. These systems predict the tool wear and give alarms to the system operator to prevent any damage to the machine tool and workpiece. Therefore it is essential to know how the mechatronics is helping in monitoring the tool wear. Tool wear can be observed in a variety of ways. These can be classified in two groups (Table 1.2.1).

Table 1.2.1 Tool monitoring systems [2]

Direct methods	**Indirect methods**
Electrical resistance	Torque and power
Optical measurements	Temperature
Machining hours	Vibration & acoustic emission
Contact sensing	Cutting forces & strain measurements

Direct methods deal with the application of various sensing and measurement instruments such as micro-scope, machine/camera vision; radioactive techniques to measure the tool wear. The *used or worn-out* cutting tools will be taken to the metrology or inspection section of the tool room or shop floor where they will be examined by using one of direct methods. However, these methods can easily be applied in practice when the cutting tool is not in contact with the work piece. Therefore they are called as offline tool monitoring system. Figure 1.2.2 shows a schematic of tool edge grinding or replacement scheme based on the measurement carried out using offline tool monitoring system. Offline methods are time consuming and difficult to employ during the course of an actual machining operation at the shop floor.

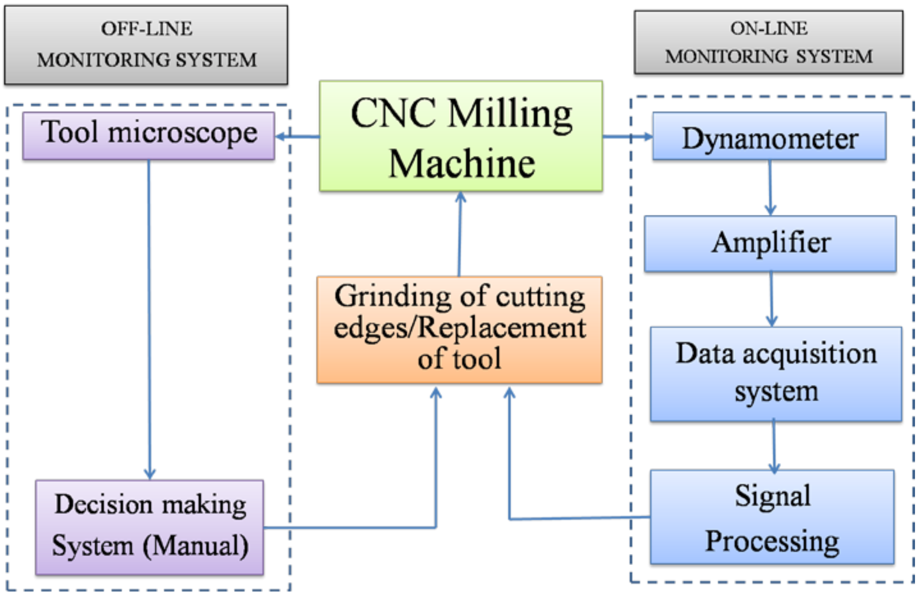

Figure 1.2.2 Off-line and on-line tool monitoring system for tool edge grinding

Indirect methods predict the condition of the cutting tool by analyzing the relationship between cutting conditions and response of machining process as a measurable quantity through sensor signals output such as force, acoustic emission, vibration, or current.

Figure 1.2.2 shows a typical example of an on-line tool monitoring system. It employs the cutting forces recoded during the real-time cutting operation to predict the tool-wear. The cutting forces can be sensed by using either piezo-electric or strain gauge based force transducer. A micro-processor based control system continuously monitors 'conditioned' signals received from the Data Acquisition System (DAS). It is generally programmed/trained with the past recorded empirical data for a wide range of process conditions for a variety of materials. Artificial Intelligence (AI) tools such as Artificial Neural Network (ANN), Genetic Algorithm (GA) are used to train the microprocessor based system on a regular basis. Based on this training the control system takes the decision to change the tool or gives an alarm to the operator. Various steps followed in On-line approach to measure the tool wear and to take the appropriate action are shown in Figure 1.2.3.

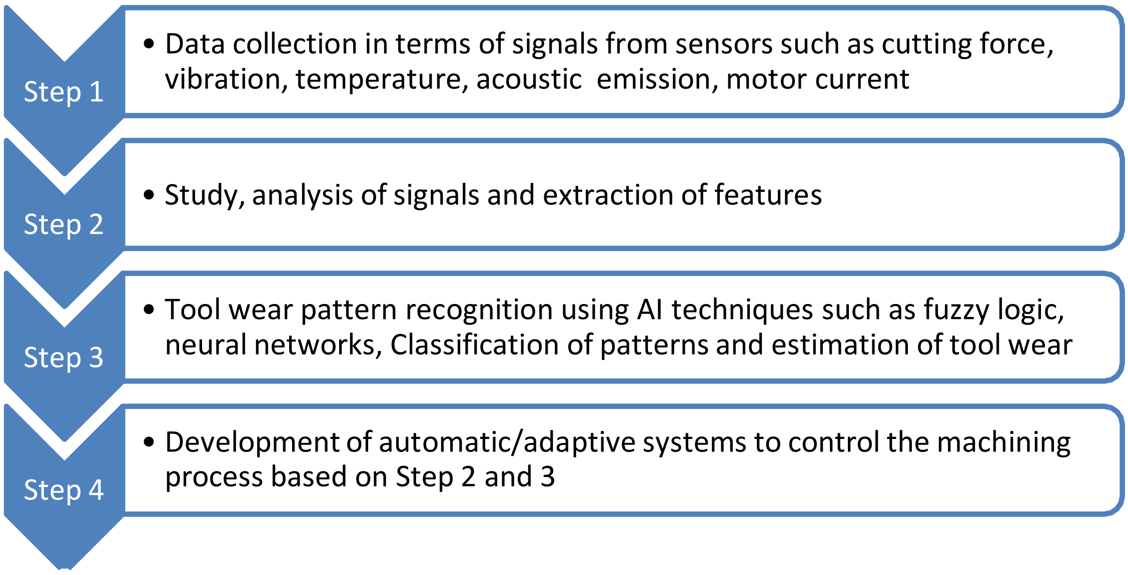

Figure 1.2.3 Steps followed in an indirect tool monitoring system

A lot of academic as well as industrial research has been carried out on numerical and experimental studies of design, development and analysis of 'Tool Condition Monitoring Systems'. Readers are suggested to browse various international journals such as International Journal of Advanced Manufacturing Technology (Springer), International Journal of Machine Tool and Manufacture; International Journal of Materials Processing Technology (Elsevier), etc. to learn more about these techniques.

3. Advanced Manufacturing Systems

3.1 Flexible Manufacturing System

Nowadays customers are demanding a wide variety of products. To satisfy this demand, the manufacturers' "production" concept has moved away from "mass" to small "batch" type of production. Batch production offers more flexibility in product manufacturing. To cater this need, Flexible Manufacturing Systems (FMS) have been evolved.

As per Rao, P. N. [3], *FMS combines microelectronics and mechanical engineering to bring the economies of the scale to batch work. A central online computer controls the machine tools, other work stations, and the transfer of components and tooling. The computer also provides monitoring and information control. This combination of flexibility and overall control makes possible the production of a wide range of products in small numbers.*

FMS is a manufacturing cell or system consisting of one or more CNC machines, connected by automated material handling system, pick-and-place robots and all operated under the control of a central computer. It also has auxiliary sub-systems like component load/unload station, automatic tool handling system, tool pre-setter, component measuring station, wash station etc. Figure 1.2.4 shows a typical arrangement of FMS system and its constituents. Each of these will have further elements depending upon the requirement as given below,

A. Workstations

- CNC machine tools
- Assembly equipment
- Measuring Equipment
- Washing stations

B. Material handing Equipment

- Load unload stations (Palletizing)
- Robotics
- Automated Guided Vehicles (AGVs)
- Automated Storage and retrieval Systems (AS/RS)

C. Tool systems

- Tool setting stations
- Tool transport systems

D. Control system

- Monitoring equipments
- Networks

It can be noticed that the FMS is shown with two machining centers viz. milling center and turning center. Besides it has the load/unload stations, AS/RS for part and raw material storage, and a wire guided AGV for transporting the parts between various elements of the FMS. This system is fully automatic means it has automatic tool changing (ATC) and automatic pallet changing (APC) facilities. The central computer controls the overall operation and coordination amongst the various constituents of the FMS system.

Video attached herewith gives an overview of a FMS system

Figure 1.2.4 A FMS Setup

The characteristic features of an FMS system are as follows,

1. FMS solves the mid-variety and mid-volume production problems for which neither the high production rate transfer lines nor the highly flexible stand-alone CNC machines are suitable.
2. Several types of a defined mix can be processed simultaneously.
3. Tool change-over time is negligible.
4. Part handling from machine to machine is easier and faster due to employment of computer controlled material handling system.

Benefits of an FMS

- Flexibility to change part variety
- Higher productivity
- Higher machine utilization
- Less rejections
- High product quality
- Reduced work-in-process and inventory
- Better control over production
- Just-in-time manufacturing
- Minimally manned operation
- Easier to expand

3.2 Computer Integrated Manufacturing (CIM)

In the last lecture, we have seen that a number of activities and operations viz. designing, analyzing, testing, manufacturing, packaging, quality control, etc. are involved in the life cycle of a *product* or a *system* (*see* Figure 1.1.4). Application of principles of automation to each of these activities enhances the productivity only at the individual level. These are termed as '*islands of automation'*. Integrating all these islands of automation into a single system enhances the overall productivity. Such a system is called as "*Computer Integrated Manufacturing* (CIM)".

The Society of Manufacturing Engineers (SME) defined CIM as *'CIM is the integration of the total manufacturing enterprise through the use of integrated systems and data communications coupled with new managerial philosophies that improve organizational and personal efficiency'.*

CIM basically involves the integration of advanced technologies such as computer aided design (CAD), computer aided manufacturing (CAM), computer numerical control (CNC), robots, automated material handling systems, etc. Today CIM has moved a step ahead by including and integrating the business improvement activities such as customer satisfaction, total quality and continuous improvement. These activities are now managed by computers. Business and marketing teams continuously feed the customer feedback to the design and production teams by using the networking systems. Based on the customer requirements, design and manufacturing teams can immediately improve the existing product design or can develop an entirely new product. Thus, the use of computers and automation technologies made the manufacturing industry capable to provide rapid response to the changing needs of customers.

4. Industrial robots

Industrial robots are general-purpose, re-programmable machines which respond to the sensory signals received from the system environment. Based on these signals, robots carry out programmed work or activity. They also take simple independent decisions and communicate/interact with the other machines and the central computer. Robots are widely employed in the following applications in manufacturing [3]:

A. Parts handling: it involves various activities such as:
    - Recognizing, sorting/separating the parts
    - Picking and placing parts at desired locations
    - Palletizing and de-palletizing
    - Loading and unloading of the parts on required machines

B. Parts processing: this may involves many manufacturing operations such as:
    - Routing
    - Drilling
    - Riveting
    - Arc welding
    - Grinding
    - Flame cutting
    - Deburring
    - Spray painting
    - Coating
    - Sand blasting
    - Dip coating
    - Gluing
    - Polishing
    - Heat treatment

C. Product building: this involves development and building of various products such as:
    - Electrical motors
    - Car bodies
    - Solenoids
    - Circuit boards and operations like
        - Bolting
        - Riveting
        - Spot welding
        - Seam welding
        - Inserting
        - Nailing
        - Fitting
        - Adhesive bonding
        - Inspection

Further detail discussion on various aspects of industrial robots such as its configuration, building blocks, sensors, and languages has been carried out in the last module of this course.

5. *Automatic quality control and inspection systems*

Supply of a good quality product or a system to the market is the basic aim of the manufacturing industry. The product should satisfy the needs of the customers and it must be reliable. To achieve this important product-parameter during a short lead time is really a challenge to the manufacturing industry. This can be achieved by building up the 'quality' right from the product design stage; and maintaining the standards during the 'production stages' till the product-delivery to the market.

A number of sensors and systems have been developed that can monitor quality continuously with or without the assistance of the operator. These technologies include various sensors and data acquisition systems, machine vision systems, metrology instruments such as co-ordinate measuring machine (CMM), optical profilometers, digital calipers and screw gauges etc. Now days the quality control activities are being carried out right from the design stage of product development. Various physics based simulation software is used to predict the performance of the product or the system to be developed. In the manufacture of products such as spacecrafts or airplanes, all the components are being critically monitored by using the digital imaging systems throughout their development.

In the next module we will study the various sensors, signal conditioning devices and data conversion devices which are commonly used in mechatronics and manufacturing automation.

Assignment 1 Visit to your nearby tool room or CNC work shop and prepare a case study on a real life example on tool wear monitoring system employed in the same.

Assignment 2 Differentiate between an FMS and a CIM system. Prepare a report on how automation can enhance the productivity of a mold-making tool room to cater the changing customer demands in terms of shape, size and quality of molds.

References:

1. HMT Ltd. Mechatronics, Tata McGraw-Hill, New Delhi, 1988.
2. H. Chelladurai, V. K. Jain and N. S. Vyas, Development of a cutting tool condition monitoring system for high speed turning operation by vibration and strain analysis, Int. J. Adv. Manuf. Technol. 2008, 37:471–485.
3. P. N. Rao, CAD/CAM Principles and Applications, Tata McGraw Hill, 2011.

Module 2: Sensors and signal processing
Lecture 1
Sensors and transducers

Measurement is an important subsystem of a mechatronics system. Its main function is to collect the information on system status and to feed it to the micro-processor(s) for controlling the whole system.

Measurement system comprises of sensors, transducers and signal processing devices. Today a wide variety of these elements and devices are available in the market. For a mechatronics system designer it is quite difficult to choose suitable sensors/transducers for the desired application(s). It is therefore essential to learn the principle of working of commonly used sensors/transducers. A detailed consideration of the full range of measurement technologies is, however, out of the scope of this course. Readers are advised to refer "Sensors for mechatronics" by Paul P.L. Regtien, Elsevier, 2012 [2] for more information.

Sensors in manufacturing are basically employed to automatically carry out the production operations as well as process monitoring activities. Sensor technology has the following important advantages in transforming a conventional manufacturing unit into a modern one.

1. Sensors alarm the system operators about the failure of any of the sub units of manufacturing system. It helps operators to reduce the downtime of complete manufacturing system by carrying out the preventative measures.
2. Reduces requirement of skilled and experienced labors.
3. Ultra-precision in product quality can be achieved.

Sensor

It is defined as an element which produces signal relating to the quantity being measured [1]. According to the Instrument Society of America, sensor can be defined as "*A device which provides a usable output in response to a specified measurand.*" Here, the output is usually an 'electrical quantity' and measurand is a 'physical quantity, property or condition which is to be measured'. Thus in the case of, say, a variable inductance displacement element, the quantity being measured is displacement and the sensor transforms an input of displacement into a change in inductance.

Transducer

It is defined as an element when subjected to some physical change experiences a related change [1] or an element which converts a specified measurand into a usable output by using a transduction principle.

It can also be defined as a device that converts a signal from one form of energy to another form.

A wire of Constantan alloy (copper-nickel 55-45% alloy) can be called as a sensor because variation in mechanical displacement (tension or compression) can be sensed as change in electric resistance. This wire becomes a transducer with appropriate electrodes and input-output mechanism attached to it. Thus we can say that 'sensors are transducers'.

Sensor/transducers specifications

Transducers or measurement systems are not perfect systems. Mechatronics design engineer must know the capability and shortcoming of a transducer or measurement system to properly assess its performance. There are a number of performance related parameters of a transducer or measurement system. These parameters are called as sensor specifications.

Sensor specifications inform the user to the about deviations from the ideal behavior of the sensors. Following are the various specifications of a sensor/transducer system.

1. Range

The range of a sensor indicates the limits between which the input can vary. For example, a thermocouple for the measurement of temperature might have a range of 25-225 °C.

2. Span

The span is difference between the maximum and minimum values of the input. Thus, the above-mentioned thermocouple will have a span of 200 °C.

3. Error

Error is the difference between the result of the measurement and the true value of the quantity being measured. A sensor might give a displacement reading of 29.8 mm, when the actual displacement had been 30 mm, then the error is –0.2 mm.

4. *Accuracy*

The accuracy defines the closeness of the agreement between the actual measurement result and a true value of the measurand. It is often expressed as a percentage of the full range output or full–scale deflection. A piezoelectric transducer used to evaluate dynamic pressure phenomena associated with explosions, pulsations, or dynamic pressure conditions in motors, rocket engines, compressors, and other pressurized devices is capable to detect pressures between 0.1 and 10,000 psig (0.7 KPa to 70 MPa). If it is specified with the accuracy of about ±1% full scale, then the reading given can be expected to be within ± 0.7 MPa.

5. *Sensitivity*

Sensitivity of a sensor is defined as the ratio of change in output value of a sensor to the per unit change in input value that causes the output change. For example, a general purpose thermocouple may have a sensitivity of 41 µV/°C.

6. *Nonlinearity*

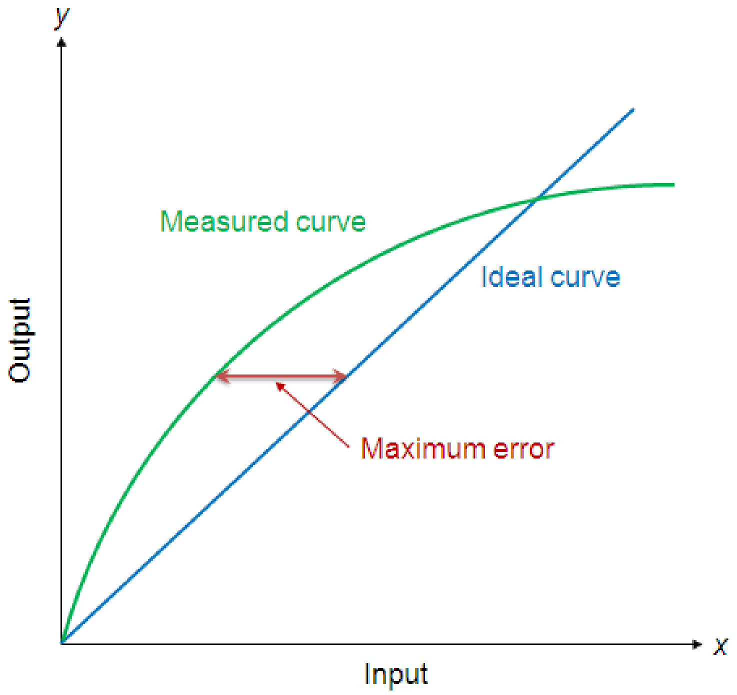

Figure 2.1.1 Non-linearity error

The nonlinearity indicates the maximum deviation of the actual measured curve of a sensor from the ideal curve. Figure 2.1.1 shows a somewhat exaggerated relationship between the ideal, or least squares fit, line and the actual measured or *calibration* line. Linearity is often specified in terms of *percentage of nonlinearity*, which is defined as:

Nonlinearity (%) = Maximum deviation in input ⁄ Maximum full scale input (2.1.1)

The static nonlinearity defined by Equation 2.1.1 is dependent upon environmental factors, including temperature, vibration, acoustic noise level, and humidity. Therefore it is important to know under what conditions the specification is valid.

7. Hysteresis

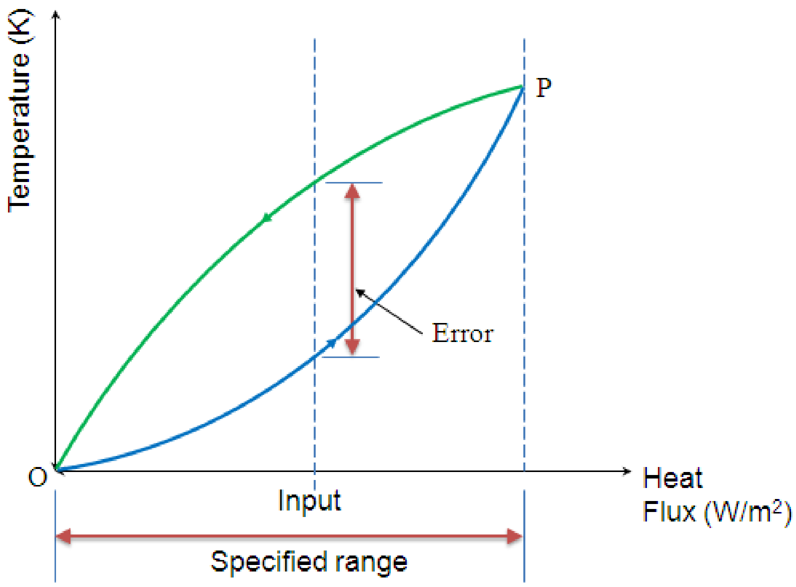

Figure 2.1.2 Hysteresis error curve

The hysteresis is an error of a sensor, which is defined as the maximum difference in output at any measurement value within the sensor's specified range when approaching the point first with increasing and then with decreasing the input parameter. Figure 2.1.2 shows the hysteresis error might have occurred during measurement of temperature using a thermocouple. The hysteresis error value is normally specified as a positive or negative percentage of the specified input range.

8. Resolution

Resolution is the smallest detectable incremental change of input parameter that can be detected in the output signal. Resolution can be expressed either as a proportion of the full-scale reading or in absolute terms. For example, if a LVDT sensor measures a displacement up to 20 mm and it provides an output as a number between 1 and 100 then the resolution of the sensor device is 0.2 mm.

9. Stability

Stability is the ability of a sensor device to give same output when used to measure a constant input over a period of time. The term 'drift' is used to indicate the change in output that occurs over a period of time. It is expressed as the percentage of full range output.

10. Dead band/time

The dead band or dead space of a transducer is the range of input values for which there is no output. The dead time of a sensor device is the time duration from the application of an input until the output begins to respond or change.

11. Repeatability

It specifies the ability of a sensor to give same output for repeated applications of same input value. It is usually expressed as a percentage of the full range output:

Repeatability = (maximum – minimum values given) X 100 ⁄ full range (2.1.2)

12. Response time

Response time describes the speed of change in the output on a step-wise change of the measurand. It is always specified with an indication of input step and the output range for which the response time is defined.

Classification of sensors

Sensors can be classified into various groups according to the factors such as measurand, application fields, conversion principle, energy domain of the measurand and thermodynamic considerations. These general classifications of sensors are well described in the references [2, 3].

Detail classification of sensors in view of their applications in manufacturing is as follows.

A. Displacement, position and proximity sensors
    - Potentiometer
    - Strain-gauged element
    - Capacitive element
    - Differential transformers
    - Eddy current proximity sensors
    - Inductive proximity switch
    - Optical encoders
    - Pneumatic sensors
    - Proximity switches (magnetic)
    - Hall effect sensors
B. Velocity and motion
    - Incremental encoder
    - Tachogenerator
    - Pyroelectric sensors

C. Force
    - Strain gauge load cell
D. Fluid pressure
    - Diaphragm pressure gauge
    - Capsules, bellows, pressure tubes
    - Piezoelectric sensors
    - Tactile sensor
    -
E. Liquid flow
    - Orifice plate
    - Turbine meter
F. Liquid level
    - Floats
    - Differential pressure
G. Temperature
    - Bimetallic strips
    - Resistance temperature detectors
    - Thermistors
    - Thermo-diodes and transistors
    - Thermocouples
    - Light sensors
    - Photo diodes
    - Photo resistors

- Photo transistor

Principle of operation of these transducers and their applications in manufacturing are presented in the next lectures.

Quiz:

1. Define sensors and list the various specifications that need to be carefully studied before using a Thermocouple for reading the temperature of a furnace.
2. Differentiate between span and range of a transducer system.
3. What do you mean by nonlinearity error? How it is different than Hysteresis error?
4. Explain the significance of the following information given in the specification of the following transducer,
   Thermocouple
   Sensitivity: nickel chromium/nickel aluminum thermocouple: 0.039 mV/ºC when the cold junction is at 0 ºC.

References:

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.
2. Regtien, P. P. L., Sensors for mechatronics, Elesevier, USA, 2012.
3. Tonshoff, H.K. and I. Inasaki, Sensors in manufacturing, Wiley-VCH, 2001.

Module 2: Sensors and signal processing
Lecture 2
Displacement and position sensors

Displacement sensors are basically used for the measurement of movement of an object. Position sensors are employed to determine the position of an object in relation to some reference point.

Proximity sensors are a type of position sensor and are used to trace when an object has moved with in particular critical distance of a transducer.

Displacement sensors

1. Potentiometer Sensors

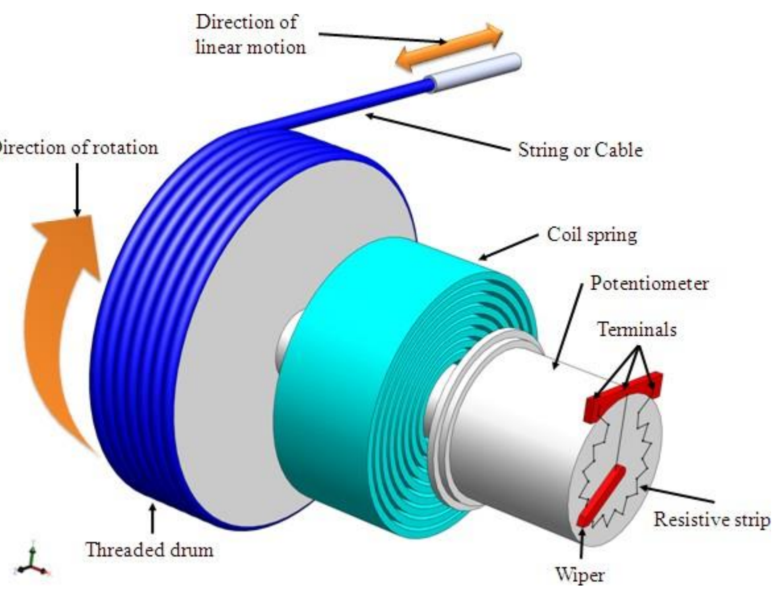

Figure 2.2.1 Schematic of a potentiometer sensor for measurement of linear displacement

Figure 2.2.1 shows the construction of a rotary type potentiometer sensor employed to measure the linear displacement. The potentiometer can be of linear or angular type. It works on the principle of conversion of mechanical displacement into an electrical signal. The sensor has a resistive element and a sliding contact (wiper). The slider moves along this conductive body, acting as a movable electric contact.

The object of whose displacement is to be measured is connected to the slider by using

- a rotating shaft (for angular displacement)
- a moving rod (for linear displacement)
- a cable that is kept stretched during operation

The resistive element is a wire wound track or conductive plastic. The track comprises of large number of closely packed turns of a resistive wire. Conductive plastic is made up of plastic resin embedded with the carbon powder. Wire wound track has a resolution of the order of ± 0.01 % while the conductive plastic may have the resolution of about 0.1 µm.

During the sensing operation, a voltage V_s is applied across the resistive element. A voltage divider circuit is formed when slider comes into contact with the wire. The output voltage (V_A) is measured as shown in the figure 2.2.2. The output voltage is proportional to the displacement of the slider over the wire. Then the output parameter displacement is calibrated against the output voltage V_A.

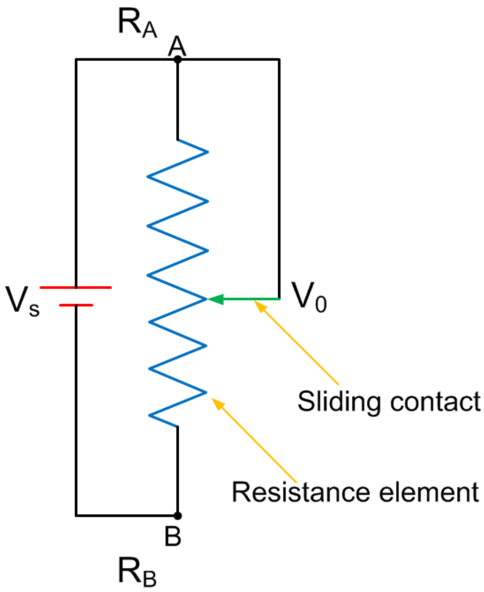

Figure 2.2.2 Potentiometer: electric circuit

$V_A = I\ R_A$ (2.2.1)

But $I = V_S / (R_A + R_B)$ (2.2.2)

Therefore $V_A = V_S\ R_A / (R_A + R_B)$ (2.2.3)

As we know that $R = \rho\ L / A$, where ρ is electrical resistivity, L is length of resistor and A is area of cross section

$V_A = V_S\ L_A / (L_A + L_B)$ (2.2.4)

Applications of potentiometer

These sensors are primarily used in the control systems with a feedback loop to ensure that the moving member or component reaches its commanded position.

These are typically used on machine-tool controls, elevators, liquid-level assemblies, forklift trucks, automobile throttle controls. In manufacturing, these are used in control of injection molding machines, woodworking machinery, printing, spraying, robotics, etc. These are also used in computer-controlled monitoring of sports equipment.

2. *Strain Gauges*

The strain in an element is a ratio of change in length in the direction of applied load to the original length of an element. The strain changes the resistance *R* of the element. Therefore, we can say,

$\Delta R/R \propto \varepsilon$;

$$\Delta R/R = G\,\varepsilon \qquad (2.2.5)$$

where G is the constant of proportionality and is called as gauge factor. In general, the value of G is considered in between 2 to 4 and the resistances are taken of the order of 100 Ω.

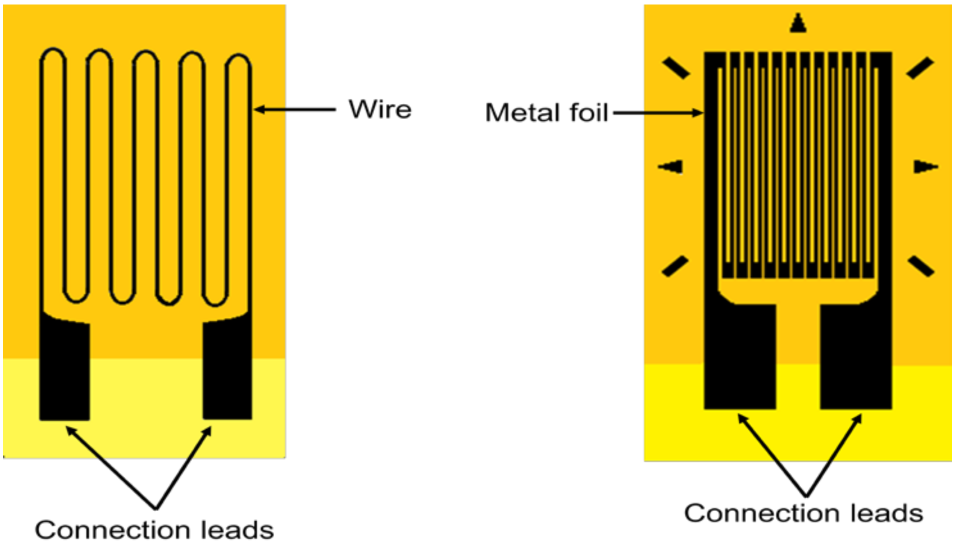

Figure 2.2.3 A pattern of resistive foils

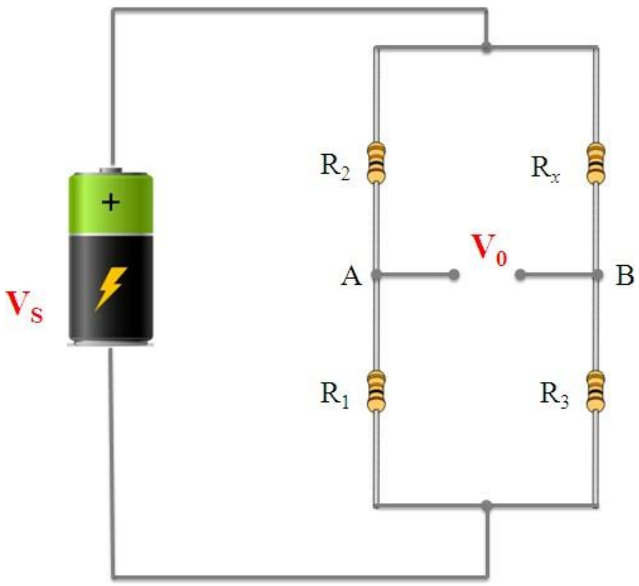

Figure 2.2.4 Wheatstone's bridge

Resistance strain gauge follows the principle of change in resistance as per the equation 2.2.5. It comprises of a pattern of resistive foil arranged as shown in Figure 2.2.3. These foils are made of Constantan alloy (copper-nickel 55-45% alloy) and are bonded to a backing material plastic (ployimide), epoxy or glass fiber reinforced epoxy. The strain gauges are secured to the workpiece by using epoxy or Cyanoacrylate cement Eastman 910 SL. As the workpiece undergoes change in its shape due to external loading, the resistance of strain gauge element changes. This change in resistance can be detected by a using a Wheatstone's resistance bridge as shown in Figure 2.2.4. In the balanced bridge we can have a relation,

$$R_2 / R_1 = R_x / R_3 \qquad (2.2.6)$$

where R_x is resistance of strain gauge element, R_2 is balancing/adjustable resistor, R_1 and R_3 are known constant value resistors. The measured deformation or displacement by the stain gauge is calibrated against change in resistance of adjustable resistor R_2 which makes the voltage across nodes A and B equal to zero.

Applications of strain gauges

Strain gauges are widely used in experimental stress analysis and diagnosis on machines and failure analysis. They are basically used for multi-axial stress fatigue testing, proof testing, residual stress and vibration measurement, torque measurement, bending and deflection measurement, compression and tension measurement and strain measurement.

Strain gauges are primarily used as sensors for machine tools and safety in automotives. In particular, they are employed for force measurement in machine tools, hydraulic or pneumatic press and as impact sensors in aerospace vehicles.

3. *Capacitive element based sensor*

Capacitive sensor is of non-contact type sensor and is primarily used to measure the linear displacements from few millimeters to hundreds of millimeters. It comprises of three plates, with the upper pair forming one capacitor and the lower pair another. The linear displacement might take in two forms:

a. one of the plates is moved by the displacement so that the plate separation changes
b. area of overlap changes due to the displacement.

Figure 2.2.5 shows the schematic of three-plate capacitive element sensor and displacement measurement of a mechanical element connected to the plate 2.

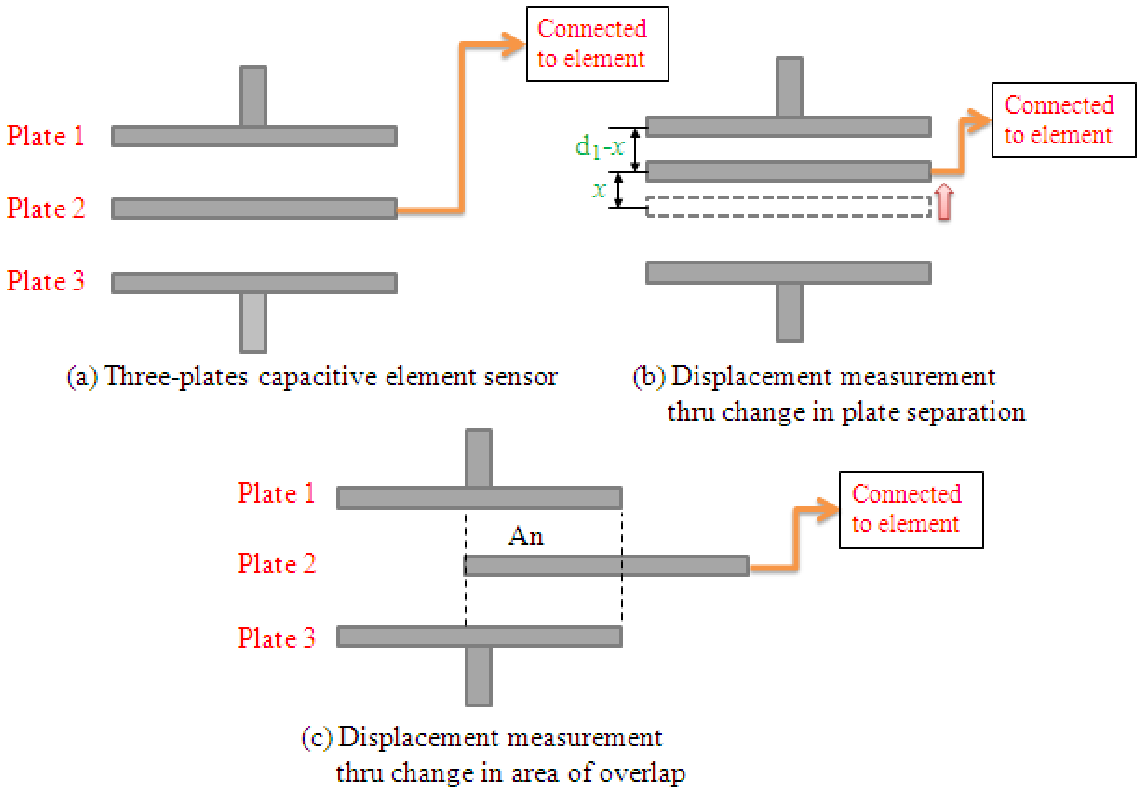

Figure 2.2.5 Displacement measurement using capacitive element sensor

The capacitance C of a parallel plate capacitor is given by,

$$C = \varepsilon_r \varepsilon_o A / d \qquad (2.2.7)$$

where ε_r is the relative permittivity of the dielectric between the plates, ε_o permittivity of free space, *A* area of overlap between two plates and *d* the plate separation.

As the central plate moves near to top plate or bottom one due to the movement of the element/workpiece of which displacement is to be measured, separation in between the plate changes. This can be given as,

$$C_1 = (\varepsilon_r \varepsilon_o A) / (d + x) \qquad (2.2.8)$$

$$C_2 = (\varepsilon_r \varepsilon_o A) / (d - x) \qquad (2.2.9)$$

When C1 and C2 are connected to a Wheatsone's bridge, then the resulting out-of-balance voltage would be in proportional to displacement x.

Capacitive elements can also be used as proximity sensor. The approach of the object towards the sensor plate is used for induction of change in plate separation. This changes the capacitance which is used to detect the object.

Applications of capacitive element sensors

- Feed hopper level monitoring
- Small vessel pump control
- Grease level monitoring
- Level control of liquids
- Metrology applications
  - to measure shape errors in the part being produced
  - to analyze and optimize the rotation of spindles in various machine tools such as surface grinders, lathes, milling machines, and air bearing spindles by measuring errors in the machine tools themselves
- Assembly line testing
  - to test assembled parts for uniformity, thickness or other design features
  - to detect the presence or absence of a certain component, such as glue etc.

4. Linear variable differential transformer (LVDT)

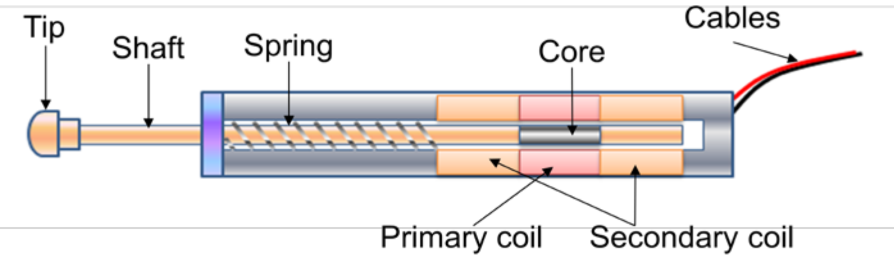

Figure 2.2.6 Construction of a LVDT sensor

Linear variable differential transformer (LVDT) is a primary transducer used for measurement of linear displacement with an input range of about ± 2 to ± 400 mm in general. It has non-linearity error ± 0.25% of full range. Figure 2.2.6 shows the construction of a LVDT sensor. It has three coils symmetrically spaced along an insulated tube. The central coil is primary coil and the other two are secondary coils. Secondary coils are connected in series in such a way that their outputs oppose each other. A magnetic core attached to the element of which displacement is to be monitored is placed inside the insulated tube.

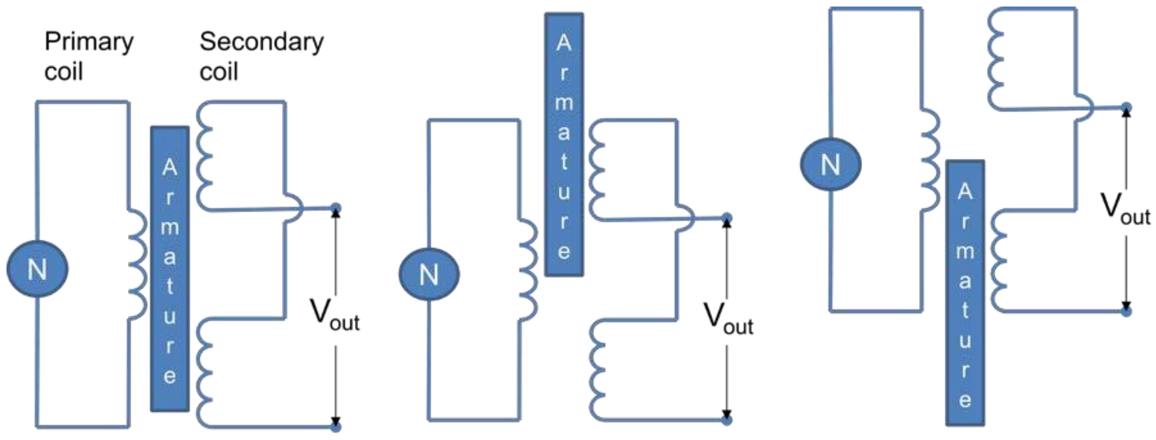

Figure 2.2.7 Working of LVDT sensor

Due to an alternating voltage input to the primary coil, alternating electro-magnetic forces (emfs) are generated in secondary coils. When the magnetic core is centrally placed with its half portion in each of the secondary coil regions then the resultant voltage is zero. If the core is displaced from the central position as shown in Figure 2.2.7, say, more in secondary coil 1 than in coil 2, then more emf is generated in one coil i.e. coil 1 than the other, and there is a resultant voltage from the coils. If the magnetic core is further displaced, then the value of resultant voltage increases in proportion with the displacement. With the help of signal processing devices such as low pass filters and demodulators, precise displacement can be measured by using LVDT sensors.

LVDT exhibits good repeatability and reproducibility. It is generally used as an absolute position sensor. Since there is no contact or sliding between the constituent elements of the sensor, it is highly reliable. These sensors are completely sealed and are widely used in Servomechanisms, automated measurement in machine tools.

A rotary variable differential transformer (RVDT) can be used for the measurement of rotation. Readers are suggested to prepare a report on principle of working and construction of RVDT sensor.

Applications of LVDT sensors

- Measurement of spool position in a wide range of servo valve applications
- To provide displacement feedback for hydraulic cylinders
- To control weight and thickness of medicinal products viz. tablets or pills
- For automatic inspection of final dimensions of products being packed for dispatch
- To measure distance between the approaching metals during Friction welding process
- To continuously monitor fluid level as part of leak detection system
- To detect the number of currency bills dispensed by an ATM

Quiz:

1. Explain the principle of working of LVDT.
2. Describe the working of RVDT with a neat sketch.
3. List the applications of potentiometer sensor in/around your home and office/university.

References

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.

Module 2: Sensors and signal processing
Lecture 3
Displacement, position and proximity sensors

1. Eddy current proximity sensors

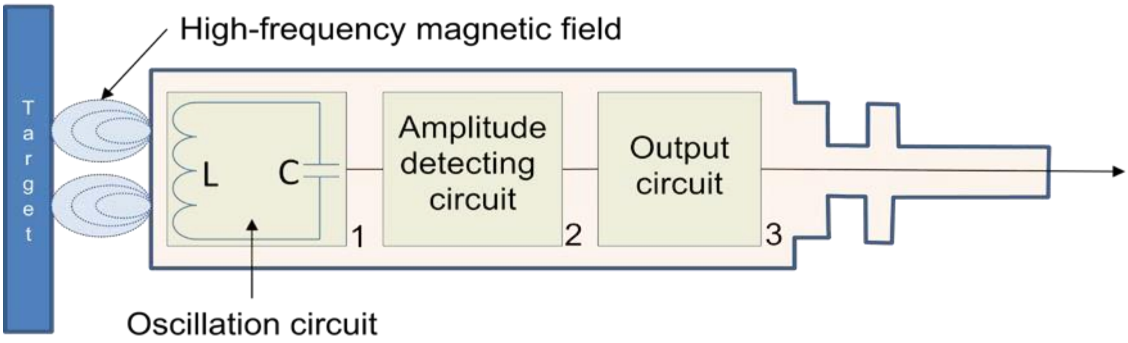

Figure 2.3.1 Schematic of Inductive Proximity Sensor

Eddy current proximity sensors are used to detect non-magnetic but conductive materials. They comprise of a coil, an oscillator, a detector and a triggering circuit. Figure 2.3.1 shows the construction of eddy current proximity switch. When an alternating current is passed thru this coil, an alternative magnetic field is generated. If a metal object comes in the close proximity of the coil, then eddy currents are induced in the object due to the magnetic field. These eddy currents create their own magnetic field which distorts the magnetic field responsible for their generation. As a result, impedance of the coil changes and so the amplitude of alternating current. This can be used to trigger a switch at some pre-determined level of change in current.

Eddy current sensors are relatively inexpensive, available in small in size, highly reliable and have high sensitivity for small displacements.

Applications of eddy current proximity sensors

- Automation requiring precise location
- Machine tool monitoring
- Final assembly of precision equipment such as disk drives
- Measuring the dynamics of a continuously moving target, such as a vibrating element,
- Drive shaft monitoring
- Vibration measurements

2. *Inductive proximity switch*

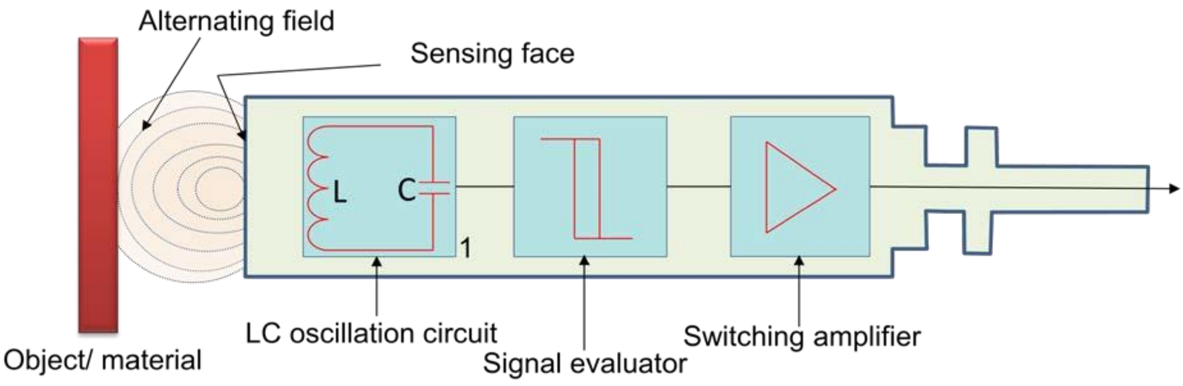

Figure 2.3.2 Schematic of Inductive Proximity Switch

Inductive proximity switches are basically used for detection of metallic objects. Figure 2.3.2 shows the construction of inductive proximity switch. An inductive proximity sensor has four components; the coil, oscillator, detection circuit and output circuit. An alternating current is supplied to the coil which generates a magnetic field. When, a metal object comes closer to the end of the coil, inductance of the coil changes. This is continuously monitored by a circuit which triggers a switch when a preset value of inductance change is occurred.

Applications of inductive proximity switches

- Industrial automation: counting of products during production or transfer
- Security: detection of metal objects, arms, land mines

3. *Optical encoders*

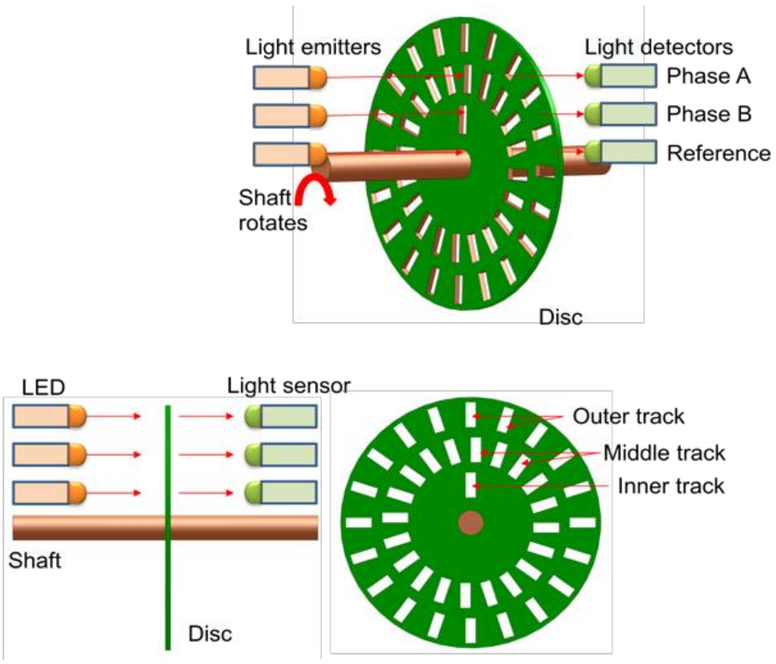

Figure 2.3.3 Construction and working of optical encoder

Optical encoders provide digital output as a result of linear / angular displacement. These are widely used in the Servo motors to measure the rotation of shafts. Figure 2.3.3 shows the construction of an optical encoder. It comprises of a disc with three concentric tracks of equally spaced holes. Three light sensors are employed to detect the light passing thru the holes. These sensors produce electric pulses which give the angular displacement of the mechanical element e.g. shaft on which the Optical encoder is mounted. The inner track has just one hole which is used locate the 'home' position of the disc. The holes on the middle track offset from the holes of the outer track by one-half of the width of the hole. This arrangement provides the direction of rotation to be determined. When the disc rotates in clockwise direction, the pulses in the outer track lead those in the inner; in counter clockwise direction they lag behind. The resolution can be determined by the number of holes on disc. With 100 holes in one revolution, the resolution would be,

$360^o/100 = 3.6^o$.

4. *Pneumatic Sensors*

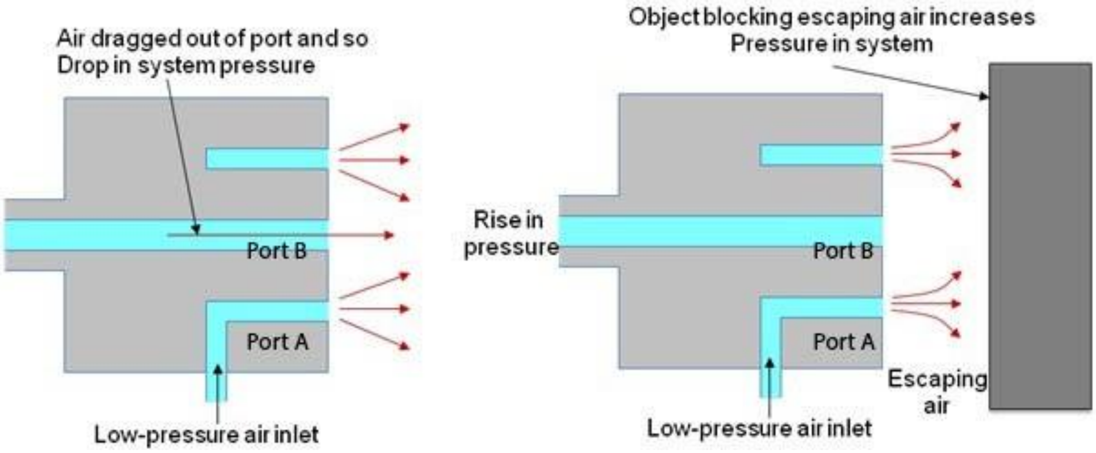

Figure 2.3.4 Working of Pneumatic Sensors [1]

Pneumatic sensors are used to measure the displacement as well as to sense the proximity of an object close to it. The displacement and proximity are transformed into change in air pressure. Figure 2.3.4 shows a schematic of construction and working of such a sensor. It comprises of three ports. Low pressure air is allowed to escape through port A. In the absence of any obstacle / object, this low pressure air escapes and in doing so, reduces the pressure in the port B. However when an object obstructs the low pressure air (Port A), there is rise in pressure in output port B. This rise in pressure is calibrated to measure the displacement or to trigger a switch. These sensors are used in robotics, pneumatics and for tooling in CNC machine tools.

5. *Proximity Switches*

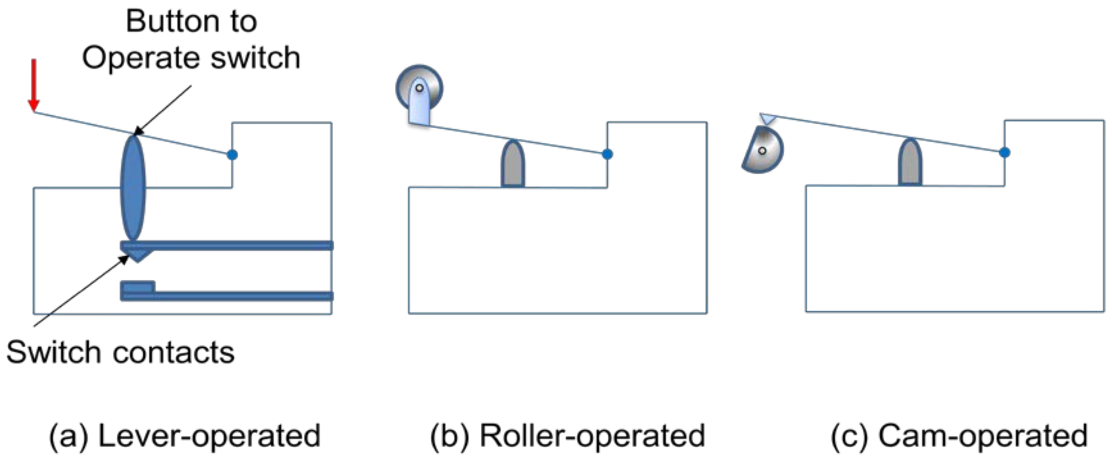

Figure 2.3.5 Configurations of contact type proximity switch [1]

Figure 2.3.5 shows a number of configurations of contact-type proximity switch being used in manufacturing automation. These are small electrical switches which require physical contact and a small operating force to close the contacts. They are basically employed on conveyor systems to detect the presence of an item on the conveyor belt.

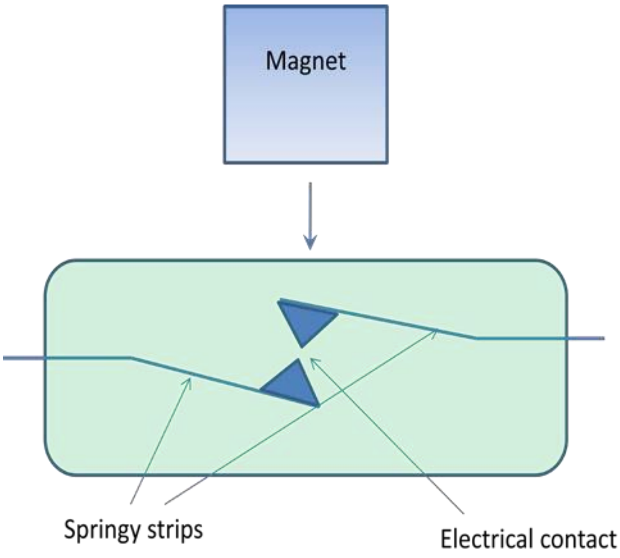

Figure 2.3.6 Reed Switch [1]

Magnet based Reed switches are used as proximity switches. When a magnet attached to an object brought close to the switch, the magnetic reeds attract to each other and close the switch contacts. A schematic is shown in Figure 2.3.6.

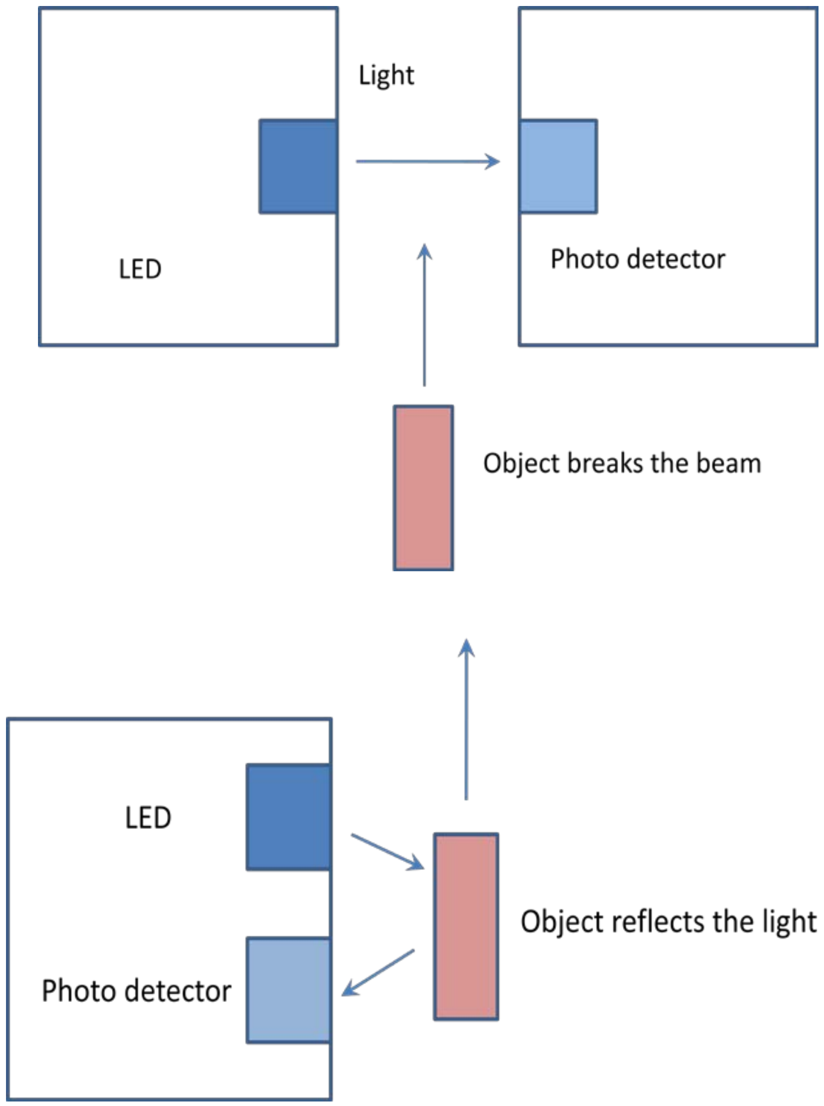

Figure 2.3.7 LED based proximity sensors [1]

Photo emitting devices such as Light emitting diodes (LEDs) and photosensitive devices such as photo diodes and photo transistors are used in combination to work as proximity sensing devices. Figure 2.3.7 shows two typical arrangements of LEDs and photo diodes to detect the objects breaking the beam and reflecting light.

6. *Hall effect sensor*

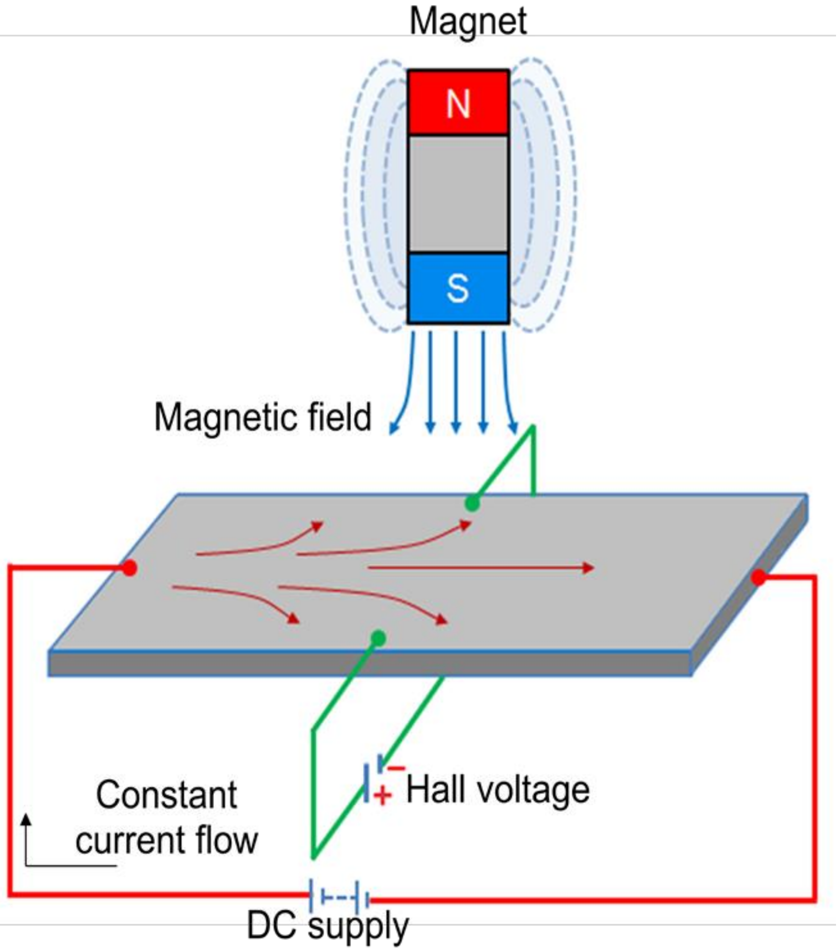

Figure 2.3.8 Principle of working of Hall effect sensor

Figure 2.3.8 shows the principle of working of Hall effect sensor. Hall effect sensors work on the principle that when a beam of charge particles passes through a magnetic field, forces act on the particles and the current beam is deflected from its straight line path. Thus one side of the disc will become negatively charged and the other side will be of positive charge. This charge separation generates a potential difference which is the measure of distance of magnetic field from the disc carrying current.

The typical application of Hall effect sensor is the measurement of fluid level in a container. The container comprises of a float with a permanent magnet attached at its top. An electric circuit with a current carrying disc is mounted in the casing. When the fluid level increases, the magnet will come close to the disc and a potential difference generates. This voltage triggers a switch to stop the fluid to come inside the container.

These sensors are used for the measurement of displacement and the detection of position of an object. Hall effect sensors need necessary signal conditioning circuitry. They can be operated at 100 kHz. Their non-contact nature of operation, good immunity to environment contaminants and ability to sustain in severe conditions make them quite popular in industrial automation.

Quiz:

1. To detect non-conducting metallic objects which sensor would be useful?
2. If a digital optical encoder has 7 tracks, then the minimum angular motion that can be measured by this device_________________.
3. Explain in brief two applications of "Reed switch".
4. Explain the principle of working of Hall effect sensor.

References

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.

Module 2: Sensors and signal processing
Lecture 4

Velocity, motion, force and pressure sensors

1. Tachogenerator

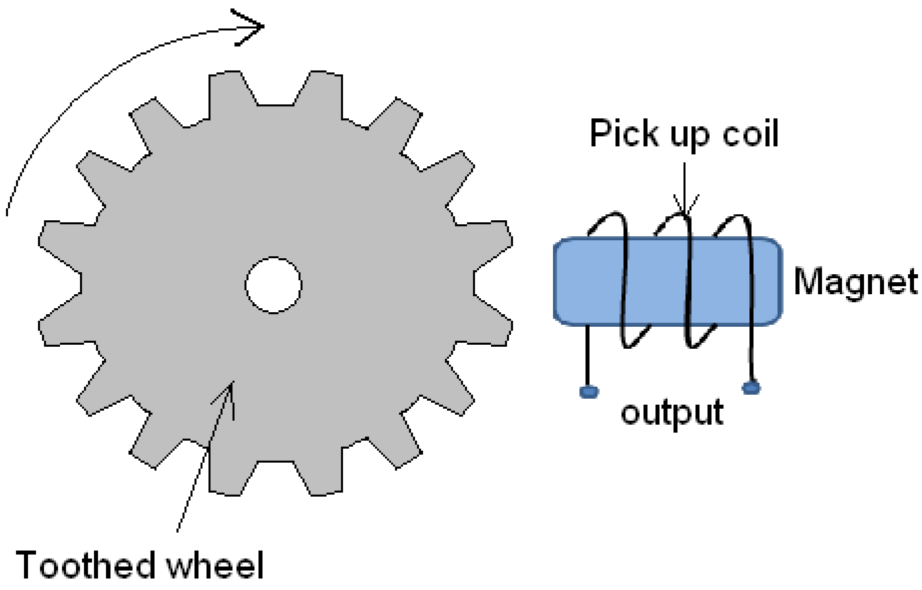

Figure 2.4.1 Principle of working of Techogenerator [1]

Tachogenerator works on the principle of variable reluctance. It consists of an assembly of a toothed wheel and a magnetic circuit as shown in figure 2.4.1. Toothed wheel is mounted on the shaft or the element of which angular motion is to be measured. Magnetic circuit comprising of a coil wound on a ferromagnetic material core. As the wheel rotates, the air gap between wheel tooth and magnetic core changes which results in cyclic change in flux linked with the coil. The alternating emf generated is the measure of angular motion. A pulse shaping signal conditioner is used to transform the output into a number of pulses which can be counted by a counter.

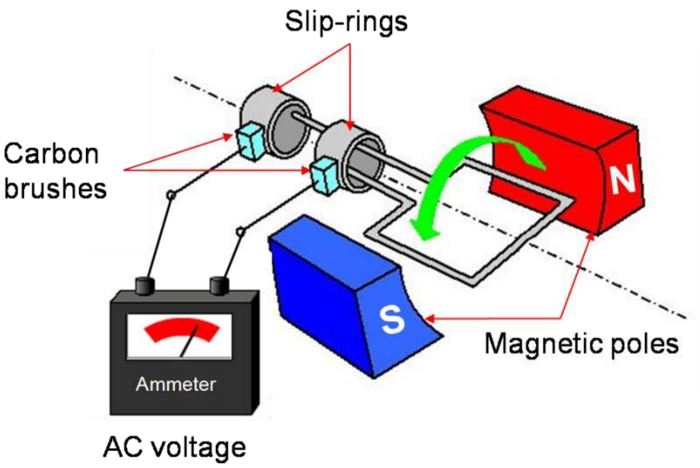

Figure 2.4.2 Construction and working of AC generator

An alternating current (AC) generator can also be used as a techogneratior. It comprises of rotor coil which rotates with the shaft. Figure 2.4.2 shows the schematic of AC generator. The rotor rotates in the magnetic field produced by a stationary permanent magnet or electromagnet. During this process, an alternating emf is produced which is the measure of the angular velocity of the rotor. In general, these sensors exhibit nonlinearity error of about ± 0.15% and are employed for the rotations up to about 10000 rev/min.

2. *Pyroelectric sensors*

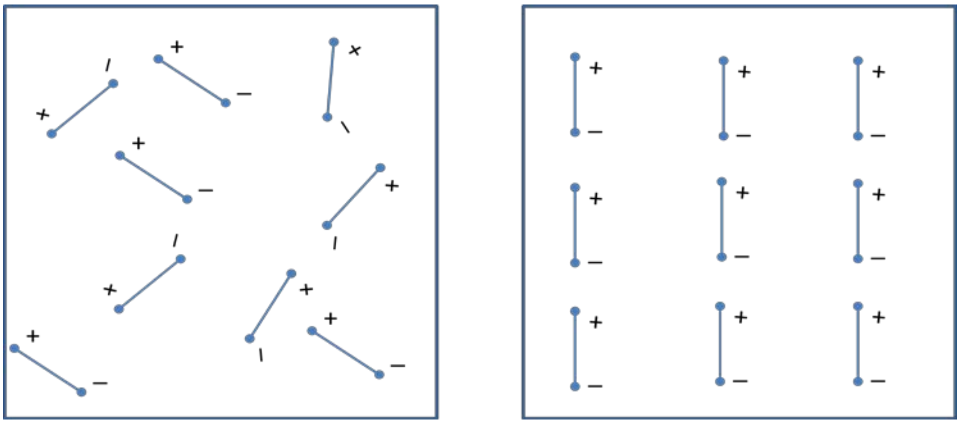

Figure 2.4.3 Principle of pyroelectricity

These sensors work on the principle of *pyroelectricity*, which states that a crystal material such as Lithium tantalite generates charge in response to heat flow. In presence of an electric field, when such a crystal material heats up, its electrical dipoles line up as shown in figure 2.4.3. This is called as polarization. On cooling, the material retains its polarization. In absence of electric field, when this polarized material is subjected to infra red irradiation, its polarization reduces. This phenomenon is the measure of detection of movement of an object.

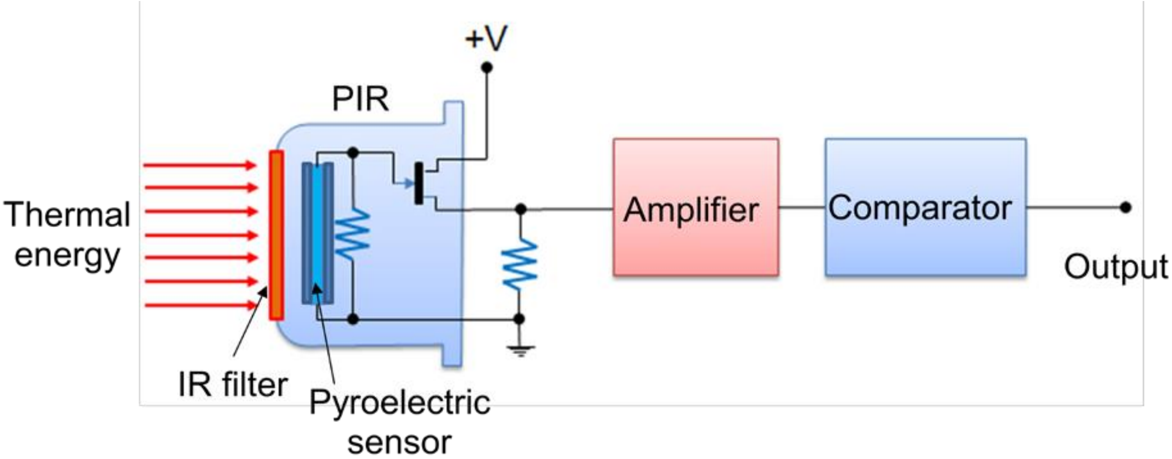

Figure 2.4.4 Construction and working a Pyroelectric sensor

Pyroelectric sensor comprises of a thick element of polarized material coated with thin film electrodes on opposite faces as shown in figure 2.4.4. Initially the electrodes are in electrical equilibrium with the polarized material. On incident of infra red, the material heats up and reduces its polarization. This leads to charge imbalance at the interface of crystal and electrodes. To balance this disequilibrium, measurement circuit supplies the charge, which is calibrated against the detection of an object or its movement.

Applications of Pyroelectric sensors [2]

- Intrusion detector
- Optothermal detector
- Pollution detector
- Position sensor
- Solar cell studies
- Engine analysis

3. *Strain Gauge as force Sensor*

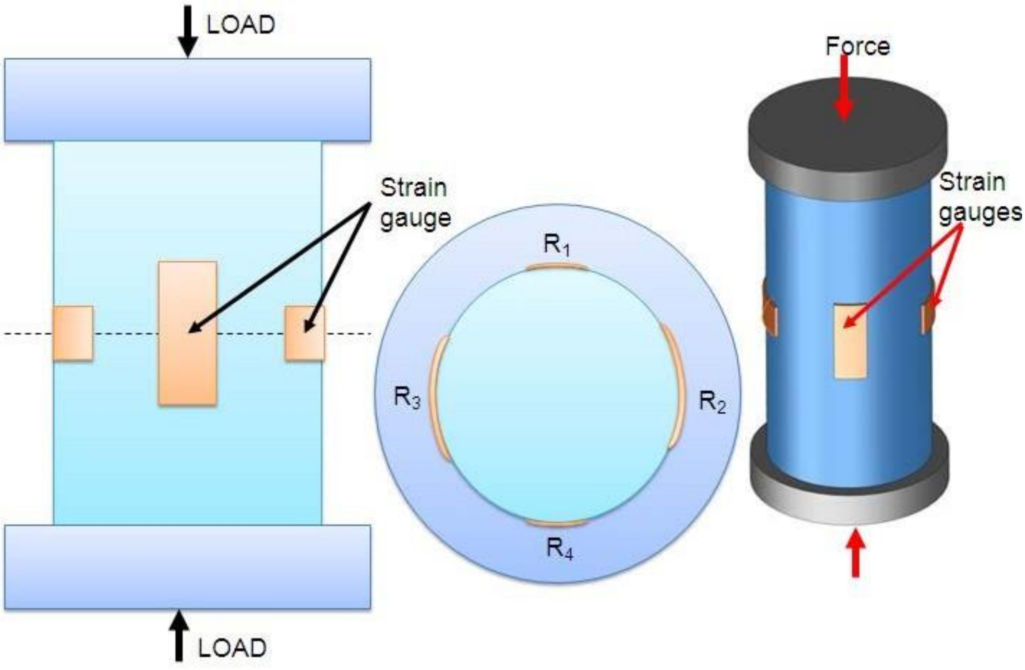

Figure 2.4.5 Strain gauge based Load cell

Strain gauge based sensors work on the principle of change in electrical resistance. When, a mechanical element subjects to a tension or a compression the electric resistance of the material changes. This is used to measure the force acted upon the element. The details regarding the construction of strain gauge transducer are already presented in Lecture 2 of Module 2.

Figure 2.4.5 shows a strain gauge load cell. It comprises of cylindrical tube to which strain gauges are attached. A load applied on the top collar of the cylinder compress the strain gauge element which changes its electrical resistance. Generally strain gauges are used to measure forces up to 10 MN. The non-linearity and repeatability errors of this transducer are ±0.03% and ±0.02% respectively.

4. *Fluid pressure*

Chemical, petroleum, power industry often need to monitor fluid pressure. Various types of instruments such as diaphragms, capsules, and bellows are used to monitor the fluid pressure. Specially designed strain gauges doped in diaphragms are generally used to measure the inlet manifold pressure in applications such as automobiles. A typical arrangement of strain gauges on a diaphragm is shown in figure 2.4.6. Application of pressurized fluid displaces the diaphragm. This displacement is measured by the stain gauges in terms of radial and/or lateral strains. These strain gauges are connected to form the arms of a Wheatstone bridge.

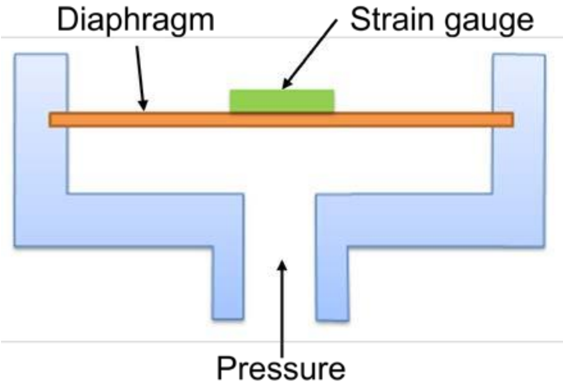

Figure 2.4.6 A diaphragm

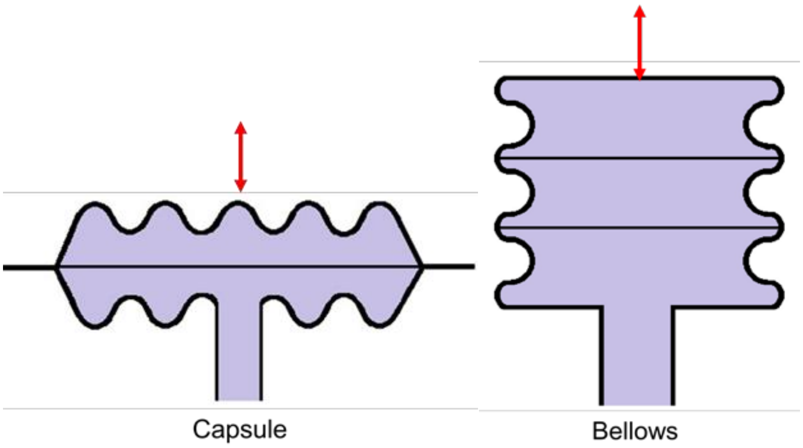

Figure 2.4.7 Schematic of Capsule and Bellow

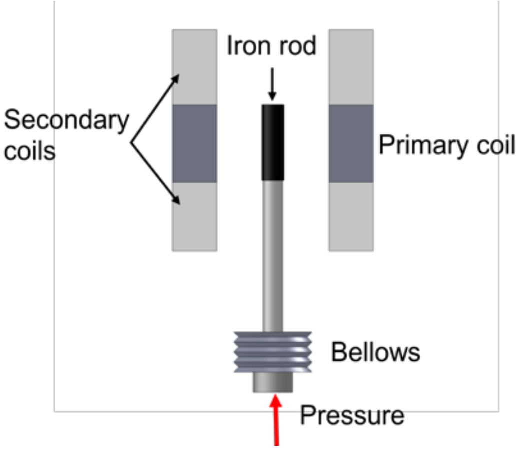

Figure 2.4.8 Bellow with a LVDT [1]

Capsule is formed by combining two corrugated diaphragms. It has enhanced sensitivity in comparison with that of diaphragms. Figure 2.4.7 shows a schematic of a Capsule and a Bellow. A stack of capsules is called as 'Bellows'. Bellows with a LVDT sensor measures the fluid pressure in terms of change in resultant voltage across the secondary coils of LVDT. Figure 2.4.8 shows a typical arrangement of the same.

5. Tactile sensors

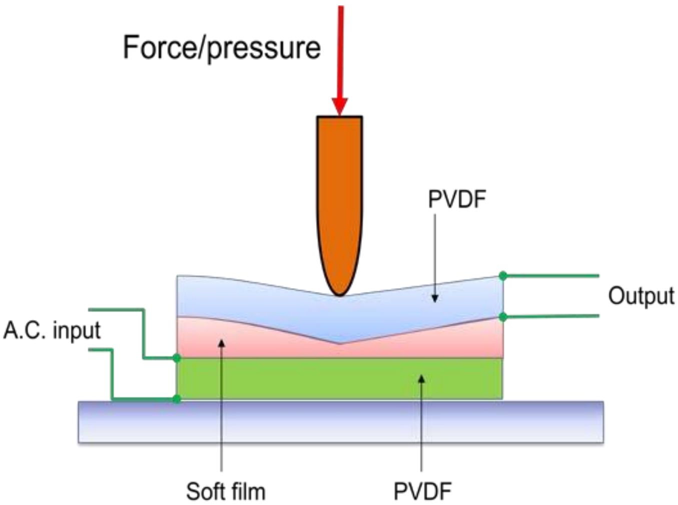

Figure 2.4.9 Schematic of a tactile sensor [1]

In general, tactile sensors are used to sense the contact of fingertips of a robot with an object. They are also used in manufacturing of 'touch display' screens of visual display units (VDUs) of CNC machine tools. Figure 2.4.9 shows the construction of piezo-electric polyvinylidene fluoride (PVDF) based tactile sensor. It has two PVDF layers separated by a soft film which transmits the vibrations. An alternating current is applied to lower PVDF layer which generates vibrations due to reverse piezoelectric effect. These vibrations are transmitted to the upper PVDF layer via soft film. These vibrations cause alternating voltage across the upper PVDF layer. When some pressure is applied on the upper PVDF layer the vibrations gets affected and the output voltage changes. This triggers a switch or an action in robots or touch displays.

6. Piezoelectric sensor

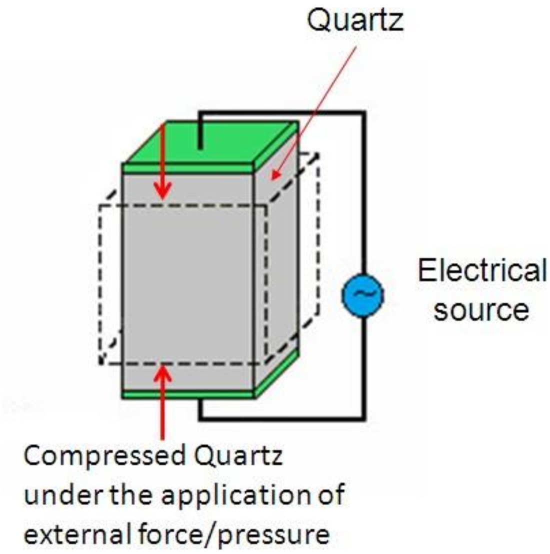

Figure 2.4.10 Principle of working of Piezoelectric sensor

Piezoelectric sensor is used for the measurement of pressure, acceleration and dynamic-forces such as oscillation, impact, or high speed compression or tension. It contains piezoelectric ionic crystal materials such as Quartz (Figure 2.4.10). On application of force or pressure these materials get stretched or compressed. During this process, the charge over the material changes and redistributes. One face of the material becomes positively charged and the other negatively charged. The net charge q on the surface is proportional to the amount x by which the charges have been displaced. The displacement is proportion to force. Therefore we can write,

$$q = kx = SF \qquad (2.4.1)$$

where k is constant and S is a constant termed the charge sensitivity.

7. Liquid flow

Liquid flow is generally measured by applying the Bernoulli's principle of fluid flow through a constriction. The quantity of fluid flow is computed by using the pressure drop measured. The fluid flow volume is proportional to square root of pressure difference at the two ends of the constriction. There are various types of fluid flow measurement devices being used in manufacturing automation such as Orifice plate, Turbine meter etc.

7.a Orifice plate:

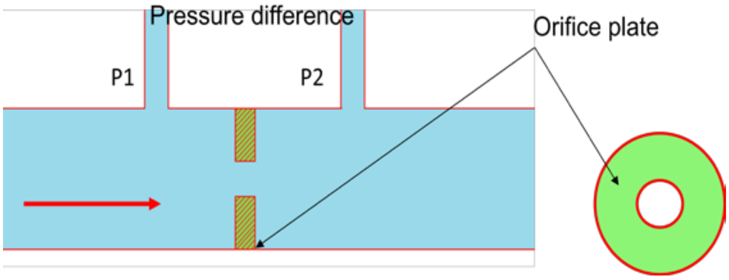

Figure 2.4.11 Orifice Plate [1]

Figure 2.4.11 shows a schematic of Orifice plate device. It has a disc with a hole at its center, through which the fluid flows. The pressure difference is measured between a point equal to the diameter of the tube upstream and a point equal to the half the diameter downstream. Orifice plate is inexpensive and simple in construction with no moving parts. It exhibits nonlinear behavior and does not work with slurries. It has accuracy of ± 1.5%.

7.b Turbine meter

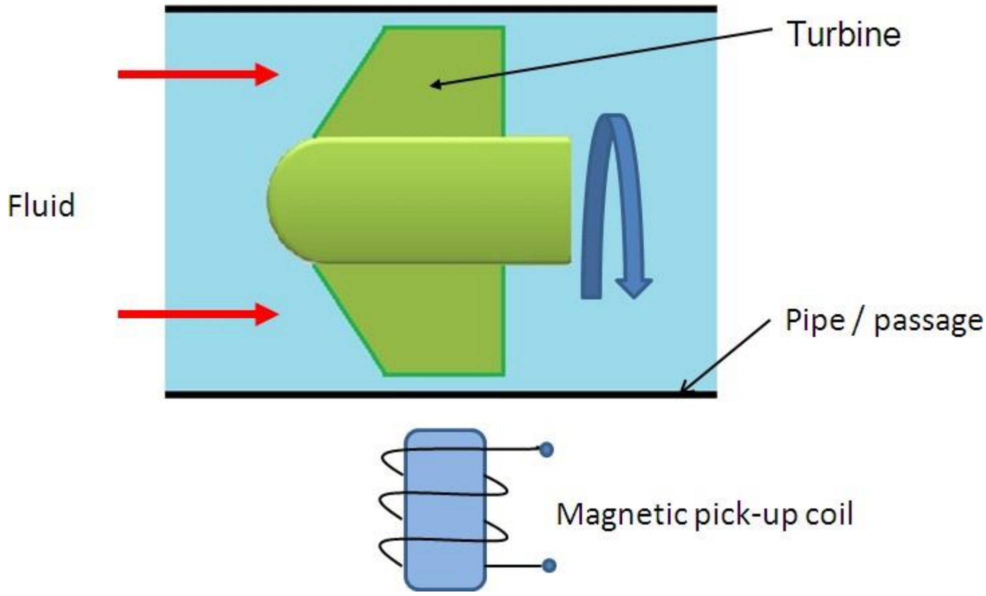

Figure 2.4.12 Schematic of turbine meter [1]

Turbine flow meter has an accuracy of ±0.3%. It has a multi blade rotor mounted centrally in the pipe along which the flow is to be measured. Figure 2.4.12 shows the typical arrangement of the rotor and a magnetic pick up coil. The fluid flow rotates the rotor. Accordingly the magnetic pick up coil counts the number of magnetic pulses generated due to the distortion of magnetic field by the rotor blades. The angular velocity is proportional to the number of pulses and fluid flow is proportional to angular velocity.

8. *Fluid level*

The level of liquid in a vessel or container can be measured,

a. directly by monitoring the position of liquid surface
b. indirectly by measuring some variable related to the height.

Direct measurements involve the use of floats however the indirect methods employ load cells. Potentiometers or LVDT sensors can be used along with the floats to measure the height of fluid column. Force sensed by the load cells is proportional to the height of fluid column.

Quiz:

1. PVDF piezoelectric polyvinylidene fluoride is used in the manufacture of__________________________sensor.
2. Suggest a suitable sensor to measure the level of sulphuric acid in a storage tank. The sensor must give an electric signal as output.
3. 'Bellows are more sensitive than capsules'. State true or false and justify your answer.
4. State the applications of pyroelectric sensors.

References

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.
2. Hossain A. and Rashid M. H., Pyroelectric Detectors and Their Applications, IEEE Trans. on Ind. Appl., 27 (5), 824-829, 1991.

Module 2: Sensors and signal processing
Lecture 5
Temperature and light sensors

Temperature conveys the state of a mechanical system in terms of expansion or contraction of solids, liquids or gases, change in electrical resistance of conductors, semiconductors and thermoelectric emfs. Temperature sensors such as bimetallic strips, thermocouples, thermistors are widely used in monitoring of manufacturing processes such as casting, molding, metal cutting etc. The construction details and principle of working of some of the temperature sensors are discussed in following sections.

1. Bimetallic strips

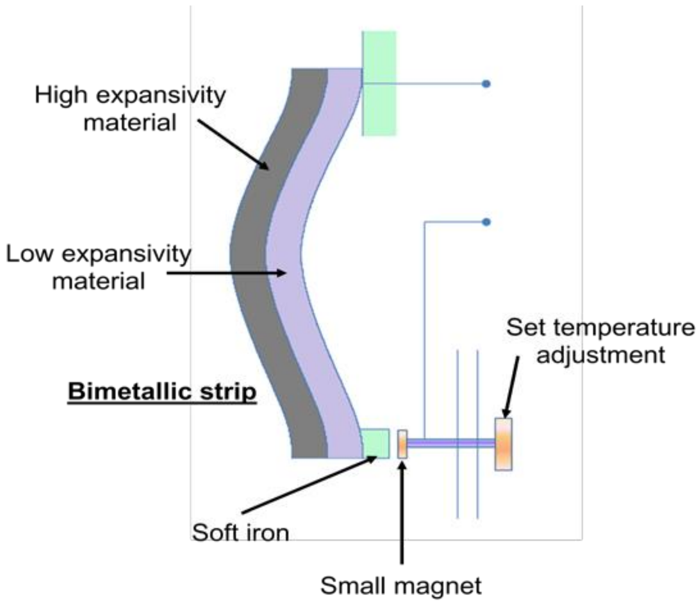

Figure 2.5.1 Construction and working of Bi-metallic strip

Bimetallic strips are used as thermal switch in controlling the temperature or heat in a manufacturing process or system. It contains two different metal strips bonded together. The metals have different coefficients of expansion. On heating the strips bend into curved strips with the metal with higher coefficient of expansion on the outside of the curve. Figure 2.5.1 shows a typical arrangement of a bimetallic strip used with a setting-up magnet. As the strips bend, the soft iron comes in closer proximity of the small magnet and further touches. Then the electric circuit completes and generates an alarm. In this way bimetallic strips help to protect the desired application from heating above the pre-set value of temperature.

2. *Resistance temperature detectors (RTDs)*

RTDs work on the principle that the electric resistance of a metal changes due to change in its temperature. On heating up metals, their resistance increases and follows a linear relationship as shown in Figure 2.5.2. The correlation is

$$R_t = R_0 (1 + \alpha T) \qquad (2.5.1)$$

where R_t is the resistance at temperature T (^{0}C) and R_0 is the temperature at 0^0C and α is the constant for the metal termed as temperature coefficient of resistance. The sensor is usually made to have a resistance of 100 Ω at 0 °C

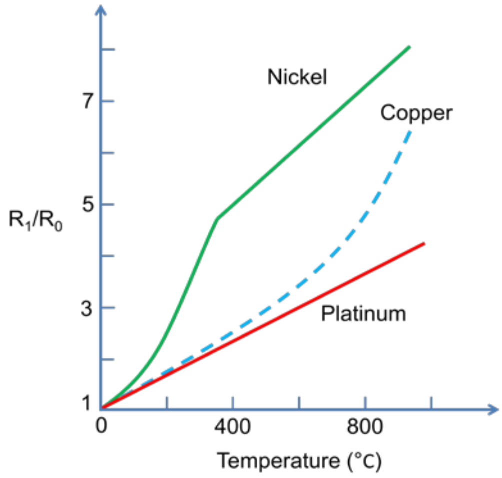

Figure 2.5.2 Behavior of RTD materials [1]

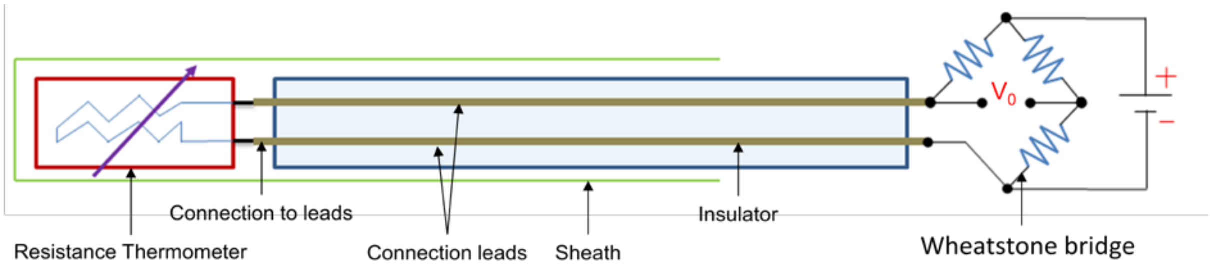

Figure 2.5.3 Construction of a Resistance temperature detector (RTD)

Figure 2.5.3 shows the construction of a RTD. It has a resistor element connected to a Wheatstone bridge. The element and the connection leads are insulated and protected by a sheath. A small amount of current is continuously passing though the coil. As the temperature changes the resistance of the coil changes which is detected at the Wheatstone bridge.

RTDs are used in the form of thin films, wire wound or coil. They are generally made of metals such as platinum, nickel or nickel-copper alloys. Platinum wire held by a high-temperature glass adhesive in a ceramic tube is used to measure the temperature in a metal furnace. Other applications are:

- Air conditioning and refrigeration servicing
- Food Processing
- Stoves and grills
- Textile production
- Plastics processing
- Petrochemical processing
- Micro electronics
- Air, gas and liquid temperature measurement in pipes and tanks
- Exhaust gas temperature measurement

3. Thermistors

Thermistors follow the principle of decrease in resistance with increasing temperature. The material used in thermistor is generally a semiconductor material such as a sintered metal oxide (mixtures of metal oxides, chromium, cobalt, iron, manganese and nickel) or doped polycrystalline ceramic containing barium titanate (BaTiO3) and other compounds. As the temperature of semiconductor material increases the number of electrons able to move about increases which results in more current in the material and reduced resistance. Thermistors are rugged and small in dimensions. They exhibit nonlinear response characteristics.

Thermistors are available in the form of a bead (pressed disc), probe or chip. Figure 2.5.4 shows the construction of a bead type thermistor. It has a small bead of dimension from 0.5 mm to 5 mm coated with ceramic or glass material. The bead is connected to an electric circuit through two leads. To protect from the environment, the leads are contained in a stainless steel tube.

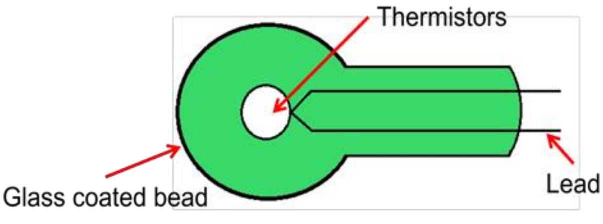

Figure 2.5.4 Schematic of a thermistor

Applications of Thermistors

- To monitor the coolant temperature and/or oil temperature inside the engine
- To monitor the temperature of an incubator
- Thermistors are used in modern digital thermostats
- To monitor the temperature of battery packs while charging
- To monitor temperature of hot ends of 3D printers
- To maintain correct temperature in the food handling and processing industry equipments
- To control the operations of consumer appliances such as toasters, coffee makers, refrigerators, freezers, hair dryers, etc.

4. *Thermocouple*

Thermocouple works on the fact that when a junction of dissimilar metals heated, it produces an electric potential related to temperature. As per Thomas Seebeck (1821), when two wires composed of dissimilar metals are joined at both ends and one of the ends is heated, then there is a continuous current which flows in the thermoelectric circuit. Figure 2.5.5 shows the schematic of thermocouple circuit. The net open circuit voltage (the Seebeck voltage) is a function of junction temperature and composition of two metals. It is given by,

$$\Delta V_{AB} = \alpha \, \Delta T \qquad (2.5.2)$$

where α, the Seebeck coefficient, is the constant of proportionality.

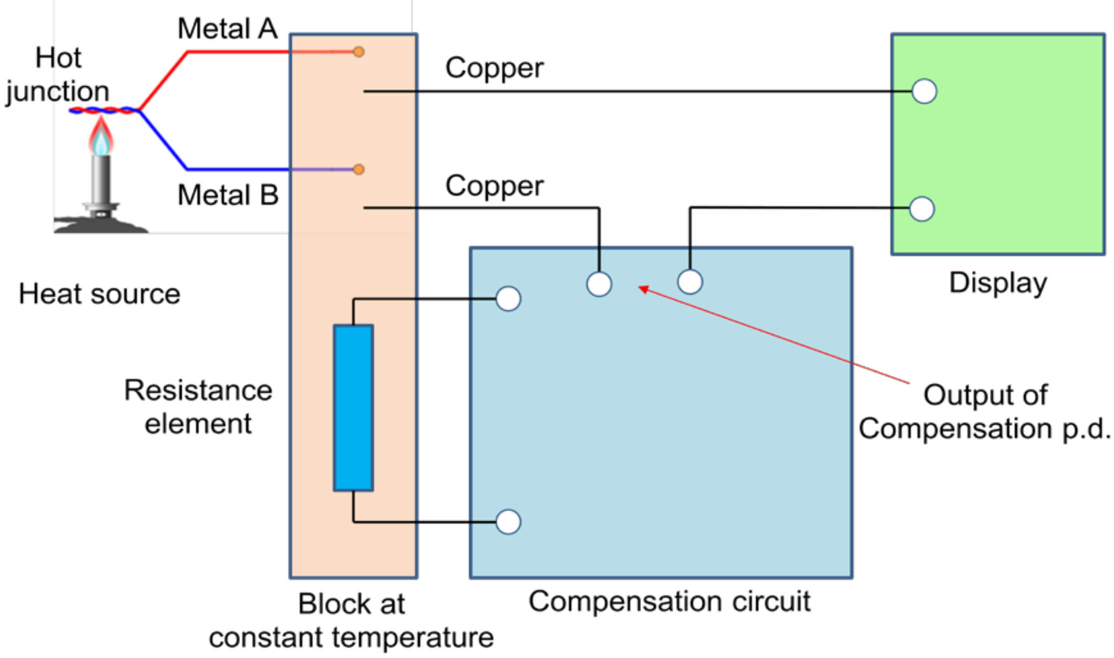

Figure 2.5.5 Schematic of thermocouple circuit

Generally, Chromel (90% nickel and 10% chromium)–Alumel (95% nickel, 2% manganese, 2% aluminium and 1% silicon) are used in the manufacture of a thermocouple. Table 2.5.1 shows the various other materials, their combinations and application temperature ranges.

Table 2.5.1 Thermocouple materials and temperature ranges [1]

Materials	**Range (ºC)**	**(µV/ºC)**
Platinum 30% rhodium/platinum 6% rhodium	0 to 1800	3
Chromel/constantan	-200 to 1000	63
Iron/constantan	-200 to 900	53
Chromel/alumel	-200 to 1300	41
Nirosil/nisil	-200 to 1300	28
Platinum/platinum 13% rhodium	0 to 1400	6
Platinum/platinum 10% rhodium	0 to 1400	6
Copper/constantan	-200 to 400	43

Applications of Thermocouples

- To monitor temperatures and chemistry throughout the steel making process
- Testing temperatures associated with process plants e.g. chemical production and petroleum refineries
- Testing of heating appliance safety
- Temperature profiling in ovens, furnaces and kilns
- Temperature measurement of gas turbine and engine exhausts
- Monitoring of temperatures throughout the production and smelting process in the steel, iron and aluminum industry

Light sensors

A light sensor is a device that is used to detect light. There are different types of light sensors such as photocell/photoresistor and photo diodes being used in manufacturing and other industrial applications.

Photoresistor is also called as light dependent resistor (LDR). It has a resistor whose resistance decreases with increasing incident light intensity. It is made of a high resistance semiconductor material, cadmium sulfide (CdS). The resistance of a CdS photoresistor varies inversely to the amount of light incident upon it. Photoresistor follows the principle of photoconductivity which results from the generation of mobile carriers when photons are absorbed by the semiconductor material.

Figure 2.5.6 shows the construction of a photo resistor. The CdS resistor coil is mounted on a ceramic substrate. This assembly is encapsulated by a resin material. The sensitive coil electrodes are connected to the control system though lead wires. On incidence of high intensity light on the electrodes, the resistance of resistor coil decreases which will be used further to generate the appropriate signal by the microprocessor via lead wires.

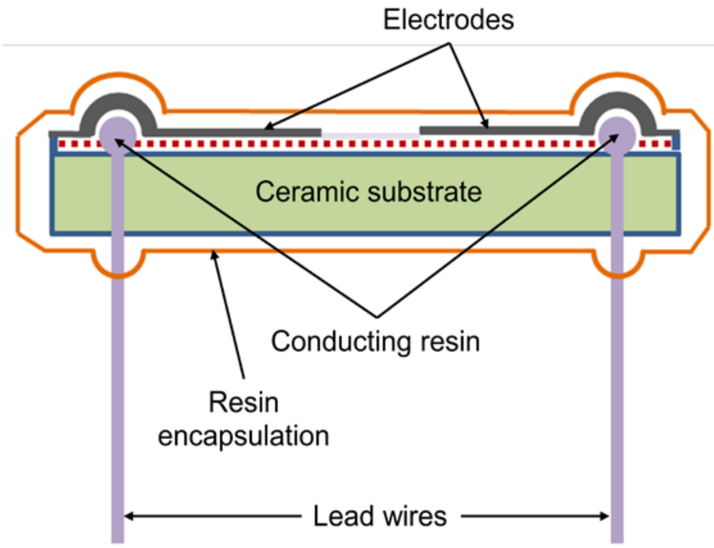

Figure 2.5.6 Construction of a photo resistor

Photoresistors are used in science and in almost any branch of industry for control, safety, amusement, sound reproduction, inspection and measurement.

Applications of photo resistor

- Computers, wireless phones, and televisions, use ambient light sensors to automatically control the brightness of a screen
- Barcode scanners used in retailer locations work using light sensor technology
- In space and robotics: for controlled and guided motions of vehicles and robots. The light sensor enables a robot to detect light. Robots can be programmed to have a specific reaction if a certain amount of light is detected.
- Auto Flash for camera
- Industrial process control

Photo diodes

Photodiode is a solid-state device which converts incident light into an electric current. It is made of Silicon. It consists of a shallow diffused p-n junction, normally a p-on-n configuration. When photons of energy greater than 1.1eV (the bandgap of silicon) fall on the device, they are absorbed and electron-hole pairs are created. The depth at which the photons are absorbed depends upon their energy. The lower the energy of the photons, the deeper they are absorbed. Then the electron-hole pairs drift apart. When the minority carriers reach the junction, they are swept across by the electric field and an electric current establishes.

Photodiodes are one of the types of photodetector, which convert light into either current or voltage. These are regular semiconductor diodes except that they may be either exposed to detect vacuum UV or X-rays or packaged with a opening or optical fiber connection to allow light to reach the sensitive part of the device.

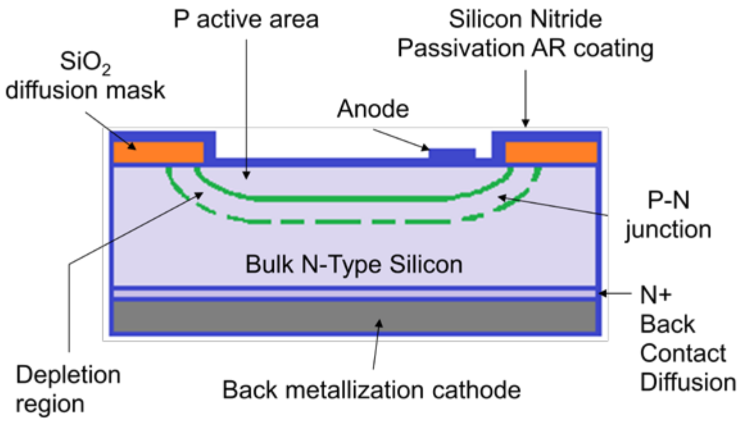

Figure 2.5.7 Construction of photo diode detector

Figure 2.5.7 shows the construction of Photo diode detector. It is constructed from single crystal silicon wafers. It is a p-n junction device. The upper layer is p layer. It is very thin and formed by thermal diffusion or ion implantation of doping material such as boron. Depletion region is narrow and is sandwiched between p layer and bulk n type layer of silicon. Light irradiates at front surface, anode, while the back surface is cathode. The incidence of light on anode generates a flow of electron across the p-n junction which is the measure of light intensity.

Applications of photo diodes

Camera: Light Meters, Automatic Shutter Control, Auto-focus, Photographic Flash Control

Medical: CAT Scanners - X ray Detection, Pulse Oximeters, Blood Particle Analyzers

Industry
- Bar Code Scanners
- Light Pens
- Brightness Controls
- Encoders
- Position Sensors
- Surveying Instruments
- Copiers - Density of Toner

Safety Equipment
- Smoke Detectors
- Flame Monitors
- Security Inspection Equipment - Airport X ray
- Intruder Alert - Security System

Automotive
• Headlight Dimmer
• Twilight Detectors
• Climate Control - Sunlight Detector

Communications
• Fiber Optic Links
• Optical Communications
• Optical Remote Control

Quiz:

1. 'In thermistor sensors, resistance decreases in a very nonlinear manner with increase in temperature.' State true or false and justify.
2. List the various temperature sensors used by we in/around our home/office/university.
3. Develop a conceptual design of a Light sensors based control system for counting a number of milk packets being packed for discharge. Assume suitable data if necessary.

References

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.

Module 2: Sensors and signal processing
Lecture 6
Signal Conditioning Devices

Signal Conditioning Operations

In previous lectures we have studied various sensors and transducers used in a mechatronics system. Transducers sense physical phenomenon such as rise in temperature and convert the measurand into an electrical signal viz. voltage or current. However these signals may not be in their appropriate forms to employ them to control a mechatronics system. Figure 2.6.1 shows various signal conditioning operations which are being carried out in controlling a mechatronics based system. The signals given by a transducer may be nonlinear in nature or may contain noise. Thus before sending these signals to the mechatronics control unit it is essential to remove the noise, nonlinearity associated with the raw output from a sensor or a transducer. It is also needed to modify the amplitude (low/high) and form (analogue/digital) of the output signals into respective acceptable limits and form which will be suitable to the control system. These activities are carried out by using signal conditioning devices and the process is termed as 'signal conditioning'.

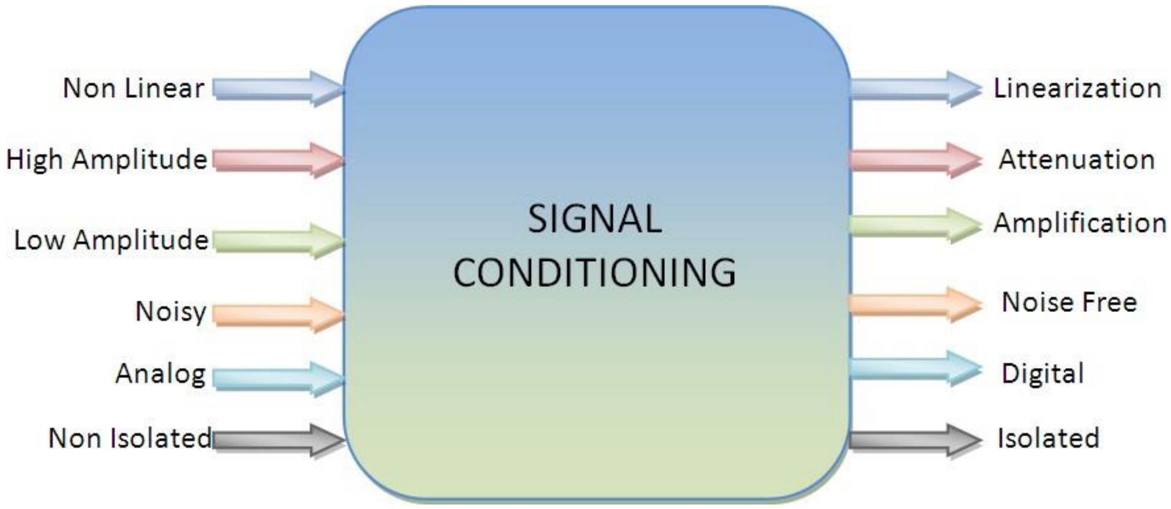

Figure 2.6.1 Signal conditioning operations

Signal conditioning system enhances the quality of signal coming from a sensor in terms of:

1. Protection
   To protect the damage to the next element of mechatronics system such microprocessors from the high current or voltage signals.

2. Right type of signal
   To convert the output signal from a transducer into the desired form i.e. voltage / current.

3. Right level of the signal
To amplify or attenuate the signals to a right /acceptable level for the next element.

4. Noise
To eliminate noise from a signal.

5. Manipulation
To manipulate the signal from its nonlinear form to the linear form.

1. Amplification/Attenuation

Various applications of Mechatronics system such as machine tool control unit of a CNC machine tool accept voltage amplitudes in range of 0 to 10 Volts. However many sensors produce signals of the order of milli volts. This low level input signals from sensors must be amplified to use them for further control action. Operational amplifiers (op-amp) are widely used for amplification of input signals. The details are as follows.

1.1 Operational amplifier (op-amp)

Operational Amplifier is a basic and an important part of a signal conditioning system. It is often abbreviated as op-amp. Op-amp is a high gain voltage amplifier with a differential input. The gain is of the order of 100000 or more. Differential input is a method of transmitting information with two different electronic signals which are generally complementary to each other. Figure 2.6.2 shows the block diagram of an op-amp. It has five terminals. Two voltages are applied at two input terminals. The output terminal provides the amplified value of difference between two input voltages. Op-amp works by using the external power supplied at *Vs+* and *Vs-* terminals.

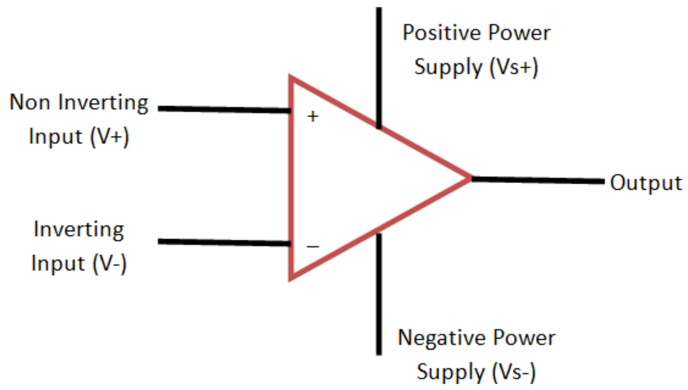

Figure 2.6.2 circuit diagram of an Op-amp

In general op-amp amplifies the difference between input voltages (V+ and V-). The output of an operational amplifier can be written as

$$V_{out} = G * (V+ - V-) \qquad (2.6.1)$$

where G is Op-amp Gain.

Figure 2.6.3 shows the inverting configuration of an op-amp. The input signal is applied at the inverting terminal of the op-amp through the input resistance R_{in}. The non-inverting terminal is grounded. The output voltage (V_{out}) is connected back to the inverting input terminal through resistive network of R_{in} and feedback resistor R_f. Now at node a, we can write,

$$I_1 = V_{in}/R_1 \qquad (2.6.2)$$

The current flowing through R_f is also I_1, because the op-amp is not drawing any current. Therefore the output voltage is given by,

$$V_{out} = -I_1 R_f = -V_{in} R_f/R_1 \qquad (2.6.3)$$

Thus the closed loop gain of op-amp can be given as,

$$G = V_{out}/V_{in} = -R_f/R_1 \qquad (2.6.4)$$

The negative sign indicates a phase shift between V_{in} and V_{out}.

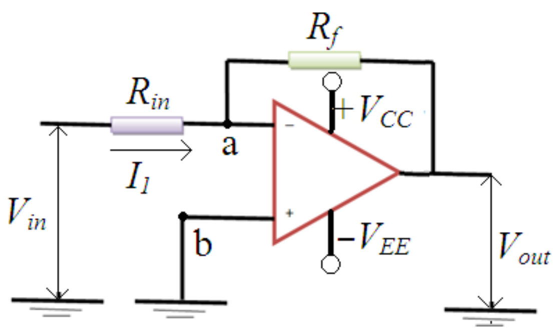

Figure 2.6.3 Inverting op-amp

1.2 Amplification of input signal by using Op-amp

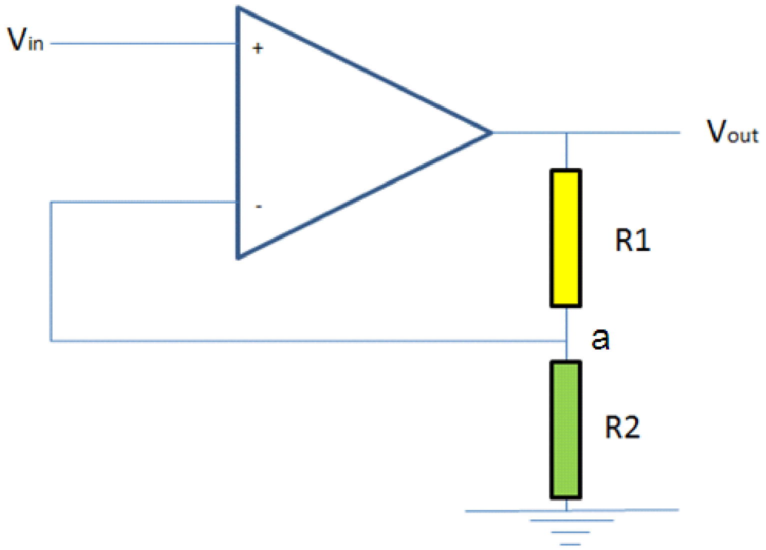

Figure 2.6.4 Amplification using an Op-amp

Figure 2.6.4 shows a configuration to amplify an input voltage signal. It has two registers connected at node a. If we consider that the voltage at positive terminal is equal to voltage at negative terminal then the circuit can be treated as two resistances in series. In series connection of resistances, the current flowing through circuit is same. Therefore we can write,

$$\frac{V_{out} - V_{in}}{R_1} = \frac{V_{in} - 0}{R_2} \qquad (2.6.5)$$

$$\frac{V_{out} - V_{in}}{R_1} = \frac{V_{in}}{R_2} \qquad (2.6.6)$$

Thus by selecting suitable values of resistances, we can obtain the desired (amplified/attenuated) output voltage for known input voltage.

There are other configurations such as Non-inverting amplifier, Summing amplifier, Subtractor, Logarithmic amplifier are being used in mechatronics applications. The detail study of all these is out of scope of the present course. Readers can refer Bolton for more details.

2. Filtering

Output signals from sensors contain noise due to various external factors like improper hardware connections, environment etc. Noise gives an error in the final output of system. Therefore it must be removed. In practice, change in desired frequency level of output signal is a commonly noted noise. This can be rectified by suing filters. Following types of filters are used in practice:

1. Low Pass Filter
2. High Pass Filter
3. Band Pass Filter
4. Band Reject Filter

2.1 Low Pass Filter

Low pass filter is used to allow low frequency content and to reject high frequency content of an input signal. Its configuration is shown in Figure 2.6.5

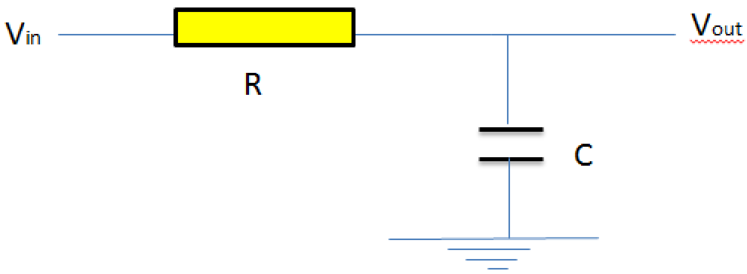

Figure 2.6.5 Circuitry of Low Pass Filter

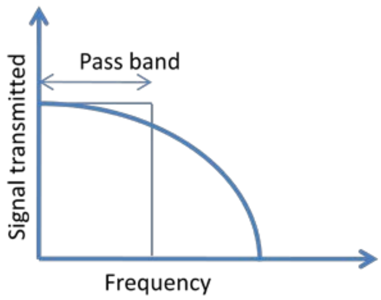

Figure 2.6.6 Pass band for low pass filter

In the circuit shown in Figure 2.6.5, resistance and capacitance are in series with voltage at resistance terminal is input voltage and voltage at capacitance terminal is output voltage. Then by applying the Ohm's Law, we can write,

$$V_{out} = \frac{\frac{1}{j\omega C}}{R + \left(\frac{1}{j\omega C}\right)} V_{in} \qquad (2.6.7)$$

$$V_{out} = \frac{1}{1 + j\omega CR} V_{in} \qquad (2.6.8)$$

From equation 2.6.8 we can say that if frequency of Input signal is low then $j\omega CR$ would be low. Thus $\frac{1}{1+j\omega CR}$ would be nearly equal to 1. However at higher frequency $j\omega CR$ would be higher, then $\frac{1}{1+j\omega CR}$ would be nearly equal to 0. Thus above circuit will act as Low Pass Filter. It selects frequencies below a breakpoint frequency ω = 1/RC as shown in Figure 2.6.6. By selecting suitable values of R and C we can obtain desired values of frequency to pass in.

2.2 High Pass Filter

These types of filters allow high frequencies to pass through it and block the lower frequencies. The figure 2.6.7 shows circuitry for high pass filter.

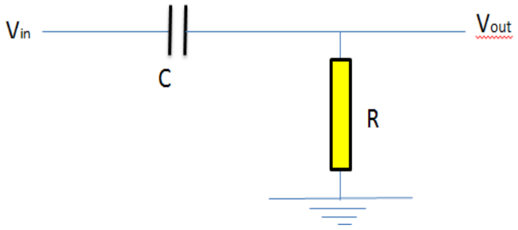

Figure 2.6.7 Circuitry of High Pass Filter

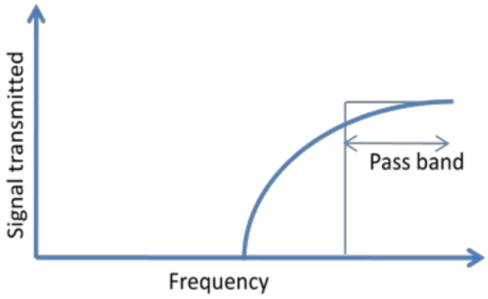

Figure 2.6.8 Pass band for high pass filter

$$V_{out} = \frac{R}{R + \left(\frac{1}{j\omega C}\right)} V_{in} \qquad (2.6.9)$$

$$V_{out} = \frac{j\omega CR}{1 + j\omega CR} V_{in} \qquad (2.6.10)$$

From equation 2.6.10, we can say that if frequency of input signal is low then $\frac{1}{j\omega C}$ would be high and thus $\frac{R}{R+\left(\frac{1}{j\omega C}\right)}$ would be nearly equal to 0. For high frequency signal, $\frac{1}{j\omega C}$ would be low and $\frac{R}{R+\left(\frac{1}{j\omega C}\right)}$ would be nearly equal to 1. Thus above circuit will act as High Pass Filter. It selects frequencies above a breakpoint frequency ω = 1/RC as shown in Figure 2.6.8. By selecting suitable values of R and C we can allow desired (high) frequency level to pass through.

2.3 Band Pass Filter

In some applications, we need to filter a particular band of frequencies from a wider range of mixed signals. For this purpose, the properties of low-pass and high-pass filters circuits can be combined to design a filter which is called as band pass filter. Band pass filter can be developed by connecting a low-pass and a high-pass filter in series as shown in figure 2.6.9.

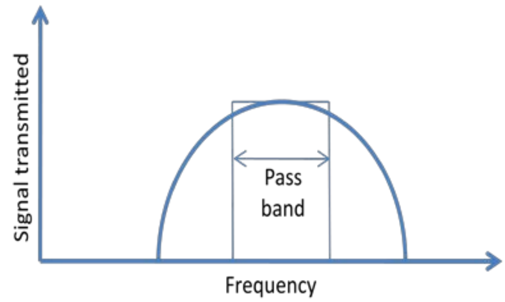

Figure 2.6.9 Band pass filter

2.4 Band Reject Filter

These filters pass all frequencies above and below a particular range set by the operator/manufacturer. They are also known as band stop filters or notch filters. They are constructed by connecting a low-pass and a high-pass filter in parallel as shown in Figure 2.6.10.

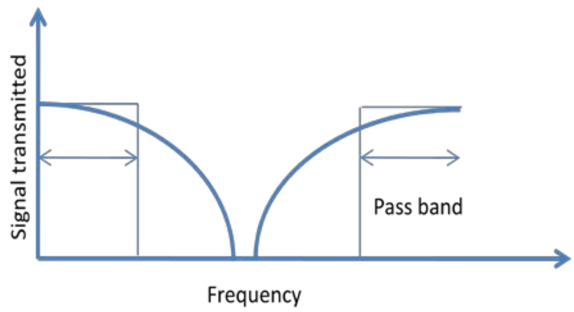

Figure 2.6.10 Band reject filter

Quiz

1. Explain the principle of working of op-amp as an inverting amplifier.
2. What kind of signal conditioning operations will be required to develop a table top CNC turning center for small job works?

Module 2: Sensors and signal processing
Lecture 7
Protection, conversion and pulse width modulation

1. Protection

In many situations sensors or transducers provide very high output signals such as high current or high voltage which may damage the next element of the control system such as microprocessor.

1.1 Protection from high current

The high current to flow in a sensitive control system can be limited by:

1. Using a series of resistors
2. Using fuse to break the circuit if current value exceeds a preset or safe value

1.2 Protection from high voltage

Zener diode circuits are widely used to protect a mechatronics control system from high values of voltages and wrong polarity. Figure 2.7.1 shows a typical Zener diode circuit.

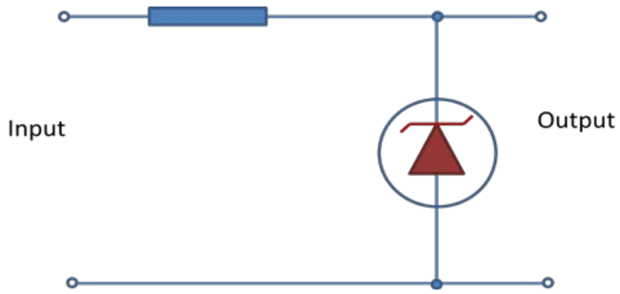

Figure 2.7.1 Zener diode circuit diagram

Zener diode acts as ordinary or regular diodes upto certain breakdown voltage level when they are conducting. When the voltage rises to the breakdown voltage level, Zener diode breaks down and stops the voltage to pass to the next circuit.

Zener diode as being a diode has low resistance for current to flow in one direction through it and high resistance for the opposite direction. When connected in correct polarity, a high resistance produces high voltage drop. If the polarity reverses, the diode will have less resistance and therefore results in less voltage drop.

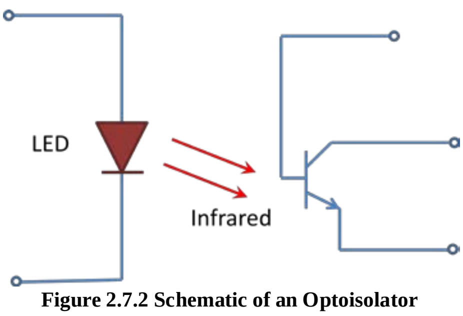

Figure 2.7.2 Schematic of an Optoisolator

In many high voltage scenarios, it is required to isolate the control circuit completely from the input high voltages to avoid the possible damage. This can be achieved by Optoisolators. Figure 2.7.2 shows the typical circuit of an Optoisolator. It comprises of a Light emitting diode (LED) and a photo transistor. LED irradiates infra red due to the voltage supplied to it from a microprocessor circuit. The transistor detects irradiation and produces a current in proportion to the voltage applied. In case of high voltages, output current from Optoisolator is utilized for disconnecting the power supply to the circuit and thus the circuit gets protected.

2. Wheatstone bridge

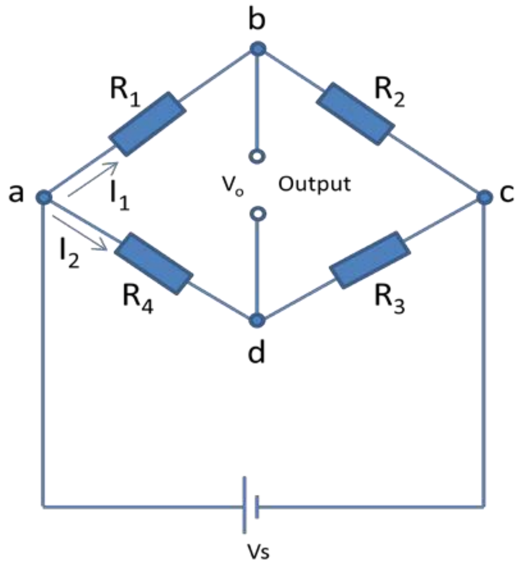

Figure 2.7.3 Configuration of a Wheatstone bridge

Wheatstone bridge is used to convert a resistance change detected by a transducer to a voltage change. Figure 2.7.3 shows the basic configuration of a Wheatstone bridge. When the output voltage *Vout* is zero then the potential at B must be equal to D and we can say that,

$$Vab = Vad, \qquad (2.7.1)$$
$$I1\,R\,1 = I2\,R2 \qquad (2.7.2)$$

Also,

$Vbc = Vdc,$ (2.7.3)

$I1\,R2 = I2\,R4$ (2.7.4)

Dividing equation 2.7.2 by 2.7.4,

$R1/R2 = R3/R4$ (2.7.5)

The bridge is thus balanced.

The potential drop across $R1$ due to supply voltage *Vs*,

$Vab = Vs\,R1/(R1 + R2)$ (2.7.6)

Similarly,

$$Vad = VsR3/(R3 + R4) \qquad (2.7.7)$$

Thus the output voltage Vo is given by,

$$Vo = Vab - Vad \qquad (2.7.8)$$

$$Vo = Vs\,\{(R1/[R1 + R2]) - (R3/[R3 + R4])\} \qquad (2.7.9)$$

When Vo = 0, above equation gives balanced condition.

Assume that a transducer produces a resistance change from $R1$ to $R1 + \delta R1$ which gives a change in output from $Vo + \delta Vo$,

From equation 2.7.9 we can write,

$$Vo + \delta Vo = Vs\left[\frac{R1+\delta R1}{R1+\delta R1+R2} - \frac{R3}{R3+R4}\right] \qquad (2.7.10)$$

Hence,

$$(Vo + \delta Vo) - Vo = Vs\left[\frac{R1+\delta R1}{R1+\delta R1+R2} - \frac{R1}{R1+R2}\right] \qquad (2.7.11)$$

If $\delta R1$ is much smaller than $R1$ the equation 2.7.11 can be written as

$$\delta Vo \approx Vs\left[\frac{\delta R1}{R1+R2}\right] \qquad (2.7.12)$$

We can say that change in resistance $R1$ produces a change in output voltage. Thus we can convert a change in resistance signal into voltage signal.

3. Pulse modulation

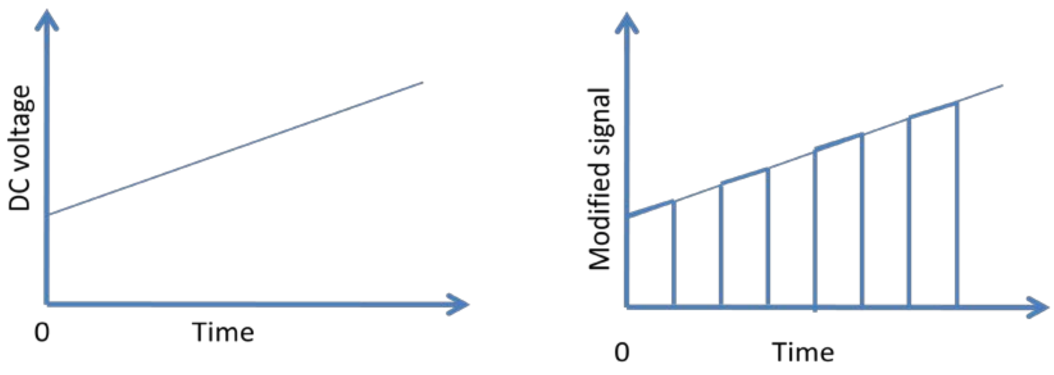

Figure 2.7.4 Pulse amplitude modulation

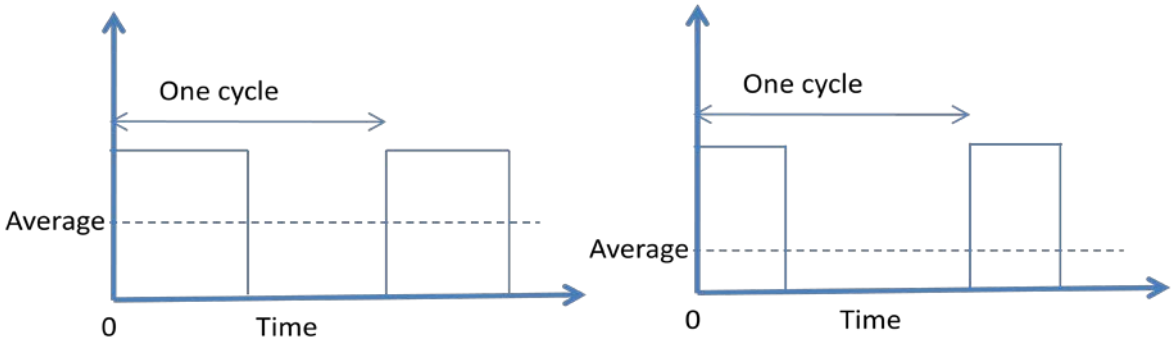

Figure 2.7.5 Pulse width modulation

During amplification of low level DC signals from a sensor by using Op-amp, the output gets drifted due to drift in the gain of Op-amp. This problem is solved by converting the analogue DC signal into a sequence of pulses. This can be achieved by chopping the DC signal in to a chain of pulses as shown in Figure 2.7.4. The heights of pulses are related to the DC level of the input signal. This process is called as Pulse Width Modulation (PWM). It is widely used in control systems as a mean of controlling the average value of the DC voltage. If the width of pulses is changed then the average value of the voltage can be changed as shown in Figure 2.7.5. A term Duty Cycle is used to define the fraction of each cycle for which the voltage is high. Duty cycle of 50% means that for half of the each cycle, the output is high.

Quiz:

1. State the applications of Wheatstone bridge in Mechatronics based Manufacturing Automation. Explain one of them in detail.
2. Why do we need pulse width modulation?
3. How Zener diode is different than ordinary diode?

Module 2: Sensors and signal processing
Lecture 8

Data conversion devices

Data Conversion Devices are very important components of a Machine Control Unit (MCU). MCUs are controlled by various computers or microcontrollers which are accepting signals only in Digital Form i.e. in the form of 0s and 1s, while the signals received from signal conditioning module or sensors are generally in analogue form (continuous). Therefore a system is essentially required to convert analog signals into digital form and vis-à-vis. Analog to Digital Converter is abbreviated as ADC. Figure 2.8.1 shows a typical control system with data conversion devices.

Based on the signals received from sensors, MCU generates actuating signals in the Digital form. Most of the actuators e.g. DC servo motors only accept analogue signals. Therefore the digital signals must be converted into Analog form so that the required actuator can be operated accordingly. For this purpose Digital to Analog Converters are used, which are abbreviated as DACs. In subsequent sections we will be discussing about various types of ADC and DAC devices, their principle of working and circuitry.

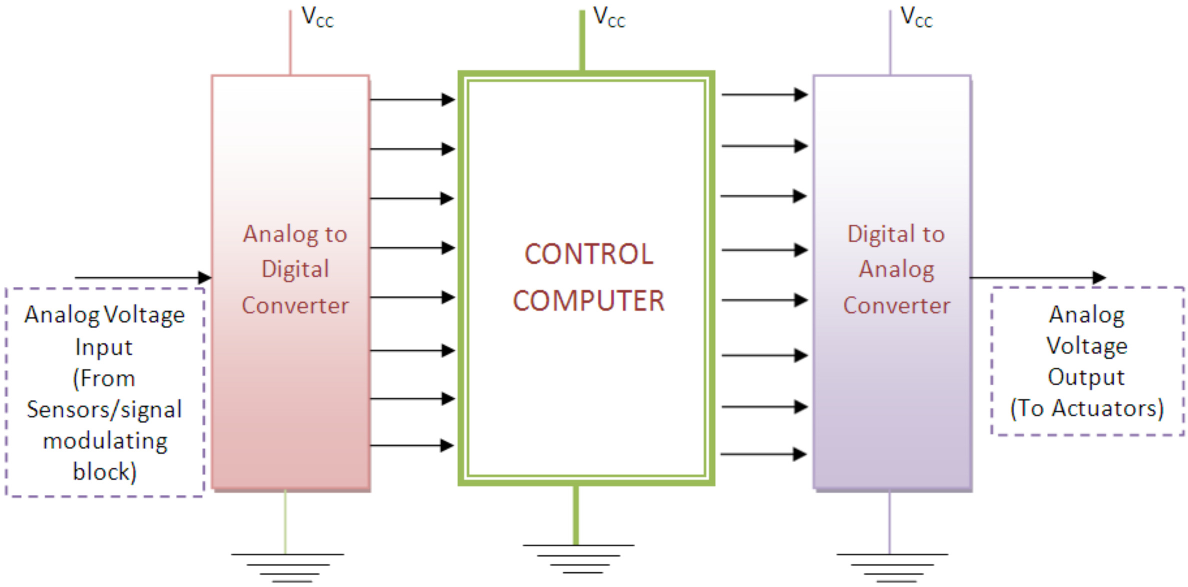

Figure 2.8.1 A control system with ADC and DAC devices

Basic components used in ADCs and DACs

1. Comparators

In general ADCs and DACs comprise of Comparators. Comparator is a combination of diodes and Operational Amplifiers. A comparator is a device which compares the voltage input or current input at its two terminals and gives output in form of digital signal i.e. in form of 0s and 1s indicating which voltage is higher. If V+ and V- be input voltages at two terminals of comparator then output of comparator will be as

$$V+ > V- \rightarrow \text{Output } 1$$

$$V+ < V- \rightarrow \text{Output } 0$$

2. Encoders

Though the output obtained from comparators are in the form of 0s and 1s, but can't be called as binary output. A sequence of 0s and 1s will be converted into binary form by using a circuit called Encoder. A simple encoder converts 2^n input lines into 'n' output lines. These 'n' output lines follow binary algebra.

3. Analog to Digital Converter (ADC)

As discussed in previous section ADCs are used to convert analog signals into Digital Signals. There are various techniques of converting Analog Signals into Digital signals which are enlisted as follows. However we will be discussing only Direct Conversion ADC, detail study of other techniques is out of the scope of the present course.

1. Direct Conversion ADC or Flash ADC
2. Successive Approximation ADC
3. A ramp-compare ADC
4. Wilkinson ADC
5. Integrating ADC
6. Delta-encoded ADC or counter-ramp
7. Pipeline ADC (also called subranging quantizer)
8. Sigma-delta ADC (also known as a delta-sigma ADC)
9. Time-interleaved ADC

3.1 Direct Conversion ADC or Flash ADC

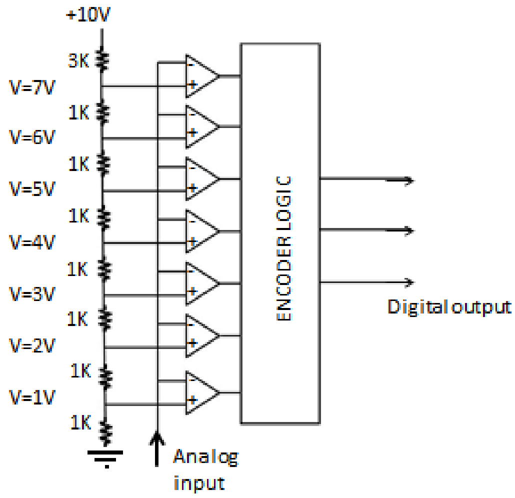

Figure 2.8.2 Circuit of Flash ADC

Figure 2.8.2 shows the circuit of Direct conversion or Flash ADC. To convert a digital signal of N-bits, Flash ADC requires 2^N-1 comparators and 2^N resistors. The circuit provides the reference voltage to all the comparators. Each comparator gives an output of 1 when its analog voltage is higher than reference voltage or otherwise the output is 0. In the above circuit, reference voltages to comparators are provided by means of resistor ladder logic.

The circuit described in figure 2.8.2 acts as 3 Bit ADC device. Let us assume this ADC works between the range of 0-10 Volts. The circuit requires 7 comparators and 8 resisters. Now the voltages across each resistor are divided in such a way that a ladder of 1 volt is built with the help of 1K-Ohm resistances. Therefore the reference voltages across all the comparators are 1-7 volts.

Now let us assume that an input voltage signal of 2.5 V is to be converted into its related digital form. As 2.5V is greater than 1V and 2V, first two comparators will give output as 1, 1. But 2.5V is less than 3,4,5,6,7 V values therefore all other comparators will give 0s. Thus we will have output from comparators as 0000011 (from top). This will be fed to the encoder logic circuit. This circuit will first change the output in single high line format and then converts it into 3 output lines format by using binary algebra. Then this digital output from ADC may be used for manipulation or actuation by the microcontrollers or computers.

4. Digital to Analog Converters

As discussed in previous section DACs are used to convert digital signals into Analog Signals. There are various techniques of converting Digital Signals into Analog signals which are as follows however we will be discussing only few important techniques in detail:

1. Pulse-width modulator
2. Oversampling DACs or interpolating DACs
3. The binary-weighted DAC
4. Switched resistor DAC
5. Switched current source DAC
6. Switched capacitor DAC
7. The R-2R ladder
8. The Successive-Approximation or Cyclic DAC,
9. The thermometer-coded DAC

4.1 Binary Weighted DAC

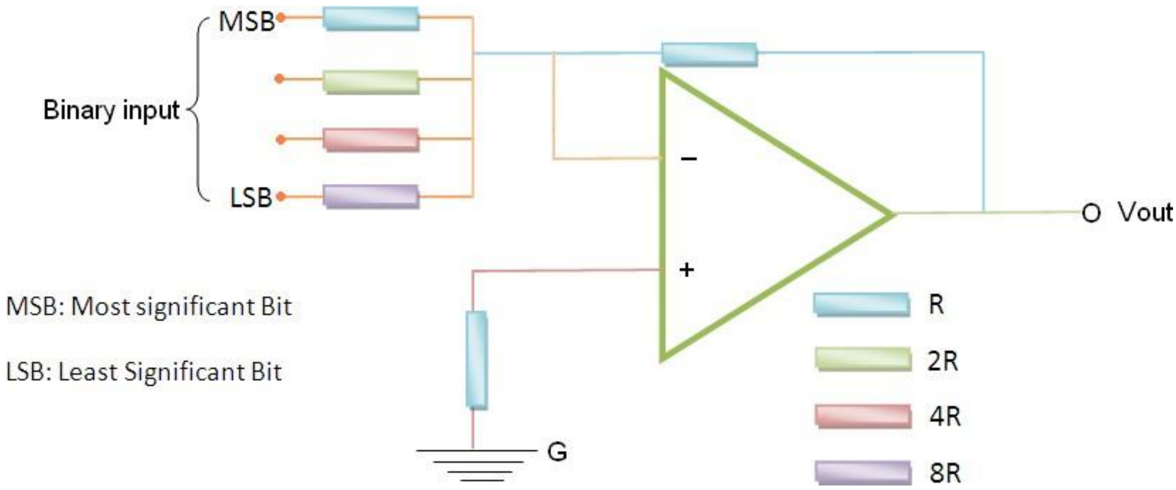

Figure 2.8.3 Circuit of binary weighted DAC

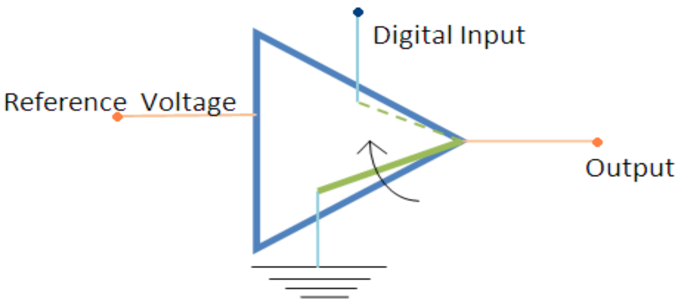

Figure 2.8.4 An op-amp used in DAC

As name indicates, in binary weighted DAC, output voltage can be calculated by expression which works on binary weights. Its circuit can be realized in Figure 2.8.3. From the figure it can be noted that most significant bit of digital input is connected to minimum resistance and vice versa. Digital bits can be connected to resistance through a switch which connects resistance-end to the ground. The digital input is zero when former bit is connected to reference voltage and if it is 1. This can be understood from Figure 2.8.4. DAC output voltage can be calculated from property of operational amplifiers. If V1 be input voltage at MSB (most significant bit), V2 be input voltage at next bit and so on then for four bit DAC we can write,

$$\frac{V1}{R}+\frac{V2}{2R}+\frac{V3}{4R}+\frac{V4}{8R}=\frac{Vout}{R} \qquad (2.8.1)$$

Note: Here V1,V2 V3,V4 will be Vref if digital input is 1 or otherwise it will be zero.

Hence output voltage can be found as:

$$V_{OUT}\ \alpha\ (2^3 * V1 + 2^2 * V2 + 2^1 * V3 + 2^0 * V4) \qquad (2.8.2)$$

However Binary weighted DAC doesn't work for multiple or higher bit systems as the value of resistance doubles in each case.

Thus simple and low bit digital signals from a transducer can be converted into a related continuous value of voltages (analogue) by using binary weighted DAC. These will further be used for manipulation or actuation.

4.2 R-2R Ladder based DAC

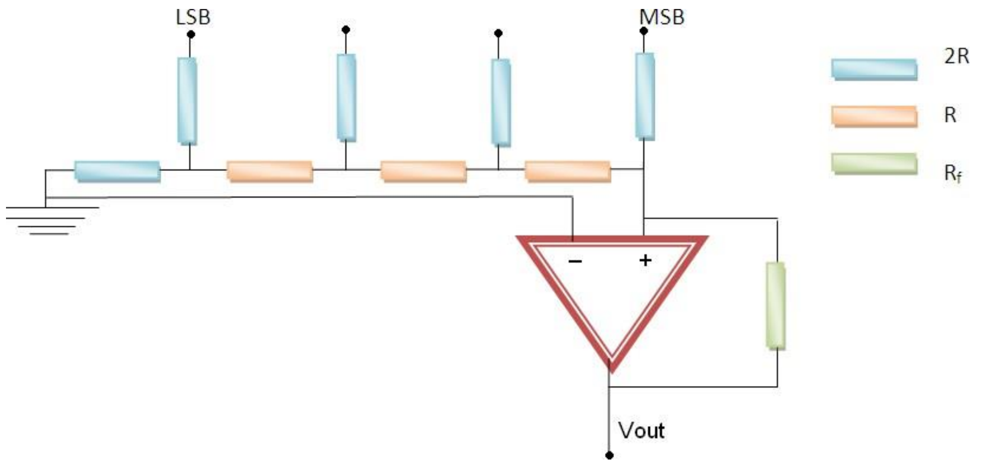

Figure 2.8.5 R-2R Ladder based DAC

In R-2R ladder logic, shortcoming of Binary Logic has been removed by making the value of maximum resistance double however the rest of the circuit remains same. Figure 2.8.5 shows the circuit of R-2R Ladder based DAC. If we apply voltage division rule in above case, then we can calculate that output voltage as,

$$V_{out} = \frac{V_{ref} * R_f}{R} * VAL \qquad (2.8.3)$$

Where VAL can be calculated from the digital signal input as,

$$VAL = \frac{D0}{2^4} + \frac{D1}{2^3} + \frac{D2}{2^2} + \frac{D3}{2^3} \qquad (2.8.4)$$

In this way output voltage is obtained by converting the digital signals received from microprocessor/ microcontroller. These voltages will further be used to actuate the desired actuator viz. DC/AC motors.

In this module we have studied the principle of operation of various sensors which are commonly used in mechatronics and manufacturing automation. Also the signal conditioning operations and the devices which are used to generate the proper signals for desired automation application have been studied. In the next module we will study the construction and working of microprocessor and the devices which are being used in controlling the various operations of automation using the microprocessors.

Quiz

1. Differentiate between Binary weighted DAC and R-2R ladder based DAC.
2. Explain the importance of data conversion devices in mechatronics with suitable example.

Module 2: Sensors and signal processing
Lecture 1
Sensors and transducers

Measurement is an important subsystem of a mechatronics system. Its main function is to collect the information on system status and to feed it to the micro-processor(s) for controlling the whole system.

Measurement system comprises of sensors, transducers and signal processing devices. Today a wide variety of these elements and devices are available in the market. For a mechatronics system designer it is quite difficult to choose suitable sensors/transducers for the desired application(s). It is therefore essential to learn the principle of working of commonly used sensors/transducers. A detailed consideration of the full range of measurement technologies is, however, out of the scope of this course. Readers are advised to refer "Sensors for mechatronics" by Paul P.L. Regtien, Elsevier, 2012 [2] for more information.

Sensors in manufacturing are basically employed to automatically carry out the production operations as well as process monitoring activities. Sensor technology has the following important advantages in transforming a conventional manufacturing unit into a modern one.

1. Sensors alarm the system operators about the failure of any of the sub units of manufacturing system. It helps operators to reduce the downtime of complete manufacturing system by carrying out the preventative measures.
2. Reduces requirement of skilled and experienced labors.
3. Ultra-precision in product quality can be achieved.

Sensor

It is defined as an element which produces signal relating to the quantity being measured [1]. According to the Instrument Society of America, sensor can be defined as "*A device which provides a usable output in response to a specified measurand.*" Here, the output is usually an 'electrical quantity' and measurand is a 'physical quantity, property or condition which is to be measured'. Thus in the case of, say, a variable inductance displacement element, the quantity being measured is displacement and the sensor transforms an input of displacement into a change in inductance.

Transducer

It is defined as an element when subjected to some physical change experiences a related change [1] or an element which converts a specified measurand into a usable output by using a transduction principle.

It can also be defined as a device that converts a signal from one form of energy to another form.

A wire of Constantan alloy (copper-nickel 55-45% alloy) can be called as a sensor because variation in mechanical displacement (tension or compression) can be sensed as change in electric resistance. This wire becomes a transducer with appropriate electrodes and input-output mechanism attached to it. Thus we can say that 'sensors are transducers'.

Sensor/transducers specifications

Transducers or measurement systems are not perfect systems. Mechatronics design engineer must know the capability and shortcoming of a transducer or measurement system to properly assess its performance. There are a number of performance related parameters of a transducer or measurement system. These parameters are called as sensor specifications.

Sensor specifications inform the user to the about deviations from the ideal behavior of the sensors. Following are the various specifications of a sensor/transducer system.

1. Range

The range of a sensor indicates the limits between which the input can vary. For example, a thermocouple for the measurement of temperature might have a range of 25-225 °C.

2. Span

The span is difference between the maximum and minimum values of the input. Thus, the above-mentioned thermocouple will have a span of 200 °C.

3. Error

Error is the difference between the result of the measurement and the true value of the quantity being measured. A sensor might give a displacement reading of 29.8 mm, when the actual displacement had been 30 mm, then the error is –0.2 mm.

4. *Accuracy*

The accuracy defines the closeness of the agreement between the actual measurement result and a true value of the measurand. It is often expressed as a percentage of the full range output or full–scale deflection. A piezoelectric transducer used to evaluate dynamic pressure phenomena associated with explosions, pulsations, or dynamic pressure conditions in motors, rocket engines, compressors, and other pressurized devices is capable to detect pressures between 0.1 and 10,000 psig (0.7 KPa to 70 MPa). If it is specified with the accuracy of about ±1% full scale, then the reading given can be expected to be within ± 0.7 MPa.

5. *Sensitivity*

Sensitivity of a sensor is defined as the ratio of change in output value of a sensor to the per unit change in input value that causes the output change. For example, a general purpose thermocouple may have a sensitivity of 41 µV/°C.

6. *Nonlinearity*

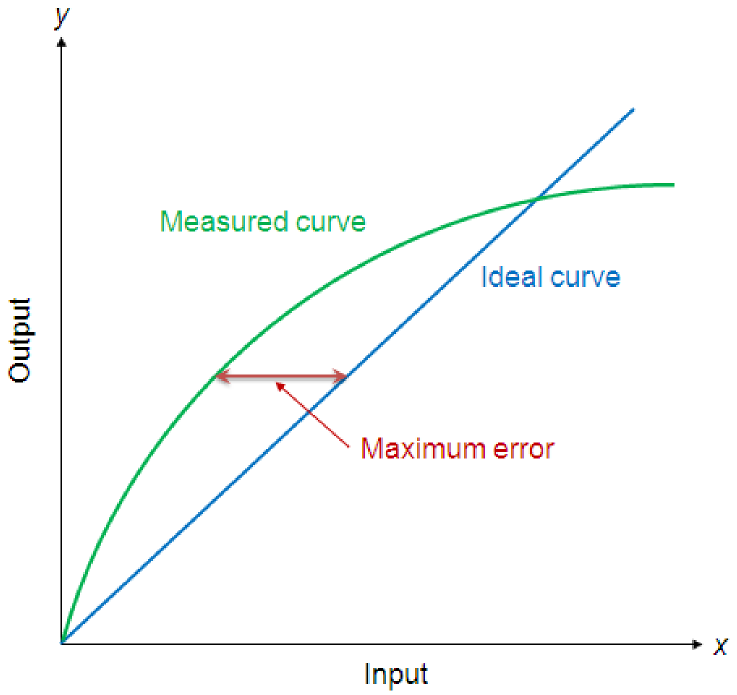

Figure 2.1.1 Non-linearity error

The nonlinearity indicates the maximum deviation of the actual measured curve of a sensor from the ideal curve. Figure 2.1.1 shows a somewhat exaggerated relationship between the ideal, or least squares fit, line and the actual measured or *calibration* line. Linearity is often specified in terms of *percentage of nonlinearity*, which is defined as:

Nonlinearity (%) = Maximum deviation in input ⁄ Maximum full scale input (2.1.1)

The static nonlinearity defined by Equation 2.1.1 is dependent upon environmental factors, including temperature, vibration, acoustic noise level, and humidity. Therefore it is important to know under what conditions the specification is valid.

7. Hysteresis

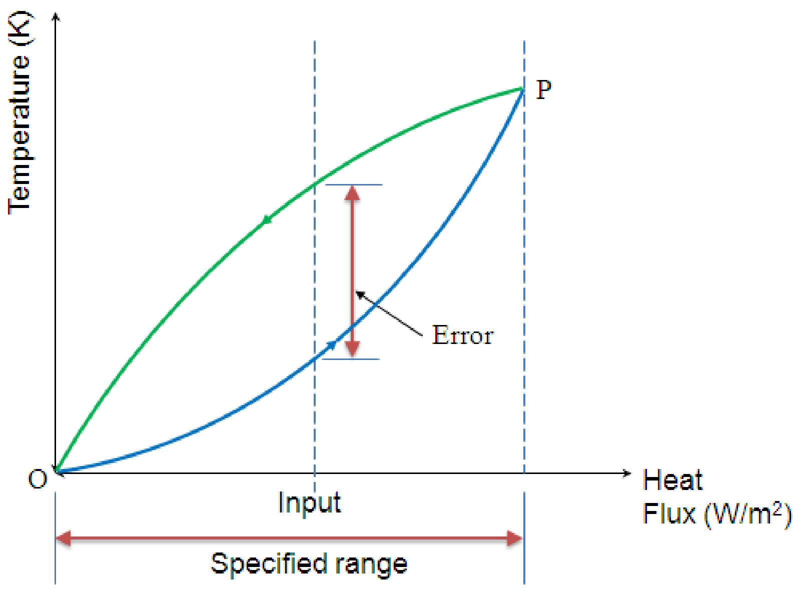

Figure 2.1.2 Hysteresis error curve

The hysteresis is an error of a sensor, which is defined as the maximum difference in output at any measurement value within the sensor's specified range when approaching the point first with increasing and then with decreasing the input parameter. Figure 2.1.2 shows the hysteresis error might have occurred during measurement of temperature using a thermocouple. The hysteresis error value is normally specified as a positive or negative percentage of the specified input range.

8. Resolution

Resolution is the smallest detectable incremental change of input parameter that can be detected in the output signal. Resolution can be expressed either as a proportion of the full-scale reading or in absolute terms. For example, if a LVDT sensor measures a displacement up to 20 mm and it provides an output as a number between 1 and 100 then the resolution of the sensor device is 0.2 mm.

9. Stability

Stability is the ability of a sensor device to give same output when used to measure a constant input over a period of time. The term 'drift' is used to indicate the change in output that occurs over a period of time. It is expressed as the percentage of full range output.

10. Dead band/time

The dead band or dead space of a transducer is the range of input values for which there is no output. The dead time of a sensor device is the time duration from the application of an input until the output begins to respond or change.

11. Repeatability

It specifies the ability of a sensor to give same output for repeated applications of same input value. It is usually expressed as a percentage of the full range output:

Repeatability = (maximum – minimum values given) X 100 ⁄ full range (2.1.2)

12. Response time

Response time describes the speed of change in the output on a step-wise change of the measurand. It is always specified with an indication of input step and the output range for which the response time is defined.

Classification of sensors

Sensors can be classified into various groups according to the factors such as measurand, application fields, conversion principle, energy domain of the measurand and thermodynamic considerations. These general classifications of sensors are well described in the references [2, 3].

Detail classification of sensors in view of their applications in manufacturing is as follows.

A. Displacement, position and proximity sensors
    - Potentiometer
    - Strain-gauged element
    - Capacitive element
    - Differential transformers
    - Eddy current proximity sensors
    - Inductive proximity switch
    - Optical encoders
    - Pneumatic sensors
    - Proximity switches (magnetic)
    - Hall effect sensors

B. Velocity and motion
    - Incremental encoder
    - Tachogenerator
    - Pyroelectric sensors

C. Force
    - Strain gauge load cell

D. Fluid pressure
    - Diaphragm pressure gauge
    - Capsules, bellows, pressure tubes
    - Piezoelectric sensors
    - Tactile sensor
    -

E. Liquid flow
    - Orifice plate
    - Turbine meter

F. Liquid level
    - Floats
    - Differential pressure

G. Temperature
    - Bimetallic strips
    - Resistance temperature detectors
    - Thermistors
    - Thermo-diodes and transistors
    - Thermocouples
    - Light sensors
    - Photo diodes
    - Photo resistors

- Photo transistor

Principle of operation of these transducers and their applications in manufacturing are presented in the next lectures.

Quiz:

1. Define sensors and list the various specifications that need to be carefully studied before using a Thermocouple for reading the temperature of a furnace.
2. Differentiate between span and range of a transducer system.
3. What do you mean by nonlinearity error? How it is different than Hysteresis error?
4. Explain the significance of the following information given in the specification of the following transducer,
   Thermocouple
   Sensitivity: nickel chromium/nickel aluminum thermocouple: 0.039 mV/ºC when the cold junction is at 0 ºC.

References:

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.
2. Regtien, P. P. L., Sensors for mechatronics, Elesevier, USA, 2012.
3. Tonshoff, H.K. and I. Inasaki, Sensors in manufacturing, Wiley-VCH, 2001.

Module 2: Sensors and signal processing
Lecture 2
Displacement and position sensors

Displacement sensors are basically used for the measurement of movement of an object. Position sensors are employed to determine the position of an object in relation to some reference point.

Proximity sensors are a type of position sensor and are used to trace when an object has moved with in particular critical distance of a transducer.

Displacement sensors

1. Potentiometer Sensors

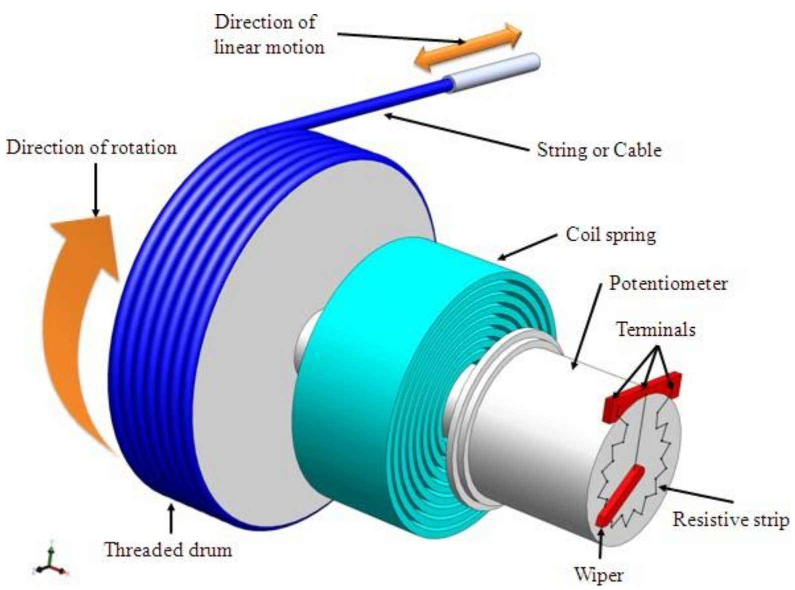

Figure 2.2.1 Schematic of a potentiometer sensor for measurement of linear displacement

Figure 2.2.1 shows the construction of a rotary type potentiometer sensor employed to measure the linear displacement. The potentiometer can be of linear or angular type. It works on the principle of conversion of mechanical displacement into an electrical signal. The sensor has a resistive element and a sliding contact (wiper). The slider moves along this conductive body, acting as a movable electric contact.

The object of whose displacement is to be measured is connected to the slider by using

- a rotating shaft (for angular displacement)
- a moving rod (for linear displacement)
- a cable that is kept stretched during operation

The resistive element is a wire wound track or conductive plastic. The track comprises of large number of closely packed turns of a resistive wire. Conductive plastic is made up of plastic resin embedded with the carbon powder. Wire wound track has a resolution of the order of ± 0.01 % while the conductive plastic may have the resolution of about 0.1 µm.

During the sensing operation, a voltage V_s is applied across the resistive element. A voltage divider circuit is formed when slider comes into contact with the wire. The output voltage (V_A) is measured as shown in the figure 2.2.2. The output voltage is proportional to the displacement of the slider over the wire. Then the output parameter displacement is calibrated against the output voltage V_A.

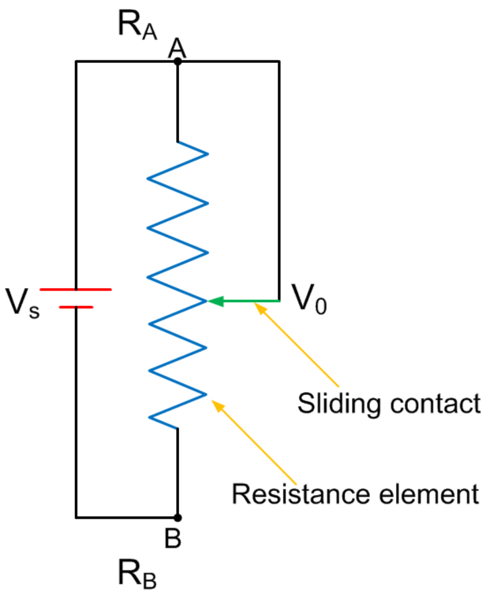

Figure 2.2.2 Potentiometer: electric circuit

$V_A = I\, R_A$ (2.2.1)

But $I = V_S / (R_A + R_B)$ (2.2.2)

Therefore $V_A = V_S\, R_A / (R_A + R_B)$ (2.2.3)

As we know that $R = \rho\, L / A$, where ρ is electrical resistivity, L is length of resistor and A is area of cross section

$V_A = V_S\, L_A / (L_A + L_B)$ (2.2.4)

Applications of potentiometer

These sensors are primarily used in the control systems with a feedback loop to ensure that the moving member or component reaches its commanded position.

These are typically used on machine-tool controls, elevators, liquid-level assemblies, forklift trucks, automobile throttle controls. In manufacturing, these are used in control of injection molding machines, woodworking machinery, printing, spraying, robotics, etc. These are also used in computer-controlled monitoring of sports equipment.

2. *Strain Gauges*

The strain in an element is a ratio of change in length in the direction of applied load to the original length of an element. The strain changes the resistance *R* of the element. Therefore, we can say,

$\Delta R/R \; \alpha \; \varepsilon$;

$$\Delta R/R = G\,\varepsilon \qquad (2.2.5)$$

where G is the constant of proportionality and is called as gauge factor. In general, the value of G is considered in between 2 to 4 and the resistances are taken of the order of 100 Ω.

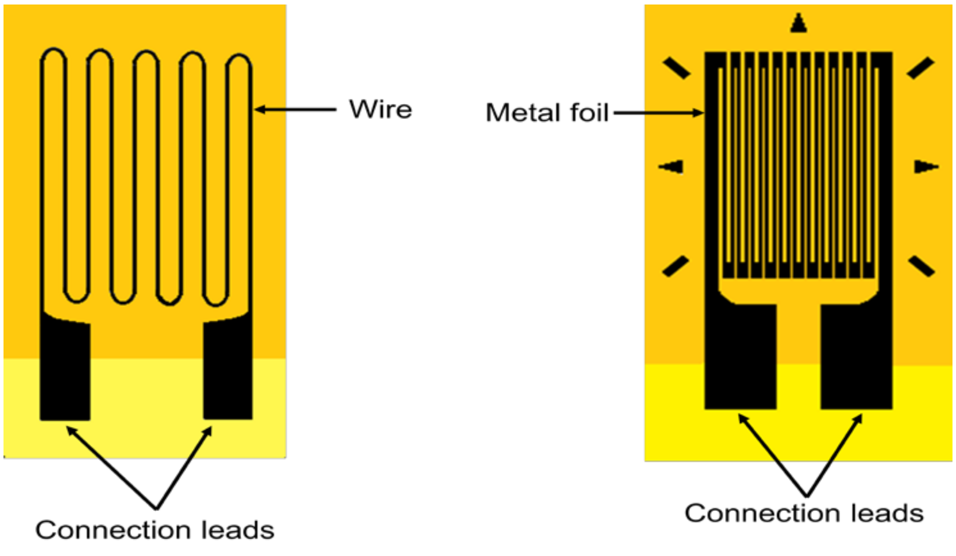

Figure 2.2.3 A pattern of resistive foils

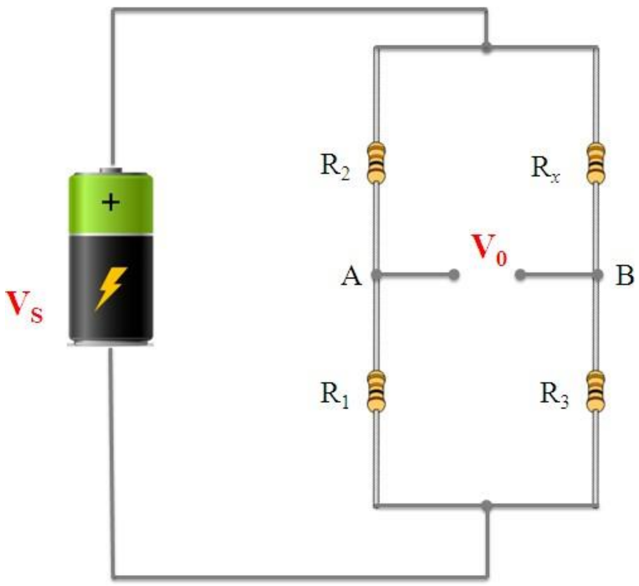

Figure 2.2.4 Wheatstone's bridge

Resistance strain gauge follows the principle of change in resistance as per the equation 2.2.5. It comprises of a pattern of resistive foil arranged as shown in Figure 2.2.3. These foils are made of Constantan alloy (copper-nickel 55-45% alloy) and are bonded to a backing material plastic (ployimide), epoxy or glass fiber reinforced epoxy. The strain gauges are secured to the workpiece by using epoxy or Cyanoacrylate cement Eastman 910 SL. As the workpiece undergoes change in its shape due to external loading, the resistance of strain gauge element changes. This change in resistance can be detected by a using a Wheatstone's resistance bridge as shown in Figure 2.2.4. In the balanced bridge we can have a relation,

$$R_2/R_1 = R_x/R_3 \quad (2.2.6)$$

where R_x is resistance of strain gauge element, R_2 is balancing/adjustable resistor, R_1 and R_3 are known constant value resistors. The measured deformation or displacement by the stain gauge is calibrated against change in resistance of adjustable resistor R_2 which makes the voltage across nodes A and B equal to zero.

Applications of strain gauges

Strain gauges are widely used in experimental stress analysis and diagnosis on machines and failure analysis. They are basically used for multi-axial stress fatigue testing, proof testing, residual stress and vibration measurement, torque measurement, bending and deflection measurement, compression and tension measurement and strain measurement.

Strain gauges are primarily used as sensors for machine tools and safety in automotives. In particular, they are employed for force measurement in machine tools, hydraulic or pneumatic press and as impact sensors in aerospace vehicles.

3. *Capacitive element based sensor*

Capacitive sensor is of non-contact type sensor and is primarily used to measure the linear displacements from few millimeters to hundreds of millimeters. It comprises of three plates, with the upper pair forming one capacitor and the lower pair another. The linear displacement might take in two forms:

a. one of the plates is moved by the displacement so that the plate separation changes
b. area of overlap changes due to the displacement.

Figure 2.2.5 shows the schematic of three-plate capacitive element sensor and displacement measurement of a mechanical element connected to the plate 2.

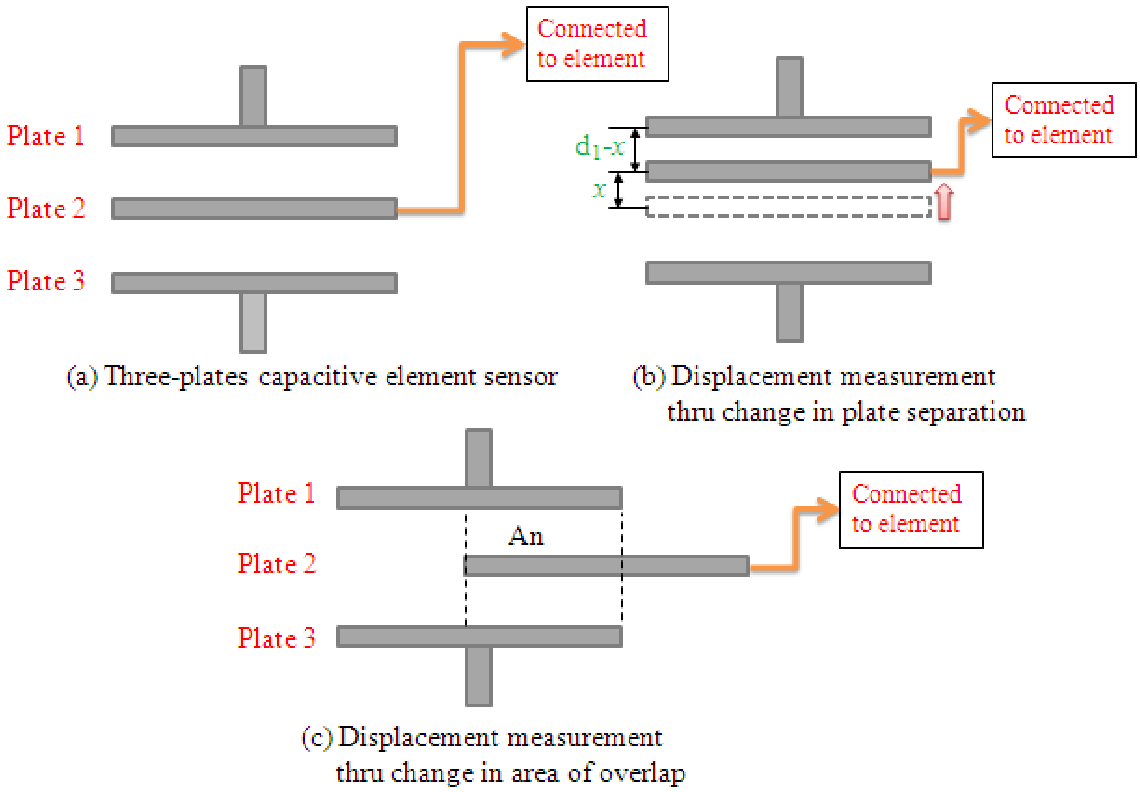

Figure 2.2.5 Displacement measurement using capacitive element sensor

The capacitance C of a parallel plate capacitor is given by,

$$C = \varepsilon_r \varepsilon_o A / d \tag{2.2.7}$$

where ε_r is the relative permittivity of the dielectric between the plates, ε_o permittivity of free space, *A* area of overlap between two plates and *d* the plate separation.

As the central plate moves near to top plate or bottom one due to the movement of the element/workpiece of which displacement is to be measured, separation in between the plate changes. This can be given as,

$$C_1 = (\varepsilon_r \varepsilon_o A) / (d + x) \quad (2.2.8)$$

$$C_2 = (\varepsilon_r \varepsilon_o A) / (d - x) \quad (2.2.9)$$

When C1 and C2 are connected to a Wheatsone's bridge, then the resulting out-of-balance voltage would be in proportional to displacement x.

Capacitive elements can also be used as proximity sensor. The approach of the object towards the sensor plate is used for induction of change in plate separation. This changes the capacitance which is used to detect the object.

Applications of capacitive element sensors

- Feed hopper level monitoring
- Small vessel pump control
- Grease level monitoring
- Level control of liquids
- Metrology applications
  - to measure shape errors in the part being produced
  - to analyze and optimize the rotation of spindles in various machine tools such as surface grinders, lathes, milling machines, and air bearing spindles by measuring errors in the machine tools themselves
- Assembly line testing
  - to test assembled parts for uniformity, thickness or other design features
  - to detect the presence or absence of a certain component, such as glue etc.

4. *Linear variable differential transformer (LVDT)*

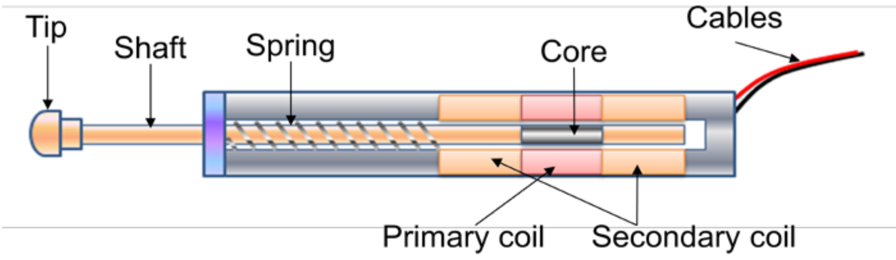

Figure 2.2.6 Construction of a LVDT sensor

Linear variable differential transformer (LVDT) is a primary transducer used for measurement of linear displacement with an input range of about ± 2 to ± 400 mm in general. It has non-linearity error ± 0.25% of full range. Figure 2.2.6 shows the construction of a LVDT sensor. It has three coils symmetrically spaced along an insulated tube. The central coil is primary coil and the other two are secondary coils. Secondary coils are connected in series in such a way that their outputs oppose each other. A magnetic core attached to the element of which displacement is to be monitored is placed inside the insulated tube.

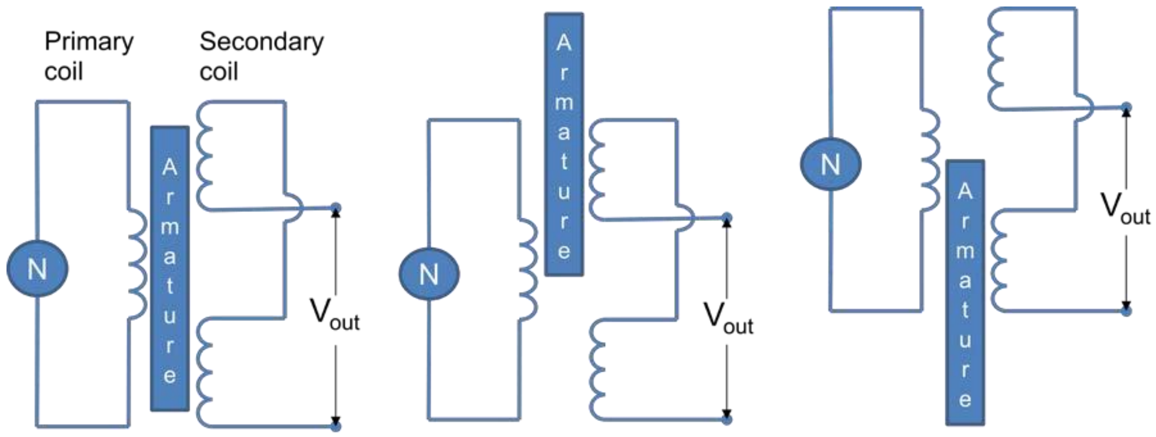

Figure 2.2.7 Working of LVDT sensor

Due to an alternating voltage input to the primary coil, alternating electro-magnetic forces (emfs) are generated in secondary coils. When the magnetic core is centrally placed with its half portion in each of the secondary coil regions then the resultant voltage is zero. If the core is displaced from the central position as shown in Figure 2.2.7, say, more in secondary coil 1 than in coil 2, then more emf is generated in one coil i.e. coil 1 than the other, and there is a resultant voltage from the coils. If the magnetic core is further displaced, then the value of resultant voltage increases in proportion with the displacement. With the help of signal processing devices such as low pass filters and demodulators, precise displacement can be measured by using LVDT sensors.

LVDT exhibits good repeatability and reproducibility. It is generally used as an absolute position sensor. Since there is no contact or sliding between the constituent elements of the sensor, it is highly reliable. These sensors are completely sealed and are widely used in Servomechanisms, automated measurement in machine tools.

A rotary variable differential transformer (RVDT) can be used for the measurement of rotation. Readers are suggested to prepare a report on principle of working and construction of RVDT sensor.

Applications of LVDT sensors

- Measurement of spool position in a wide range of servo valve applications
- To provide displacement feedback for hydraulic cylinders
- To control weight and thickness of medicinal products viz. tablets or pills
- For automatic inspection of final dimensions of products being packed for dispatch
- To measure distance between the approaching metals during Friction welding process
- To continuously monitor fluid level as part of leak detection system
- To detect the number of currency bills dispensed by an ATM

Quiz:

1. Explain the principle of working of LVDT.
2. Describe the working of RVDT with a neat sketch.
3. List the applications of potentiometer sensor in/around your home and office/university.

References

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.

Module 2: Sensors and signal processing
Lecture 3
Displacement, position and proximity sensors

1. Eddy current proximity sensors

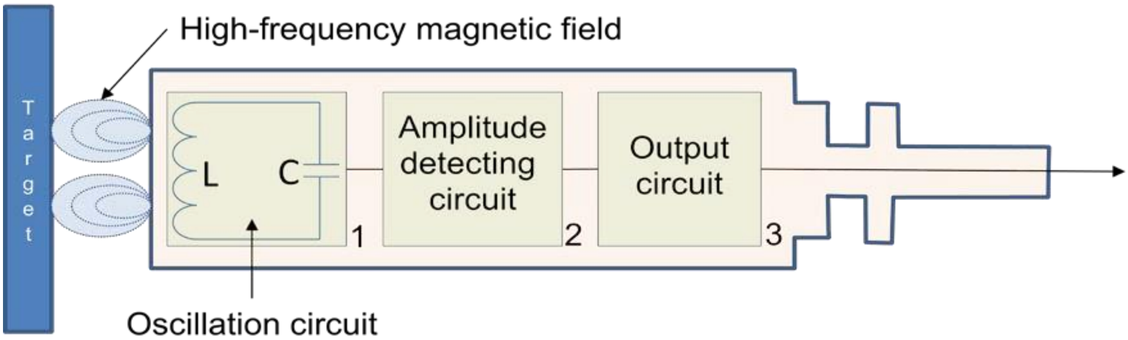

Figure 2.3.1 Schematic of Inductive Proximity Sensor

Eddy current proximity sensors are used to detect non-magnetic but conductive materials. They comprise of a coil, an oscillator, a detector and a triggering circuit. Figure 2.3.1 shows the construction of eddy current proximity switch. When an alternating current is passed thru this coil, an alternative magnetic field is generated. If a metal object comes in the close proximity of the coil, then eddy currents are induced in the object due to the magnetic field. These eddy currents create their own magnetic field which distorts the magnetic field responsible for their generation. As a result, impedance of the coil changes and so the amplitude of alternating current. This can be used to trigger a switch at some pre-determined level of change in current.

Eddy current sensors are relatively inexpensive, available in small in size, highly reliable and have high sensitivity for small displacements.

Applications of eddy current proximity sensors

- Automation requiring precise location
- Machine tool monitoring
- Final assembly of precision equipment such as disk drives
- Measuring the dynamics of a continuously moving target, such as a vibrating element,
- Drive shaft monitoring
- Vibration measurements

2. *Inductive proximity switch*

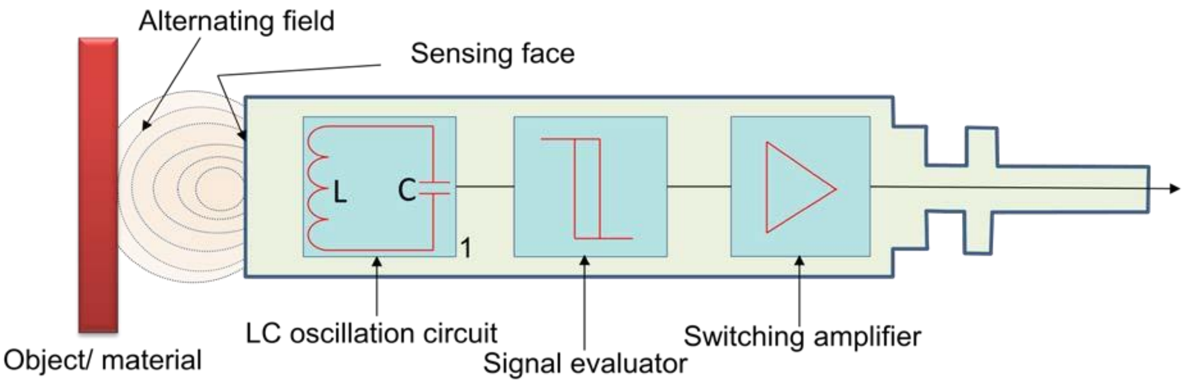

Figure 2.3.2 Schematic of Inductive Proximity Switch

Inductive proximity switches are basically used for detection of metallic objects. Figure 2.3.2 shows the construction of inductive proximity switch. An inductive proximity sensor has four components; the coil, oscillator, detection circuit and output circuit. An alternating current is supplied to the coil which generates a magnetic field. When, a metal object comes closer to the end of the coil, inductance of the coil changes. This is continuously monitored by a circuit which triggers a switch when a preset value of inductance change is occurred.

Applications of inductive proximity switches

- Industrial automation: counting of products during production or transfer
- Security: detection of metal objects, arms, land mines

3. *Optical encoders*

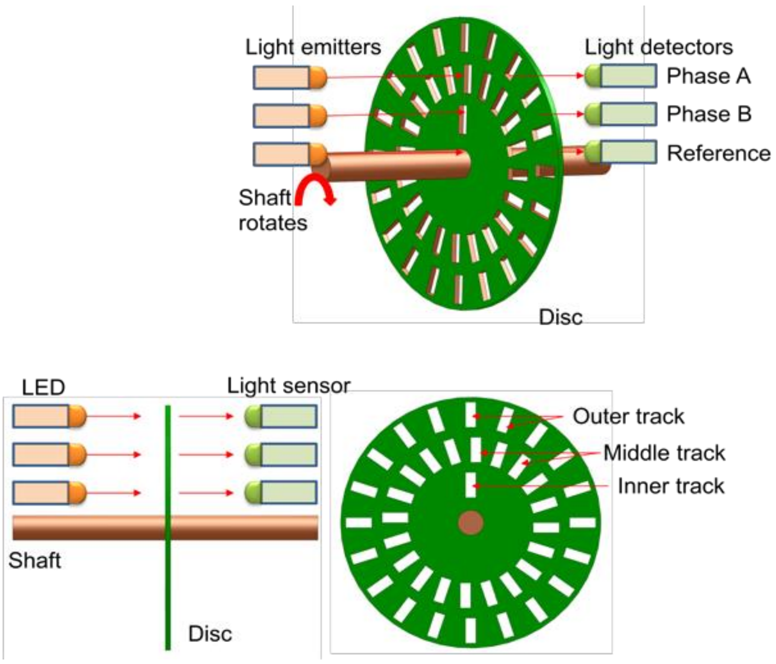

Figure 2.3.3 Construction and working of optical encoder

Optical encoders provide digital output as a result of linear / angular displacement. These are widely used in the Servo motors to measure the rotation of shafts. Figure 2.3.3 shows the construction of an optical encoder. It comprises of a disc with three concentric tracks of equally spaced holes. Three light sensors are employed to detect the light passing thru the holes. These sensors produce electric pulses which give the angular displacement of the mechanical element e.g. shaft on which the Optical encoder is mounted. The inner track has just one hole which is used locate the 'home' position of the disc. The holes on the middle track offset from the holes of the outer track by one-half of the width of the hole. This arrangement provides the direction of rotation to be determined. When the disc rotates in clockwise direction, the pulses in the outer track lead those in the inner; in counter clockwise direction they lag behind. The resolution can be determined by the number of holes on disc. With 100 holes in one revolution, the resolution would be,

$360^0/100 = 3.6^0$.

4. *Pneumatic Sensors*

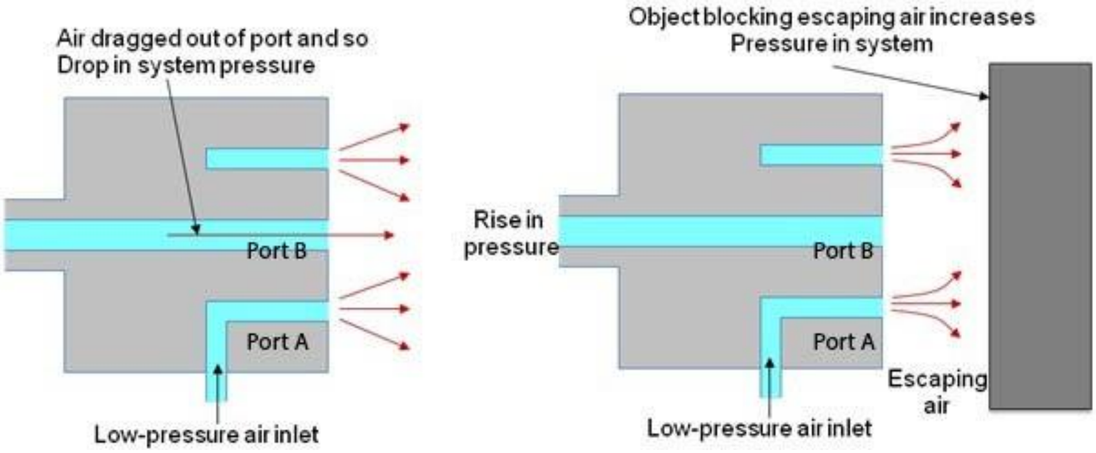

Figure 2.3.4 Working of Pneumatic Sensors [1]

Pneumatic sensors are used to measure the displacement as well as to sense the proximity of an object close to it. The displacement and proximity are transformed into change in air pressure. Figure 2.3.4 shows a schematic of construction and working of such a sensor. It comprises of three ports. Low pressure air is allowed to escape through port A. In the absence of any obstacle / object, this low pressure air escapes and in doing so, reduces the pressure in the port B. However when an object obstructs the low pressure air (Port A), there is rise in pressure in output port B. This rise in pressure is calibrated to measure the displacement or to trigger a switch. These sensors are used in robotics, pneumatics and for tooling in CNC machine tools.

5. *Proximity Switches*

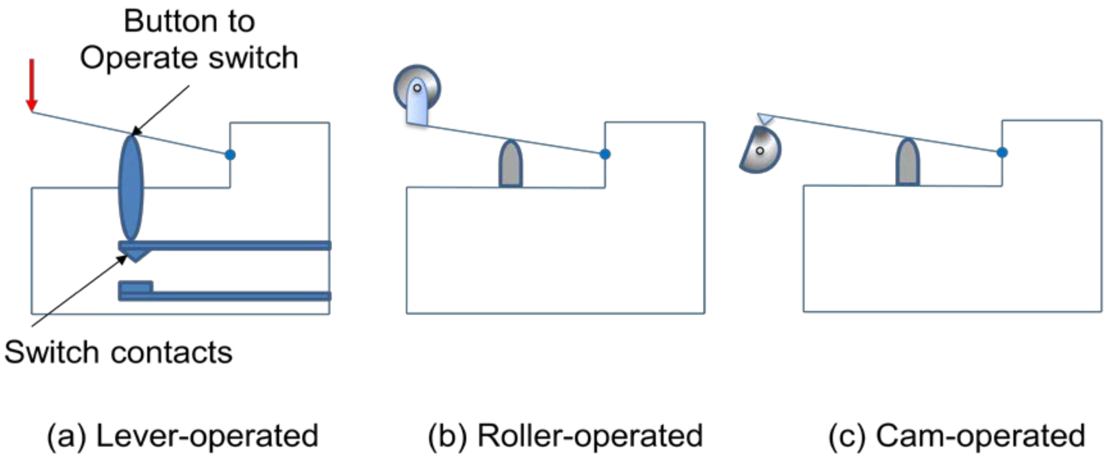

Figure 2.3.5 Configurations of contact type proximity switch [1]

Figure 2.3.5 shows a number of configurations of contact-type proximity switch being used in manufacturing automation. These are small electrical switches which require physical contact and a small operating force to close the contacts. They are basically employed on conveyor systems to detect the presence of an item on the conveyor belt.

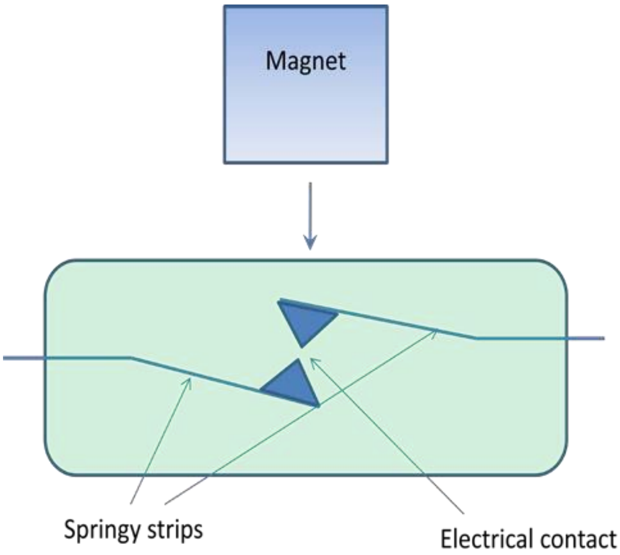

Figure 2.3.6 Reed Switch [1]

Magnet based Reed switches are used as proximity switches. When a magnet attached to an object brought close to the switch, the magnetic reeds attract to each other and close the switch contacts. A schematic is shown in Figure 2.3.6.

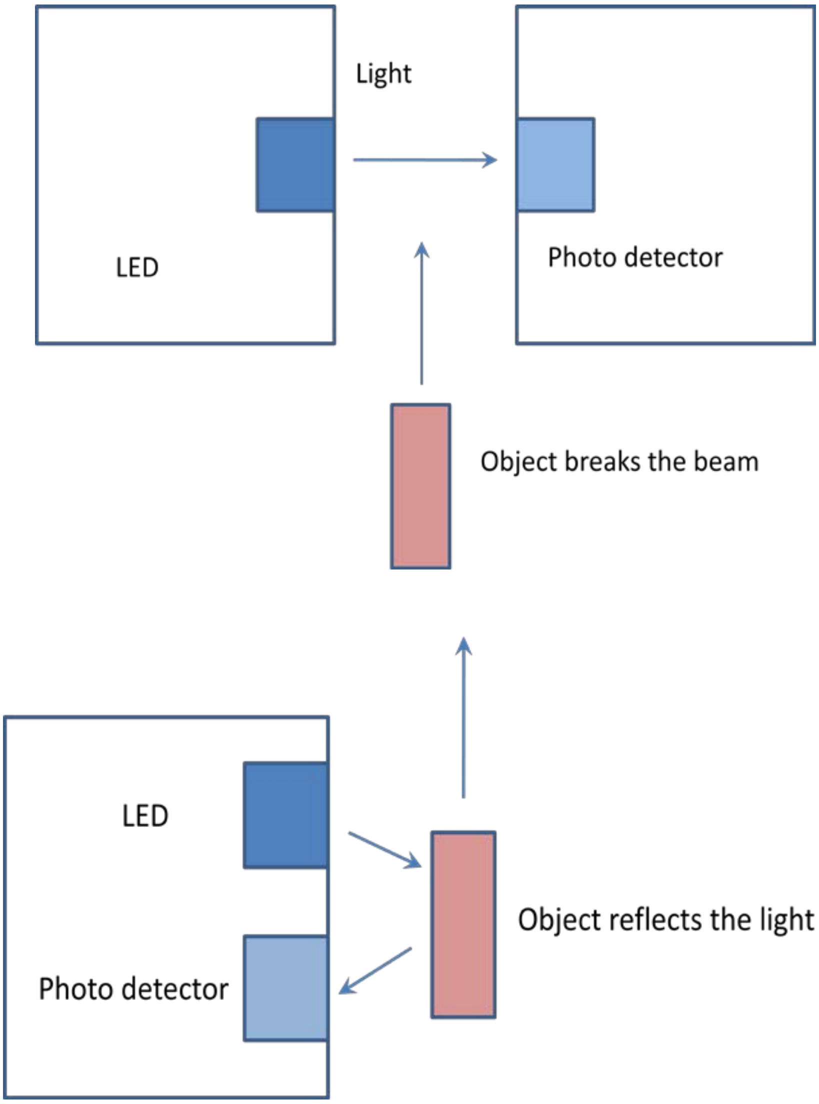

Figure 2.3.7 LED based proximity sensors [1]

Photo emitting devices such as Light emitting diodes (LEDs) and photosensitive devices such as photo diodes and photo transistors are used in combination to work as proximity sensing devices. Figure 2.3.7 shows two typical arrangements of LEDs and photo diodes to detect the objects breaking the beam and reflecting light.

6. *Hall effect sensor*

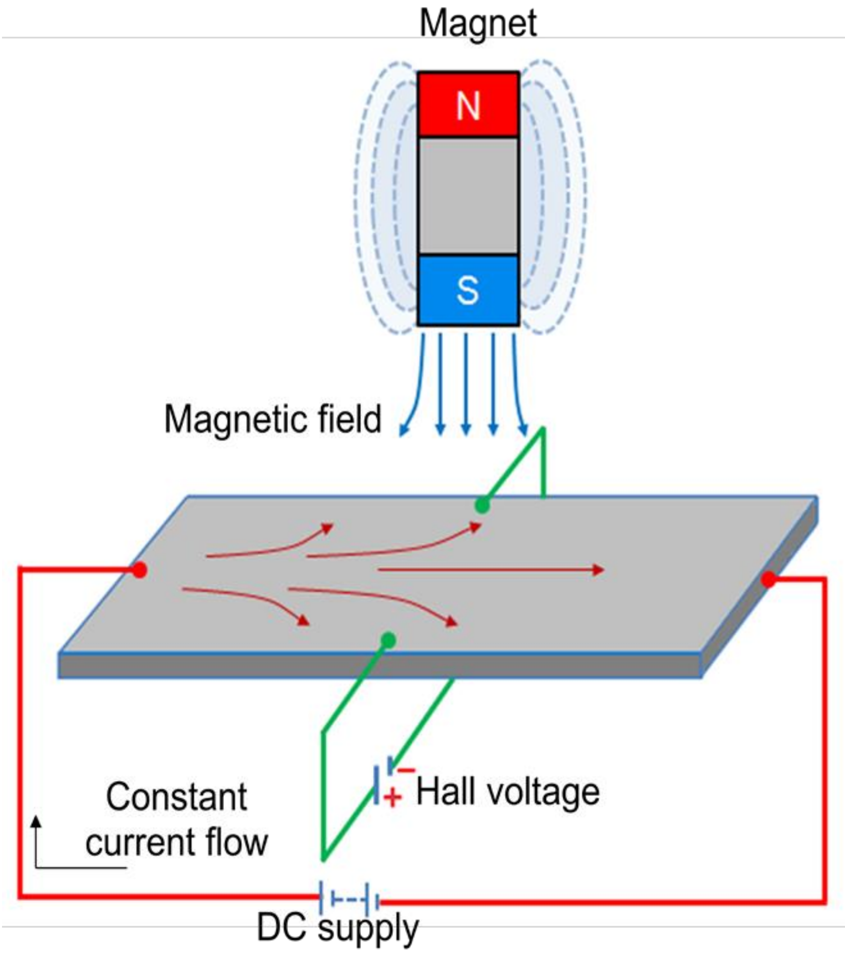

Figure 2.3.8 Principle of working of Hall effect sensor

Figure 2.3.8 shows the principle of working of Hall effect sensor. Hall effect sensors work on the principle that when a beam of charge particles passes through a magnetic field, forces act on the particles and the current beam is deflected from its straight line path. Thus one side of the disc will become negatively charged and the other side will be of positive charge. This charge separation generates a potential difference which is the measure of distance of magnetic field from the disc carrying current.

The typical application of Hall effect sensor is the measurement of fluid level in a container. The container comprises of a float with a permanent magnet attached at its top. An electric circuit with a current carrying disc is mounted in the casing. When the fluid level increases, the magnet will come close to the disc and a potential difference generates. This voltage triggers a switch to stop the fluid to come inside the container.

These sensors are used for the measurement of displacement and the detection of position of an object. Hall effect sensors need necessary signal conditioning circuitry. They can be operated at 100 kHz. Their non-contact nature of operation, good immunity to environment contaminants and ability to sustain in severe conditions make them quite popular in industrial automation.

Quiz:

1. To detect non-conducting metallic objects which sensor would be useful?
2. If a digital optical encoder has 7 tracks, then the minimum angular motion that can be measured by this device_________________.
3. Explain in brief two applications of “Reed switch”.
4. Explain the principle of working of Hall effect sensor.

References

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.

Module 2: Sensors and signal processing
Lecture 4

Velocity, motion, force and pressure sensors

1. Tachogenerator

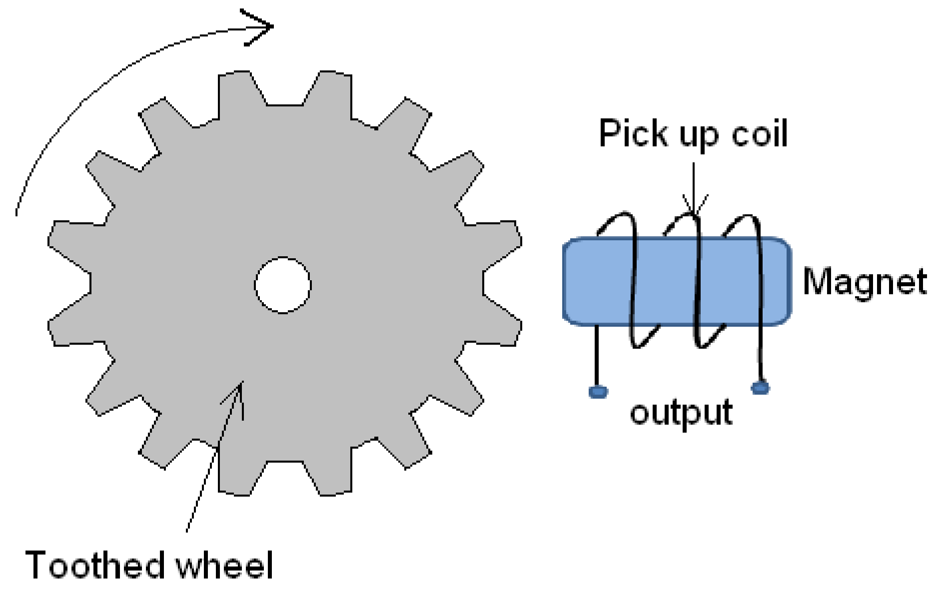

Figure 2.4.1 Principle of working of Techogenerator [1]

Tachogenerator works on the principle of variable reluctance. It consists of an assembly of a toothed wheel and a magnetic circuit as shown in figure 2.4.1. Toothed wheel is mounted on the shaft or the element of which angular motion is to be measured. Magnetic circuit comprising of a coil wound on a ferromagnetic material core. As the wheel rotates, the air gap between wheel tooth and magnetic core changes which results in cyclic change in flux linked with the coil. The alternating emf generated is the measure of angular motion. A pulse shaping signal conditioner is used to transform the output into a number of pulses which can be counted by a counter.

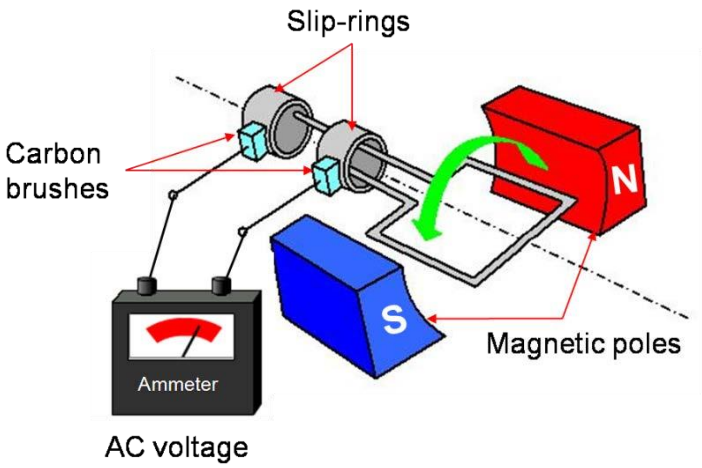

Figure 2.4.2 Construction and working of AC generator

An alternating current (AC) generator can also be used as a techognerator. It comprises of rotor coil which rotates with the shaft. Figure 2.4.2 shows the schematic of AC generator. The rotor rotates in the magnetic field produced by a stationary permanent magnet or electromagnet. During this process, an alternating emf is produced which is the measure of the angular velocity of the rotor. In general, these sensors exhibit nonlinearity error of about ± 0.15% and are employed for the rotations up to about 10000 rev/min.

2. Pyroelectric sensors

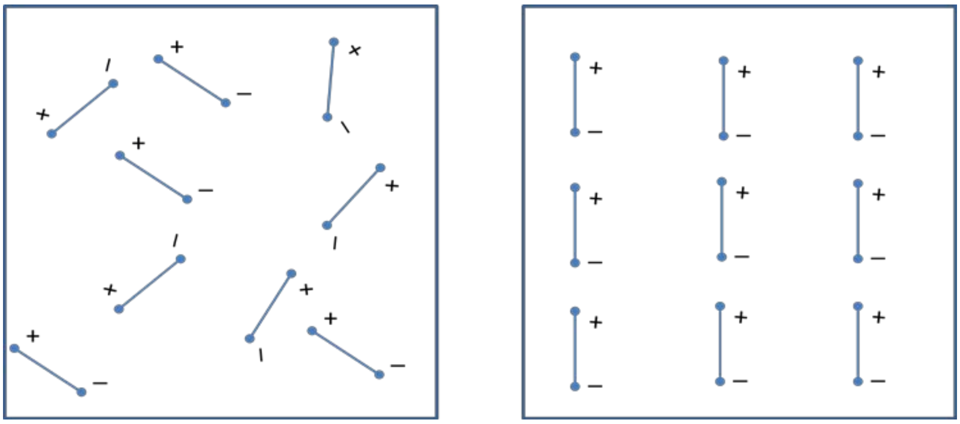

Figure 2.4.3 Principle of pyroelectricity

These sensors work on the principle of *pyroelectricity*, which states that a crystal material such as Lithium tantalite generates charge in response to heat flow. In presence of an electric field, when such a crystal material heats up, its electrical dipoles line up as shown in figure 2.4.3. This is called as polarization. On cooling, the material retains its polarization. In absence of electric field, when this polarized material is subjected to infra red irradiation, its polarization reduces. This phenomenon is the measure of detection of movement of an object.

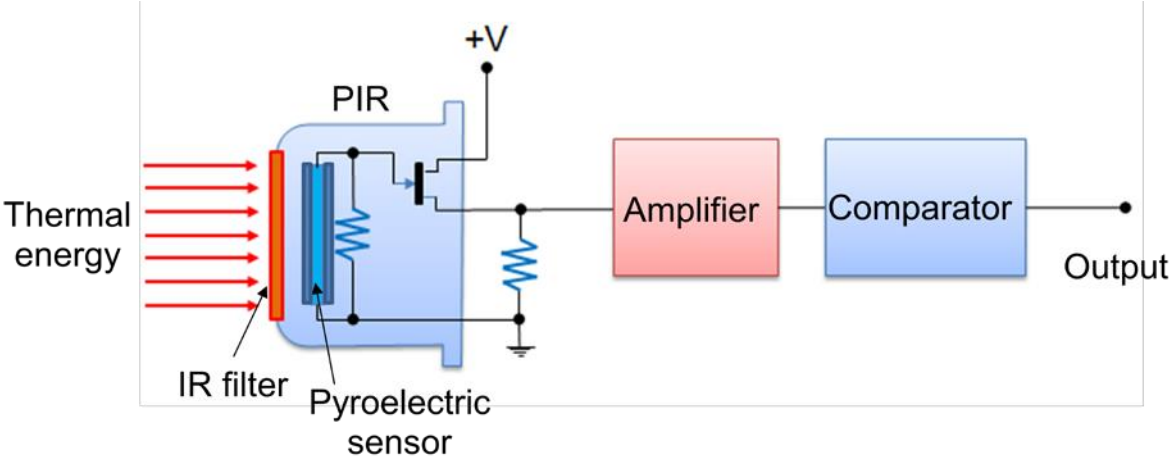

Figure 2.4.4 Construction and working a Pyroelectric sensor

Pyroelectric sensor comprises of a thick element of polarized material coated with thin film electrodes on opposite faces as shown in figure 2.4.4. Initially the electrodes are in electrical equilibrium with the polarized material. On incident of infra red, the material heats up and reduces its polarization. This leads to charge imbalance at the interface of crystal and electrodes. To balance this disequilibrium, measurement circuit supplies the charge, which is calibrated against the detection of an object or its movement.

Applications of Pyroelectric sensors [2]

- Intrusion detector
- Optothermal detector
- Pollution detector
- Position sensor
- Solar cell studies
- Engine analysis

3. *Strain Gauge as force Sensor*

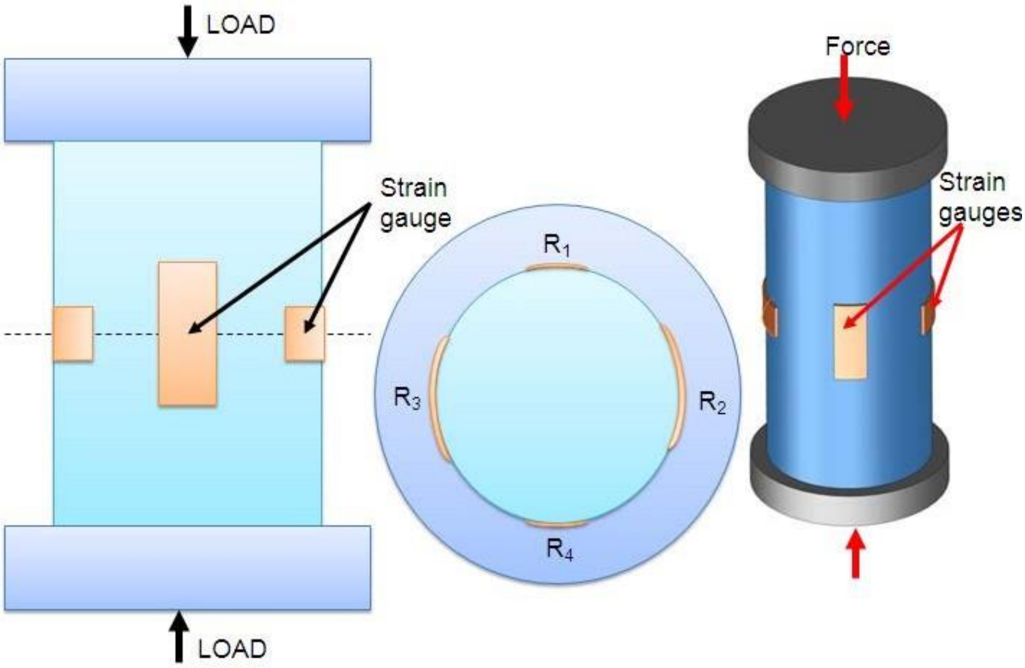

Figure 2.4.5 Strain gauge based Load cell

Strain gauge based sensors work on the principle of change in electrical resistance. When, a mechanical element subjects to a tension or a compression the electric resistance of the material changes. This is used to measure the force acted upon the element. The details regarding the construction of strain gauge transducer are already presented in Lecture 2 of Module 2.

Figure 2.4.5 shows a strain gauge load cell. It comprises of cylindrical tube to which strain gauges are attached. A load applied on the top collar of the cylinder compress the strain gauge element which changes its electrical resistance. Generally strain gauges are used to measure forces up to 10 MN. The non-linearity and repeatability errors of this transducer are ±0.03% and ±0.02% respectively.

4. *Fluid pressure*

Chemical, petroleum, power industry often need to monitor fluid pressure. Various types of instruments such as diaphragms, capsules, and bellows are used to monitor the fluid pressure. Specially designed strain gauges doped in diaphragms are generally used to measure the inlet manifold pressure in applications such as automobiles. A typical arrangement of strain gauges on a diaphragm is shown in figure 2.4.6. Application of pressurized fluid displaces the diaphragm. This displacement is measured by the stain gauges in terms of radial and/or lateral strains. These strain gauges are connected to form the arms of a Wheatstone bridge.

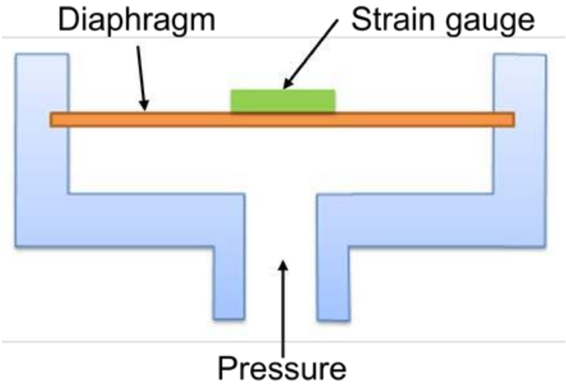

Figure 2.4.6 A diaphragm

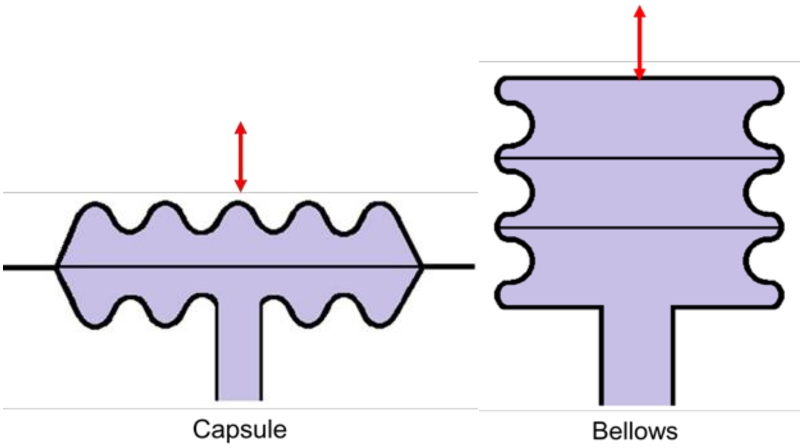

Figure 2.4.7 Schematic of Capsule and Bellow

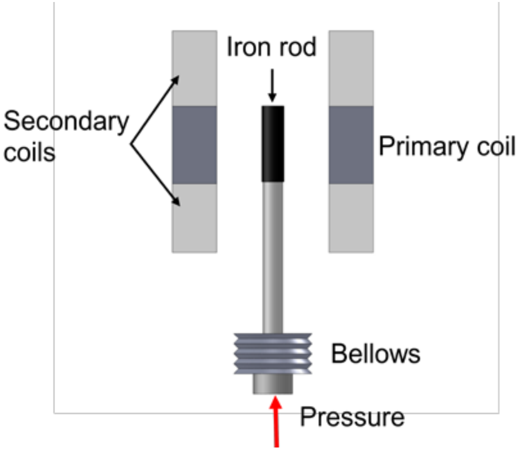

Figure 2.4.8 Bellow with a LVDT [1]

Capsule is formed by combining two corrugated diaphragms. It has enhanced sensitivity in comparison with that of diaphragms. Figure 2.4.7 shows a schematic of a Capsule and a Bellow. A stack of capsules is called as 'Bellows'. Bellows with a LVDT sensor measures the fluid pressure in terms of change in resultant voltage across the secondary coils of LVDT. Figure 2.4.8 shows a typical arrangement of the same.

5. Tactile sensors

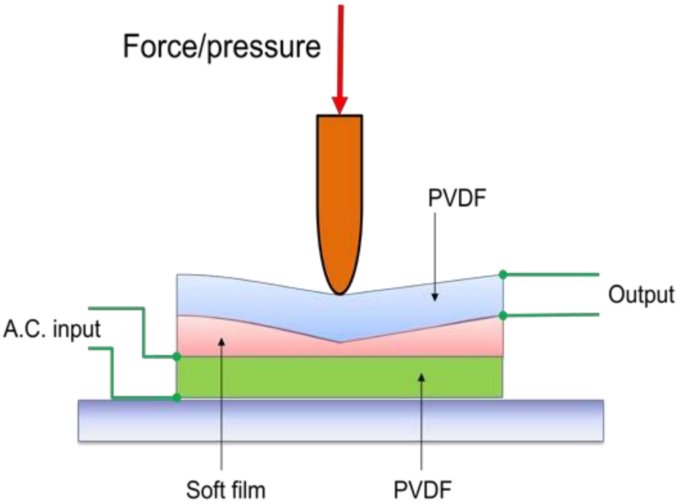

Figure 2.4.9 Schematic of a tactile sensor [1]

In general, tactile sensors are used to sense the contact of fingertips of a robot with an object. They are also used in manufacturing of 'touch display' screens of visual display units (VDUs) of CNC machine tools. Figure 2.4.9 shows the construction of piezo-electric polyvinylidene fluoride (PVDF) based tactile sensor. It has two PVDF layers separated by a soft film which transmits the vibrations. An alternating current is applied to lower PVDF layer which generates vibrations due to reverse piezoelectric effect. These vibrations are transmitted to the upper PVDF layer via soft film. These vibrations cause alternating voltage across the upper PVDF layer. When some pressure is applied on the upper PVDF layer the vibrations gets affected and the output voltage changes. This triggers a switch or an action in robots or touch displays.

6. Piezoelectric sensor

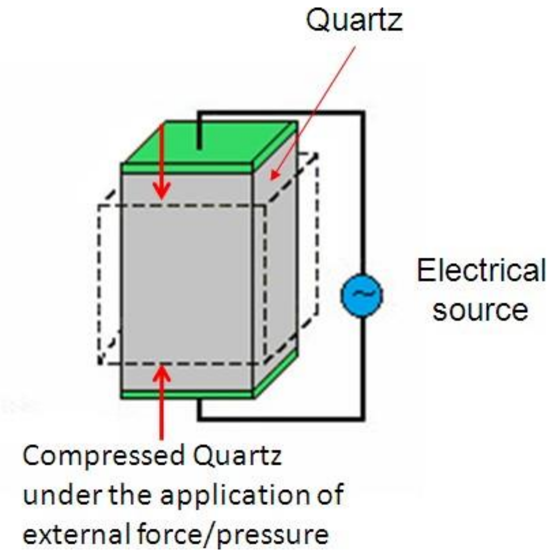

Figure 2.4.10 Principle of working of Piezoelectric sensor

Piezoelectric sensor is used for the measurement of pressure, acceleration and dynamic-forces such as oscillation, impact, or high speed compression or tension. It contains piezoelectric ionic crystal materials such as Quartz (Figure 2.4.10). On application of force or pressure these materials get stretched or compressed. During this process, the charge over the material changes and redistributes. One face of the material becomes positively charged and the other negatively charged. The net charge q on the surface is proportional to the amount x by which the charges have been displaced. The displacement is proportion to force. Therefore we can write,

$$q = \mathrm{k}x = \mathrm{S}F \qquad (2.4.1)$$

where k is constant and S is a constant termed the charge sensitivity.

7. Liquid flow

Liquid flow is generally measured by applying the Bernoulli's principle of fluid flow through a constriction. The quantity of fluid flow is computed by using the pressure drop measured. The fluid flow volume is proportional to square root of pressure difference at the two ends of the constriction. There are various types of fluid flow measurement devices being used in manufacturing automation such as Orifice plate, Turbine meter etc.

7.a Orifice plate:

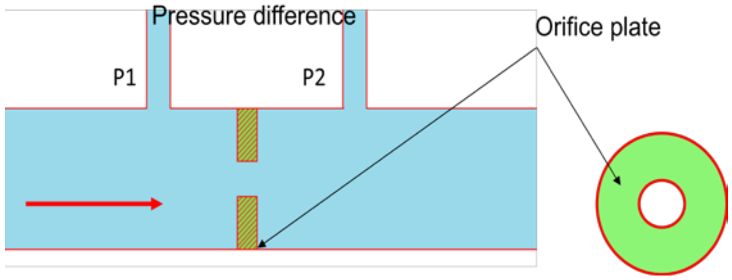

Figure 2.4.11 Orifice Plate [1]

Figure 2.4.11 shows a schematic of Orifice plate device. It has a disc with a hole at its center, through which the fluid flows. The pressure difference is measured between a point equal to the diameter of the tube upstream and a point equal to the half the diameter downstream. Orifice plate is inexpensive and simple in construction with no moving parts. It exhibits nonlinear behavior and does not work with slurries. It has accuracy of ± 1.5%.

7.b Turbine meter

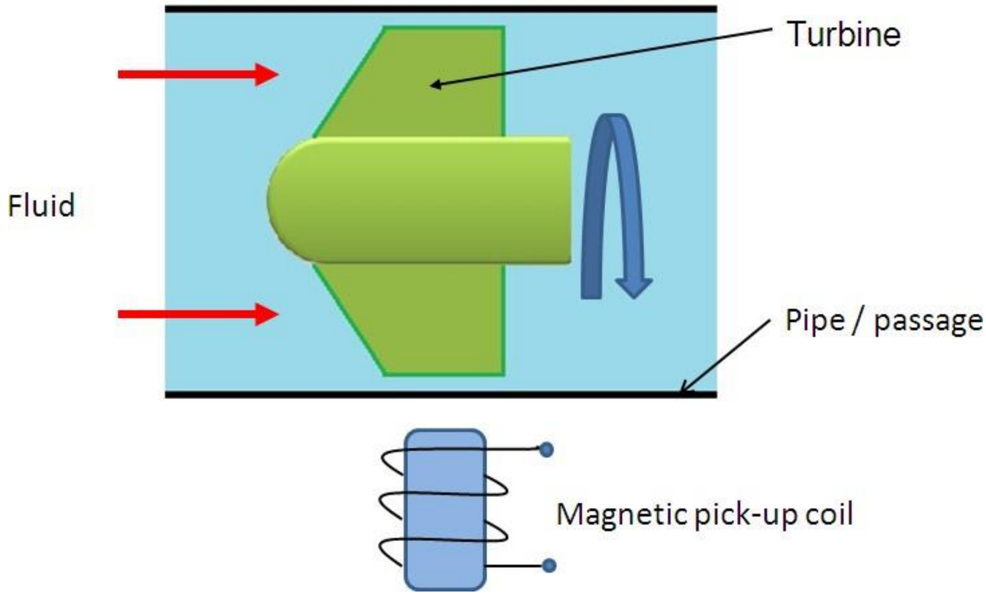

Figure 2.4.12 Schematic of turbine meter [1]

Turbine flow meter has an accuracy of ±0.3%. It has a multi blade rotor mounted centrally in the pipe along which the flow is to be measured. Figure 2.4.12 shows the typical arrangement of the rotor and a magnetic pick up coil. The fluid flow rotates the rotor. Accordingly the magnetic pick up coil counts the number of magnetic pulses generated due to the distortion of magnetic field by the rotor blades. The angular velocity is proportional to the number of pulses and fluid flow is proportional to angular velocity.

8. *Fluid level*

The level of liquid in a vessel or container can be measured,

a. directly by monitoring the position of liquid surface
b. indirectly by measuring some variable related to the height.

Direct measurements involve the use of floats however the indirect methods employ load cells. Potentiometers or LVDT sensors can be used along with the floats to measure the height of fluid column. Force sensed by the load cells is proportional to the height of fluid column.

Quiz:

1. PVDF piezoelectric polyvinylidene fluoride is used in the manufacture of__________________________sensor.
2. Suggest a suitable sensor to measure the level of sulphuric acid in a storage tank. The sensor must give an electric signal as output.
3. 'Bellows are more sensitive than capsules'. State true or false and justify your answer.
4. State the applications of pyroelectric sensors.

References

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.
2. Hossain A. and Rashid M. H., Pyroelectric Detectors and Their Applications, IEEE Trans. on Ind. Appl., 27 (5), 824-829, 1991.

Module 2: Sensors and signal processing
Lecture 5
Temperature and light sensors

Temperature conveys the state of a mechanical system in terms of expansion or contraction of solids, liquids or gases, change in electrical resistance of conductors, semiconductors and thermoelectric emfs. Temperature sensors such as bimetallic strips, thermocouples, thermistors are widely used in monitoring of manufacturing processes such as casting, molding, metal cutting etc. The construction details and principle of working of some of the temperature sensors are discussed in following sections.

1. Bimetallic strips

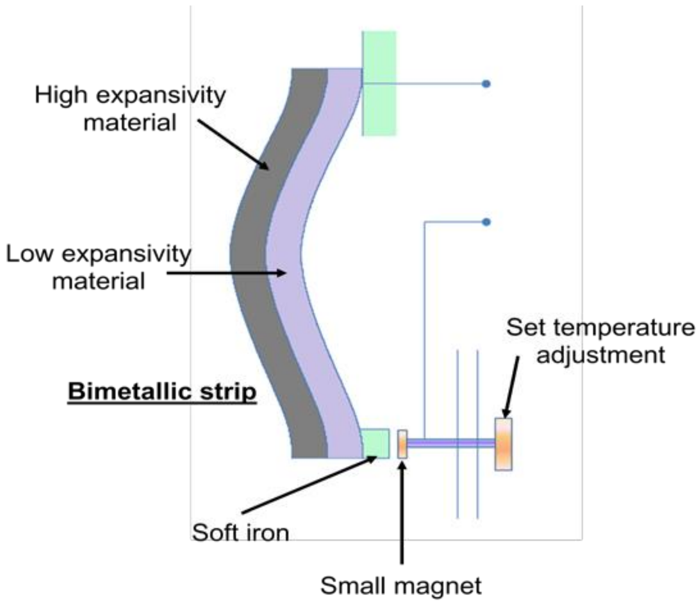

Figure 2.5.1 Construction and working of Bi-metallic strip

Bimetallic strips are used as thermal switch in controlling the temperature or heat in a manufacturing process or system. It contains two different metal strips bonded together. The metals have different coefficients of expansion. On heating the strips bend into curved strips with the metal with higher coefficient of expansion on the outside of the curve. Figure 2.5.1 shows a typical arrangement of a bimetallic strip used with a setting-up magnet. As the strips bend, the soft iron comes in closer proximity of the small magnet and further touches. Then the electric circuit completes and generates an alarm. In this way bimetallic strips help to protect the desired application from heating above the pre-set value of temperature.

2. *Resistance temperature detectors (RTDs)*

RTDs work on the principle that the electric resistance of a metal changes due to change in its temperature. On heating up metals, their resistance increases and follows a linear relationship as shown in Figure 2.5.2. The correlation is

$$R_t = R_0 (1 + \alpha T) \qquad (2.5.1)$$

where R_t is the resistance at temperature T (^{0}C) and R_0 is the temperature at 0^0C and α is the constant for the metal termed as temperature coefficient of resistance. The sensor is usually made to have a resistance of 100 Ω at 0 °C

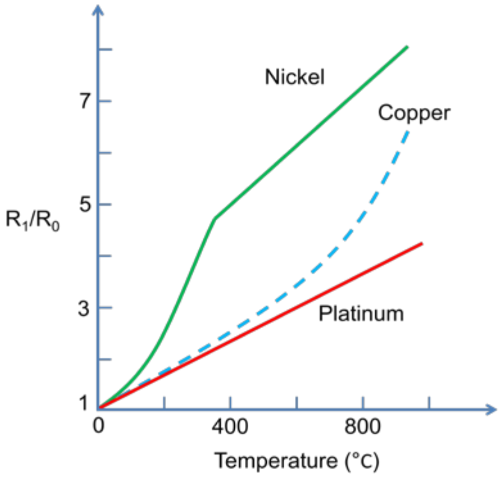

Figure 2.5.2 Behavior of RTD materials [1]

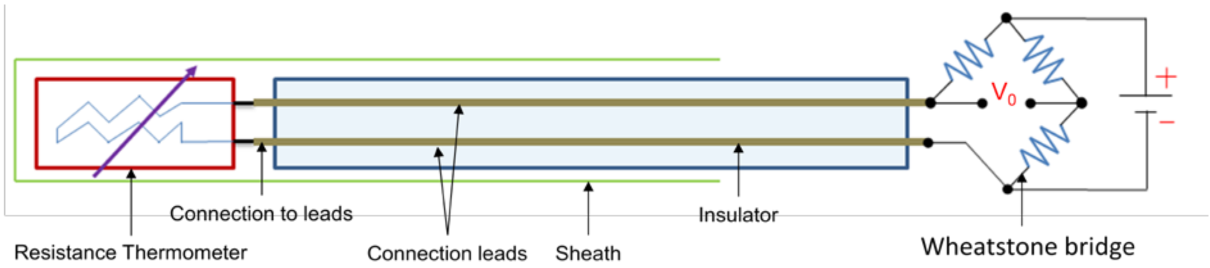

Figure 2.5.3 Construction of a Resistance temperature detector (RTD)

Figure 2.5.3 shows the construction of a RTD. It has a resistor element connected to a Wheatstone bridge. The element and the connection leads are insulated and protected by a sheath. A small amount of current is continuously passing though the coil. As the temperature changes the resistance of the coil changes which is detected at the Wheatstone bridge.

RTDs are used in the form of thin films, wire wound or coil. They are generally made of metals such as platinum, nickel or nickel-copper alloys. Platinum wire held by a high-temperature glass adhesive in a ceramic tube is used to measure the temperature in a metal furnace. Other applications are:

- Air conditioning and refrigeration servicing
- Food Processing
- Stoves and grills
- Textile production
- Plastics processing
- Petrochemical processing
- Micro electronics
- Air, gas and liquid temperature measurement in pipes and tanks
- Exhaust gas temperature measurement

3. Thermistors

Thermistors follow the principle of decrease in resistance with increasing temperature. The material used in thermistor is generally a semiconductor material such as a sintered metal oxide (mixtures of metal oxides, chromium, cobalt, iron, manganese and nickel) or doped polycrystalline ceramic containing barium titanate (BaTiO3) and other compounds. As the temperature of semiconductor material increases the number of electrons able to move about increases which results in more current in the material and reduced resistance. Thermistors are rugged and small in dimensions. They exhibit nonlinear response characteristics.

Thermistors are available in the form of a bead (pressed disc), probe or chip. Figure 2.5.4 shows the construction of a bead type thermistor. It has a small bead of dimension from 0.5 mm to 5 mm coated with ceramic or glass material. The bead is connected to an electric circuit through two leads. To protect from the environment, the leads are contained in a stainless steel tube.

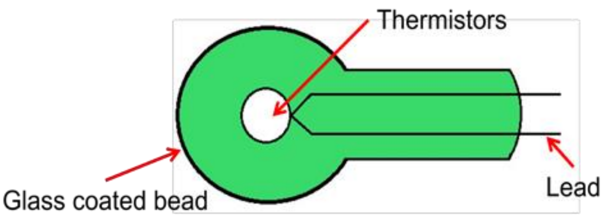

Figure 2.5.4 Schematic of a thermistor

Applications of Thermistors

- To monitor the coolant temperature and/or oil temperature inside the engine
- To monitor the temperature of an incubator
- Thermistors are used in modern digital thermostats
- To monitor the temperature of battery packs while charging
- To monitor temperature of hot ends of 3D printers
- To maintain correct temperature in the food handling and processing industry equipments
- To control the operations of consumer appliances such as toasters, coffee makers, refrigerators, freezers, hair dryers, etc.

4. Thermocouple

Thermocouple works on the fact that when a junction of dissimilar metals heated, it produces an electric potential related to temperature. As per Thomas Seebeck (1821), when two wires composed of dissimilar metals are joined at both ends and one of the ends is heated, then there is a continuous current which flows in the thermoelectric circuit. Figure 2.5.5 shows the schematic of thermocouple circuit. The net open circuit voltage (the Seebeck voltage) is a function of junction temperature and composition of two metals. It is given by,

$$\Delta V_{AB} = \alpha \, \Delta T \qquad (2.5.2)$$

where α, the Seebeck coefficient, is the constant of proportionality.

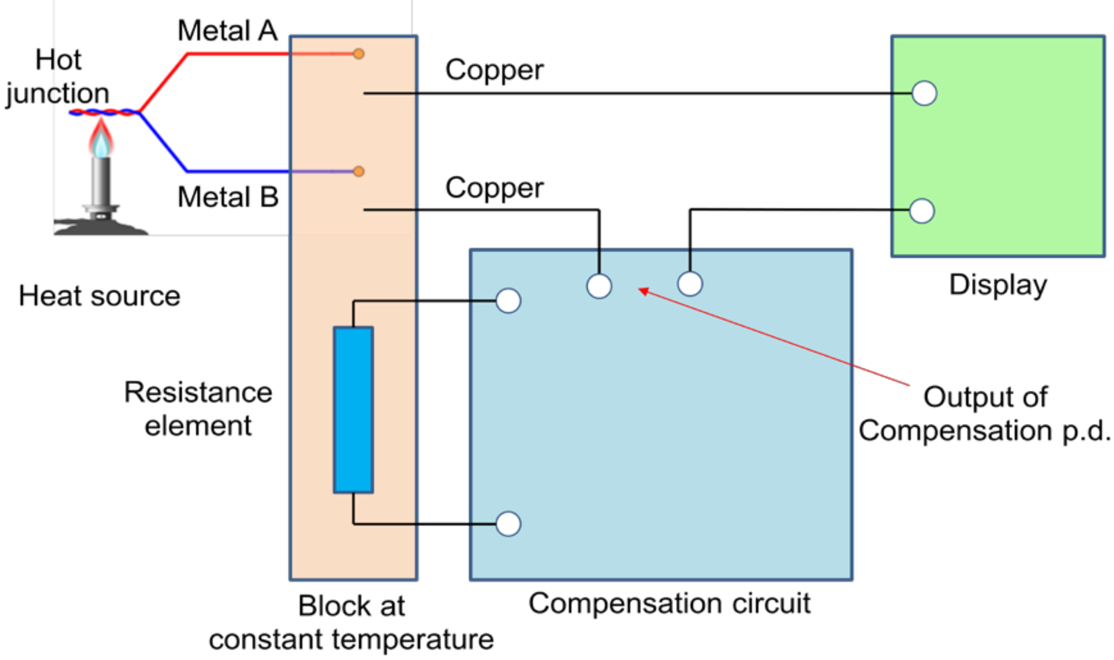

Figure 2.5.5 Schematic of thermocouple circuit

Generally, Chromel (90% nickel and 10% chromium)–Alumel (95% nickel, 2% manganese, 2% aluminium and 1% silicon) are used in the manufacture of a thermocouple. Table 2.5.1 shows the various other materials, their combinations and application temperature ranges.

Table 2.5.1 Thermocouple materials and temperature ranges [1]

Materials	**Range (ºC)**	**(µV/ºC)**
Platinum 30% rhodium/platinum 6% rhodium	0 to 1800	3
Chromel/constantan	-200 to 1000	63
Iron/constantan	-200 to 900	53
Chromel/alumel	-200 to 1300	41
Nirosil/nisil	-200 to 1300	28
Platinum/platinum 13% rhodium	0 to 1400	6
Platinum/platinum 10% rhodium	0 to 1400	6
Copper/constantan	-200 to 400	43

Applications of Thermocouples

- To monitor temperatures and chemistry throughout the steel making process
- Testing temperatures associated with process plants e.g. chemical production and petroleum refineries
- Testing of heating appliance safety
- Temperature profiling in ovens, furnaces and kilns
- Temperature measurement of gas turbine and engine exhausts
- Monitoring of temperatures throughout the production and smelting process in the steel, iron and aluminum industry

Light sensors

A light sensor is a device that is used to detect light. There are different types of light sensors such as photocell/photoresistor and photo diodes being used in manufacturing and other industrial applications.

Photoresistor is also called as light dependent resistor (LDR). It has a resistor whose resistance decreases with increasing incident light intensity. It is made of a high resistance semiconductor material, cadmium sulfide (CdS). The resistance of a CdS photoresistor varies inversely to the amount of light incident upon it. Photoresistor follows the principle of photoconductivity which results from the generation of mobile carriers when photons are absorbed by the semiconductor material.

Figure 2.5.6 shows the construction of a photo resistor. The CdS resistor coil is mounted on a ceramic substrate. This assembly is encapsulated by a resin material. The sensitive coil electrodes are connected to the control system though lead wires. On incidence of high intensity light on the electrodes, the resistance of resistor coil decreases which will be used further to generate the appropriate signal by the microprocessor via lead wires.

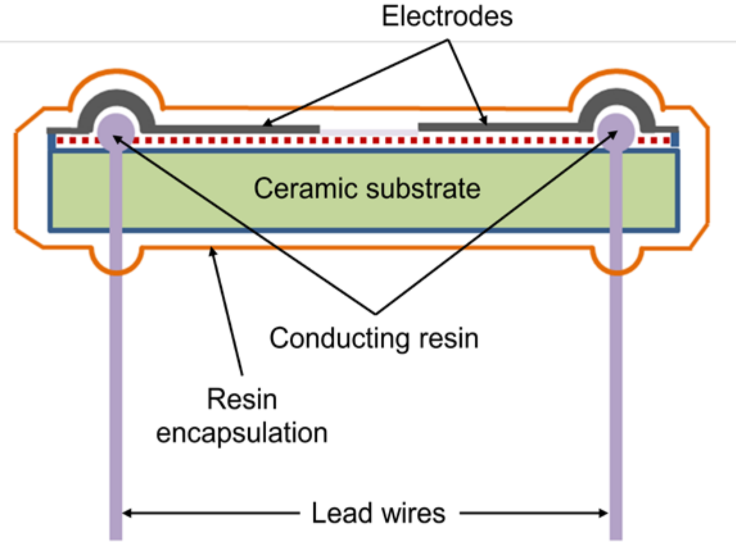

Figure 2.5.6 Construction of a photo resistor

Photoresistors are used in science and in almost any branch of industry for control, safety, amusement, sound reproduction, inspection and measurement.

Applications of photo resistor

- Computers, wireless phones, and televisions, use ambient light sensors to automatically control the brightness of a screen
- Barcode scanners used in retailer locations work using light sensor technology
- In space and robotics: for controlled and guided motions of vehicles and robots. The light sensor enables a robot to detect light. Robots can be programmed to have a specific reaction if a certain amount of light is detected.
- Auto Flash for camera
- Industrial process control

Photo diodes

Photodiode is a solid-state device which converts incident light into an electric current. It is made of Silicon. It consists of a shallow diffused p-n junction, normally a p-on-n configuration. When photons of energy greater than 1.1eV (the bandgap of silicon) fall on the device, they are absorbed and electron-hole pairs are created. The depth at which the photons are absorbed depends upon their energy. The lower the energy of the photons, the deeper they are absorbed. Then the electron-hole pairs drift apart. When the minority carriers reach the junction, they are swept across by the electric field and an electric current establishes.

Photodiodes are one of the types of photodetector, which convert light into either current or voltage. These are regular semiconductor diodes except that they may be either exposed to detect vacuum UV or X-rays or packaged with a opening or optical fiber connection to allow light to reach the sensitive part of the device.

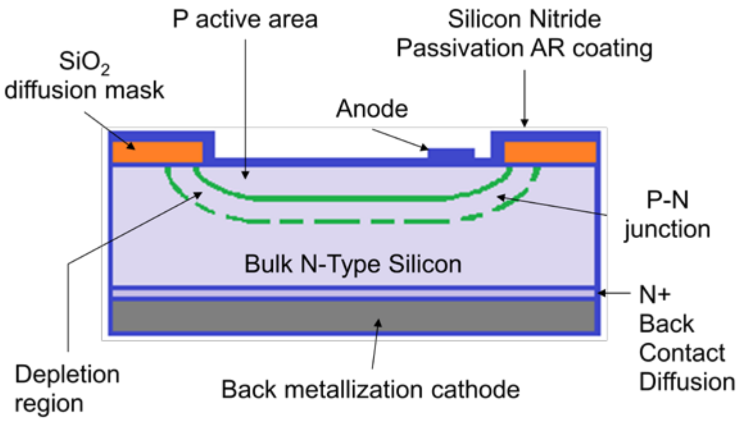

Figure 2.5.7 Construction of photo diode detector

Figure 2.5.7 shows the construction of Photo diode detector. It is constructed from single crystal silicon wafers. It is a p-n junction device. The upper layer is p layer. It is very thin and formed by thermal diffusion or ion implantation of doping material such as boron. Depletion region is narrow and is sandwiched between p layer and bulk n type layer of silicon. Light irradiates at front surface, anode, while the back surface is cathode. The incidence of light on anode generates a flow of electron across the p-n junction which is the measure of light intensity.

Applications of photo diodes

Camera: Light Meters, Automatic Shutter Control, Auto-focus, Photographic Flash Control

Medical: CAT Scanners - X ray Detection, Pulse Oximeters, Blood Particle Analyzers

Industry
- Bar Code Scanners
- Light Pens
- Brightness Controls
- Encoders
- Position Sensors
- Surveying Instruments
- Copiers - Density of Toner

Safety Equipment
- Smoke Detectors
- Flame Monitors
- Security Inspection Equipment - Airport X ray
- Intruder Alert - Security System

Automotive

• Headlight Dimmer
• Twilight Detectors
• Climate Control - Sunlight Detector

Communications

• Fiber Optic Links
• Optical Communications
• Optical Remote Control

Quiz:

1. 'In thermistor sensors, resistance decreases in a very nonlinear manner with increase in temperature.' State true or false and justify.
2. List the various temperature sensors used by we in/around our home/office/university.
3. Develop a conceptual design of a Light sensors based control system for counting a number of milk packets being packed for discharge. Assume suitable data if necessary.

References

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.

Module 2: Sensors and signal processing
Lecture 6
Signal Conditioning Devices

Signal Conditioning Operations

In previous lectures we have studied various sensors and transducers used in a mechatronics system. Transducers sense physical phenomenon such as rise in temperature and convert the measurand into an electrical signal viz. voltage or current. However these signals may not be in their appropriate forms to employ them to control a mechatronics system. Figure 2.6.1 shows various signal conditioning operations which are being carried out in controlling a mechatronics based system. The signals given by a transducer may be nonlinear in nature or may contain noise. Thus before sending these signals to the mechatronics control unit it is essential to remove the noise, nonlinearity associated with the raw output from a sensor or a transducer. It is also needed to modify the amplitude (low/high) and form (analogue/digital) of the output signals into respective acceptable limits and form which will be suitable to the control system. These activities are carried out by using signal conditioning devices and the process is termed as 'signal conditioning'.

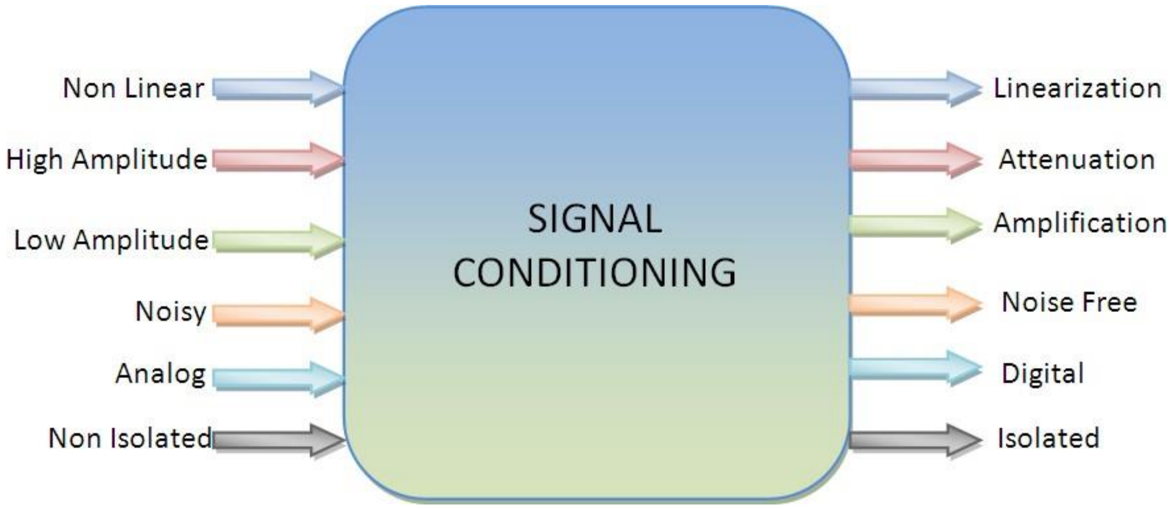

Figure 2.6.1 Signal conditioning operations

Signal conditioning system enhances the quality of signal coming from a sensor in terms of:

1. Protection
To protect the damage to the next element of mechatronics system such microprocessors from the high current or voltage signals.

2. Right type of signal
To convert the output signal from a transducer into the desired form i.e. voltage / current.

3. Right level of the signal
To amplify or attenuate the signals to a right /acceptable level for the next element.

4. Noise
To eliminate noise from a signal.

5. Manipulation
To manipulate the signal from its nonlinear form to the linear form.

1. Amplification/Attenuation

Various applications of Mechatronics system such as machine tool control unit of a CNC machine tool accept voltage amplitudes in range of 0 to 10 Volts. However many sensors produce signals of the order of milli volts. This low level input signals from sensors must be amplified to use them for further control action. Operational amplifiers (op-amp) are widely used for amplification of input signals. The details are as follows.

1.1 Operational amplifier (op-amp)

Operational Amplifier is a basic and an important part of a signal conditioning system. It is often abbreviated as op-amp. Op-amp is a high gain voltage amplifier with a differential input. The gain is of the order of 100000 or more. Differential input is a method of transmitting information with two different electronic signals which are generally complementary to each other. Figure 2.6.2 shows the block diagram of an op-amp. It has five terminals. Two voltages are applied at two input terminals. The output terminal provides the amplified value of difference between two input voltages. Op-amp works by using the external power supplied at *Vs+* and *Vs-* terminals.

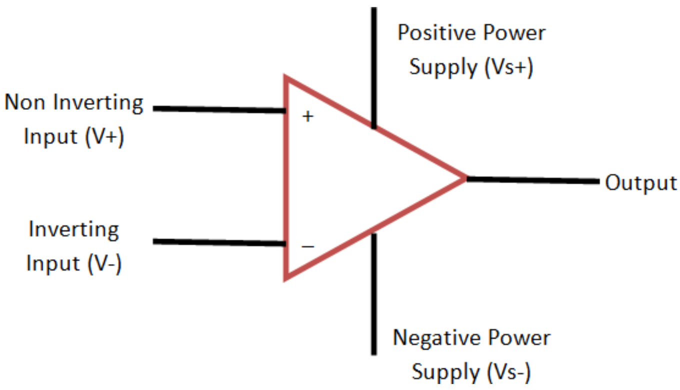

Figure 2.6.2 circuit diagram of an Op-amp

In general op-amp amplifies the difference between input voltages (V+ and V-). The output of an operational amplifier can be written as

$$V_{out} = G * (V+ - V-) \qquad (2.6.1)$$

where G is Op-amp Gain.

Figure 2.6.3 shows the inverting configuration of an op-amp. The input signal is applied at the inverting terminal of the op-amp through the input resistance R_{in}. The non-inverting terminal is grounded. The output voltage (V_{out}) is connected back to the inverting input terminal through resistive network of R_{in} and feedback resistor R_f. Now at node a, we can write,

$$I_1 = V_{in}/R_1 \qquad (2.6.2)$$

The current flowing through R_f is also I_1, because the op-amp is not drawing any current. Therefore the output voltage is given by,

$$V_{out} = -I_1 R_f = -V_{in} R_f/R_1 \qquad (2.6.3)$$

Thus the closed loop gain of op-amp can be given as,

$$G = V_{out}/V_{in} = -R_f/R_1 \qquad (2.6.4)$$

The negative sign indicates a phase shift between V_{in} and V_{out}.

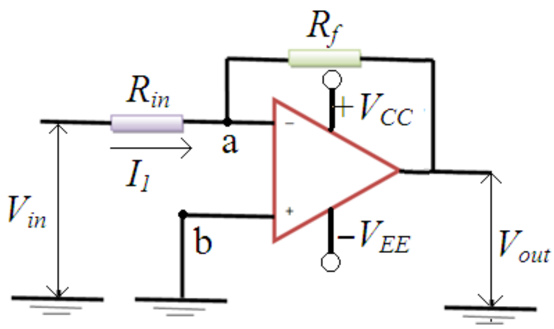

Figure 2.6.3 Inverting op-amp

1.2 Amplification of input signal by using Op-amp

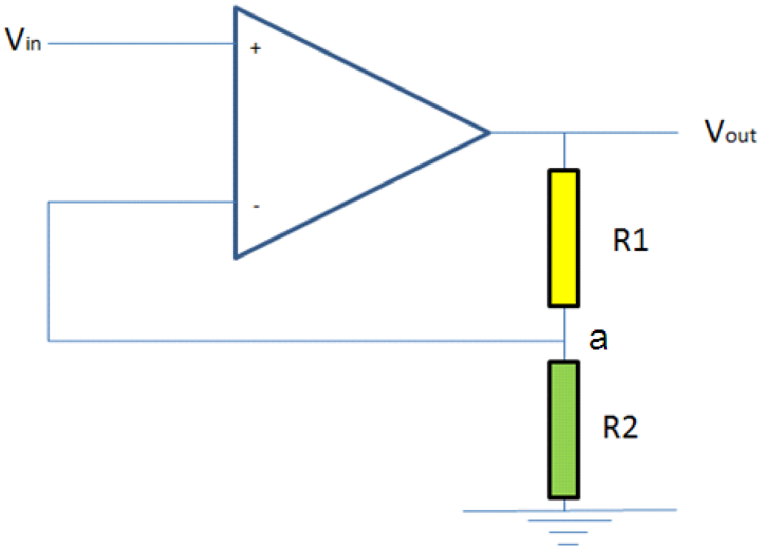

Figure 2.6.4 Amplification using an Op-amp

Figure 2.6.4 shows a configuration to amplify an input voltage signal. It has two registers connected at node a. If we consider that the voltage at positive terminal is equal to voltage at negative terminal then the circuit can be treated as two resistances in series. In series connection of resistances, the current flowing through circuit is same. Therefore we can write,

$$\frac{V_{out}-V_{in}}{R_1} = \frac{V_{in}-0}{R_2} \qquad (2.6.5)$$

$$\frac{V_{out}-V_{in}}{R_1} = \frac{V_{in}}{R_2} \qquad (2.6.6)$$

Thus by selecting suitable values of resistances, we can obtain the desired (amplified/attenuated) output voltage for known input voltage.

There are other configurations such as Non-inverting amplifier, Summing amplifier, Subtractor, Logarithmic amplifier are being used in mechatronics applications. The detail study of all these is out of scope of the present course. Readers can refer Bolton for more details.

2. Filtering

Output signals from sensors contain noise due to various external factors like improper hardware connections, environment etc. Noise gives an error in the final output of system. Therefore it must be removed. In practice, change in desired frequency level of output signal is a commonly noted noise. This can be rectified by suing filters. Following types of filters are used in practice:

1. Low Pass Filter
2. High Pass Filter
3. Band Pass Filter
4. Band Reject Filter

2.1 Low Pass Filter

Low pass filter is used to allow low frequency content and to reject high frequency content of an input signal. Its configuration is shown in Figure 2.6.5

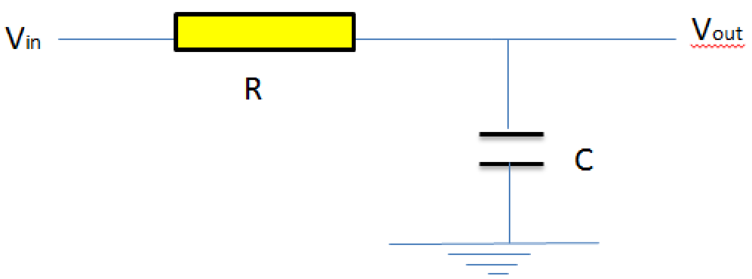

Figure 2.6.5 Circuitry of Low Pass Filter

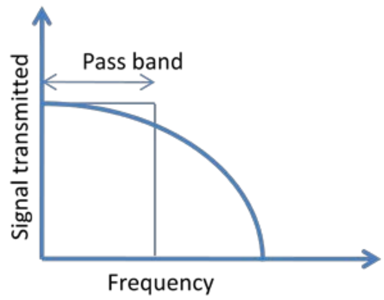

Figure 2.6.6 Pass band for low pass filter

In the circuit shown in Figure 2.6.5, resistance and capacitance are in series with voltage at resistance terminal is input voltage and voltage at capacitance terminal is output voltage. Then by applying the Ohm's Law, we can write,

$$V_{out} = \frac{\frac{1}{j\omega C}}{R + \left(\frac{1}{j\omega C}\right)} V_{in} \qquad (2.6.7)$$

$$V_{out} = \frac{1}{1 + j\omega CR} V_{in} \qquad (2.6.8)$$

From equation 2.6.8 we can say that if frequency of Input signal is low then $j\omega CR$ would be low. Thus $\frac{1}{1+j\omega CR}$ would be nearly equal to 1. However at higher frequency $j\omega CR$ would be higher, then $\frac{1}{1+j\omega CR}$ would be nearly equal to 0. Thus above circuit will act as Low Pass Filter. It selects frequencies below a breakpoint frequency ω = 1/RC as shown in Figure 2.6.6. By selecting suitable values of R and C we can obtain desired values of frequency to pass in.

2.2 High Pass Filter

These types of filters allow high frequencies to pass through it and block the lower frequencies. The figure 2.6.7 shows circuitry for high pass filter.

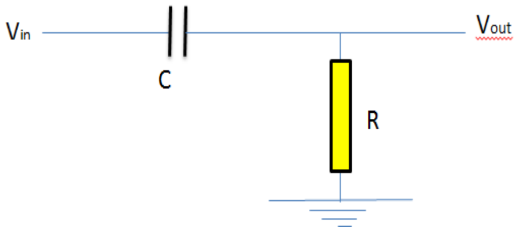

Figure 2.6.7 Circuitry of High Pass Filter

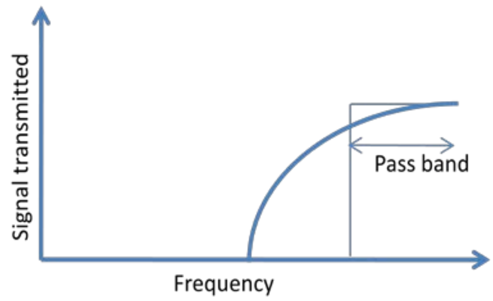

Figure 2.6.8 Pass band for high pass filter

$$V_{out} = \frac{R}{R + \left(\frac{1}{j\omega C}\right)} V_{in} \qquad (2.6.9)$$

$$V_{out} = \frac{j\omega CR}{1 + j\omega CR} V_{in} \qquad (2.6.10)$$

From equation 2.6.10, we can say that if frequency of input signal is low then $\frac{1}{j\omega C}$ would be high and thus $\frac{R}{R+\left(\frac{1}{j\omega C}\right)}$ would be nearly equal to 0. For high frequency signal, $\frac{1}{j\omega C}$ would be low and $\frac{R}{R+\left(\frac{1}{j\omega C}\right)}$ would be nearly equal to 1. Thus above circuit will act as High Pass Filter. It selects frequencies above a breakpoint frequency ω = 1/RC as shown in Figure 2.6.8. By selecting suitable values of R and C we can allow desired (high) frequency level to pass through.

2.3 Band Pass Filter

In some applications, we need to filter a particular band of frequencies from a wider range of mixed signals. For this purpose, the properties of low-pass and high-pass filters circuits can be combined to design a filter which is called as band pass filter. Band pass filter can be developed by connecting a low-pass and a high-pass filter in series as shown in figure 2.6.9.

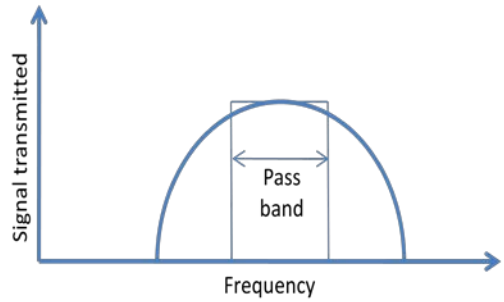

Figure 2.6.9 Band pass filter

2.4 Band Reject Filter

These filters pass all frequencies above and below a particular range set by the operator/manufacturer. They are also known as band stop filters or notch filters. They are constructed by connecting a low-pass and a high-pass filter in parallel as shown in Figure 2.6.10.

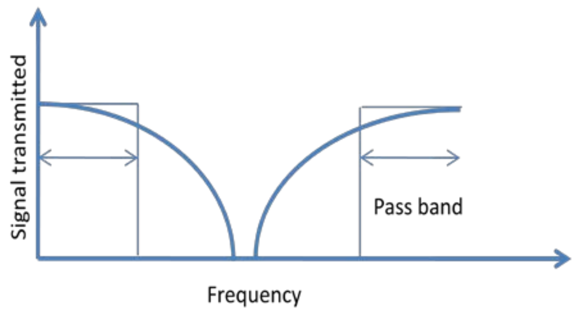

Figure 2.6.10 Band reject filter

Quiz

1. Explain the principle of working of op-amp as an inverting amplifier.
2. What kind of signal conditioning operations will be required to develop a table top CNC turning center for small job works?

Module 2: Sensors and signal processing
Lecture 7
Protection, conversion and pulse width modulation

1. Protection

In many situations sensors or transducers provide very high output signals such as high current or high voltage which may damage the next element of the control system such as microprocessor.

1.1 Protection from high current

The high current to flow in a sensitive control system can be limited by:
1. Using a series of resistors
2. Using fuse to break the circuit if current value exceeds a preset or safe value

1.2 Protection from high voltage

Zener diode circuits are widely used to protect a mechatronics control system from high values of voltages and wrong polarity. Figure 2.7.1 shows a typical Zener diode circuit.

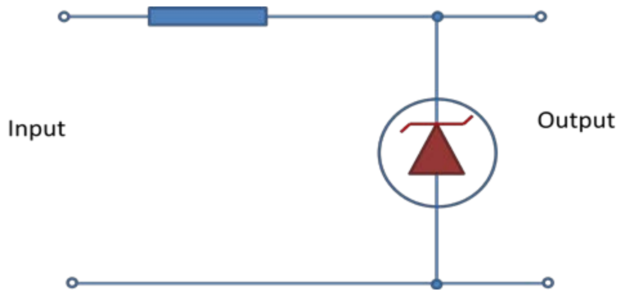

Figure 2.7.1 Zener diode circuit diagram

Zener diode acts as ordinary or regular diodes upto certain breakdown voltage level when they are conducting. When the voltage rises to the breakdown voltage level, Zener diode breaks down and stops the voltage to pass to the next circuit.

Zener diode as being a diode has low resistance for current to flow in one direction through it and high resistance for the opposite direction. When connected in correct polarity, a high resistance produces high voltage drop. If the polarity reverses, the diode will have less resistance and therefore results in less voltage drop.

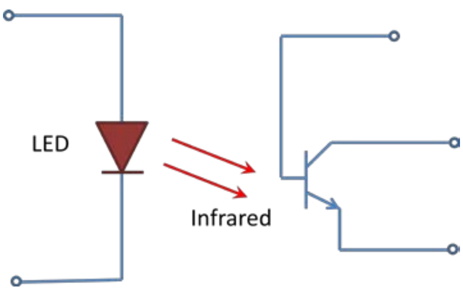

Figure 2.7.2 Schematic of an Optoisolator

In many high voltage scenarios, it is required to isolate the control circuit completely from the input high voltages to avoid the possible damage. This can be achieved by Optoisolators. Figure 2.7.2 shows the typical circuit of an Optoisolator. It comprises of a Light emitting diode (LED) and a photo transistor. LED irradiates infra red due to the voltage supplied to it from a microprocessor circuit. The transistor detects irradiation and produces a current in proportion to the voltage applied. In case of high voltages, output current from Optoisolator is utilized for disconnecting the power supply to the circuit and thus the circuit gets protected.

2. Wheatstone bridge

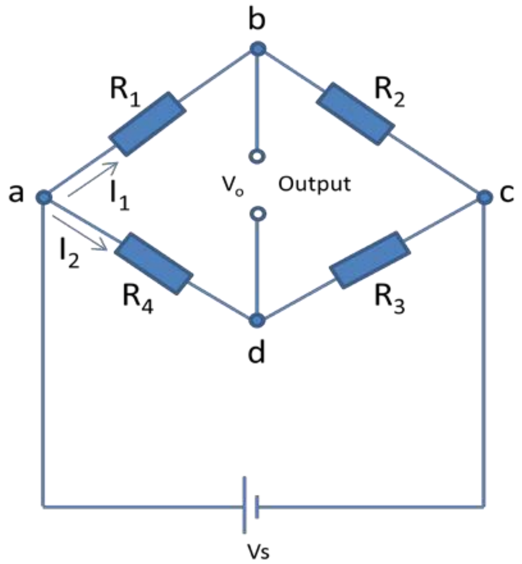

Figure 2.7.3 Configuration of a Wheatstone bridge

Wheatstone bridge is used to convert a resistance change detected by a transducer to a voltage change. Figure 2.7.3 shows the basic configuration of a Wheatstone bridge. When the output voltage *Vout* is zero then the potential at B must be equal to D and we can say that,

$$Vab = Vad, \quad (2.7.1)$$
$$I1\,R\,1 = I2\,R2 \quad (2.7.2)$$

Also,

$$Vbc = Vdc, \quad (2.7.3)$$
$$I1\,R2 = I2\,R4 \quad (2.7.4)$$

Dividing equation 2.7.2 by 2.7.4,

$$R1/R2 = R3/R4 \quad (2.7.5)$$

The bridge is thus balanced.

The potential drop across $R1$ due to supply voltage *Vs*,

$$Vab = Vs\,R1/(R1 + R2) \quad (2.7.6)$$

Similarly,

$$Vad = VsR3/(R3 + R4) \qquad (2.7.7)$$

Thus the output voltage Vo is given by,

$$Vo = Vab - Vad \qquad (2.7.8)$$

$$Vo = Vs\,\{(R1/[R1 + R2]) - (R3/[R3 + R4])\} \qquad (2.7.9)$$

When $Vo = 0$, above equation gives balanced condition.

Assume that a transducer produces a resistance change from $R1$ to $R1 + \delta R1$ which gives a change in output from $Vo + \delta Vo$,

From equation 2.7.9 we can write,

$$Vo + \delta Vo = Vs\left(\frac{R1+\delta R1}{R1+\delta R1+R2} - \frac{R3}{R3+R4}\right) \qquad (2.7.10)$$

Hence,

$$(Vo + \delta Vo) - Vo = Vs\left(\frac{R1+\delta R1}{R1+\delta R1+R2} - \frac{R1}{R1+R2}\right) \qquad (2.7.11)$$

If $\delta R1$ is much smaller than $R1$ the equation 2.7.11 can be written as

$$\delta Vo \approx Vs\left(\frac{\delta R1}{R1+R2}\right) \qquad (2.7.12)$$

We can say that change in resistance $R1$ produces a change in output voltage. Thus we can convert a change in resistance signal into voltage signal.

3. Pulse modulation

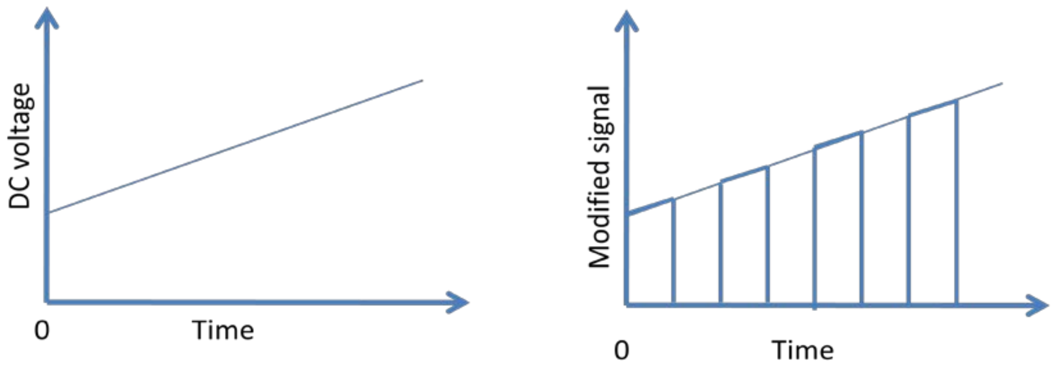

Figure 2.7.4 Pulse amplitude modulation

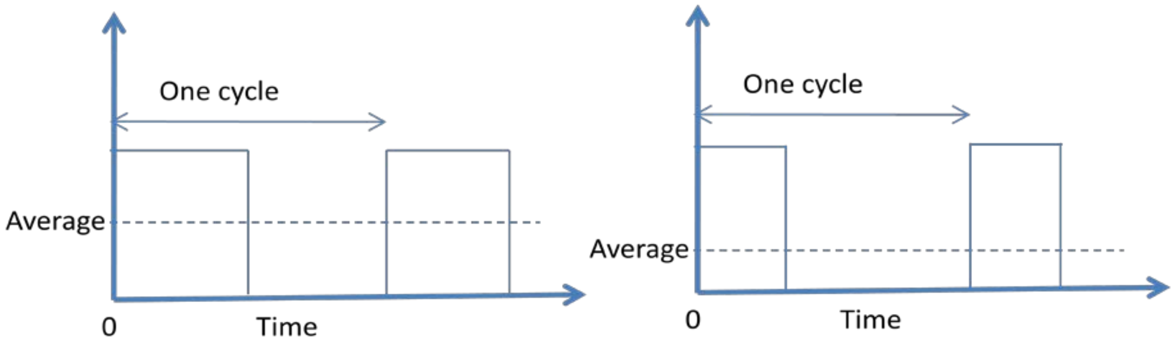

Figure 2.7.5 Pulse width modulation

During amplification of low level DC signals from a sensor by using Op-amp, the output gets drifted due to drift in the gain of Op-amp. This problem is solved by converting the analogue DC signal into a sequence of pulses. This can be achieved by chopping the DC signal in to a chain of pulses as shown in Figure 2.7.4. The heights of pulses are related to the DC level of the input signal. This process is called as Pulse Width Modulation (PWM). It is widely used in control systems as a mean of controlling the average value of the DC voltage. If the width of pulses is changed then the average value of the voltage can be changed as shown in Figure 2.7.5. A term Duty Cycle is used to define the fraction of each cycle for which the voltage is high. Duty cycle of 50% means that for half of the each cycle, the output is high.

Quiz:

1. State the applications of Wheatstone bridge in Mechatronics based Manufacturing Automation. Explain one of them in detail.
2. Why do we need pulse width modulation?
3. How Zener diode is different than ordinary diode?

Module 2: Sensors and signal processing
Lecture 8

Data conversion devices

Data Conversion Devices are very important components of a Machine Control Unit (MCU). MCUs are controlled by various computers or microcontrollers which are accepting signals only in Digital Form i.e. in the form of 0s and 1s, while the signals received from signal conditioning module or sensors are generally in analogue form (continuous). Therefore a system is essentially required to convert analog signals into digital form and vis-à-vis. Analog to Digital Converter is abbreviated as ADC. Figure 2.8.1 shows a typical control system with data conversion devices.

Based on the signals received from sensors, MCU generates actuating signals in the Digital form. Most of the actuators e.g. DC servo motors only accept analogue signals. Therefore the digital signals must be converted into Analog form so that the required actuator can be operated accordingly. For this purpose Digital to Analog Converters are used, which are abbreviated as DACs. In subsequent sections we will be discussing about various types of ADC and DAC devices, their principle of working and circuitry.

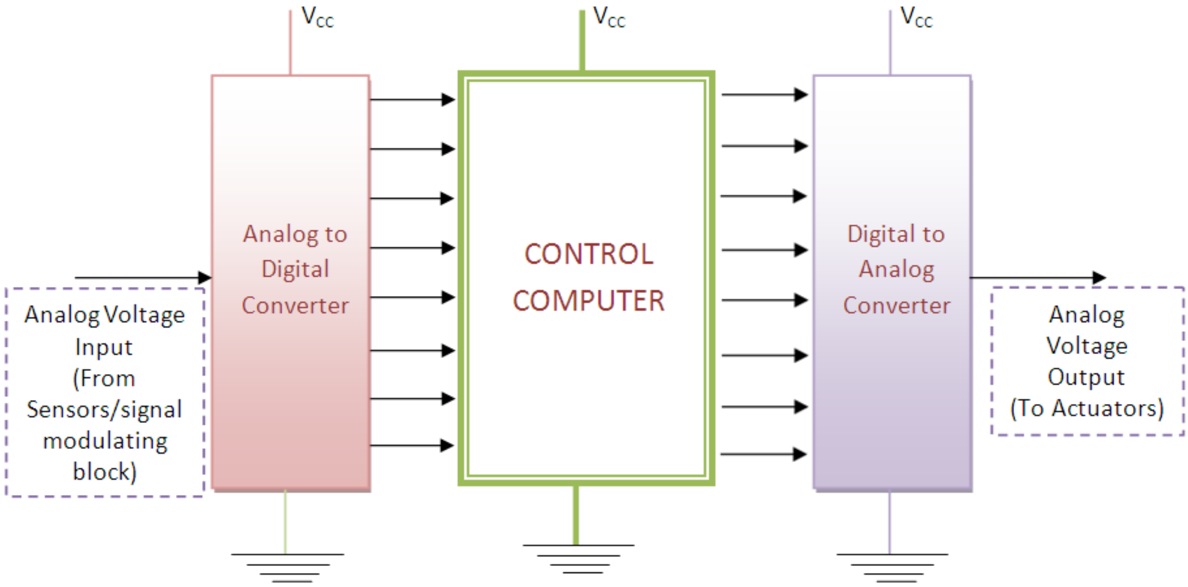

Figure 2.8.1 A control system with ADC and DAC devices

Basic components used in ADCs and DACs

1. Comparators

In general ADCs and DACs comprise of Comparators. Comparator is a combination of diodes and Operational Amplifiers. A comparator is a device which compares the voltage input or current input at its two terminals and gives output in form of digital signal i.e. in form of 0s and 1s indicating which voltage is higher. If V+ and V- be input voltages at two terminals of comparator then output of comparator will be as

$$V+ > V- \rightarrow \text{Output } 1$$

$$V+ < V- \rightarrow \text{Output } 0$$

2. Encoders

Though the output obtained from comparators are in the form of 0s and 1s, but can't be called as binary output. A sequence of 0s and 1s will be converted into binary form by using a circuit called Encoder. A simple encoder converts 2^n input lines into 'n' output lines. These 'n' output lines follow binary algebra.

3. Analog to Digital Converter (ADC)

As discussed in previous section ADCs are used to convert analog signals into Digital Signals. There are various techniques of converting Analog Signals into Digital signals which are enlisted as follows. However we will be discussing only Direct Conversion ADC, detail study of other techniques is out of the scope of the present course.

1. Direct Conversion ADC or Flash ADC
2. Successive Approximation ADC
3. A ramp-compare ADC
4. Wilkinson ADC
5. Integrating ADC
6. Delta-encoded ADC or counter-ramp
7. Pipeline ADC (also called subranging quantizer)
8. Sigma-delta ADC (also known as a delta-sigma ADC)
9. Time-interleaved ADC

3.1 Direct Conversion ADC or Flash ADC

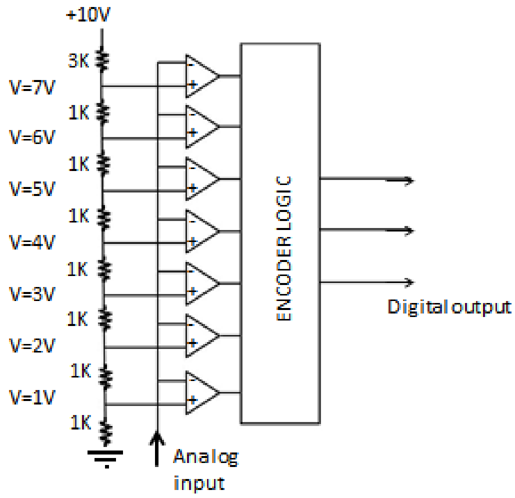

Figure 2.8.2 Circuit of Flash ADC

Figure 2.8.2 shows the circuit of Direct conversion or Flash ADC. To convert a digital signal of N-bits, Flash ADC requires 2^N-1 comparators and 2^N resistors. The circuit provides the reference voltage to all the comparators. Each comparator gives an output of 1 when its analog voltage is higher than reference voltage or otherwise the output is 0. In the above circuit, reference voltages to comparators are provided by means of resistor ladder logic.

The circuit described in figure 2.8.2 acts as 3 Bit ADC device. Let us assume this ADC works between the range of 0-10 Volts. The circuit requires 7 comparators and 8 resisters. Now the voltages across each resistor are divided in such a way that a ladder of 1 volt is built with the help of 1K-Ohm resistances. Therefore the reference voltages across all the comparators are 1-7 volts.

Now let us assume that an input voltage signal of 2.5 V is to be converted into its related digital form. As 2.5V is greater than 1V and 2V, first two comparators will give output as 1, 1. But 2.5V is less than 3,4,5,6,7 V values therefore all other comparators will give 0s. Thus we will have output from comparators as 0000011 (from top). This will be fed to the encoder logic circuit. This circuit will first change the output in single high line format and then converts it into 3 output lines format by using binary algebra. Then this digital output from ADC may be used for manipulation or actuation by the microcontrollers or computers.

4. Digital to Analog Converters

As discussed in previous section DACs are used to convert digital signals into Analog Signals. There are various techniques of converting Digital Signals into Analog signals which are as follows however we will be discussing only few important techniques in detail:

1. Pulse-width modulator
2. Oversampling DACs or interpolating DACs
3. The binary-weighted DAC
4. Switched resistor DAC
5. Switched current source DAC
6. Switched capacitor DAC
7. The R-2R ladder
8. The Successive-Approximation or Cyclic DAC,
9. The thermometer-coded DAC

4.1 Binary Weighted DAC

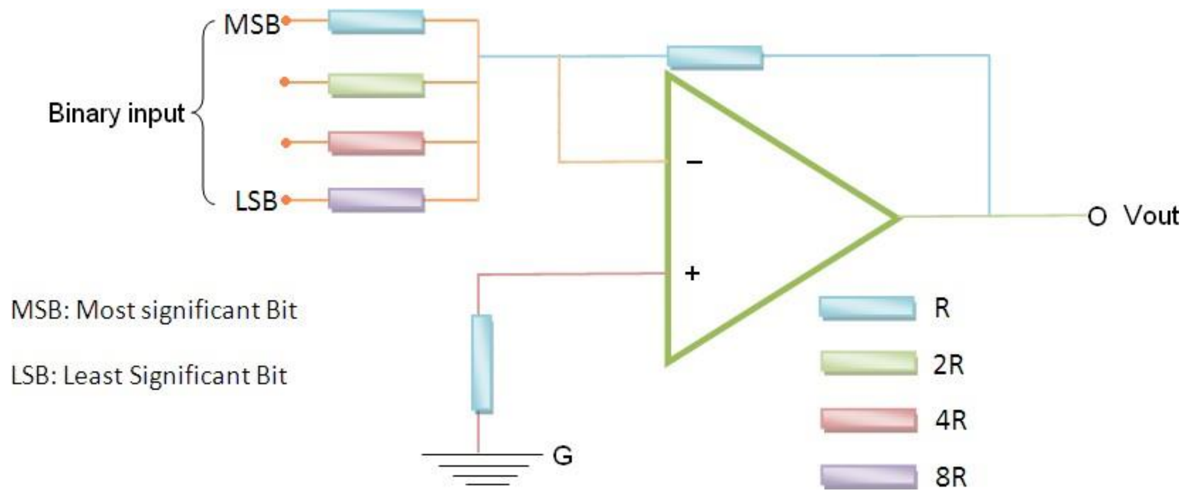

Figure 2.8.3 Circuit of binary weighted DAC

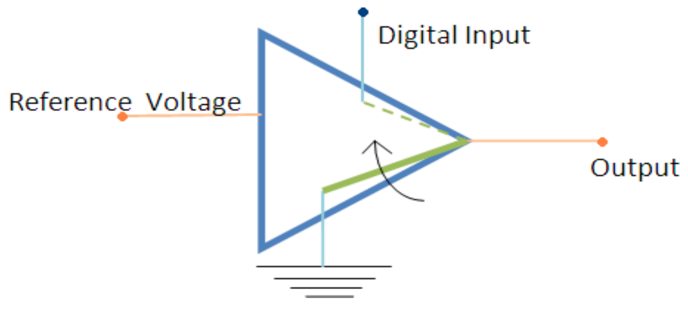

Figure 2.8.4 An op-amp used in DAC

As name indicates, in binary weighted DAC, output voltage can be calculated by expression which works on binary weights. Its circuit can be realized in Figure 2.8.3. From the figure it can be noted that most significant bit of digital input is connected to minimum resistance and vice versa. Digital bits can be connected to resistance through a switch which connects resistance-end to the ground. The digital input is zero when former bit is connected to reference voltage and if it is 1. This can be understood from Figure 2.8.4. DAC output voltage can be calculated from property of operational amplifiers. If V1 be input voltage at MSB (most significant bit), V2 be input voltage at next bit and so on then for four bit DAC we can write,

$$\frac{V1}{R} + \frac{V2}{2R} + \frac{V3}{4R} + \frac{V4}{8R} = \frac{Vout}{R} \qquad (2.8.1)$$

Note: Here V1,V2 V3,V4 will be Vref if digital input is 1 or otherwise it will be zero.

Hence output voltage can be found as:

$$V_{OUT}\ \alpha\ (2^3 * V1 + 2^2 * V2 + 2^1 * V3 + 2^0 * V4) \qquad (2.8.2)$$

However Binary weighted DAC doesn't work for multiple or higher bit systems as the value of resistance doubles in each case.

Thus simple and low bit digital signals from a transducer can be converted into a related continuous value of voltages (analogue) by using binary weighted DAC. These will further be used for manipulation or actuation.

4.2 R-2R Ladder based DAC

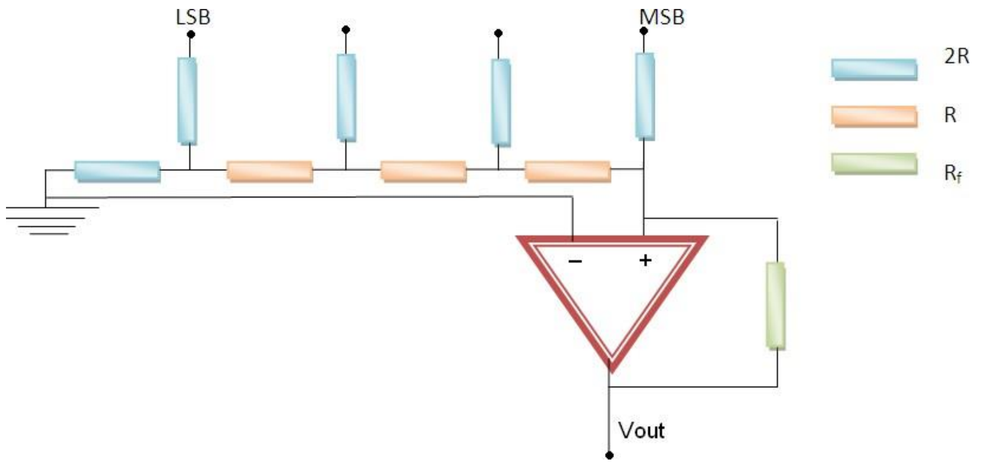

Figure 2.8.5 R-2R Ladder based DAC

In R-2R ladder logic, shortcoming of Binary Logic has been removed by making the value of maximum resistance double however the rest of the circuit remains same. Figure 2.8.5 shows the circuit of R-2R Ladder based DAC. If we apply voltage division rule in above case, then we can calculate that output voltage as,

$$V_{out} = \frac{V_{ref*} R_f}{R} * VAL \qquad (2.8.3)$$

Where VAL can be calculated from the digital signal input as,

$$VAL = \frac{D0}{2^4} + \frac{D1}{2^3} + \frac{D2}{2^2} + \frac{D3}{2^3} \qquad (2.8.4)$$

In this way output voltage is obtained by converting the digital signals received from microprocessor/ microcontroller. These voltages will further be used to actuate the desired actuator viz. DC/AC motors.

In this module we have studied the principle of operation of various sensors which are commonly used in mechatronics and manufacturing automation. Also the signal conditioning operations and the devices which are used to generate the proper signals for desired automation application have been studied. In the next module we will study the construction and working of microprocessor and the devices which are being used in controlling the various operations of automation using the microprocessors.

Quiz

1. Differentiate between Binary weighted DAC and R-2R ladder based DAC.
2. Explain the importance of data conversion devices in mechatronics with suitable example.

Module 7: CNC Programming and Industrial Robotics

Lecture 1

CNC programming: fundamentals

CNC part program contains a combination of machine tool code and machine-specific instructions. It consists of:

a. Information about part geometry
b. Motion statements to move the cutting tool
c. Cutting speed
d. Feed
e. Auxiliary functions such as coolant on and off, spindle direction

In this lecture, first we will understand the coordinate systems of the machine tools and how they work.

1. CNC Machine Tool

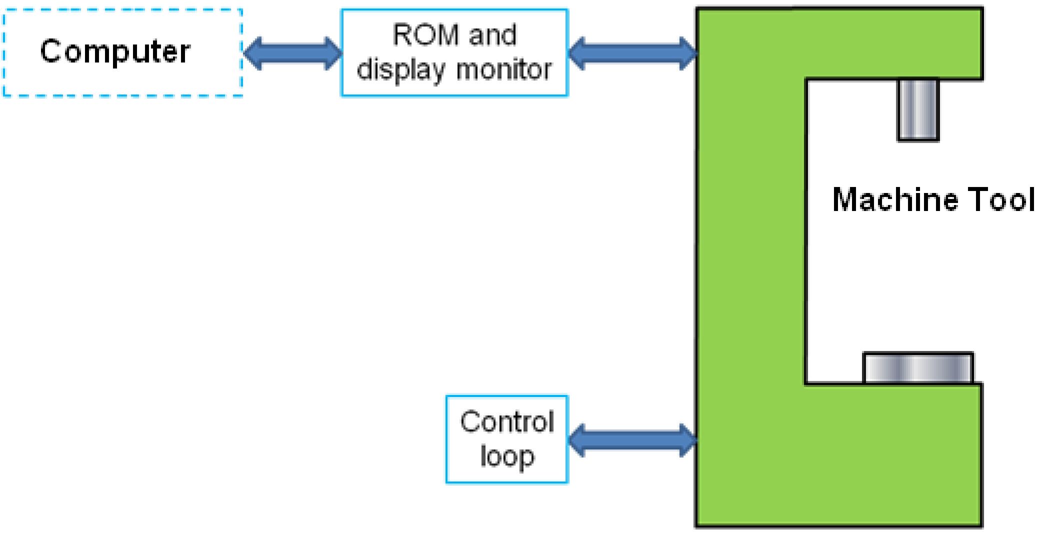

Figure 7.1.1 Schematic of a CNC machine Tool

Figure 7.1.1 shows a schematic of a machine tool controlled by a computer. It consists of a Machine Control Unit (MCU) and machine tool itself. MCU, a computer is the brain of a CNC machine tool. It reads the part programs and controls the machine tools operations. Then it decodes the part program to provide commands and instructions to the various control loops of the machine axes of motion. The details regarding the construction and working of mechatronics based system have already been studied in last lectures.

CNC systems have a limitation. If the same NC program is used on various machine tools, then it has to be loaded separately into each machine. This is time consuming and involves repetitive tasks. For this purpose direct numerical control (DNC) system is developed. Figure 7.1.2 shows the schematic of a DNC system. It consists of a central computer to which a group of CNC machine tools are connected via a communication network. The communication is usually carried out using a standard protocol such as TCP/IP or MAP. DNC system can be centrally monitored which is helpful when dealing with different operators, in different shifts, working on different machines.

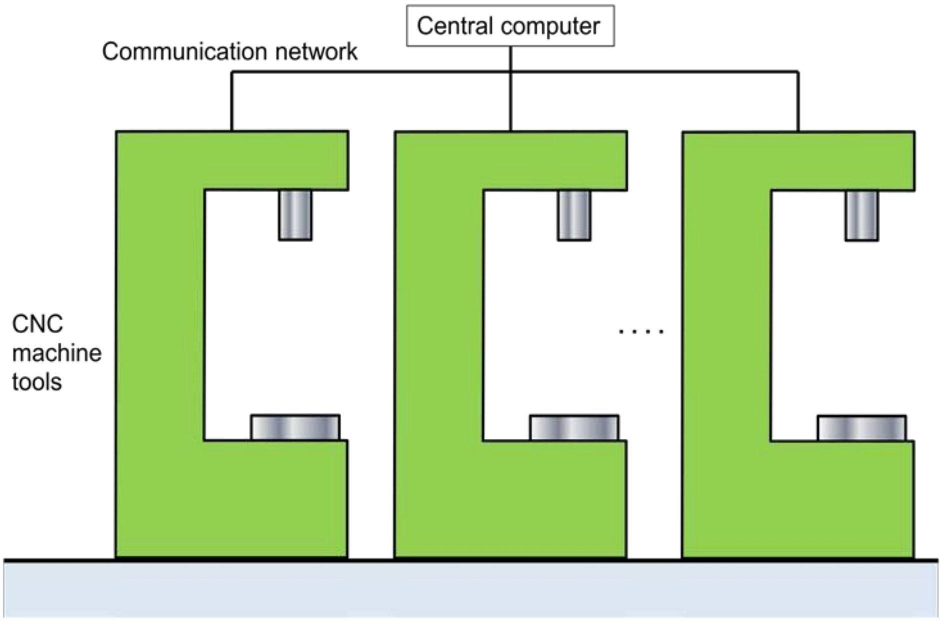

Figure 7.1.2 Direct numerical control (DNC) system

2. *Axes of CNC machine tool*

In CNC machine tool, each axis of motion is equipped with a driving device to replace the handwheel of the conventional machine tool. A axis of motion is defined as an axis where relative motion between cutting tool and workpiece occurs. The primary axes of motion are referred to as the X, Y, and Z axes and form the machine tool XYZ coordinate system. Figure 7.1.3 shows the coordinate system and the axes of motion of a typical machine tool. Conventionally machine tools are designated by the number of axes of motion they can provide to control the tool position and orientation.

2.1 Configuration of 2-axis machine tool

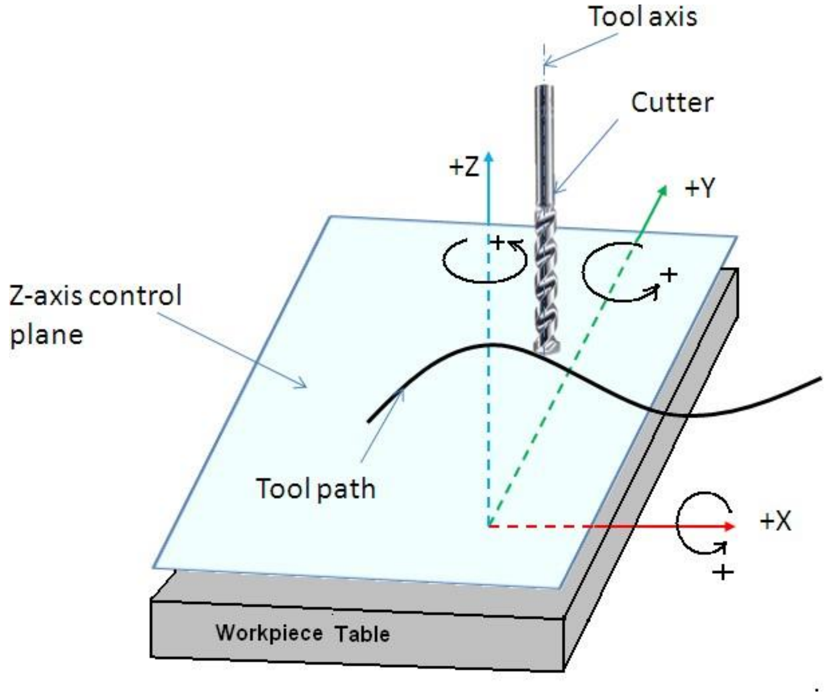

Figure 7.1.3 Axes of motion of a machine tool

If the machine tool can simultaneously control the tool along two axes, it is classified as a 2-axis machine. The tool will be parallel and independently controlled along third axis. It means that machine tool guided the cutting tool along a 2-D contour with only independent movement specified along the third axis. The Z-axis control plane is parallel to the XY plane.

2.2 Configuration of 2.5-axis machine tool

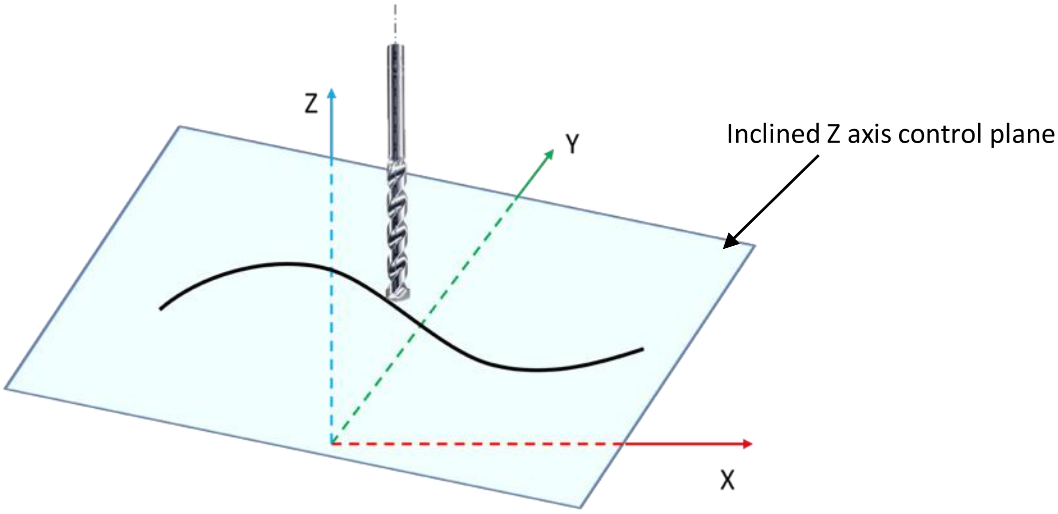

Figure 7.1.4 Axes in 2.5-axis machine tool

In this type of machine tool, the tool can be controlled to follow an *inclined* Z-axis control plane and it is termed as 2.5-axis machine tool. Figure 7.1.4 explains the axes system in 2.5-axis machine tool.

2.3 Configuration of 3-axis and multiple axis machine tool

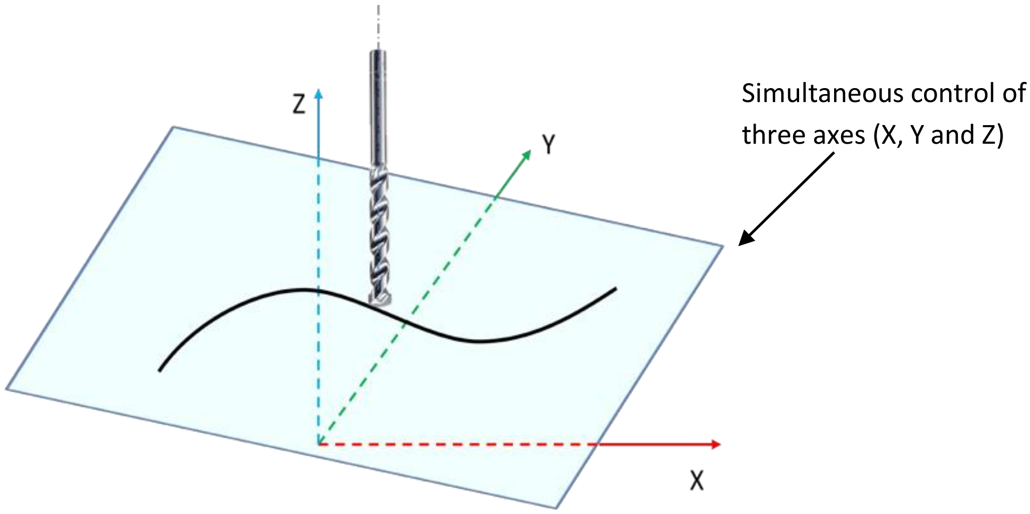

Figure 7.1.5 3-axis machine tool

In these CNC machine tools, the tool is controlled along the three axes (X, Y, and Z) simultaneously, but the tool orientation doesn't change with the tool motion as shown in Figure 7.1.5.

If the tool axis orientation varies with the tool motion in 3 dimension space, 3-axis machine gets converted into multi-axis orientation machine (4-, 5-, or 6-axis). Figure 7.1.6 shows the schematic of tool motion in a multi-axis CNC machine tool.

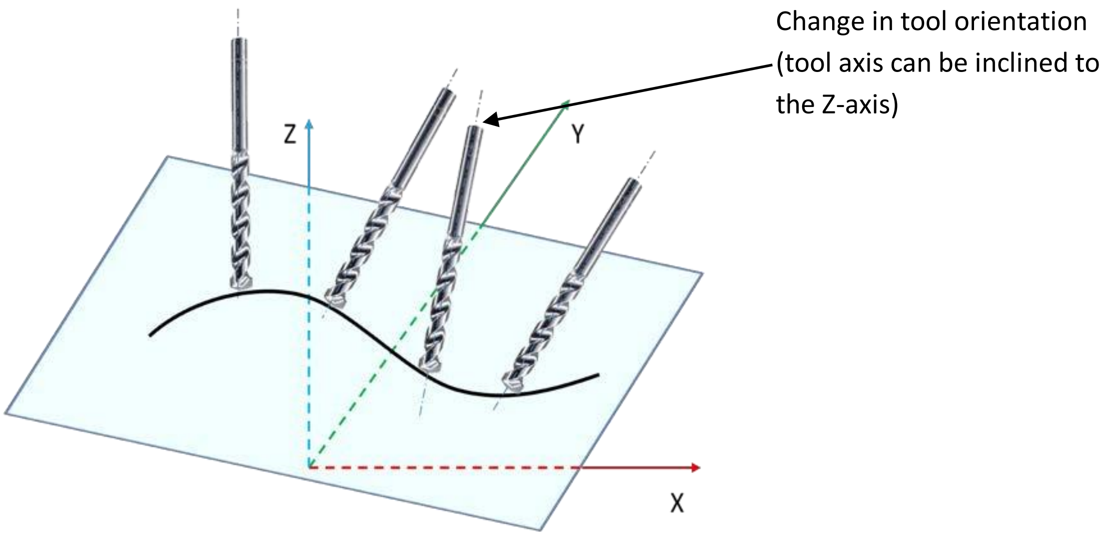

Figure 7.1.6 Multiple axes machine tool

3. CNC program structure

There are four basic terms used in CNC programming. These are a follows:

Character -> Word -> Block -> Program

- Character is the smallest unit of CNC program. It can have Digit / Letter / Symbol.
- Word is a combination of alpha-numerical characters. This creates a single instruction to the CNC machine. Each word begins with a capital letter, followed by a numeral. These are used to represent axes positions, federate, speed, preparatory commands, and miscellaneous functions.
- A program block may contain multiple words, sequenced in a logical order of processing.
- The program comprises of multiple lines of instructions, ‘blocks’ which will be executed by the machine control unit (MCU).

Figure 7.1.7 shows a sample CNC program. It has basically three sections viz. initial commands section; main section and end commands section. In the initial commands section, the program number, its ID, initial safety preparatory codes such as ‘cancel all the activated cycles by previous program’ are to be specified.

In the main section, commands/instructions related the machine tool axes movements, tool change etc. are to be mentioned. At the end, the commands instructing cancellation of cycles, homing the tool and program end are to be provided.

```
%                                                  //% symbol
O0012                                              //Program number and ID
(Sample program structure for demonstration)       //Program description
N10  G21                                           //Units setting
N20  G40  G80  G49                                 //Initial commands
N30  T01                                           //Tool T01 in waiting position
N40  M06                                           //replace present tool at spindle by T01
.
.
.
N100 G01  X20.0     Y34.0                          //Linear interpolation
N110 Y100.0                                        //Linear interpolation
N120 G00  X100.0                                   //Linear interpolation: rapid mode
N130 G01  Y20.0                                    //Linear interpolation at given feed rate
.
.
.
N200 G80  Z40.0     M09                            //Cycle cancel
N210 G28  Z40.0     M05                            //Home in z only
N220 G28  X...      Y...                           //Home in XY only
N240 M30                                           //End of program
%                                                  //Stop code
```

Figure 7.1.7 Sample CNC program.

The address G identifies a preparatory command, often called G-code. This is used to preset or to prepare the control system to a certain desired condition or to a certain mode or a state of operation. For example G01 presets linear interpolation at given feed but doesnot move any axis.

The address M in a CNC program specifies miscellaneous function. It is also called as machine function. These functions instruct the machine tool for various operations such as: spindle rotation, gear range change, automatic tool change, coolant operation, etc.

The G and M codes are controller manufacturers’ specific. In this course, we will be following the G and M codes used for FANUC, Japan controller. Other controllers such as SINUMERIC, MITSUBHISHI etc. are also being used in CNC technology.

It is suggested to the readers to study the following G and M codes for milling and turning operations. Programming exercises will be carried out in the next lectures.

Module 7: CNC Programming and Industrial Robotics

Lecture 2

CNC programming: Drilling operations

In this lecture we will learn how to write a part program to manufacture drilled holes. Let us take an exercise and study the various preparatory and miscellaneous functions associated with the problem.

Exercise:

Write an efficient CNC part program to drill 35 holes of diameter of 0.5 inch each in a machine component as shown in the figure 7.2.1. The raw material to be employed is mild steel plate of 0.4 inch thickness. Explain the important functions used in the CNC code.

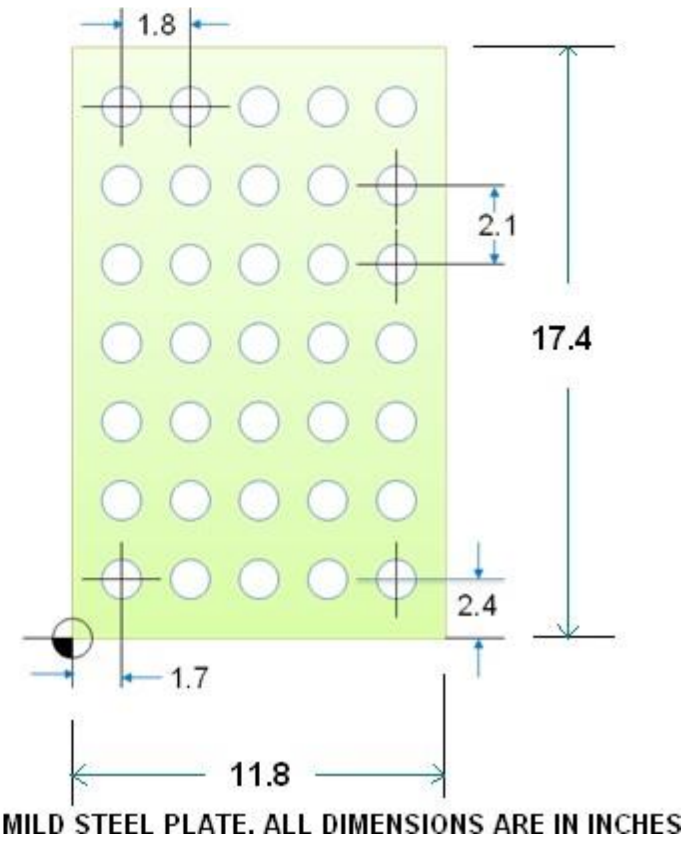

Figure 7.2.1 A component to be machined (drilled)

Solution:

Based on the G and M code discussed in the last lecture, the CNC part program for FANUC controller can be written as follows:

Block 1		%
2		O0001
3	N10	G20
4	N20	G17 G40 G80 G49 G90
5	N30	G92 X… Y… Z…
6	N40	M06 T01
7	N50	G00 X1.7 Y2.4 S900 M03
8	N60	G43 Z1.0 H01 M08
9	N70	G99 G81 R0.1 Z-0.4 F3.0
10	N80	G91 Y2.1 K6 (L6)
11	N90	X1.8
12	N100	Y-2.1 K6 (L6)
13	N110	X1.8
14	N120	Y2.1 K6 (L6)
15	N130	X1.8
16	N140	Y-2.1 K6 (L6)
17	N150	X1.8
18	N160	Y2.1 K6 (L6)
19	N170	G90 G80 M09
20	N180	G28 Z10 M05
21	N190	G28 X0 Y0
22	N200	M30
23		%

Let us now see the meaning and significance of each block of the program.

Block 1:

It indicates the start of the program.

Block 2:

It specifies the program number and ID. It is usually a alpha-numerical code and always start with an alphabet 'O'.

Block 3:

It sets the entry of dimensional units in Imperial format.

Block 4:

G17: It selects the plane of operation as X-Y plane

G40, G80, G49 are used to cancel all usual cycle that might have left in on-mode during the execution of last CNC code.

G90 selects the method of specifying dimensions between features as ‘absolute’.

Block 5:

It sets the program zero on the work part. There are three major environments in programming that require an established mathematical relationship.

Machine: machine tool and control system

Part: Workpiece + Drawing + material

Tool: Holder + Cutting tool

Machine zero point:

It is also called as home position or machine reference point. It is the origin of a machine coordinate system. On all CNC machines, machine zero is located at the positive end of each axis travel range. Figure 7.2.2 shows the machining volume and various planes. The machine reference point is located at the end of positive ranges of X, Y and Z axes. Figure 7.2.3 and 7.2.4 provide the clear views of the machine reference point. Machine control unit (MCU) understands the dimensions provided with respect to the machine reference point. But the programmer is providing the dimensions on the drawings based on the local coordinate system i.e. part coordinate system.

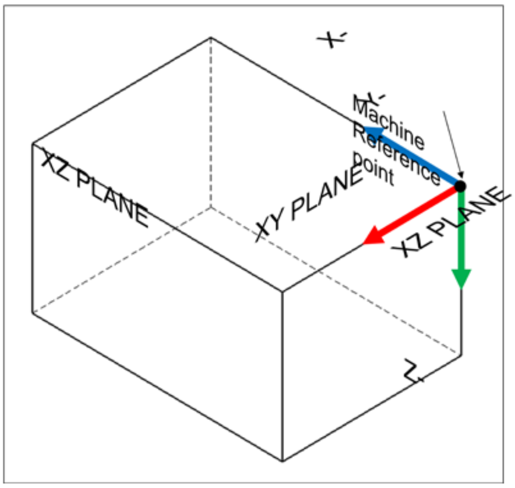

Figure 7.2.2 machining volume and machine reference point

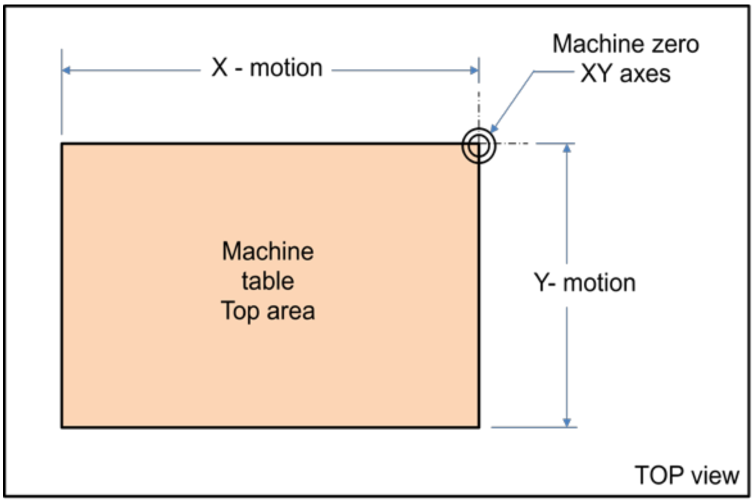

Figure 7.2.3 Top view of a vertical machine as viewed towards the table

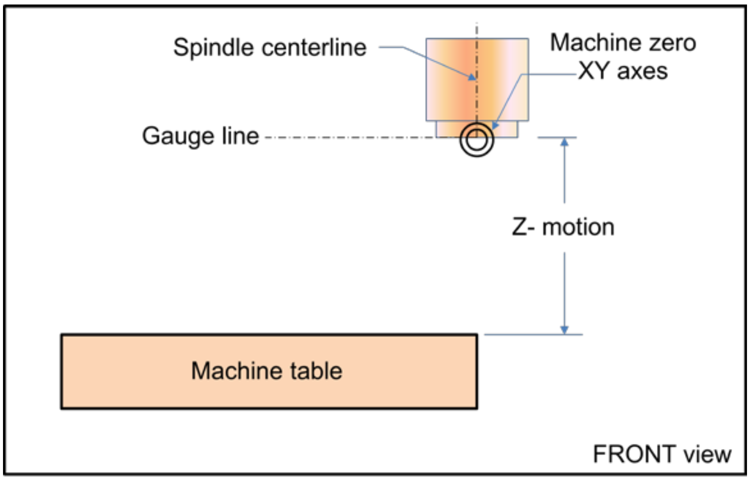

Figure 7.2.4 Front view of a vertical machine as viewed from front

A part ready for machining is located within the machine motion limits. Part reference point is commonly known as program zero or part zero. It is often selected on the part itself or on the fixtures. Figure 7.2.5 shows the part zero being set at the lower left corner on the top surface of the workpiece.

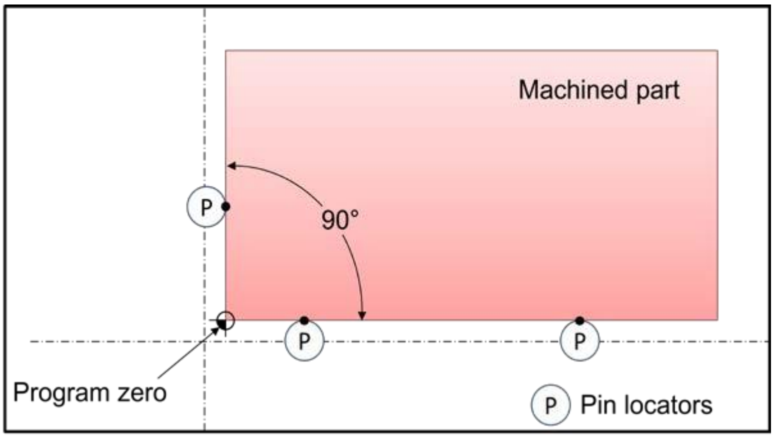

Figure 7.2.5 Part zero setting

The location coordinates of the program zero with respect to the machine reference zero must be communicated with the MCU so that the MCU will convert the part program in to required signals to control the machine tool. This can be achieved by using a Preparatory code ‘G92’. The syntax of G92 is as follows:

G92 X… Y… Z…

To use this command the operator needs to obtain the distance travelled by the tool contact point (end-point) from the machine home position to the program zero position. This is carried out by touching the tool tip at the part zero point. The X, Y, Z distances will be noted from the machine display and further used along with G92 command. Figure 7.2.6 shows the tool tip distance from the program zero to machine zero along Z-direction.

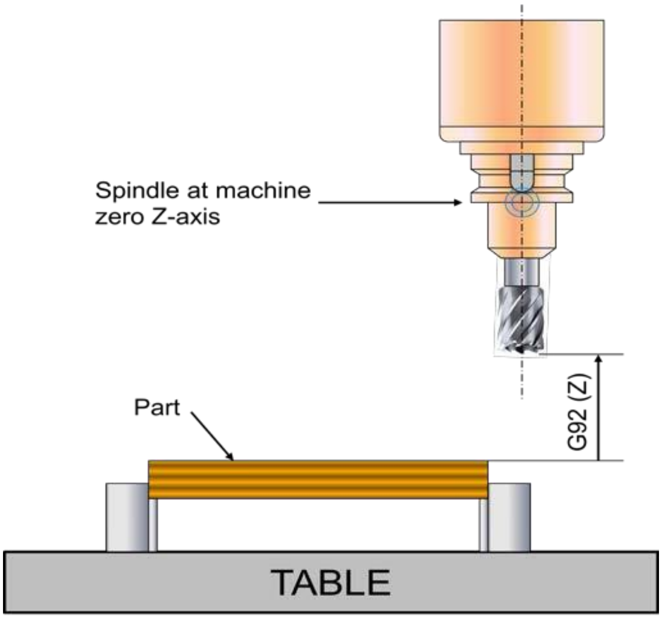

Figure 7.2.6 Program zero setting

Block 6:

Replace the existing cutting tool with tool number 1.

Block 7:

Rapid travel of tool from home position to a reference position: hole with coordinates X1.7 Y2.4.

Switch on the spindle rotation with speed of about 900 rpm.

Block 8:

Approach to a safe position at Z = 1.0 rapidly. Meanwhile the tool length compensation is activated by using G43. It is used to communicate the length of tool registered in register number H01 to the MCU. Switch on the coolant flow.

Block 9:

In the given task, number of holes is to be drilled. For this purpose a special function or cycle is used. It is called as drilling canned cycle. Its syntax and meaning are shown below. The number of motions/action elements of drilling operations is specified only at once. Later only the locations of holes to be drilled are given to the MCU.

G81 – Drilling Cycle

G98 (G99) G81 X.. Y.. R.. Z.. F..

Step	Description of G81 Cycle
1	Rapid motion to XY position
2	Rapid motion to *R-level*
3	Feed rate motion to *Z-depth*
4	Rapid retract to *initial level* (with G98) *or* Rapid retract to *R-level* (with G99)

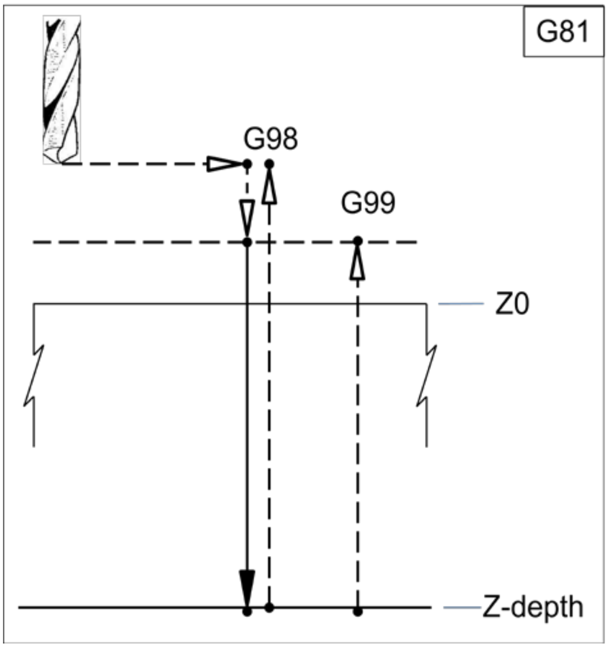

Figure 7.2.7 Drilling canned cycle.

Block 10:

It suggests the distance of next location of the hole. It is also suggested to carry out the same drilling operation 6 times along the Y-axis with an increment of 2.1.

Block 11:

Drill the hole at increment of 1.8 along X-direction.

Block 12:

Carry out the drilling operation 6 times along the Y-axis with decrement of 2.1.

Block 13:

Drill the hole at increment of 1.8 along X-direction.

Block 14:

Carry out the drilling operation 6 times along the Y-axis with increment of 2.1.

Block 15:

Drill the hole at increment of 1.8 along X-direction.

Block 16:

Carry out the drilling operation 6 times along the Y-axis with decrement of 2.1.

Block 17:

Drill the hole at increment of 1.8 along X-direction.

Block 18:

Carry out the drilling operation 6 times along the Y-axis with increment of 2.1.

Block 19:

Cancel the canned cycle and switch off the coolant flow.

Block 20:

Stop the spindle and go to safe position along Z direction at 0.0.

Block 21:

Go to home position via X= 0 and Y=0.

Block 22:

Stop the program from execution.

Block 23:

End the program.

Module 7: CNC Programming and Industrial Robotics

Lecture 3

CNC programming: Milling operations

In this lecture we will learn to write part program for contouring operations being carried out on a CNC milling machine. Let us take an exercise:

Figure 7.3.1 shows the final profile required to be finish-contoured and the holes to be drilled by using a CNC Vertical Machining Center. Write an EFFICIENT CNC part program for the same. Assume the finishing allowance of about 2 mm.

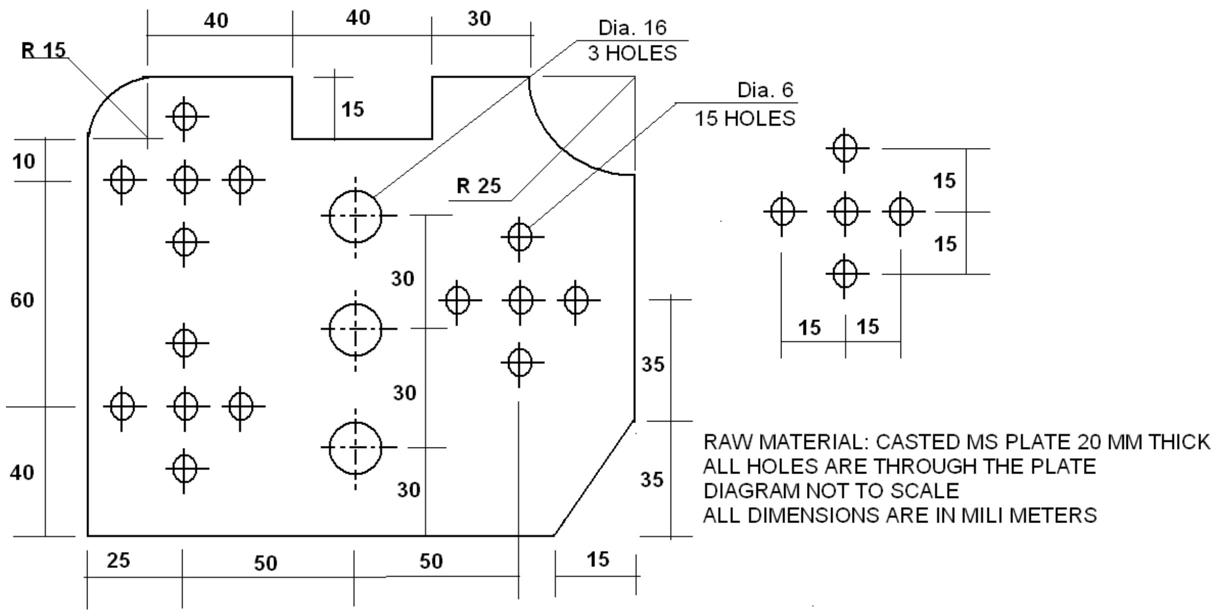

Figure 7.3.1 A component to machined on a vertical machining center (VMC)

After studying the required part geometry and features the following main program and its sub-program are prepared.

Table 7.3.1 Process plan

Operation no.	Operation	Tool name	Tool number	Length register number	Diameter register number
1	Contour finishing	End-mill	T01	H01	D01
2	Drilling of dia. 6 mm holes	End-mill	T01	H01	D01
3	Drilling of dia. 16 mm holes	Drill bit	T02	H02	D02

MAIN PROGRAM:

Block 1		%
2		O0001
3	N10	G21
4	N20	G40 G80 G49 G90
5	N30	G92 X… Y… Z…
6	N40	M06 T01
7	N50	G00 X-20 Y-20
8	N60	G43 Z10 H01 M08
9	N70	M03 S1000
10	N80	G01 Z-20 F50
11	N90	G41 X0 D01 F25
12	N100	Y110
13	N110	G02 X15 Y125
14	N120	G01 X55
15	N130	Y115
16	N140	X95
17	N150	Y125
18	N160	X125
19	N170	G03 X150 Y100
20	N180	G01 Y35
21	N190	X135 Y0
22	N200	X-20
23	N210	G00 Z10
24	N220	X25 Y40
25	N230	G99 G81 R10 Z-20 F30
26	N240	M98 P0002
27	N250	G90 X25 Y100
28	N260	M98 P0002
29	N270	G90 X125 Y70
30	N280	M98 P1002
31	N290	G80 M09
32	N300	G28 Z10 M05
33	N310	G28 X0 Y0
34	N320	M06 T02
35	N330	G00 X75 Y30
36	N340	G43 Z10 H02 M08
37	N350	M03 S800
38	N360	G99 G81 R10 Z-20 F30
39	N370	Y60
40	N380	Y90
41	N390	G80 M09
42	N400	G28 Z10 M05
43	N410	G28 X0 Y0
44	N420	M30
45		%

SUB-PROGRAM

Block		
Block 1		%
2		O0002
3	N10	G91 X15
4	N20	X-15 Y15
5	N30	X-15 Y-15
6	N40	X15 Y-15
7	N50	M99
8		%

Let us now see the meaning and significance of each block of the main program and its sub-program. Above programs have been prepared based on the process plan shown in Table 7.6.1.

Block 1 to 5: Preparatory instructions as discussed in the last lecture

Block 6 to 8: Selection and change of tool as T01; go to a safe position.

Block 9: Spindle on

Block 10: Approach the depth at the given feed.

Block 11: Ramp-on: approach the workpiece with cutter radius compensation towards left. In this work we are programming the contour points. MCU will automatically finds out the cutter location points and accordingly he guides the cutting tool in the machine volume. CNC milling may have external machining such as contouring/contour finishing or internal machining such pocket milling/contouring as shown in Figure 7.3.2. In such cases the programmer has to specify the cutter radius offset direction by using G41/G42 commands as shown in Figure 7.3.3. Absence of these commands leads to inaccurate machining. The application of cutter radius compensation also depends upon type of milling operation being carried out. During Climb milling G41 is to be applied and for Up milling, G42 is to be used (see figure 7.3.4)

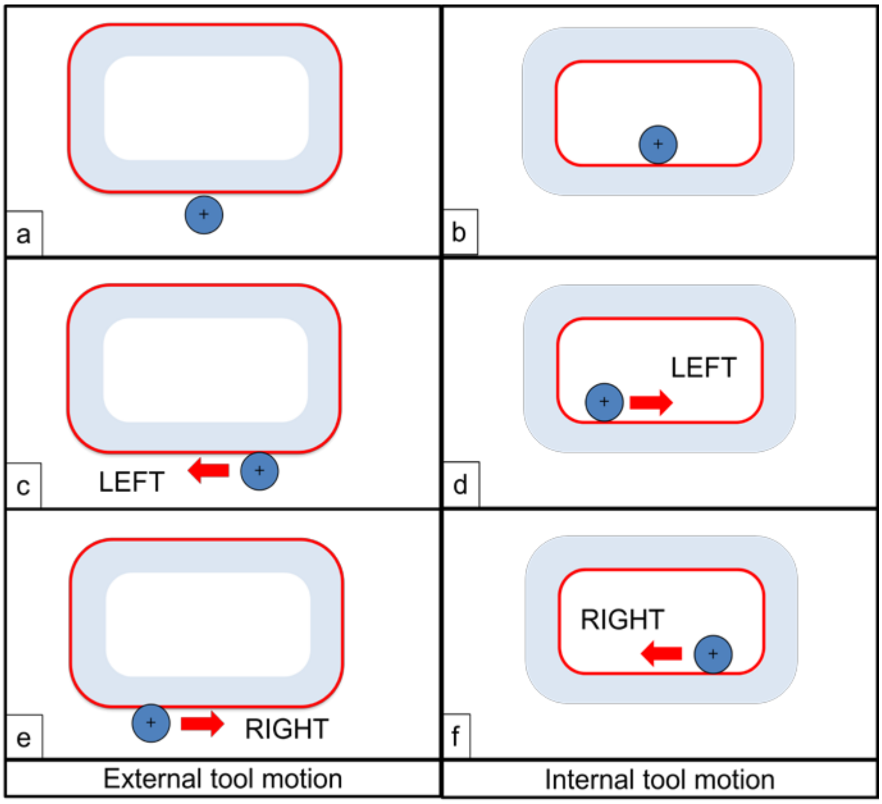

Figure 7.3.2 Tool motions in milling operations.

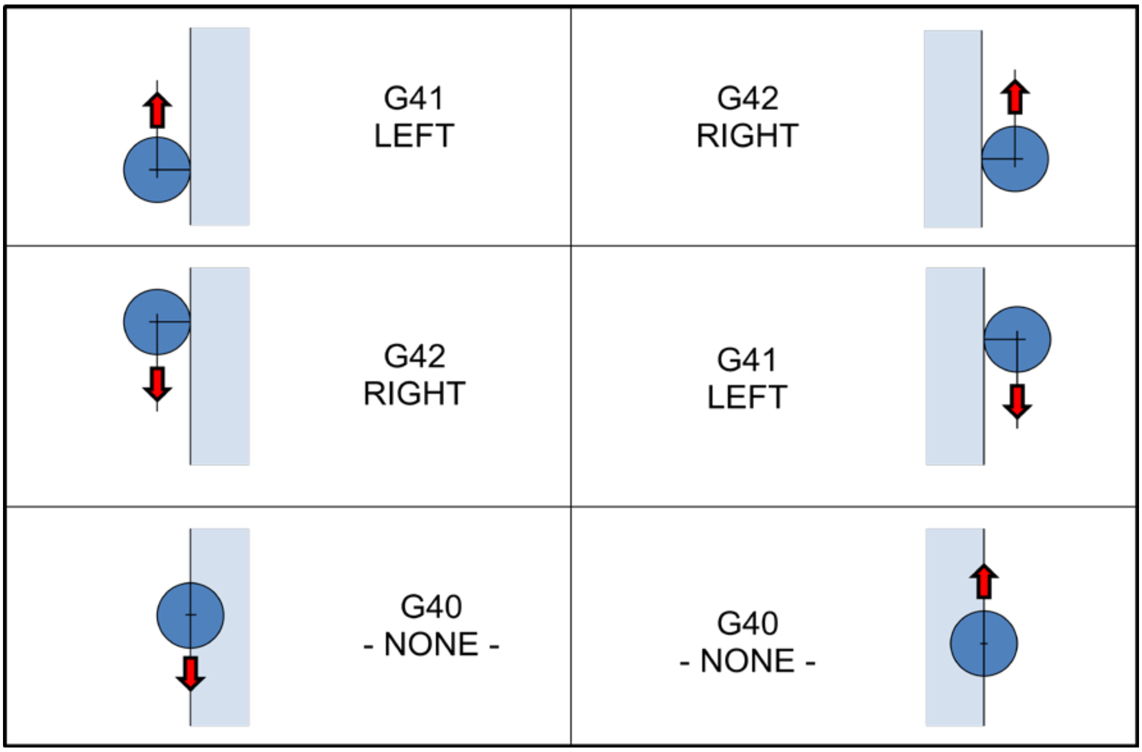

Figure 7.3.3 Cutter radius compensation in milling

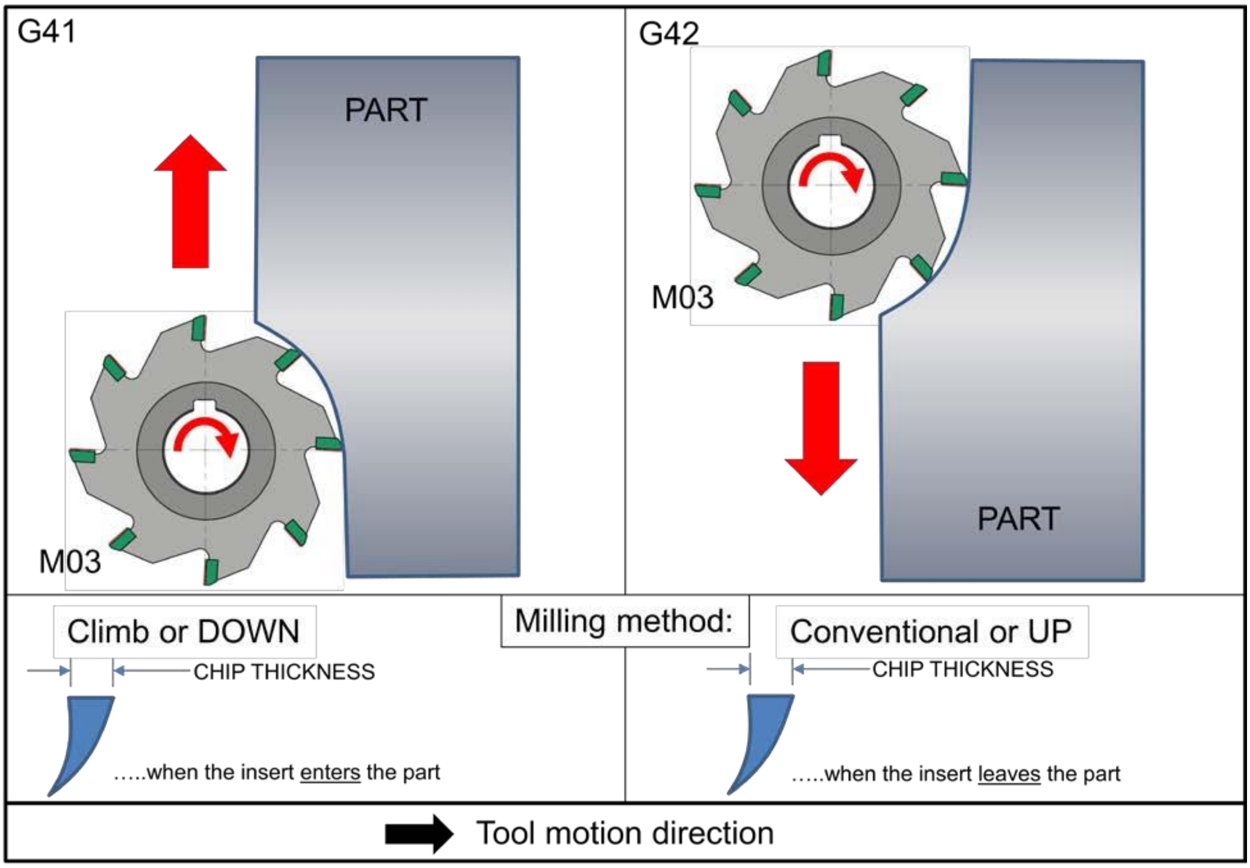

Figure 7.3.4 Cutter radius compensation in milling operations.

Block 12 to 21: the contour of the work part is programmed by using linear (G01) and circular (G02/G03) interpolation commands. These commands once activated then need not to be repeated in the subsequent blocks until a required change in them to be incorporated. These are called as MODAL commands.

Block 22: Ramp-off: the cutting tool will completely come out of the contour.

Block 23 and 24: Cutting tool will approach the next operation i.e. drilling three similar patterns of holes.

Block 25: Drilling canned cycle is activated.

Block 26 to 30: A sub-program O0002 is called-on for execution. It is an advanced option used in CNC programming. This eliminates repetition of blocks for machining of similar features at various locations. It makes the program compact and enhances the efficiency of programming.

Program O0002 facilitates the locations of the holes which are mentioned with incremental dimensions. This program can be executed to drill the shown pattern of holes anywhere on the work part.

Block 31: Cancel the canned cycle and switch-off the coolant flow.

Block 32 to 33: Go to home position safely and turn-off the spindle.

Block 34 to 37: Make the Tool 2 ready for drilling dia. 16 mm hole; change the tool; and turn-on the spindle as well as coolant.

Block 38 to 40: Execute the drilling canned cycle at three locations.

Block 41 to 45: Send the cutting tool to home position safely; switch-off the spindle as well as coolant; and stop the program.

Module 7: CNC Programming and Industrial Robotics

Lecture 4

CNC programming: Turning operations

In this lecture we will learn to write part program for turning operations being carried out on a CNC turning center. Let us take an exercise:

Figure 7.4.1 shows the final profile to be generated on a bar stock by using a CNC turning center.

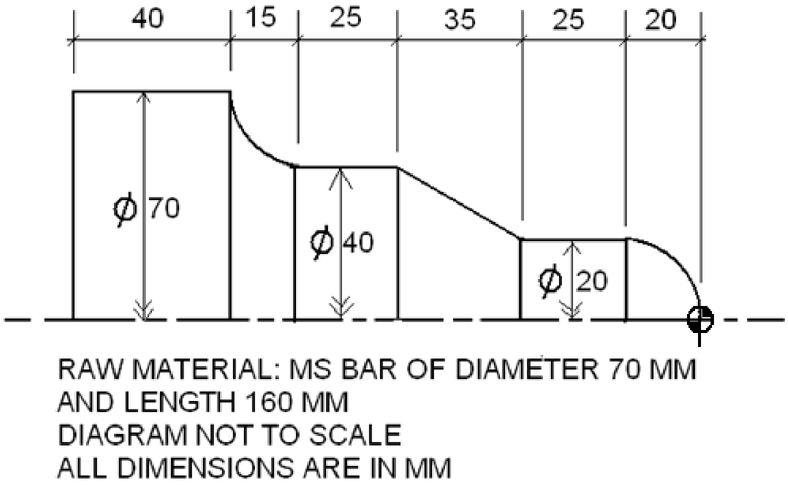

Figure 7.4.1 A component to be turned.

After studying the required part geometry and features, the main program can be written as follows.

Block 1		%
2		O0004
3	N10	G21
4	N20	G40 G90
5	N30	G54 X… Z…
6	N40	T0100 M42
7	N50	G96 S450 M03
8	N60	G00 G41 X72 Z0 T0101 M08
9	N70	G01 X0
10	N80	G00 Z5
11	N90	G42 X72
12	N100	G71 U1 R3
13	N110	G71 P120 Q190 U1 W1 F0.05
14	N120	G00 X0
15	N130	G01 Z0
16	N140	G03 X20 Z-20
17	N150	G01 Z-45
18	N160	X40 Z-80
19	N170	Z-105
20	N180	G02 X70 Z-120
21	N190	G01 X75
22	N200	G00 X100 Z20
23	N210	G70 P120 Q190 F0.03
24	N220	G00 G40 X100 Z20 T0100
25	N230	M09
26	N240	M30
27		%

Let us now see the meaning and significance of each block of the program.

Block 1 to 4: Preparatory functions and commands.

Block 5: In CNC turning, only two axes viz. X and Z are used. X axis is along the radius of work part, whereas Z axis is along the length of the work part. Figure 7.4.2 shows the axes system used in CNC turning centers. The program zero will be set by using G54 command. The program zero is assumed to be located at the tip of work contour as shown in Figure 7.4.1.

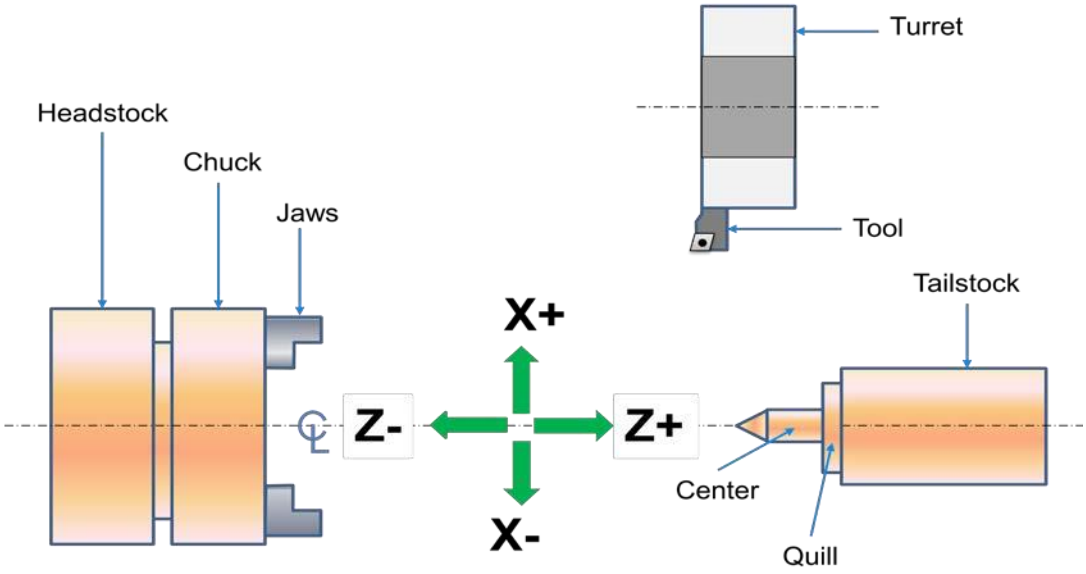

Figure 7.4.2 Axes system used in CNC turning center

Block 6: In turning programming the Tool is designated by an alphabet 'T' and four numerals. Out of the four numerals, first two indicates the tool number and the last signifies the wear offset number. In this block the tool number 1 is selected.

Block 7: G96 command maintains the constant surface speed during the reduction of diameter by using CNC turning. For efficient and proper cutting, it is essential to maintain a constant cutting speed (along the surface). It can be obtained by varying the spindle RPM according to the change in the diameter during the turning operation. Figure 7.4.3 shows that how the RPM of the spindle should be increased to maintain the constant surface speed.

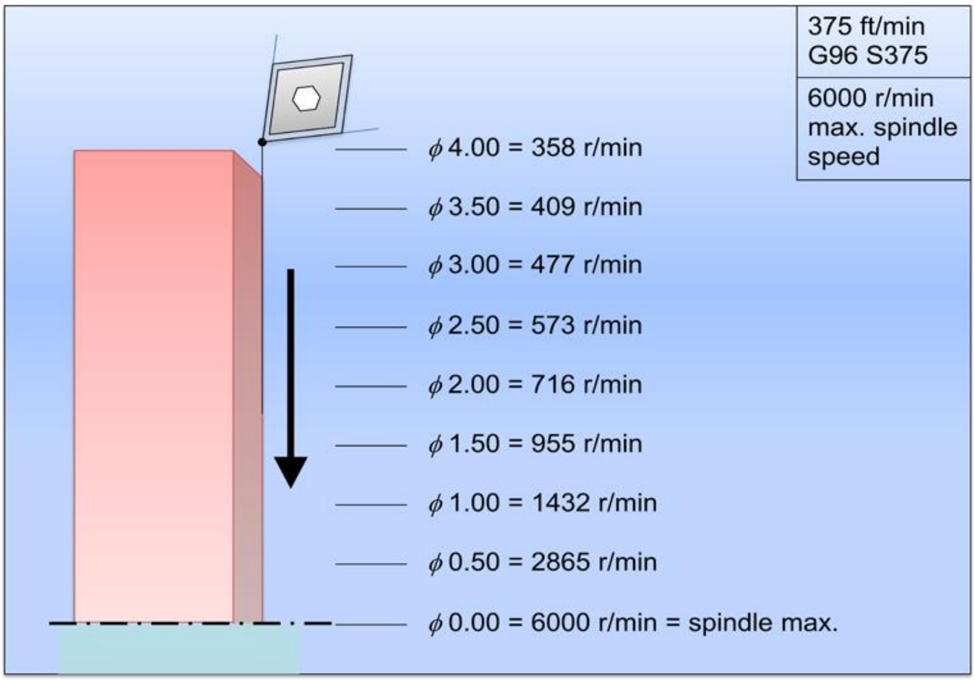

Figure 7.4.3 Constant surface speed control

Block 8: Prepare for the facing operation. During this stage, activate the tool nose radius compensation towards left when the tool moves along the radial direction (X). Also activate the wear compensation as per the offset value provided at wear offset register 01. Figure 7.4.4 shows the conventions to be followed for tool nose radius compensations in turning operations.

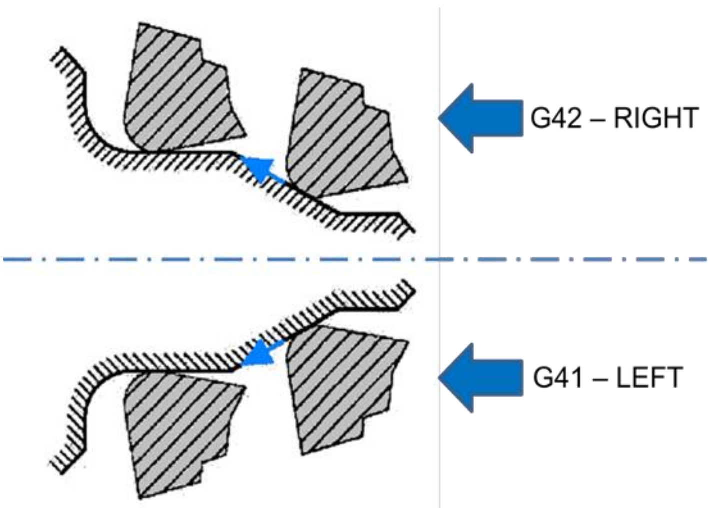

Figure 7.4.4 Tool nose radius compensation

Block 9: Carry out the facing operation.

Block 10 and 11: Go to safe position X 72 and Z 5. During this movement activate the tool nose radius compensation towards right side of the contour.

Block 12 and 13: These blocks specify the stock removal cycle G71 for external roughing. This will obtain the required shape with an allowance kept for finishing operation. The syntax of this cycle command is as follows:

```
G71  U…  R…

G71  P…  Q…  U…  W…  F…  S…
```

First block:

U = Depth of roughing cut

R = Amount of retract from each cut

Second block:

P = First block number of finishing contour

Q = Last block number of finishing contour

U = Stock amount for finishing on the X-axis diameter

W = Stock left for finishing on the Z-axis

F = Cutting feed-rate (in/rev or m/min) between P block and Q block

S = Spindle speed (ft/min or m/min) between P block and Q block

The points P and Q on the contour of the workpart can be defined as shown in the figure 7.4.5

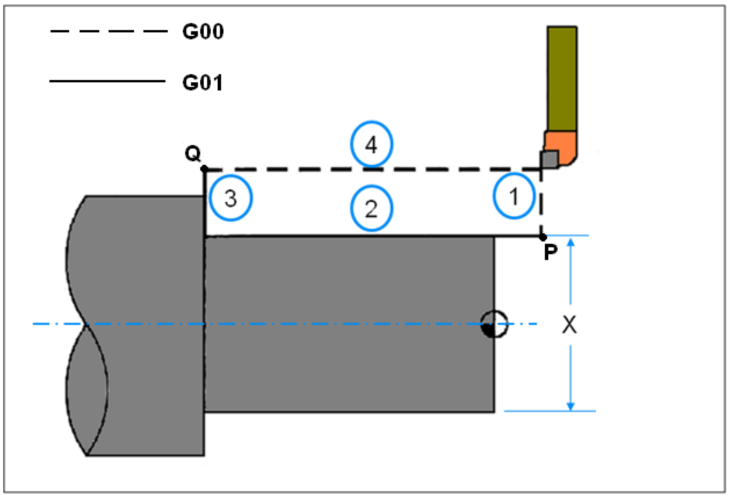

Figure 7.4.5 G71 cycle: P and Q points.

Block 14 to 21: these blocks provide the coordinates of various points on the contour of the work part.

Block 22: Go to a safe position.

Block 23: In this block the finishing cycle G70 will be executed. The syntax for this cycle is as follows:

```
G70   P…   Q…   F…  S…
```

where,
P = First block number of the finishing contour
Q = Last block number of the finishing contour
F = Cutting feed rate (in/rev or mm/rev)
S = Spindle speed (ft/min or m/min)

Block 24 to 27: Go to safe potion (home); cancel all activated cycles and stops the program.

Module 7: CNC Programming and Industrial Robotics

Lecture 5

Industrial robotics-1

1. Introduction

An industrial robot is a general-purpose, programmable machine. It possesses some anthropomorphic characteristics, i.e. human-like characteristics that resemble the human physical structure. The robots also respond to sensory signals in a manner that is similar to humans. Anthropomorphic characteristics such as mechanical arms are used for various industry tasks. Sensory perceptive devices such as sensors allow the robots to communicate and interact with other machines and to take simple decisions. The general commercial and technological advantages of robots are listed below:

- Robots are good substitutes to the human beings in hazardous or uncomfortable work environments.
- A robot performs its work cycle with a consistency and repeatability which is difficult for human beings to attain over a long period of continuous working.
- Robots can be reprogrammed. When the production run of the current task is completed, a robot can be reprogrammed and equipped with the necessary tooling to perform an altogether different task.
- Robots can be connected to the computer systems and other robotics systems. Nowadays robots can be controlled with wire-less control technologies. This has enhanced the productivity and efficiency of automation industry.

2. Robot anatomy and related attributes

2.1 Joints and Links

The manipulator of an industrial robot consists of a series of joints and links. Robot anatomy deals with the study of different joints and links and other aspects of the manipulator's physical construction. A robotic joint provides relative motion between two links of the robot. Each joint, or axis, provides a certain degree-of-freedom (dof) of motion. In most of the cases, only one degree-of-freedom is associated with each joint. Therefore the robot's complexity can be classified according to the total number of degrees-of-freedom they possess.

Each joint is connected to two links, an input link and an output link. Joint provides controlled relative movement between the input link and output link. A robotic link is the rigid component of the robot manipulator. Most of the robots are mounted upon a stationary base, such as the floor. From this base, a joint-link numbering scheme may be recognized as shown in Figure 7.5.1. The robotic base and its connection to the first joint are termed as link-0. The first joint in the sequence is joint-1. Link-0 is the input link for joint-1, while the output link from joint-1 is link-1—which leads to joint-2. Thus link 1 is, simultaneously, the output link for joint-1 and the input link for joint-2. This joint-link-numbering scheme is further followed for all joints and links in the robotic systems.

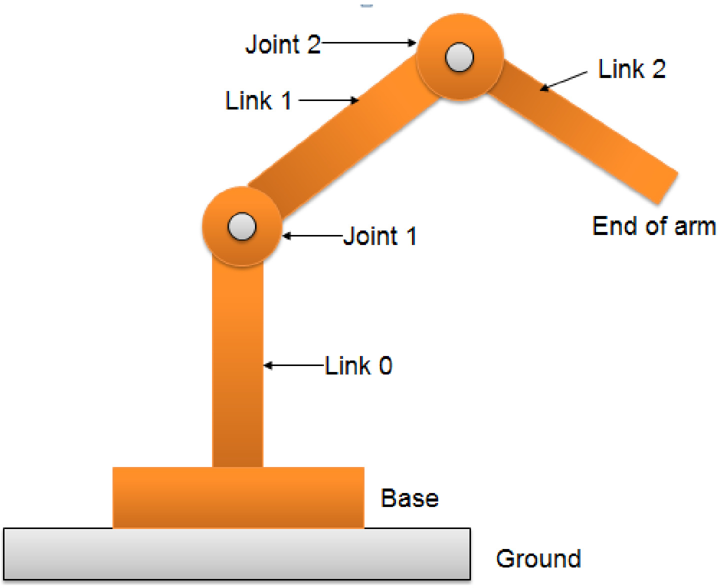

Fig. 7.5.1 Joint-link scheme for robot manipulator

Nearly all industrial robots have mechanical joints that can be classified into following five types as shown in Figure 7.5.2.

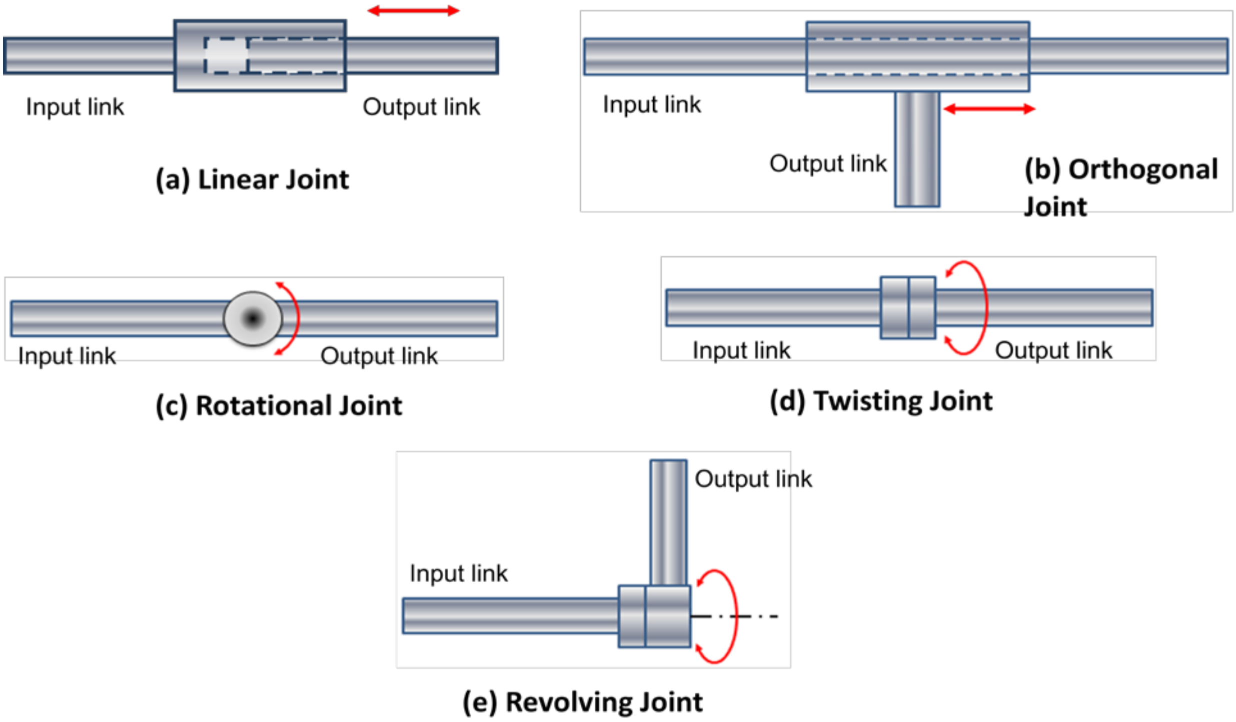

Fig. 7.5.2 Types of Joints

a) **Linear joint (type L-joint)**
The relative movement between the input link and the output link is a translational sliding motion, with the axes of the two links being parallel.

b) **Orthogonal joint (type U-joint)**
This is also a translational sliding motion, but the input and output links are perpendicular to each other during the move.

c) **Rotational joint (type R-joint)**
This type provides rotational relative motion, with the axis of rotation perpendicular to the axes of the input and output links.

d) **Twisting joint (type T-joint)**
This joint also involves rotary motion, but the axis or rotation is parallel to the axes of the two links.

e) **Revolving joint (type V-joint, V from the "v" in revolving)**
In this type, axis of input link is parallel to the axis of rotation of the joint. However the axis of the output link is perpendicular to the axis of rotation.

2.2 Common Robot Configurations

Basically the robot manipulator has two parts viz. a body-and-arm assembly with three degrees-of-freedom; and a wrist assembly with two or three degrees-of-freedom.

For body-and-arm configurations, different combinations of joint types are possible for a three-degree-of-freedom robot manipulator. Five common body-and-arm configurations are outlined in figure 7.5.3.

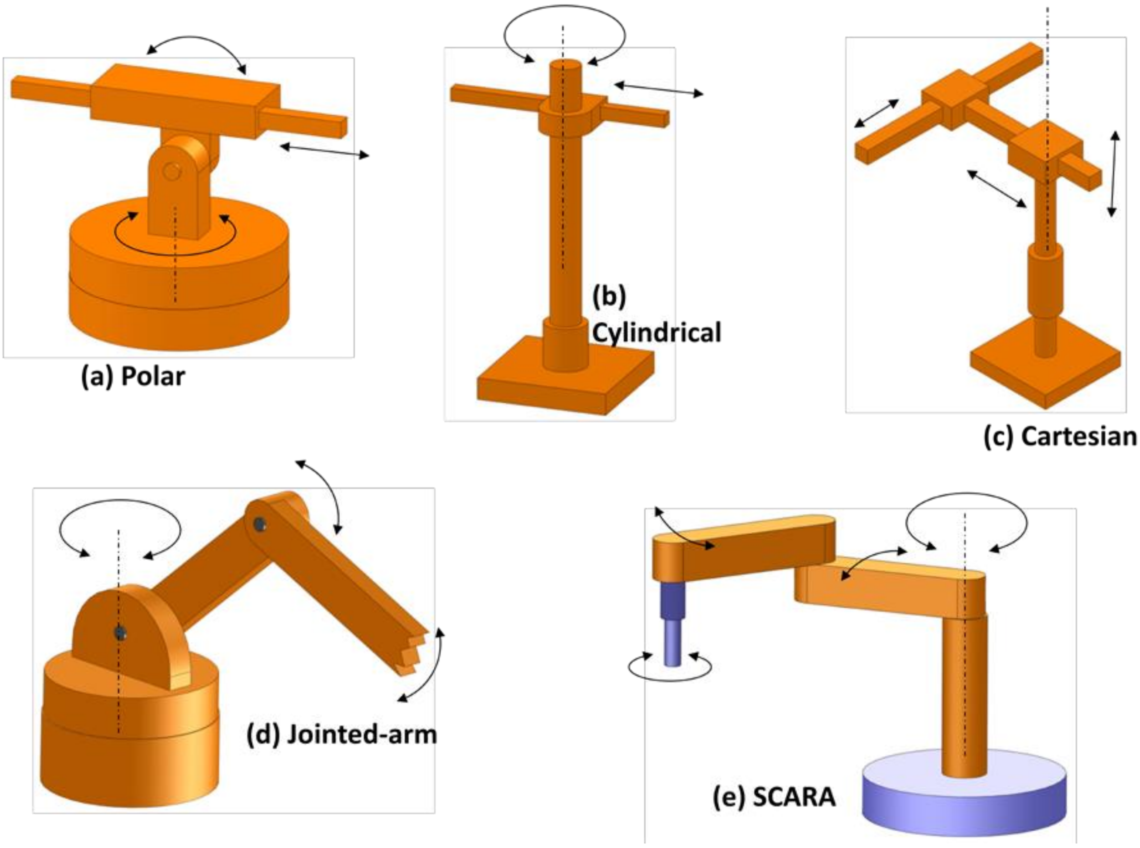

Fig.7.5.3 Common Body-and-Arm configurations

(a) Polar configuration

It consists of a sliding arm L-joint, actuated relative to the body, which rotates around both a vertical axis (T-joint), and horizontal axis (R-joint).

(b) Cylindrical configuration

It consists of a vertical column. An arm assembly is moved up or down relative to the vertical column. The arm can be moved in and out relative to the axis of the column. Common configuration is to use a T-joint to rotate the column about its axis. An L-joint is used to move the arm assembly vertically along the column, while an O-joint is used to achieve radial movement of the arm.

(c) Cartesian co-ordinate robot

It is also known as rectilinear robot and x-y-z robot. It consists of three sliding joints, two of which are orthogonal O-joints.

(d) Jointed-arm robot

It is similar to the configuration of a human arm. It consists of a vertical column that swivels about the base using a T-joint. Shoulder joint (R-joint) is located at the top of the column. The output link is an elbow joint (another R joint).

(e) SCARA

Its full form is 'Selective Compliance Assembly Robot Arm'. It is similar in construction to the jointer-arm robot, except the shoulder and elbow rotational axes are vertical. It means that the arm is very rigid in the vertical direction, but compliant in the horizontal direction.

Robot wrist assemblies consist of either two or three degrees-of-freedom. A typical three-degree-of-freedom wrist joint is depicted in Figure 7.5.4. The roll joint is accomplished by use of a T-joint. The pitch joint is achieved by recourse to an R-joint. And the yaw joint, a right-and-left motion, is gained by deploying a second R-joint.

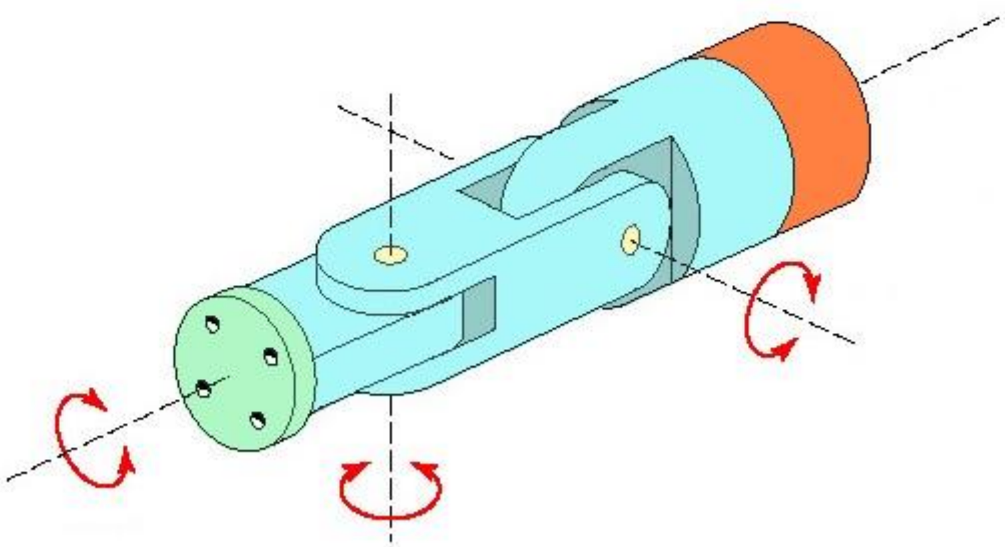

Fig. 7.5.4: Robotic wrist joint

The SCARA body-and-arm configuration typically does not use a separate wrist assembly. Its usual operative environment is for insertion-type assembly operations where wrist joints are unnecessary. The other four body-and-arm configurations more-or-less follow the wrist-joint configuration by deploying various combinations of rotary joints viz. type R and T.

2.3 Drive systems

Basically three types of drive systems are commonly used to actuate robotic joints. These are electric, hydraulic, and pneumatic drives. Electric motors are the prime movers in robots. Servo-motors or steeper motors are widely used in robotics. Hydraulic and pneumatic systems such as piston-cylinder systems, rotary vane actuators are used to accomplish linear motions, and rotary motions of joints respectively.

Pneumatic drive is regularly used for smaller, simpler robotic applications; whereas electric and hydraulic drives may be found applications on more sophisticated industrial robots. Due to the advancement in electric motor technology made in recent years, electric drives are generally favored in commercial applications. They also have compatibility to computing systems. Hydraulic systems, although not as flexible as electrical drives, are generally used where larger speeds are required. They are generally employed to carry out heavy duty operations using robots.

The combination of drive system, sensors, and feedback control system determines the dynamic response characteristics of the manipulator. Speed in robotic terms refers to the absolute velocity of the manipulator at its end-of-arm. It can be programmed into the work cycle so that different portions of the cycle are carried out at different velocities. Acceleration and deceleration control are also important factors, especially in a confined work envelope. The robot's ability to control the switching between velocities is a key determinant of the manipulator's capabilities. Other key determinants are the weight (mass) of the object being manipulated, and the precision that is required to locate and position the object correctly. All of these determinants are gathered under the term 'speed of response', which is defined as the time required for the manipulator to move from one point in space to the next. Speed of response influences the robot's cycle time, which in turn affects the production rate that can be achieved.

Stability refers to the amount of overshoot and oscillation that occurs in the robot motion at the end-of-arm as it attempts to move to the next programmed location. More oscillations in the robotic motion lead to less stability in the robotic manipulator. However, greater stability may produce a robotic system with slower response times.

Load carrying capacity is also an important factor. It is determined by weight of the gripper used to grasp the objects. A heavy gripper puts a higher load upon the robotic manipulator in addition to the object mass. Commercial robots can carry loads of up to 900 kg, while medium-sized industrial robots may have capacities of up to 45kg.

Module 7: CNC Programming and Industrial Robotics
Lecture 6
Industrial robotics-2

1. Robot Control Systems

To perform as per the program instructions, the joint movements an industrial robot must accurately be controlled. Micro-processor-based controllers are used to control the robots. Different types of control that are being used in robotics are given as follows.

(a) Limited Sequence Control

It is an elementary control type. It is used for simple motion cycles, such as pick-and-place operations. It is implemented by fixing limits or mechanical stops for each joint and sequencing the movement of joints to accomplish operation. Feedback loops may be used to inform the controller that the action has been performed, so that the program can move to the next step. Precision of such control system is less. It is generally used in pneumatically driven robots.

(b) Playback with Point-to-Point Control

Playback control uses a controller with memory to record motion sequences in a work cycle, as well as associated locations and other parameters, and then plays back the work cycle during program execution. Point-to-point control means individual robot positions are recorded in the memory. These positions include both mechanical stops for each joint, and the set of values that represent locations in the range of each joint. Feedback control is used to confirm that the individual joints achieve the specified locations in the program.

(c) Playback with Continuous Path Control

Continuous path control refers to a control system capable of continuous simultaneous control of two or more axes. The following advantages are noted with this type of playback control: greater storage capacity—the number of locations that can be stored is greater than in point-to-point; and interpolation calculations may be used, especially linear and circular interpolations.

(d) Intelligent Control

An intelligent robot exhibits behavior that makes it seems to be intelligent. For example, it may have capacity to interact with its ambient surroundings; decision-making capability; ability to communicate with humans; ability to carry out computational analysis during the work cycle; and responsiveness to advanced sensor inputs. They may also possess the playback facilities. However it requires a high level of computer control, and an advanced programming language to input the decision-making logic and other ‘intelligence’ into the memory.

2. *End Effectors*

An end effector is usually attached to the robot's wrist, and it allows the robot to accomplish a specific task. This means that end effectors are generally custom-engineered and fabricated for each different operation. There are two general categories of end effectors viz. grippers and tools.

Grippers grasp and manipulate the objects during the work cycle. Typically objects that grasped are the work parts which need to be loaded or unloaded from one station to another. Grippers may be custom-designed to suit the physical specifications of work parts. Various end-effectors, grippers are summarized in Table 7.6.1.

Table 7.6.1 End-Effectors: Grippers

Type	**Description**
Mechanical gripper	Two or more fingers which are actuated by robot controller to open and close on a workpart.
Vacuum gripper	Suction cups are used to hold flat objects.
Magnetized devices	Based on the principle of magnetism. These are used for holding ferrous workparts.
Adhesive devices	By deploying adhesive substances, these are used to hold flexible materials, such as fabric.
Simple mechanical devices	Hooks and scoops.
Dual grippers	It is a mechanical gripper with two gripping devices in one end-effecter. It is used for machine loading and unloading. It reduces cycle time per part by gripping two workparts at the same time.
Interchangeable fingers	Mechanical gripper with an arrangement to have modular fingers to accommodate different sizes workpart.
Sensory feedback fingers	Mechanical gripper with sensory feedback capabilities in the fingers to aid locating the workpart; and to determine correct grip force to apply (for fragile workparts).
Multiple fingered grippers	Mechanical gripper as per the general anatomy of human hand.
Standard grippers	Mechanical grippers that are commercially available, thus reducing the need to custom-design a gripper for separate robot applications.

The robot end effecter may also use tools. Tools are used to perform processing operations on the workpart. Typically the robot uses the tool relative to a stationary or slowly-moving object. For example, spot welding, arc welding, and spray painting robots use a tool for processing the respective operation. Tools also can be mounted at robotic manipulator spindle to carry out machining work such as drilling, routing, grinding, etc.

3. Sensors in Robotics

There are generally two categories of sensors used in robotics. These are sensors for internal purposes and for external purposes. Internal sensors are used to monitor and control the various joints of the robot. They form a feedback control loop with the robot controller. Examples of internal sensors include potentiometers and optical encoders, while tachometers of various types are deployed to control the speed of the robot arm.

External sensors are external to the robot itself, and are used when we wish to control the operations of the robot. External sensors are simple devices, such as limit switches that determine whether a part has been positioned properly, or whether a part is ready to be picked up from an unloading bay.

Various sensors used in robotics are outlined in Table 7.6.2.

Table 7.6.2 Sensor technologies for robotics

Sensor Type	Description
Tactile sensors	Used to determine whether contact is made between sensor and another object Touch sensors: indicates the contact Force sensors: indicates the magnitude of force with the object
Proximity sensors	Used to determine how close an object is to the sensor. Also called a range sensor.
Optical sensors	Photocells and other photometric devices that are used to detect the presence or absence of objects. Often used in conjunction with proximity sensors.
Machine vision	Used in robotics for inspection, parts identification, guidance, etc.
Others	Measurement of temperature, fluid pressure, fluid flow, electrical voltage, current, and other physical properties.

4. *Industrial Robot Applications:*

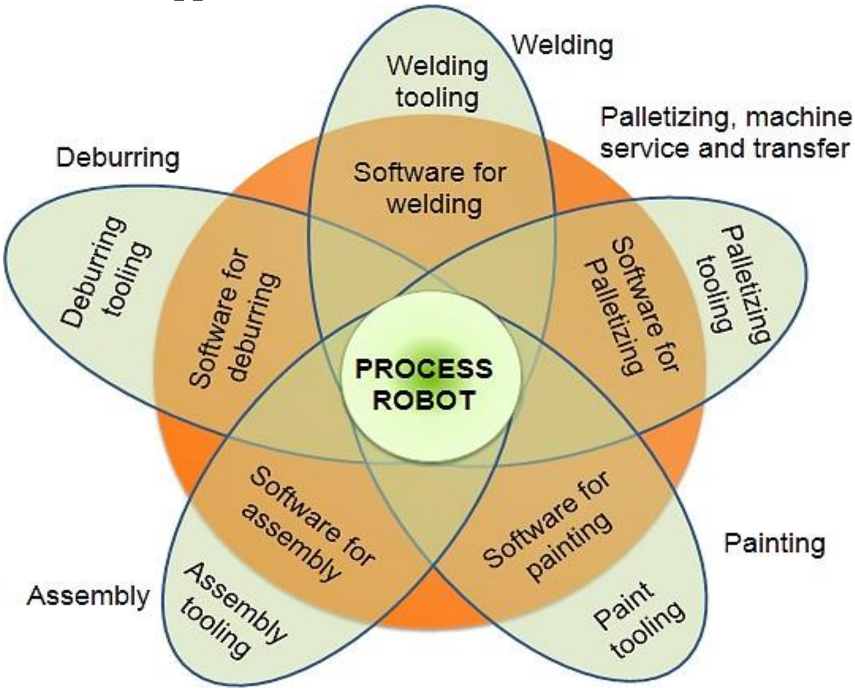

Fig. 7.6.1 Applications of robots in industry and manufacturing

Figure 7.6.1 shows a diagram which depicts an overview of applications of robots in manufacturing. The general characteristics of industrial work situations that tend to promote the substitution of robots for human labor are outlined in Table 7.6.3.

Table 7.6.3: Characteristics of situations where robots may substitute for humans

Situation	**Description**
Hazardous work environment for humans	In situations where the work environment is unsafe, unhealthy, uncomfortable, or otherwise unpleasant for humans, robot application may be considered.
Repetitive work cycle	If the sequence of elements in the work cycle is the same, and the elements consist of relatively simple motions, robots usually perform the work with greater consistency and repeatability than humans.
Difficult handling for humans	If the task requires the use of heavy or difficult-to-handle parts or tools for humans, robots may be able to perform the operation more efficiently.
Multi-shift operation	A robot can replace two or three workers at a time in second or third shifts, thus they can provide a faster financial payback.
Infrequent changeovers	Robots' use is justified for long production runs where there are infrequent changeovers, as opposed to batch or job shop production where changeovers are more frequent.
Part position and orientation are established in the work cell	Robots generally don't have vision capabilities, which means parts must be precisely placed and oriented for successful robotic operations.

4.1 Material Handling Applications

Robots are mainly used in three types of applications: material handling; processing operations; and assembly and inspection. In material handling, robots move parts between various locations by means of a gripper type end effector. Material handling activity can be sub divided into material transfer and machine loading and/or unloading. These are described in Table 7.6.4.

Table 7.6.4: Material handling applications

Application	Description
Material transfer	• Main purpose is to pick up parts at one location and place them at a new location. Part re-orientation may be accomplished during the transfer. The most basic application is a pick-and-place procedure, by a low-technology robot (often pneumatic), using only up to 4 joints. • More complex is palletizing, where robots retrieve objects from one location, and deposit them on a pallet in a specific area of the pallet, thus the deposit location is slightly different for each object transferred. The robot must be able to compute the correct deposit location via powered lead-through method, or by dimensional analysis. • Other applications of material transfer include de-palletizing, stacking, and insertion operations.
Machine loading and/or unloading	• Primary aim is to transfer parts into or out-of a production machine. • There are three classes to consider: o machine loading—where the robot loads the machine o machine unloading—where the robot unloads the machine o machine loading and unloading—where the robot performs both actions • Used in die casting, plastic molding, metal machining operations, forging, press-working, and heat treating operations.

4.2 Processing Operations

In processing operations, the robot performs some processing activities such as grinding, milling, etc. on the workpart. The end effector is equipped with the specialized tool required for the respective process. The tool is moved relative to the surface of the workpart. Table 7.6.5 outlines the examples of various processing operations that deploy robots.

Table 7.6.5: Robotic process operations

Process	Description
Spot Welding	Metal joining process in which two sheet metal parts are fused together at localized points of contact by the deployment of two electrodes that squeeze the metal together and apply an electric current. The electrodes constitute the spot welding gun, which is the end effector tool of the welding robot.
Arc Welding	Metal joining process that utilizes a continuous rather than contact welding point process, in the same way as above. Again the end effector is the electrodes used to achieve the welding arc. The robot must use continuous path control, and a jointed arm robot consisting of six joints is frequently used.
Spray Coating	Spray coating directs a spray gun at the object to be coated. Paint or some other fluid flows through the nozzle of the spray gun, which is the end effector, and is dispersed and applied over the surface of the object. Again the robot must use continuous path control, and is typically programmed using manual lead-through. Jointed arm robots seem to be the most common anatomy for this application.
Other applications	Other applications include: drilling, routing, and other machining processes; grinding, wire brushing, and similar operations; waterjet cutting; and laser cutting.

5 *Robot programming*

A robot program is a path in the space that to be followed by the manipulator, combined with peripheral actions that support the work cycle. To program a robot, specific commands are entered into the robot's controller memory, and these actions may be performed in a number of ways. Limited sequence robot programming is carried out when limit switches and mechanical stops are set to control the end-points of its motions. A sequencing device controls the occurrence of motions, which in turn controls the movement of the joints that completes the motion cycle.

5.1 Lead-through programming

For industrial robots with digital computers as controllers, three programming methods can be distinguished. These are lead-through programming; computer-like robot programming languages; and off-line programming. Lead-through methodologies, and associated programming methods, are outlined in Table 7.6.6.

Table 7.6.6 Lead-through programming methods for industrial robots

Method	Description
Lead-through programming	• Task is 'taught' to the robot by manually moving the manipulator through the required motion cycle, and simultaneously entering the program into the controller memory for playback. • Two methods are used for teaching: powered lead-through; and manual lead-through.
Motion programming	• To overcome the difficulties of co-coordinating individual joints associated with lead-through programming, two mechanical methods can be used: the world-co-ordinate system—whereby the origin and axes are defined relative to the robot base; and the tool-co-ordinate system—whereby the alignment of the axis system is defined relative to the orientation of the wrist faceplate. • These methods are typically used with Cartesian co-ordinate robots, and not for robots with rotational joints. • Robotic types with rotational joints rely on interpolation processes to gain straight line motion. • Two types of interpolation processes are used: straight line interpolation—where the control computer calculates the necessary points in space that the manipulator must move through to connect two points; and joint interpolation—where joints are moved simultaneously at their own constant speed such that all joints start/stop at the same time.

5.2 Computer-like programming

These are computer-like languages which use on-line/off-line methods of programming. The advantages of textual programming over its lead-through counterpart include:

- The use of enhanced sensor capabilities, including the use of analogue and digital inputs
- Improved output capabilities for controlling external equipment
- Extended program logic, beyond lead-through capabilities
- Advanced computation and data processing capabilities
- Communications with other computer systems

Table 7.1.1 G code for Milling and Turning Operations

G00 Rapid Linear Positioning	G55 Work Coordinate System 2 Selection
G01 Linear Feed Interpolation	G56 Work Coordinate System 3 Selection
G02 CW Circular Interpolation	G57 Work Coordinate System 4 Selection
G03 CCW Circular Interpolation	G58 Work Coordinate System 5 Selection
G04 Dwell	G59 Work Coordinate System 6 Selection
G07 Imaginary Axis Designation	G60 Single Direction Positioning
G09 Exact Stop	G61 Exact Stop Mode
G10 Offset Value Setting	G64 Cutting Mode
G17 XY Plane Selection	G65 Custom Macro Simple Call
G18 ZX Plane Selection	G66 Custom Macro Modal Call
G19 YZ plane Selection	G67 Custom Macro Modal Call Cancel
G20 Input In Inches	G68 Coordinate System Rotation On
G21 Input In Millimeters	G69 Coordinate System Rotation Off
G22 Stored Stroke Limit On	G73 Peck Drilling Cycle
G23 Stored Stroke Limit Off	G74 Counter Tapping Cycle
G27 Reference Point Return Check	G76 Fine Boring
G28 Return To Reference Point	G80 Canned Cycle Cancel
G29 Return From Reference Point	G81 Drilling Cycle, Spot Boring
G30 Return To 2nd, 3rd and 4th Ref. Point	G82 Drilling Cycle, Counter Boring
G31 Skip Cutting	G83 Peck Drilling Cycle
G33 Thread Cutting	G84 Tapping Cycle
G40 Cutter Compensation Cancel	G85 Boring Cycle
G41 Cutter Compensation Left	G86 Boring Cycle
G42 Cutter Compensation Right	G87 Back Boring Cycle
G43 Tool Length Compensation + Direction	G88 Boring Cycle
G44 Tool Length Compensation - Direction	G89 Boring Cycle
G45 Tool Offset Increase	G90 Absolute Programming
G46 Tool Offset Double	G91 Incremental Programming
G47 Tool Offset Double Increase	G92 Programming Of Absolute Zero
G48 Tool Offset Double Decrease	G94 Feed Per Minute
G49 Tool Length Compensation Cancel	G95 Feed Per Revolution
G50 Scaling Off	G96 Constant Surface Speed Control
G51 Scaling On	G97 Constant Surface Speed Control Cancel
G52 Local Coordinate System Setting	G98 Return To Initial Point In Canned Cycles
G54 Work Coordinate System 1 Selection	G99 Return To R Point In Canned Cycles

Table 7.1.2 M code for Milling operations

M00	Program Stop
M01	Optional Stop
M02	End of Program
M03	Spindle On CW
M04	Spindle On CCW
M05	Spindle Stop
M06	Tool Change
M07	Mist Coolant On
M08	Flood Coolant On
M09	Coolant Off
M19	Spindle Orientation On
M20	Spindle Orientation Off
M21	Tool Magazine Right
M22	Tool Magazine Left
M23	Tool Magazine Up
M24	Tool Magazine Down
M25	Tool Clamp
M26	Tool Unclamp
M27	Clutch Neutral On
M28	Clutch Neutral Off
M30	End Program, Stop and Rewind
M98	Call Sub Program
M99	End Sub Program

Table 7.1.3 M code for Turning operations

G00	Rapid Linear Positioning
G01	Linear Feed Interpolation
G02	CW Circular Interpolation
G03	CCW Circular Interpolation
G04	Dwell
G07	Hypothetical Axis Interpolation, Sine Curve
G09	Exact Stop
G10	Offset Value Setting
G20	Input In Inches
G21	Input In Millimeters
G22	Stored Stroke Limit On
G23	Stored Stroke Limit Off
G27	Reference Point Return Check
G28	Return To Reference Point
G29	Return From Reference Point
G30	Return To 2nd, 3rd, and 4th Reference Point
G31	Skip Cutting
G32	Thread Cutting
G34	Variable Lead Thread Cutting
G36	Automatic Tool Comp. X
G37	Automatic Tool Comp. Z
G40	Tool Nose Rad. Comp. Cancel
G41	Tool Nose Radius Comp. Left
G42	Tool Nose Radius Comp. Right
G50	Programming Of Absolute Zero
G65	User Macro Simple Call
G66	User Macro Modal Call
G67	User Macro Modal Call Cancel
G68	Mirror Image For Double Turrets On
G69	Mirror Image For Double Turrets Off
G70	Finishing Cycle
G71	Stock Removal, Turning
G72	Stock Removal, Facing
G73	Repeat Pattern
G74	Peck Drilling, Z Axis
G75	Grooving, X Axis
G76	Thread Cutting Cycle
G90	Cutting Cycle A
G92	Thread Cutting Cycle
G94	Cutting Cycle B
G96	Constant Surface Speed Control
G97	Constant Surface Speed Cancel
G98	Feed Per Minute
G99	Feed Per Revolution
G90	Absolute Programming
G91	Incremental Programming

Module 6: Pneumatic Systems

Lecture 1

Pneumatic system

Pneumatic technology deals with the study of behavior and applications of compressed air in our daily life in general and manufacturing automation in particular. Pneumatic systems use air as the medium which is abundantly available and can be exhausted into the atmosphere after completion of the assigned task.

1. Basic Components of Pneumatic System:

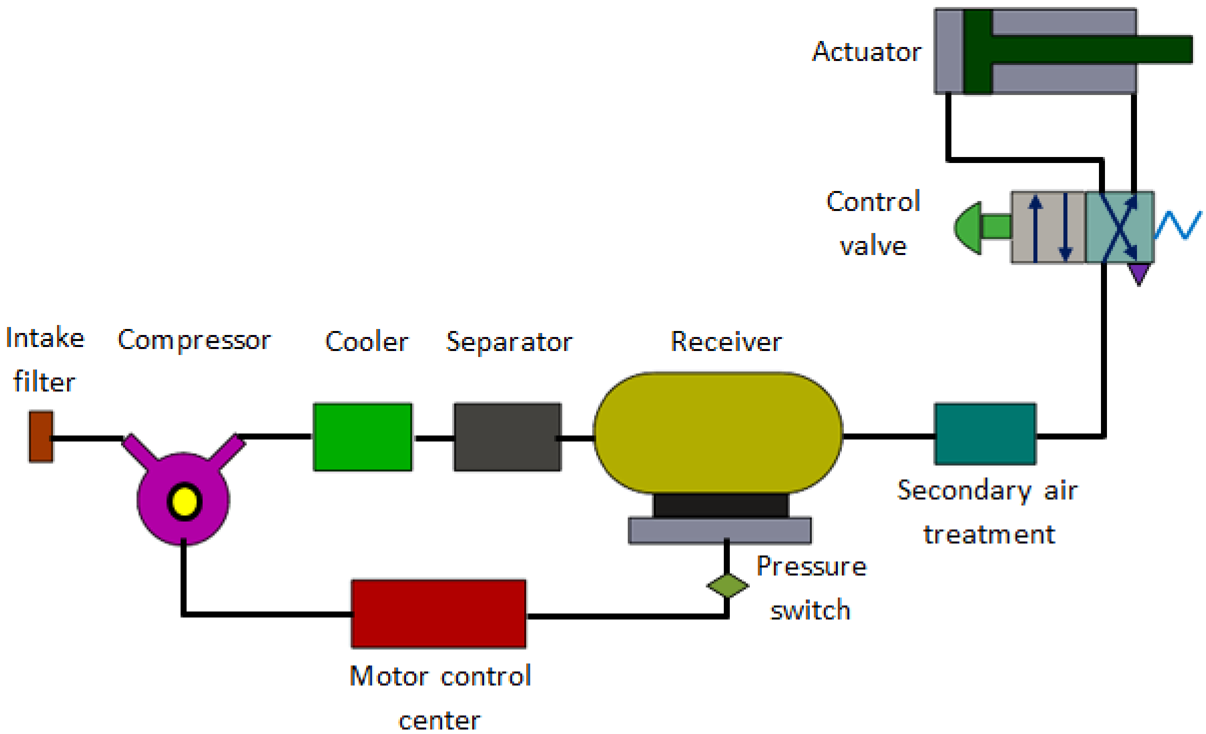

Fig. 6.1.1 Components of a pneumatic system

Important components of a pneumatic system are shown in fig.6.1.1.

a) **Air filters:** These are used to filter out the contaminants from the air.
b) **Compressor:** Compressed air is generated by using air compressors. Air compressors are either diesel or electrically operated. Based on the requirement of compressed air, suitable capacity compressors may be used.
c) **Air cooler:** During compression operation, air temperature increases. Therefore coolers are used to reduce the temperature of the compressed air.
d) **Dryer:** The water vapor or moisture in the air is separated from the air by using a dryer.
e) **Control Valves:** Control valves are used to regulate, control and monitor for control of direction flow, pressure etc.
f) **Air Actuator:** Air cylinders and motors are used to obtain the required movements of mechanical elements of pneumatic system.

g) **Electric Motor:** Transforms electrical energy into mechanical energy. It is used to drive the compressor.

h) **Receiver tank*:*** The compressed air coming from the compressor is stored in the air receiver.

These components of the pneumatic system are explained in detail on the next pages.

2. Receiver tank

The air is compressed slowly in the compressor. But since the pneumatic system needs continuous supply of air, this compressed air has to be stored. The compressed air is stored in an air receiver as shown in Figure 6.1.2. The air receiver smoothens the pulsating flow from the compressor. It also helps the air to cool and condense the moisture present. The air receiver should be large enough to hold all the air delivered by the compressor. The pressure in the receiver is held higher than the system operating pressure to compensate pressure loss in the pipes. Also the large surface area of the receiver helps in dissipating the heat from the compressed air. Generally the size of receiver depends on,

- Delivery volume of compressor.
- Air consumption.
- Pipeline network
- Type and nature of on-off regulation
- Permissible pressure difference in the pipelines

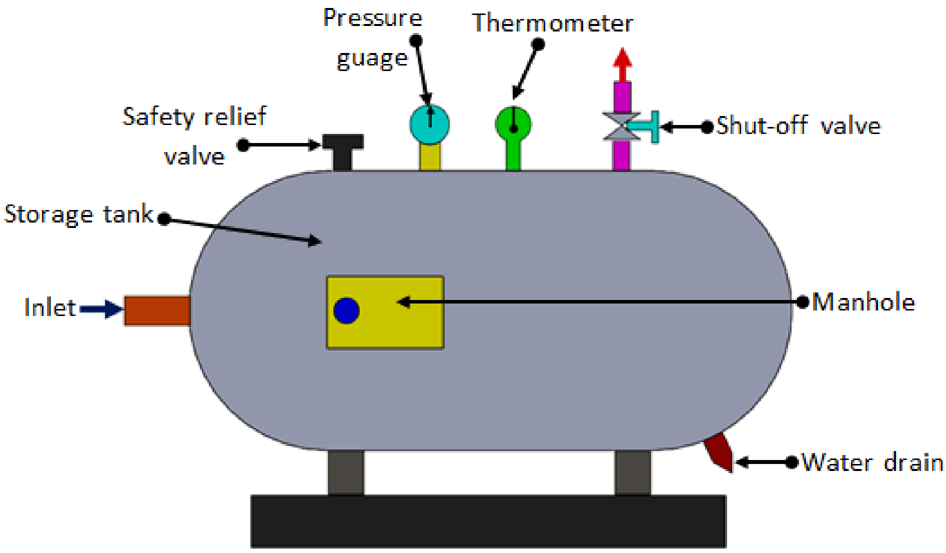

Fig.6.1.2 Air receiver

3. Compressor:

It is a mechanical device which converts mechanical energy into fluid energy. The compressor increases the air pressure by reducing its volume which also increases the temperature of the compressed air. The compressor is selected based on the pressure it needs to operate and the delivery volume.

The compressor can be classified into two main types

a. Positive displacement compressors and
b. Dynamic displacement compressor

Positive displacement compressors include piston type, vane type, diaphragm type and screw type.

3.1 Piston compressors

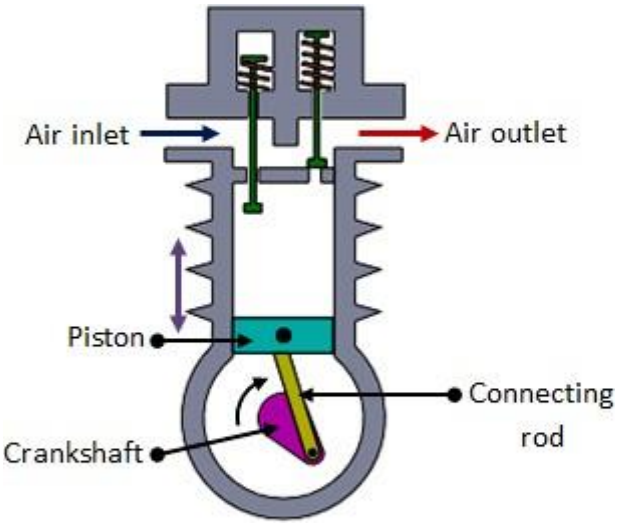

Fig. 6.1.3 Single acting piston compressor

Piston compressors are commonly used in pneumatic systems. The simplest form is single cylinder compressor (Fig. 6.1.3). It produces one pulse of air per piston stroke. As the piston moves down during the inlet stroke the inlet valve opens and air is drawn into the cylinder. As the piston moves up the inlet valve closes and the exhaust valve opens which allows the air to be expelled. The valves are spring loaded. The single cylinder compressor gives significant amount of pressure pulses at the outlet port. The pressure developed is about 3-40 bar.

3.2 Double acting compressor

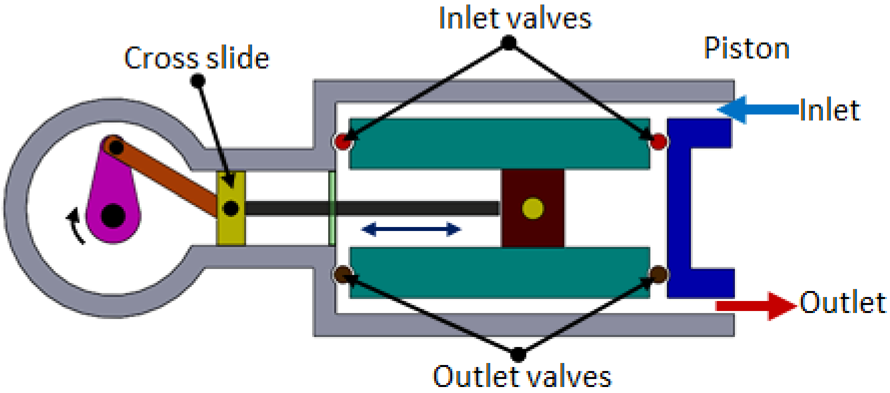

Fig. 6.1.4 Double acting piston compressor

The pulsation of air can be reduced by using double acting compressor as shown in Figure 6.1.4. It has two sets of valves and a crosshead. As the piston moves, the air is compressed on one side whilst on the other side of the piston, the air is sucked in. Due to the reciprocating action of the piston, the air is compressed and delivered twice in one piston stroke. Pressure higher than 30bar can be produced.

3.3 Multistage compressor

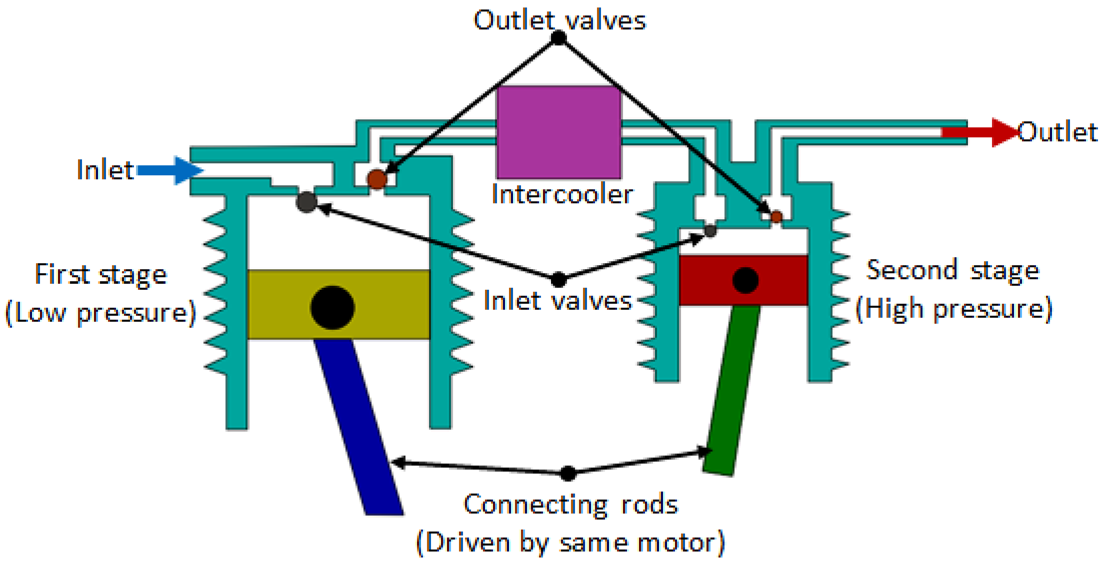

Fig. 6.1.5 Multi-stage compressor

As the pressure of the air increases, its temperature rises. It is essential to reduce the air temperature to avoid damage of compressor and other mechanical elements. The multistage compressor with intercooler in-between is shown in Figure 6.1.5. It is used to reduce the temperature of compressed air during the compression stages. The inter-cooling reduces the volume of air which used to increase due to heat. The compressed air from the first stage enters the intercooler where it is cooled. This air is given as input to the second stage where it is compressed again. The multistage compressor can develop a pressure of around 50bar.

3.4 Combined two stage compressors

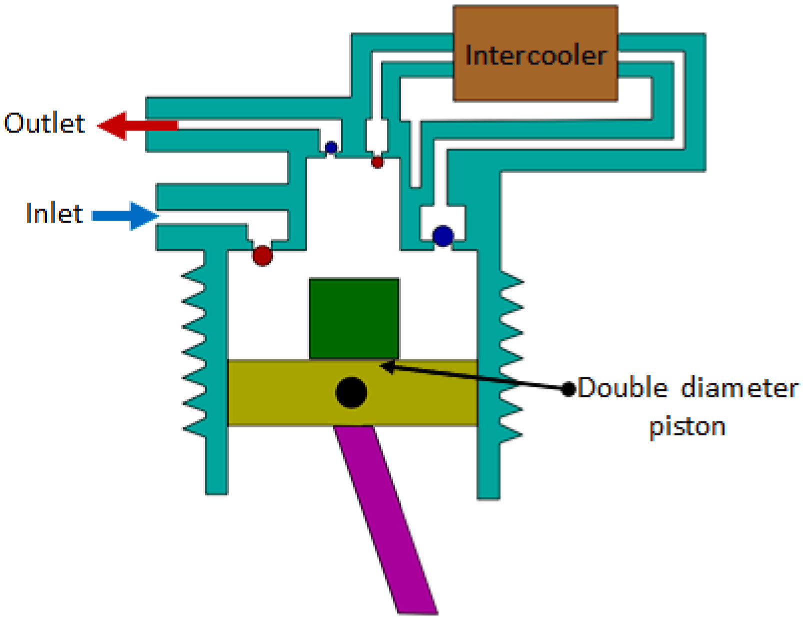

Fig. 6.1.6 Combined to stage compressor

In this type, two-stage compression is carried out by using the same piston (Fig. 6.1.6). Initially when the piston moves down, air is sucked in through the inlet valve. During the compression process, the air moves out of the exhaust valve into the intercooler. As the piston moves further the stepped head provided on the piston moves into the cavity thus causing the compression of air. Then, this is let out by the exhaust port.

Module 6: Pneumatic Systems

Lecture 2

Compressors

1. Diaphragm compressor

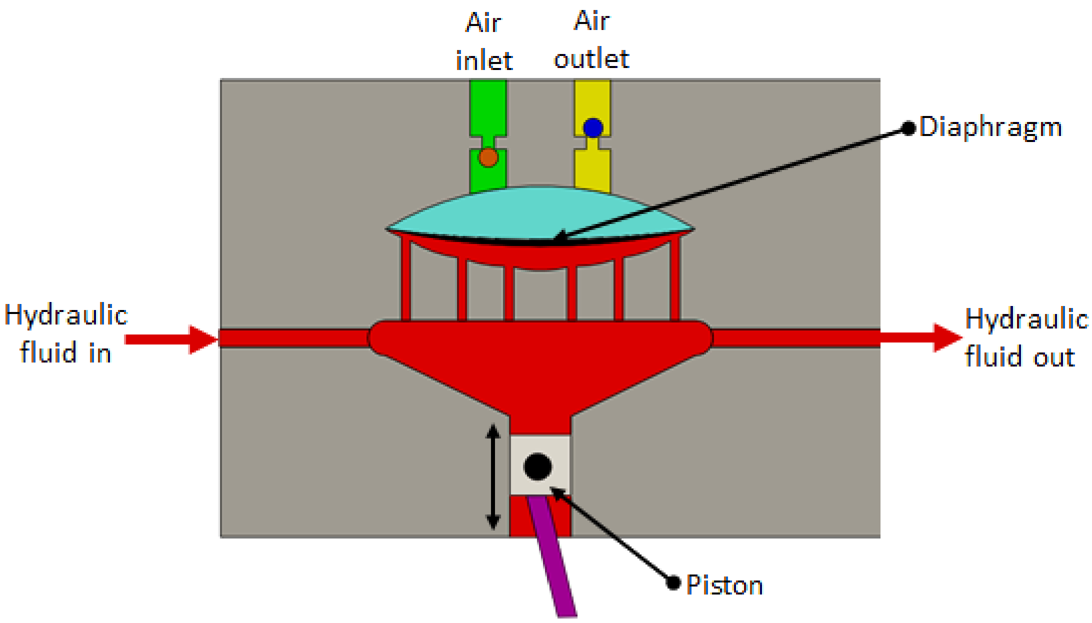

Fig. 6.2.1 Diaphragm compressor

These are small capacity compressors. In piston compressors the lubricating oil from the pistons walls may contaminate the compressed air. The contamination is undesirable in food, pharmaceutical and chemical industries. For such applications diaphragm type compressor can be used. Figure 6.2.1 shows the construction of Diaphragm compressor. The piston reciprocates by a motor driven crankshaft. As the piston moves down it pulls the hydraulic fluid down causing the diaphragm to move along and the air is sucked in. When the piston moves up the fluid pushes the diaphragm up causing the ejection of air from the outlet port. Since the flexible diaphragm is placed in between the piston and the air no contamination takes place.

2. *Screw compressor*

Piston compressors are used when high pressures and relatively low volume of air is needed. The system is complex as it has many moving parts. For medium flow and pressure applications, screw compressor can be used. It is simple in construction with less number of moving parts. The air delivered is steady with no pressure pulsation. It has two meshing screws. The air from the inlet is trapped between the meshing screws and is compressed. The contact between the two meshing surface is minimum, hence no cooling is required. These systems are quite in operation compared to piston type. The screws are synchronized by using external timing gears.

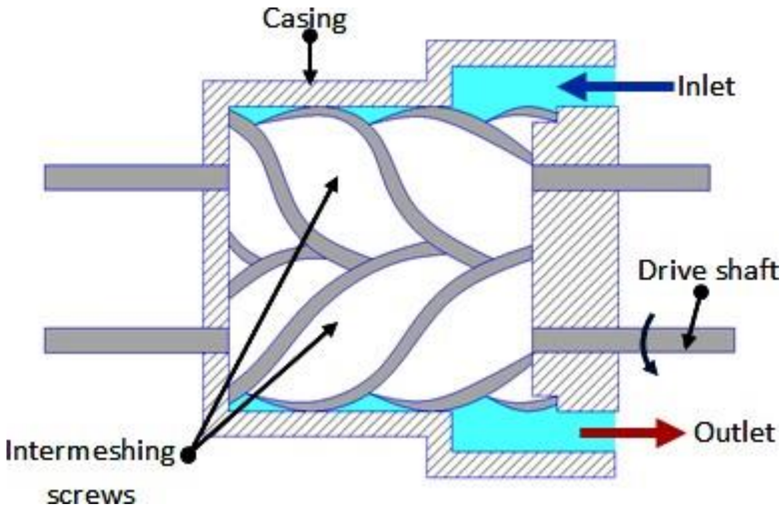

Fig. 6.2.2 Screw compressor

3. *Rotary vane compressors*

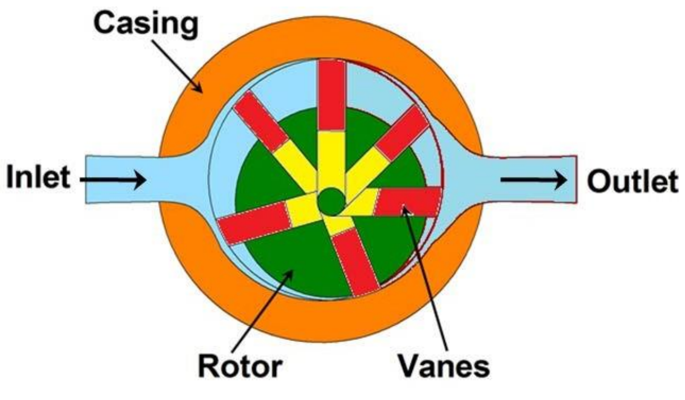

Fig. 6.2.3 Rotary vane compressor

The principle of operation of vane compressor is similar to the hydraulic vane pump. Figure 6.2.3 shows the working principle of Rotary vane compressor. The unbalanced vane compressor consists of spring loaded vanes seating in the slots of the rotor. The pumping action occurs due to movement of the vanes along a cam ring. The rotor is eccentric to the cam ring. As the rotor rotates, the vanes follow the inner surface of the cam ring. The space between the vanes decreases near the outlet due to the eccentricity. This causes compression of the air. These compressors are free from pulsation. If the eccentricity is zero no flow takes place.

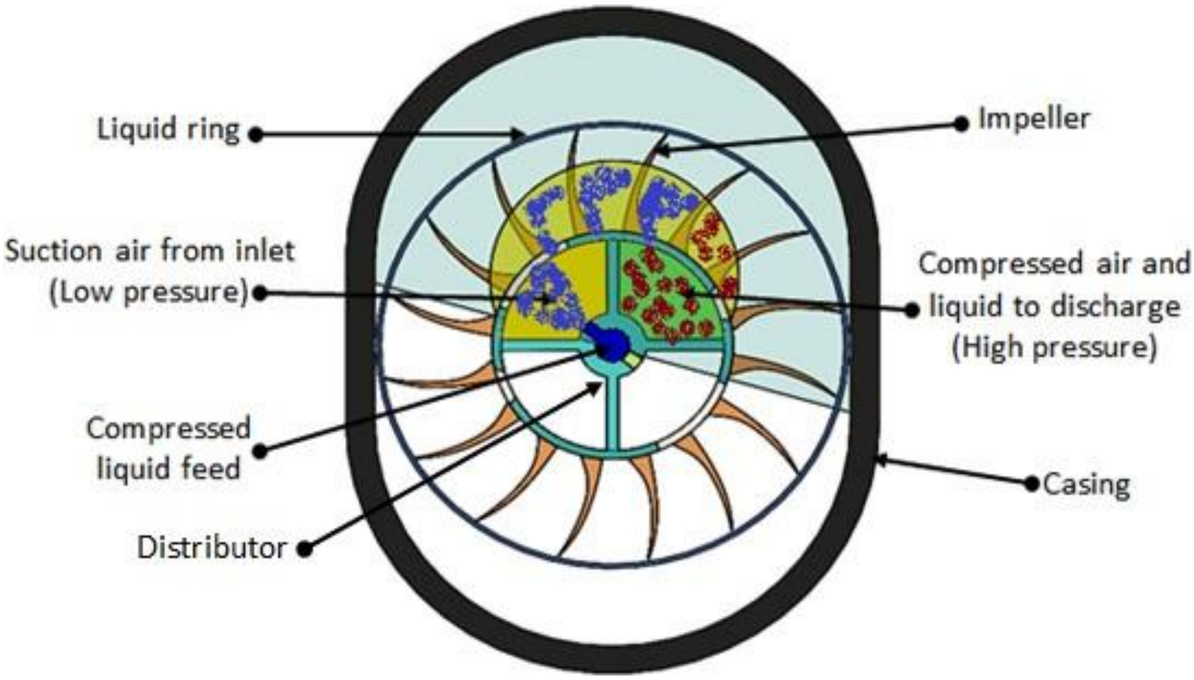

Fig. 6.2.4 Liquid ring compressor

Liquid ring vane compressor is a variation of vane compressors. Figure 6.2.4 shows the construction of Liquid ring compressor. The casing is filled with liquid up to rotor center. The air enters the compressor through the distributor fixed to the compressor. During the impeller rotation, the liquid will be centrifuged along the inner ring of the casing to form the liquid ring. There are two suction and discharge ports provided in the distributor. During the first quarter of cycle, the air is sucked in both suction chambers of the casing and during the second quarter of the cycle, the air is compressed and pushed out through the two discharge ports. During the third and fourth quarters of the cycle, the process is repeated. This type of compressor has no leakage and has minimal friction. For smooth operation, the rotation speed should be about 3000 rpm. The delivery pressure is low (about 5 bar).

4. *Lobe compressor*

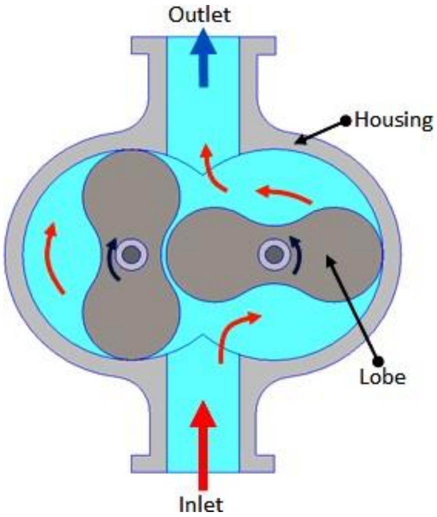

Fig. 6.2.5 Lobe compressor

The lobe compressor is used when high delivery volume but low pressure is needed. It consists of two lobes with one being driven and the other driving. Figure 6.2.5 shows the construction and working of Lobe compressor. It is similar to the Lobe pump used in hydraulic systems. The operating pressure is limited by leakage between rotors and housing. As the wear increases during the operation, the efficiency falls rapidly.

5. *Dynamic compressors*

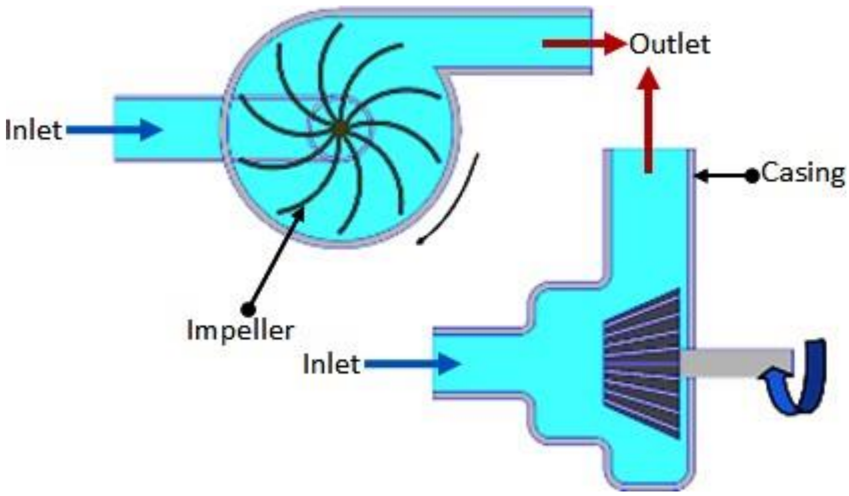

Fig. 6.2.6 Blower (Centrifugal type)

When very large volume of compressed air is required in applications such as ventilators, combustion system and pneumatic powder blower conveyors, the dynamic compressor can be used. The pressure needed is very low in such applications. Figure 6.2.6 shows a typical Centrifugal type blower. The impeller rotates at a high speed. Large volume of low pressure air can be provided by blowers. The blowers draw the air in and the impeller flings it out due to centrifugal force. Positive displacement compressors need oil to lubricate the moving parts, whereas the dynamic compressors have no such need. The efficiency of these compressors is better than that of reciprocating types.

Module 6: Pneumatic Systems

Lecture 3
Air Treatment and Pressure Regulation

1. Air treatment stages

For satisfactory operation of the pneumatic system the compressed air needs to be cleaned and dried. Atmospheric air is contaminated with dust, smoke and is humid. These particles can cause wear of the system components and presence of moisture may cause corrosion. Hence it is essential to treat the air to get rid of these impurities. The air treatment can be divided into three stages as shown in Figure 6.3.1.

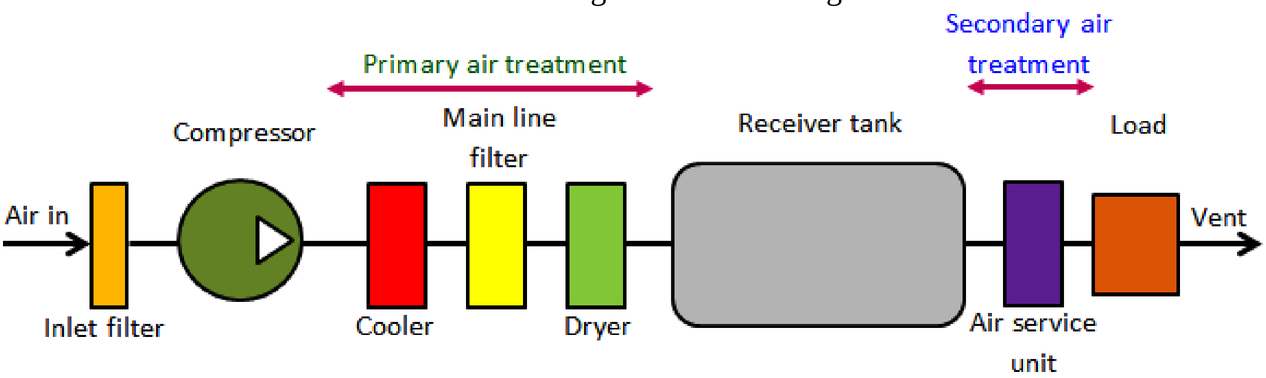

Fig. 6.3.1 Stages of air treatment

In the first stage, the large sized particles are prevented from entering the compressor by an intake filter. The air leaving the compressor may be humid and may be at high temperature. The air from the compressor is treated in the second stage. In this stage temperature of the compressed air is lowered using a cooler and the air is dried using a dryer. Also an inline filter is provided to remove any contaminant particles present. This treatment is called primary air treatment. In the third stage which is the secondary air treatment process, further filtering is carried out. A lubricator introduces a fine mist of oil into the compressed air. This will help in lubrication of the moving components of the system to which the compressed air will be applied.

1.1 Filters

To prevent any damage to the compressor, the contaminants present in the air need to be filtered out. This is done by using inlet filters. These can be dry or wet filters. Dry filters use disposable cartridges. In the wet filter, the incoming air is passed through an oil bath and then through a fine wire mesh filter. Dirt particles cling to the oil drops during bubbling and are removed by wire mesh as they pass through it. In the dry filter the cartridges are replaced during servicing. The wet filters are cleaned using detergent solution.

1.2 Cooler

As the air is compressed, the temperature of the air increases. Therefore the air needs to be cooled. This is done by using a cooler. It is a type of heat exchanger. There are two types of coolers commonly employed viz. air cooled and water cooled. In the air cooled type, ambient air is used to cool the high temperature compressed air, whereas in the water cooled type, water is used as cooling medium. These are counter flow type coolers where the cooling medium flows in the direction opposite to the compressed air. During cooling, the water vapor present will condense which can be drained away later.

2. Main line filter

These filters are used to remove the water vapors or solid contaminants present in the pneumatic systems main lines. These filters are discussed in detail as follows.

2.1 Air filter and water trap

Air filter and water trap is used to

- prevent any solid contaminants from entering in the system.
- condense and remove water vapor that is present in the compressed air.

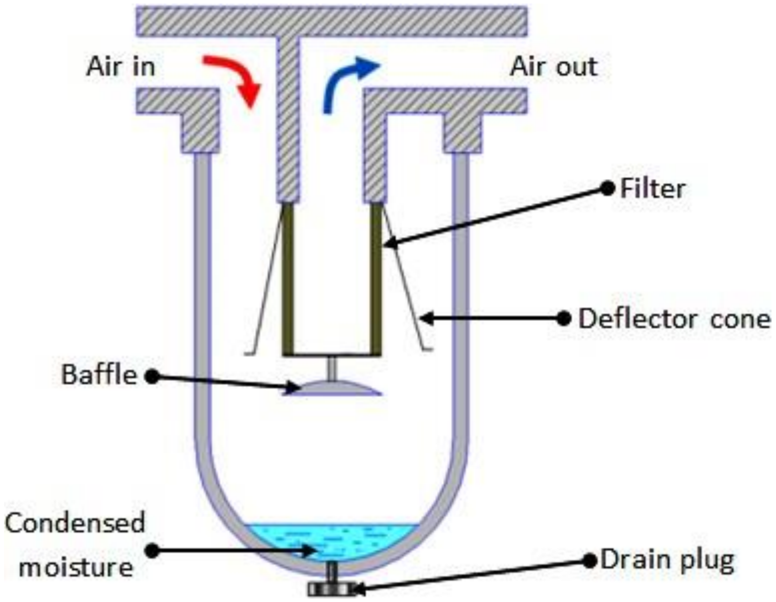

Fig. 6.3.2 Air filter and water trap

The filter cartridge is made of sintered brass. The schematic of the filter is shown in Fig. 6.3.2. The thickness of sintered cartridge provides random zigzag passage for the air to flow-in which helps in arresting the solid particles. The air entering the filter swirls around due to the deflector cone. The centrifugal action causes the large contaminants and water vapor to be flung out, which hit the glass bowl and get collected at the bottom. A baffle plate is provided to prevent the turbulent air from splashing the water into the filter cartridge. At the bottom of the filter bowl there is a drain plug which can be opened manually to drain off the settled water and solid particles.

2.2 Refrigerated dryers

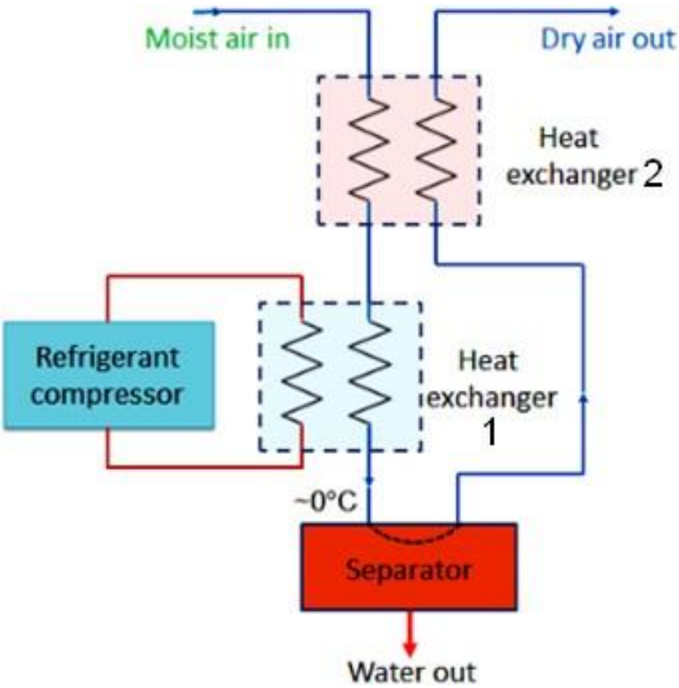

Fig. 6.3.3 Refrigerated dryers

It consists of two heat exchangers, refrigerant compressor and a separator. The system circuitry is shown in Figure 6.3.3. The dryer chills the air just above 0 °C which condenses the water vapor. The condensate is collected by the separator. However such low temperature air may not be needed at the application. Therefore this chilled air is used to cool the high temperature air coming out from the compressor at heat exchanger 2. The moderate temperature dry air coming out from the heat exchanger 2 is then used for actual application; whilst the reduced temperature air from compressor will further be cooled at heat exchanger 1. Thus, the efficiency of the system is increased by employing a second heat exchanger.

2.3 Chemical dryers

When absolute dry air is needed chemical dryers are used. These dryers are of two types viz. adsorption dryer and absorption dryer.

2.3.1 Adsorption dryers

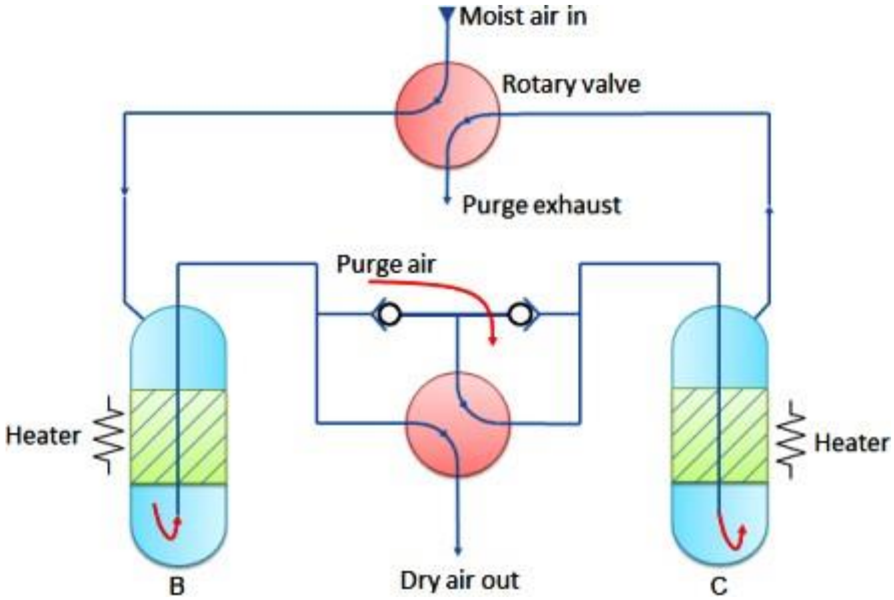

Fig. 6.3.4 Adsorption dryer

In Adsorption dryers, the moisture collects on the sharp edges of the granular material. The adsorbing materials can be silicon dioxide (silica gel) or other materials which exist in hydrated and dehydrated state (copper sulphate, activated alumina). Moisture from the adsorbing material can be released by heating in the column as shown in Fig. 6.3.4. At a given time, one column will dry the air while the other column will regenerate the adsorption material by heating and passing low purge air. The column B dries the air and column C regenerates. The rotary valves are opened using time clock at regular interval to reverse the process. These dryers are also called regenerative dryers.

2.3.2 Absorption dryers

These are also called as deliquescent dryers. Figure 6.3.5 shows a schematic of the same. It uses chemical agents like phosphoric pentoxide or calcium chloride as drying agents. The moisture in the compressed air chemically reacts with the drying agent. The agent dissolves to form a liquid compound which collects at the bottom of the dryer where it can be drained out. The deliquescent agent has to be replenished regularly as it gets consumed during the drying process.

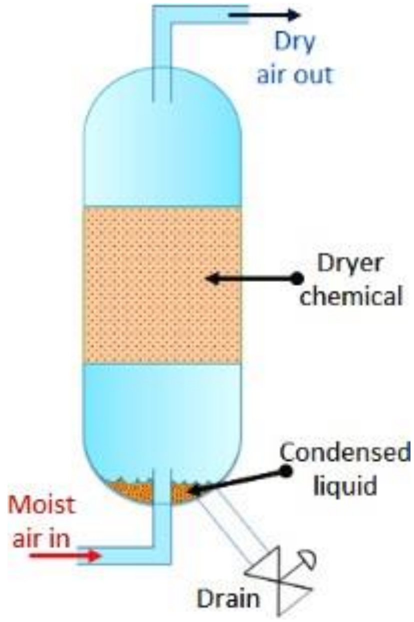

Fig. 6.3.5 Absorption dryer

3. *Lubricators*

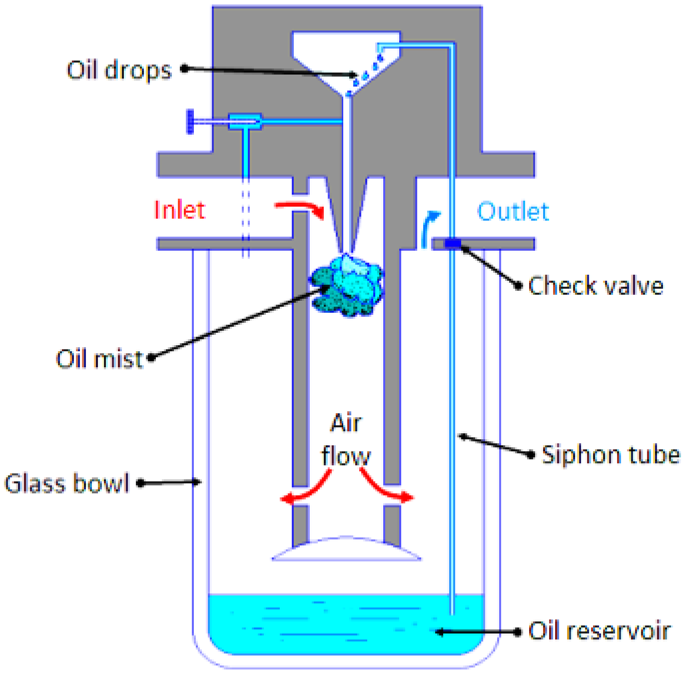

Fig. 6.3.6 Air lubricator

The compressed air is first filtered and then passed through a lubricator in order to form a mist of oil and air to provide lubrication to the mating components. Figure 6.3.6 shows the schematic of a typical lubricator. The principle of working of venturimeter is followed in the operation of lubricator. The compressed air from the dryer enters in the lubricator. Its velocity increases due to a pressure differential between the upper and lower changer (oil reservoir). Due to the low pressure in the upper chamber the oil is pushed into the upper chamber from the oil reservoir through a siphon tube with check valve. The main function of the valve is to control the amount of oil passing through it. The oil drops inside the throttled zone where the velocity of air is much higher and this high velocity air breaks the oil drops into tiny particles. Thus a mist of air and oil is generated. The pressure differential across chambers is adjusted by a needle valve. It is difficult to hold an oil mixed air in the air receiver as oil may settle down. Thus air is lubricated during secondary air treatment process. Low viscosity oil forms better mist than high viscosity oil and hence ensures that oil is always present in the air.

4. *Pressure regulation*

In pneumatic systems, during high velocity compressed air flow, there is flow-dependent pressure drop between the receiver and load (application). Therefore the pressure in the receiver is always kept higher than the system pressure. At the application site, the pressure is regulated to keep it constant. There are three ways to control the local pressure, these are shown in Figure 6.3.7.

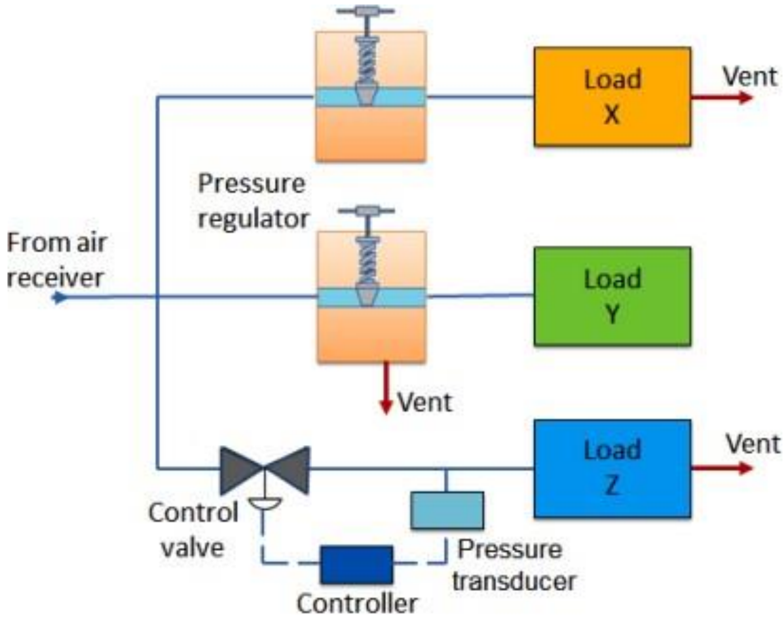

Fig. 6.3.7 Types of pressure regulation

- In the first method, load X vents the air into atmosphere continuously. The pressure regulator restricts the air flow to the load, thus controlling the air pressure. In this type of pressure regulation, some minimum flow is required to operate the regulator. If the load is a dead end type which draws no air, the pressure in the receiver will rise to the manifold pressure. These type of regulators are called as 'non-relieving regulators', since the air must pass through the load.

- In the second type, load Y is a dead end load. However the regulator vents the air into atmosphere to reduce the pressure. This type of regulator is called as 'relieving regulator'.

- The third type of regulator has a very large load Z. Therefore its requirement of air volume is very high and can't be fulfilled by using a simple regulator. In such cases, a control loop comprising of pressure transducer, controller and vent valve is used. Due to large load the system pressure may rise above its critical value. It is detected by a transducer. Then the signal will be processed by the controller which will direct the valve to be opened to vent out the air. This technique can be also be used when it is difficult to mount the pressure regulating valve close to the point where pressure regulation is needed.

5. *Relief valve*

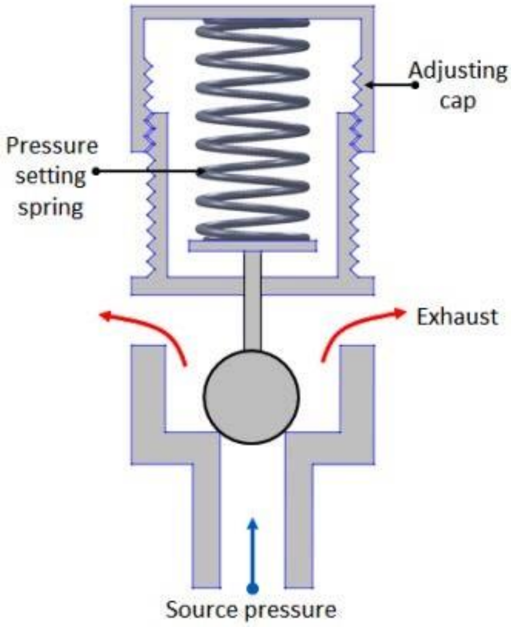

Fig. 6.3.8 Relief valve

Relief valve is the simplest type of pressure regulating device. The schematic of its construction and working is shown in the Figure 6.3.8. It is used as a backup device if the main pressure control fails. It consists of ball type valve held on to the valve seat by a spring in tension. The spring tension can be adjusted by using the adjusting cap. When the air pressure exceeds the spring tension pressure the ball is displaced from its seat, thus releasing the air and reducing the pressure. A relief is specified by its span of pressure between the cracking and full flow, pressure range and flow rate. Once the valve opens (cracking pressure), flow rate depends on the excess pressure. Once the pressure falls below the cracking pressure, the valve seals itself.

6. Non-relieving pressure regulator

In a non-relieving pressure regulator (Fig. 6.3.9) the outlet pressure is sensed by a diaphragm which is preloaded by a pressure setting spring. If outlet pressure is too low, the spring forces the diaphragm and poppet to move down thus opening the valve to admit more air and raise outlet pressure. If the outlet pressure is too high the air pressure forces the diaphragm up hence reduces the air flow and causing a reduction in air pressure. The air vents away through the load. At steady state condition the valve will balance the force on the diaphragm from the outlet pressure with the preset force on the spring.

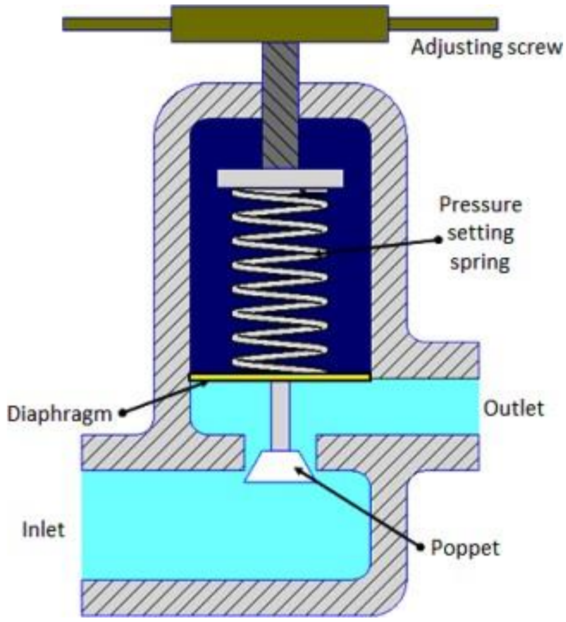

Fig. 6.3.9 Non-relieving type pressure regulator

7. Service units

During the preparation of compressed air, various processes such as filtration, regulation and lubrication are carried out by individual components. The individual components are: separator/filter, pressure regulator and lubricator.

Preparatory functions can be combined into one unit which is called as 'service unit'. Figure 6.3.10 shows symbolic representation of various processes involved in air preparation and the service unit.

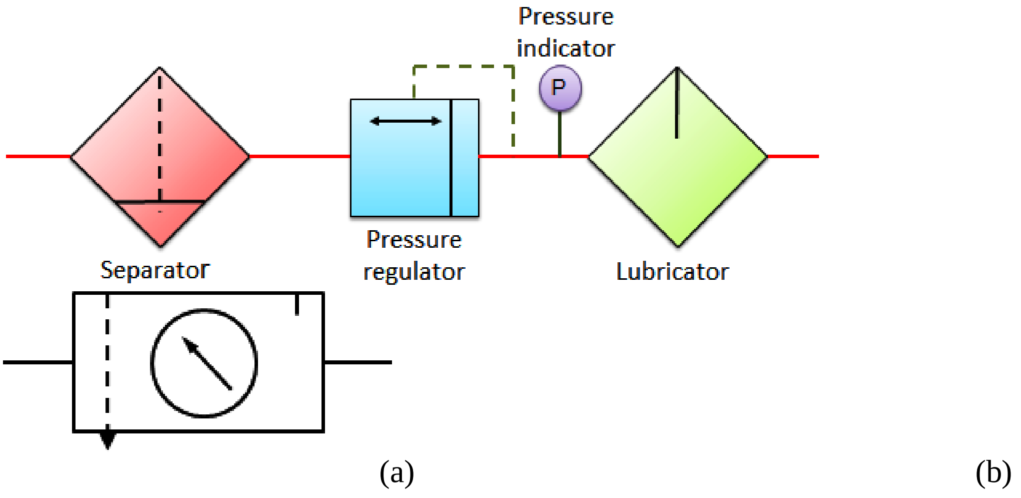

Fig. 6.3.10 (a) Service unit components (b) Service unit symbol

Module 6: Pneumatic Systems

Lecture 4
Actuators

Actuators are output devices which convert energy from pressurized hydraulic oil or compressed air into the required type of action or motion. In general, hydraulic or pneumatic systems are used for gripping and/or moving operations in industry. These operations are carried out by using actuators.

Actuators can be classified into three types.

1. Linear actuators: These devices convert hydraulic/pneumatic energy into linear motion.
2. Rotary actuators: These devices convert hydraulic/pneumatic energy into rotary motion.
3. Actuators to operate flow control valves: these are used to control the flow and pressure of fluids such as gases, steam or liquid.

The construction of hydraulic and pneumatic linear actuators is similar. However they differ at their operating pressure ranges. Typical pressure of hydraulic cylinders is about 100 bar and of pneumatic system is around 10 bar.

1. Single acting cylinder

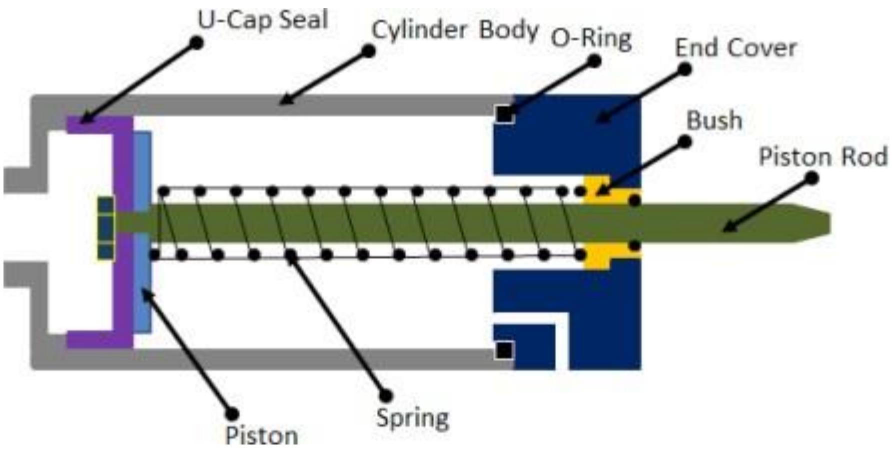

Fig. 6.4.1 Single acting cylinder

These cylinders produce work in one direction of motion hence they are named as single acting cylinders. Figure 6.4.1 shows the construction of a single acting cylinder. The compressed air pushes the piston located in the cylindrical barrel causing the desired motion. The return stroke takes place by the action of a spring. Generally the spring is provided on the rod side of the cylinder.

2. *Double acting cylinder*

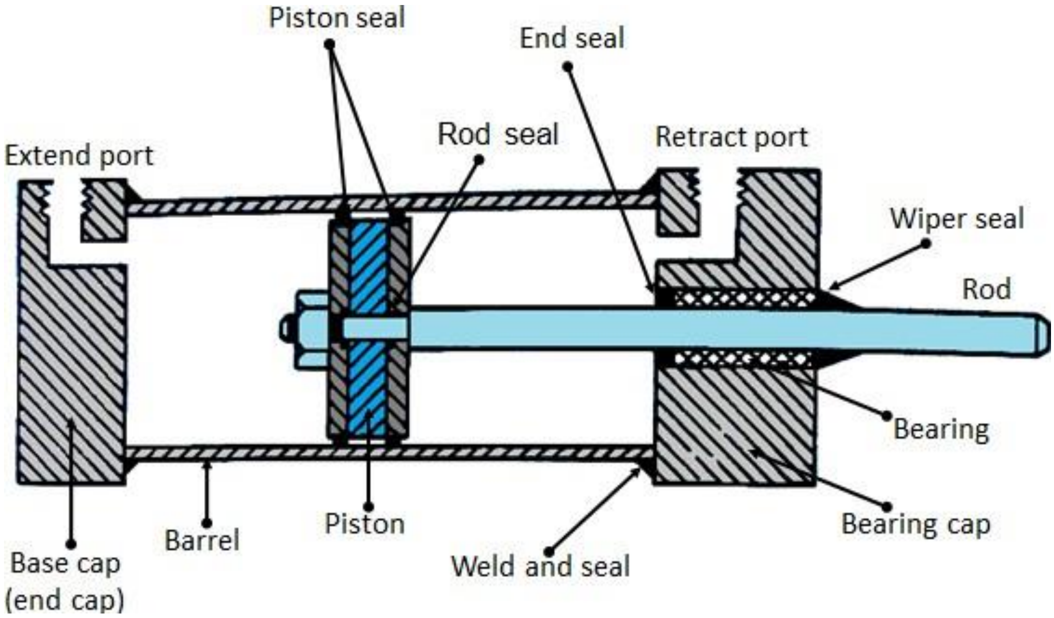

Fig. 6.4.2 Double acting cylinder

The main parts of a hydraulic double acting cylinder are: piston, piston rod, cylinder tube, and end caps. These are shown in Figure 6.4.2. The piston rod is connected to piston head and the other end extends out of the cylinder. The piston divides the cylinder into two chambers namely the rod end side and piston end side. The seals prevent the leakage of oil between these two chambers. The cylindrical tube is fitted with end caps. The pressurized oil, air enters the cylinder chamber through the ports provided. In the rod end cover plate, a wiper seal is provided to prevent the leakage of oil and entry of the contaminants into the cylinder. The combination of wiper seal, bearing and sealing ring is called as cartridge assembly. The end caps may be attached to the tube by threaded connection, welded connection or tie rod connection. The piston seal prevents metal to metal contact and wear of piston head and the tube. These seals are replaceable. End cushioning is also provided to prevent the impact with end caps.

3. Cylinder end cushions

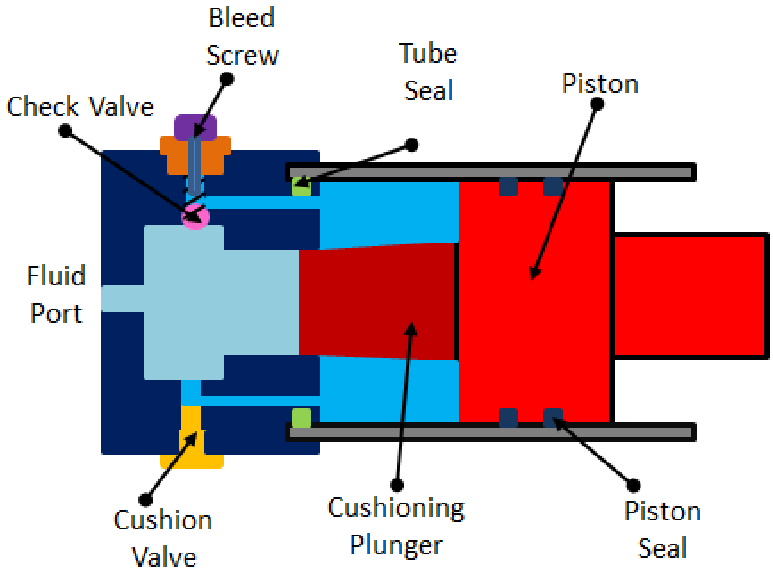

Fig. 6.4.3 Cylinder end cushioning

Double acting cylinders generally contain cylinder cushions at the end of the cylinder to slow down the movement of the piston near the end of the stroke. Figure 6.4.3 shows the construction of actuating cylinder with end cushions. Cushioning arrangement avoids the damage due to the impact occurred when a fast moving piston is stopped by the end caps. Deceleration of the piston starts when the tapered plunger enters the opening in the cap and closes the main fluid exit. This restricts the exhaust flow from the barrel to the port. This throttling causes the initial speed reduction. During the last portion of the stroke the oil has to exhaust through an adjustable opening since main fluid exit closes. Thus the remaining fluid exists through the cushioning valve. Amount of cushioning can be adjusted by means of cushion screw. A check valve is provided to achieve fast break away from the end position during retraction motion. A bleed screw is built into the check valve to remove the air bubbles present in a hydraulic type system.

4. Gear motor: a rotary actuator

Rotary actuators convert energy of pressurized fluid into rotary motion. Rotary actuators are similar to electric motors but are run on hydraulic or pneumatic power.

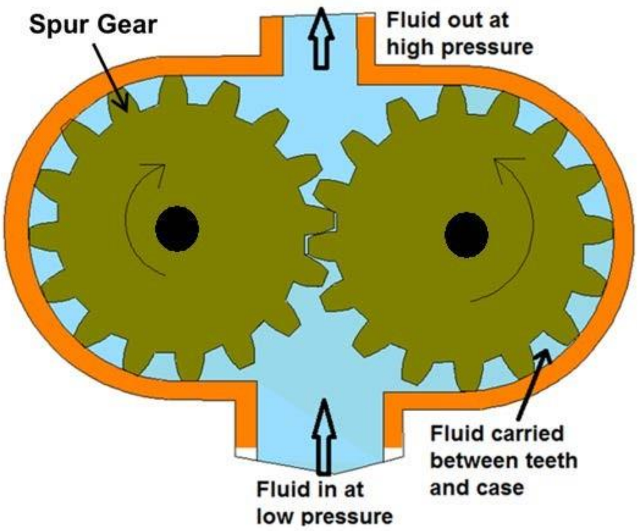

Fig. 6.4.4 Gear motor

It consists of two inter meshing gears inside a housing with one gear attached to the drive shaft. Figure 6.4.4 shows a schematic diagram of Gear motor. The air enters from the inlet, causes the rotation of the meshing gear due to difference in the pressure and produces the torque. The air exists from the exhaust port. Gear motors tend to leak at low speed, hence are generally used for medium speed applications.

5. Vane motor: a rotary actuator

A rotary vane motor consists of a rotor with sliding vanes in the slots provided on the rotor (Fig. 6.4.5). The rotor is placed eccentrically with the housing. Air enters from the inlet port, rotates the rotor and thus torque is produced. Air is then released from the exhaust port (outlet).

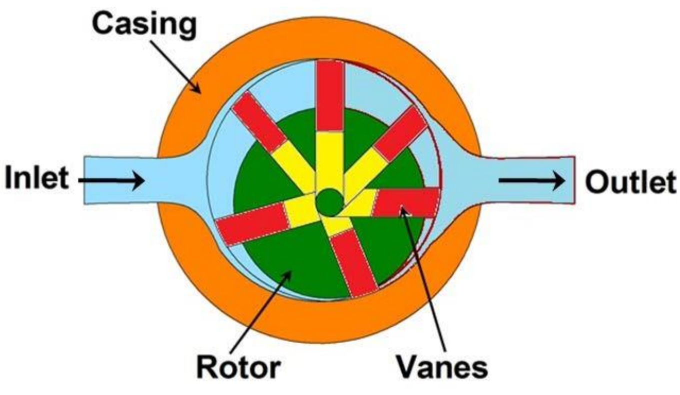

Fig. 6.4.5 Vane motor

6. *Limited rotation actuators*

It consists of a single rotating vane connected to output shaft as shown in Figure 6.4.6. It is used for double acting operation and has a maximum angle of rotation of about 270°. These are generally used to actuate dampers in robotics and material handling applications. Other type of limited rotation actuator is a rack and pinion type actuator.

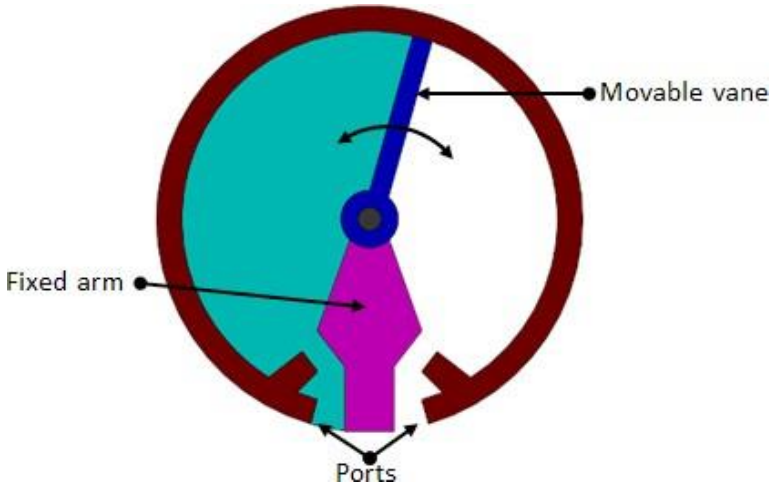

Fig. 6.4.6 Semi rotary vane type actuator

7. *Speed control*

For an actuator, the operational speed is determined by the fluid flow rate and the cylinder actuator area or the motor displacement. The speed can only be controlled by adjusting the fluid flow to the actuator, because the physical dimension of the actuator is fixed. Since the air is compressible, flow control is difficult as compared to the hydraulic system. There are various ways of controlling the fluid flow. One of the methods is discussed as below-

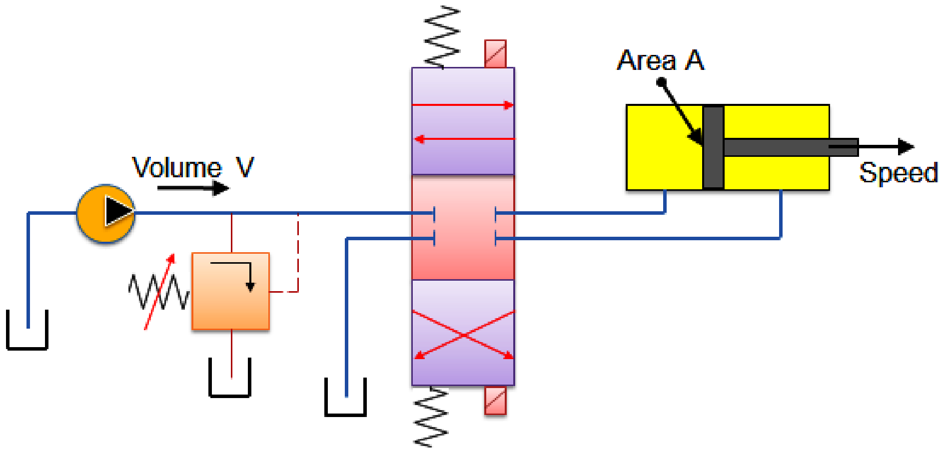

Fig. 6.4.7 Speed control by pump volume

Figure 6.4.7 shows the circuit diagram of hydraulic system developed to control the speed of motion of a piston. Consider a pump which delivers a fluid volume of '*V*' per minute. The pump has a fixed displacement. The volume of fluid goes either to the pump or to the actuator. When the direction control valve moves from its center position the actuator of area '*A*', the piston moves with a velocity,

$$v = \frac{V}{A} \tag{6.4.1}$$

If the pump delivery volume 'V' can be adjusted by altering swash plate angle of a piston pump or by using a variable displacement vane pump, no further speed control will be needed.

Module 6: Pneumatic Systems
Lecture 5
Pneumatic controllers

In automated industrial processes, it is always essential to keep the process variables such as temperature, flow rate, system pressure, fluid level, etc. at the desired value for safety and economical operation. Consider an example where the flow of water through a pipe has to be kept constant at some predetermined value (Fig. 6.5.1). Let the value of flow to be measured is 'V' (process variable PV). This flow rate is compared with the required flow value say 'V_1' (set point SP). The difference between these two values is the error which is sent to the controller. If any error exists, the controller adjusts the drive signal to the actuator, informing it to move the valve to give the required flow (zero error). This type of control system is called closed loop control system. It mainly includes a controller, actuator and a measuring device.

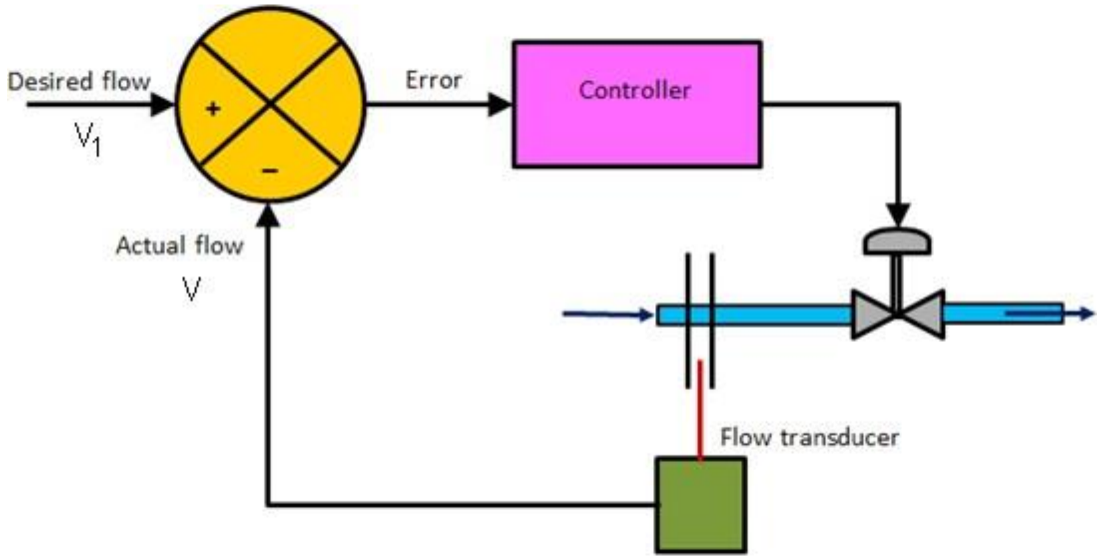

Fig. 6.5.1 Closed loop control system

The control can be achieved by using control electronics or by pneumatic process control. The pneumatic systems are quite popular because they are safe. In the process industries like refinery and chemical plants, the atmosphere is explosive. Application of electronics based systems may be dangerous in such cases. Since the pneumatic systems use air, there are very scant chances of any fire hazards. Even though electrical actuators are available, but most of the valves employed are driven by pneumatic signals.

1. Components of a pneumatic controller

- Flapper nozzle amplifier
- Air relay
- Bellows
- Springs
- Feedback arrangements

1.1 Flapper nozzle amplifier

A pneumatic control system operates with air. The signal is transmitted in the form of variable air pressure (often in the range of 0.2 to 1.0 bar (3-15 psi)) that initiates the control action. One of the basic building blocks of a pneumatic control system is the flapper nozzle amplifier. It converts very small displacement signal (in order of microns) to variation of air pressure. The basic construction of a flapper nozzle amplifier is shown in Figure 6.5.2

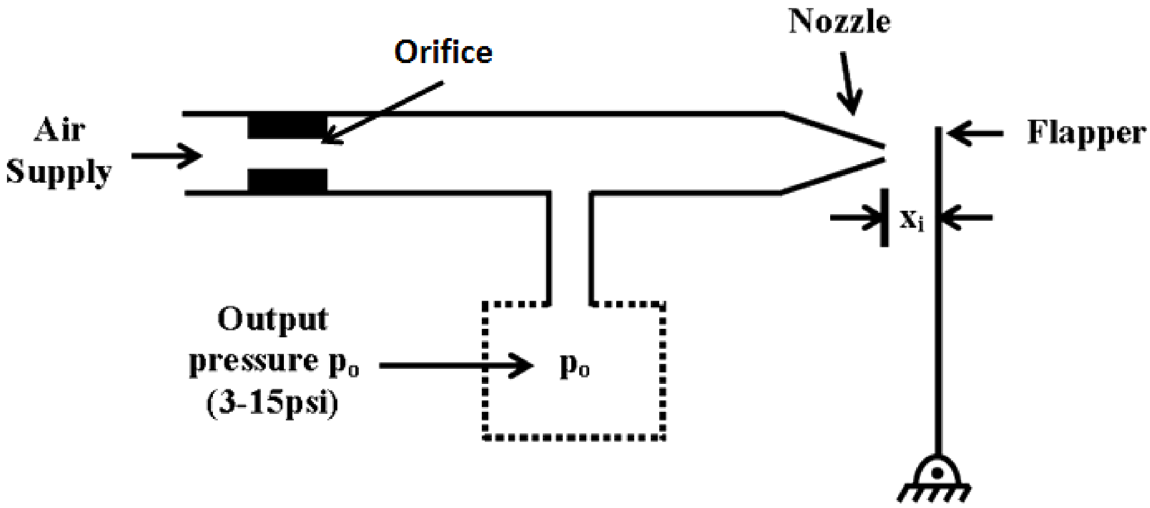

Fig 6.5.2 Nozzle flapper amplifier

Constant air pressure is supplied to one end of the pipeline. There is an orifice at this end. At the other end of the pipe, there is a nozzle and a flapper. The gap between the nozzle and the flapper is set by the input signal. As the flapper moves closer to the nozzle, there will be less airflow through the nozzle and the air pressure inside the pipe will increase. On the other hand, if the flapper moves further away from the nozzle, the air pressure decreases. At the extreme, if the nozzle is open (flapper is far off), the output pressure will be equal to the atmospheric pressure. If the nozzle is blocked, the output pressure will be equal to the supply pressure.

1.2 Air Relay

The major limitation of a flapper nozzle amplifier is its limited air handling capacity. The variation of air pressure obtained cannot be used for any useful application, unless the air handling capacity is increased. It is used after the flapper nozzle amplifier to enhance the volume of air to be handled. The principle of operation of an air relay can be explained using the schematic diagram shown in Figure 6.5.3. It can be seen that the air relay is directly connected to the supply line (no orifice in between). The output pressure of the flapper nozzle amplifier (p_2) is connected to the lower chamber of the air relay with a diaphragm on its top. The variation of the pressure p_2 causes the movement (y) of the diaphragm. There is a double-seated valve fixed on the top of the diaphragm. When the nozzle pressure p_2 increases due to decrees in x_i, the diaphragm moves up, blocking the air vent line and forming a nozzle between the output pressure line and the supply air pressure line. More air goes to the output line and the air pressure increases. When p_2 decreases, the diaphragm moves downwards, thus blocking the air supply line and connecting the output port to the vent. The air pressure will decrease.

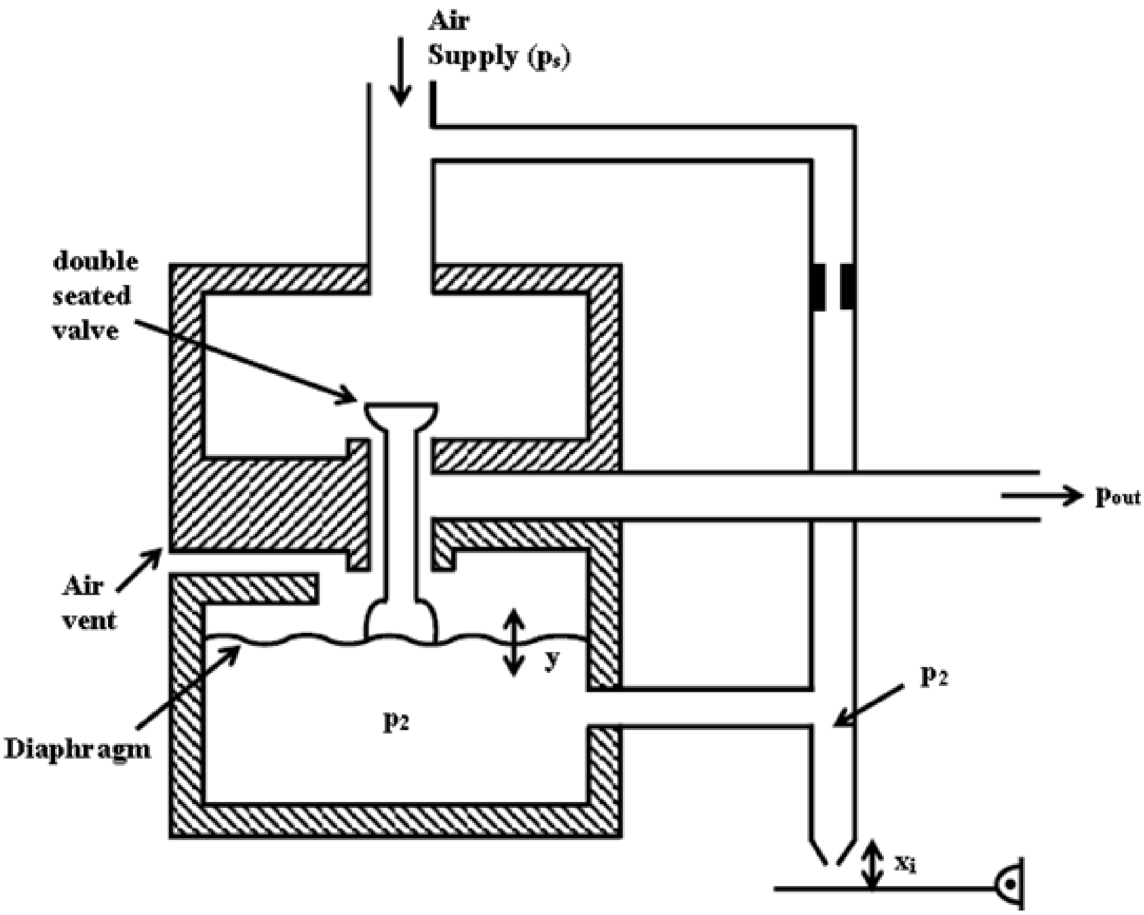

Fig 6.5.3 Air relay

2. Types of pneumatic controllers

Following is the list of variants of pneumatic controllers.

- Proportional only (P) controller
- Proportional-Derivative (PD) controller
- Proportional-Integral (PI) controller
- Proportional-Integral-Derivative (PID) controller

2.1 Proportional only (P) controller

The simplest form of pneumatic controller is proportional only controller. Figure 6.5.4 shows the pneumatic circuit of 'proportional only' controller. The output signal is the product of error signal multiplied by a gain (K).

$$\text{Output} = (\text{Error} * \text{gain}) \quad (6.5.1)$$

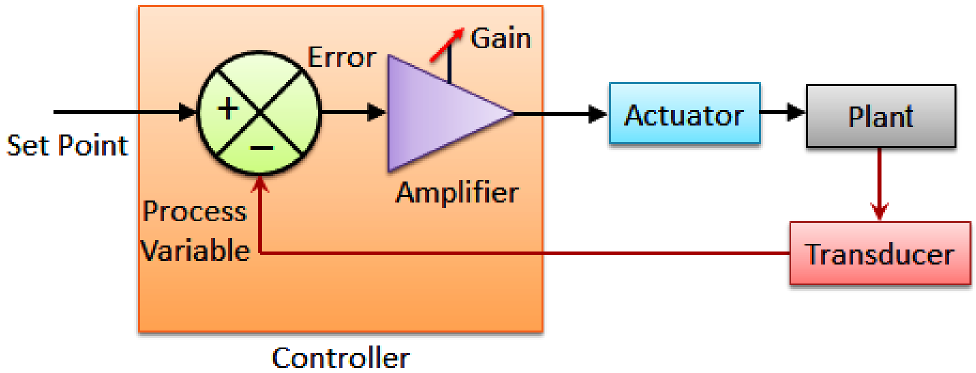

Fig. 6.5.4 Proportional only controller

Consider the pneumatic system consisting of several pneumatic components, viz. flapper nozzle amplifier, air relay, bellows and springs, feedback arrangement. The overall arrangement is known as a pneumatic proportional controller as shown in Figure 6.5.5.

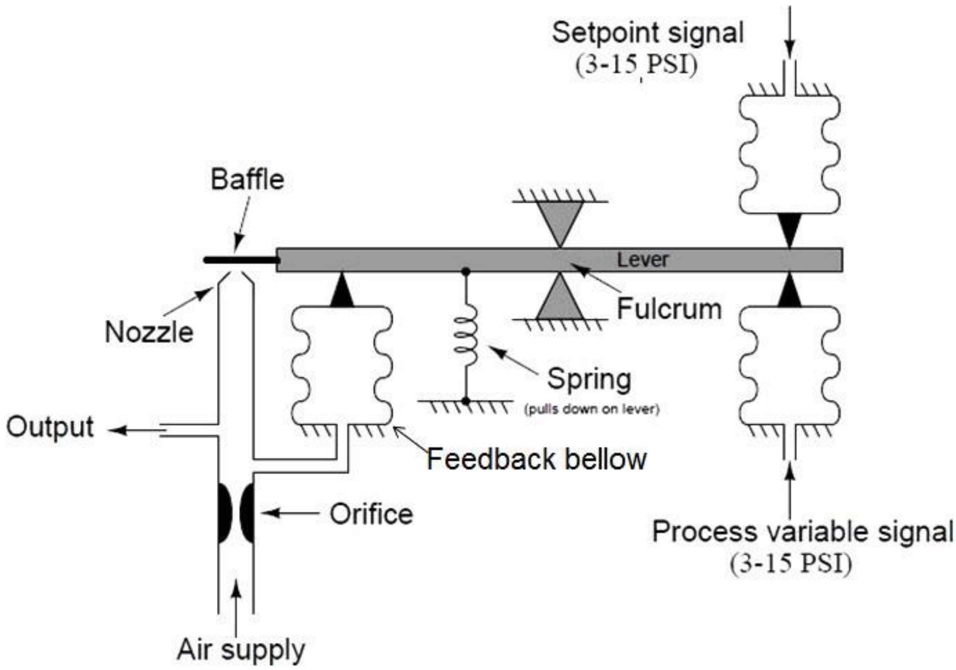

Fig 6.5.5 Proportional only (P) controller elements

It acts as a controller in a pneumatic system generating output pressure proportional to the displacement at one end of the beam. The action of this particular controller is direct, since an increase in process variable signal (pressure) results in an increase in output signal (pressure). Increasing process variable (PV) pressure attempts to push the right-hand end of the beam up, causing the baffle to approach the nozzle. This blockage of the nozzle causes the nozzle's pneumatic backpressure to increase, thus increasing the amount of force applied by the output feedback bellows on the left-hand end of the beam and returning the flapper (very nearly) to its original position. If we wish to reverse the controller's action, we need to swap the pneumatic signal connections between the input bellows, so that the PV pressure will be applied to the upper bellows and the SP pressure to the lower bellows. The ratio of input pressure(s) to output pressure is termed as a gain (proportional band) adjustment in this mechanism. Changing bellows area (either both the PV and SP bellows equally, and the output bellows by itself) influences this ratio. Gain also affects by the change in output bellows position. Moving the fulcrum left or right can be used to control the gain, and in fact is usually the most convenient to engineer.

2.2 Proportional-Derivative (PD) controller

A proportional-derivative (PD) controller is shown in Figure 6.5.6. To add derivative control action to a P-only controller, all we need to place a restrictor valve between the nozzle tube and the output feedback bellows, causing the bellows to delay filling or emptying its air pressure over time.

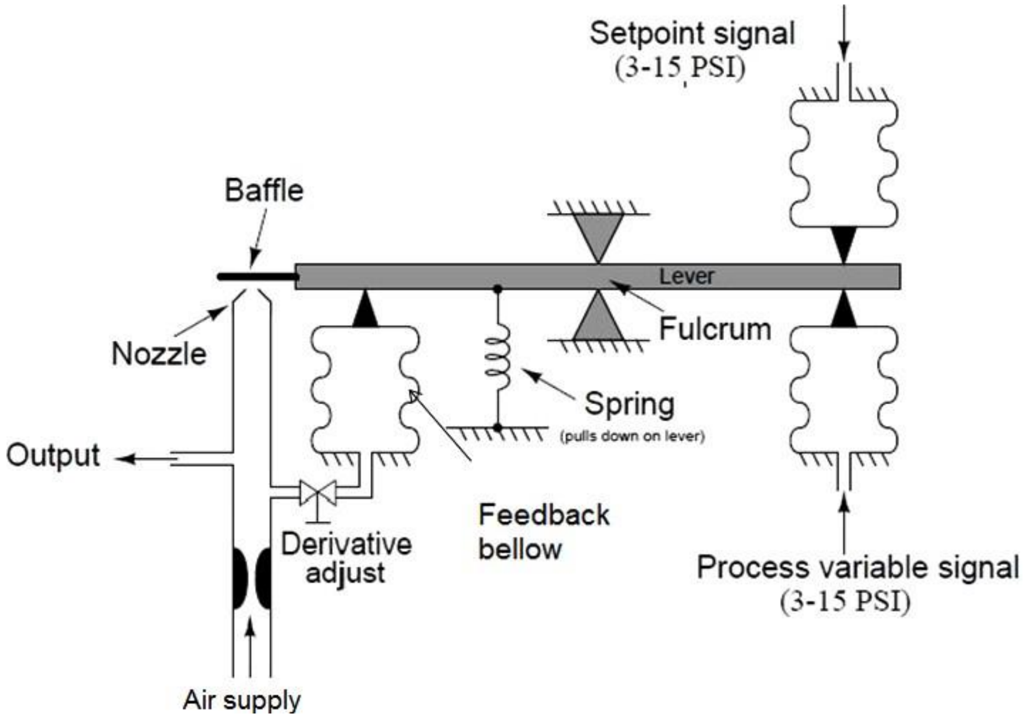

Fig 6.5.6 Proportional-Derivative (PD) controller

If any sudden change occurs in PV or SP, the output pressure will saturate before the output bellows has the opportunity to equalize in pressure with the output signal tube. Thus, the output pressure “spikes” with any sudden “step change” in input: exactly what we would expect with derivative control action. If either the PV or the SP ramps over time, the output signal will ramp in direct proportion (proportional action). But there will be an added offset of pressure at the output signal in order to keep air flowing either in or out of the output bellows at a constant rate to generate the necessary force to balance the changing input signal. Thus, derivative action causes the output pressure to shift either up or down (depending on the direction of input change) more than it would with just proportional action alone in response to a ramping input.

2.3 Proportional-Integral (PI) controller

In some systems, if the gain is too large the system may become unstable. In these circumstances the basic controller can be modified by adding the time integral of the error to control the operation (Fig 6.5.7). Thus the output can be given by an equation,

$$OP = K\left(error + \frac{1}{T_i}\int error\, dt\right) \quad (6.5.2)$$

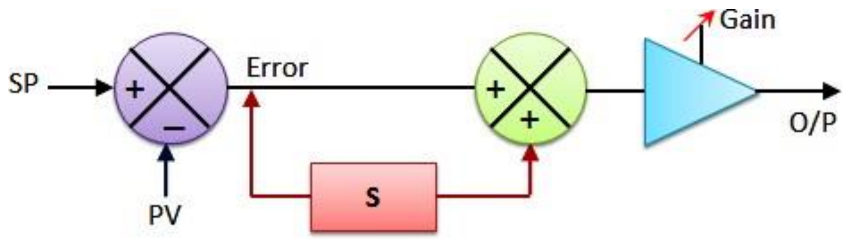

Fig. 6.5.7 Block diagram of P-I controller

The T_i is a constant called integral time. As long as there is an error the output of the controller steps up or down as per the rate determined by T_i. If there is no error then the output of the controller remains constant. The integral term in the above equation removes any offset error.

Figure 6.5.8 shows the configuration of pneumatic proportional plus integral controller. Integral action requires the addition of a second bellows (a “reset” bellows, positioned opposite the output feedback bellows) and another restrictor valve to the mechanism.

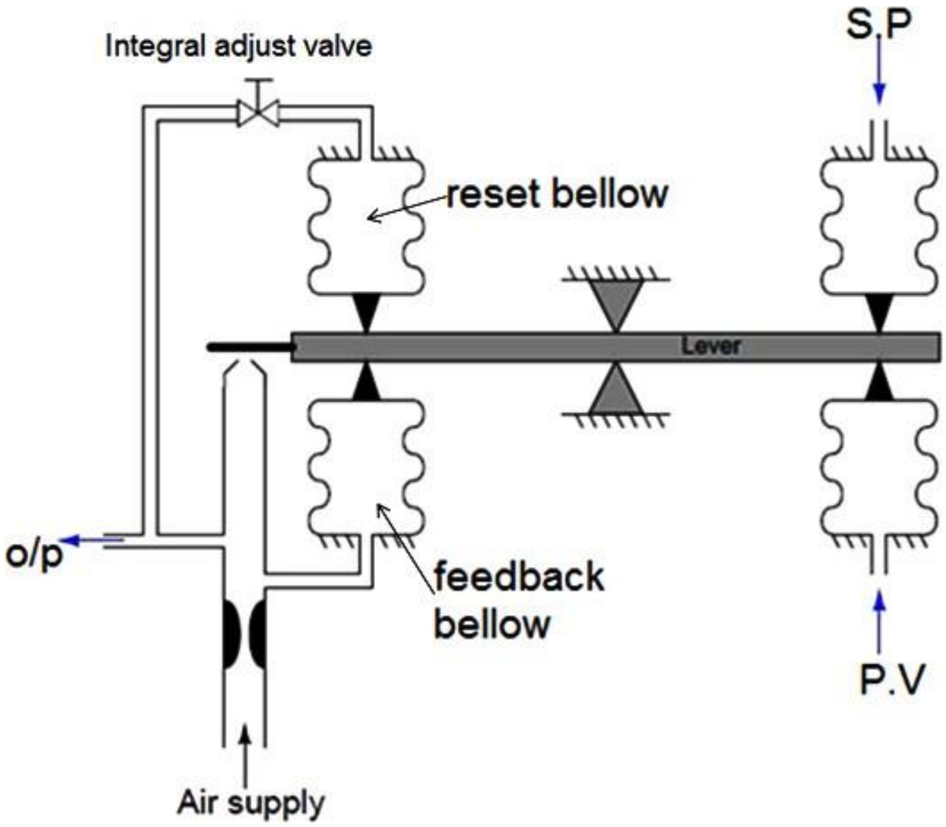

Fig. 6.5.8 Proportional-Integral (P-I) controller

As the reset bellows fills with pressurized air, it begins to push down the left-hand end of the force beam. This forces the baffle closer to the nozzle, causing the output pressure to rise. The regular output bellows has no restrictor valve to impede its filling, and so it immediately applies more upward force on the beam with the rising output pressure. With this greater output pressure, the reset bellows has an even greater “final” pressure to achieve, and so its rate of filling continues.

2.4 Proportional-Integral-Derivative (PID) controller

Three term pneumatic control can be achieved using a P-I-D controller. Here the action of the feedback bellows is delayed. The output is given by,

$$OP = K\left(error + \frac{1}{T_i}\int error\,dt + T_d\frac{d\,error}{dt}\right)$$

(6.5.3)

The terms gain K, derivative time T_d, integral time T_i which can be set by beam pivot point and two bleed valves (Fig. 6.5.9). This is a combination of all the three controllers described above. Hence it combines the advantages of all three. A derivative control valve is added to delay the response at feedback bellow. Addition of derivative term makes the control system to change the control output quickly when SP and PV are changing quickly. This makes the system more stable.

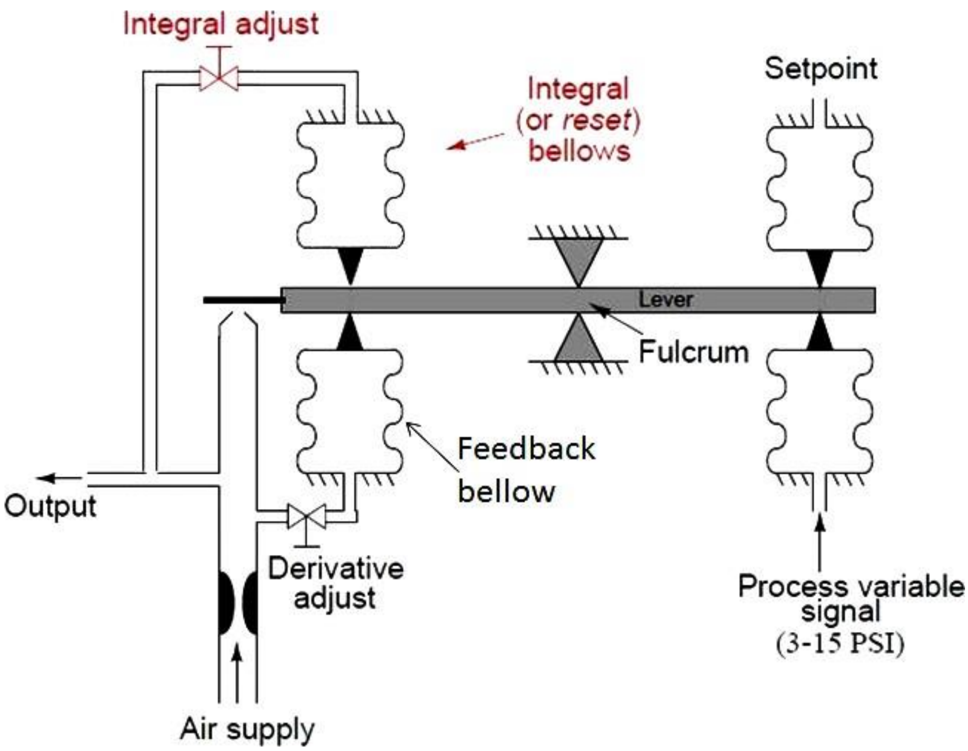

Fig. 6.5.9 Proportional-Integral-Derivative (P-I-D) controller

Advantages of pneumatic controllers

- Simplicity of the components and no complex structure
- Easy maintainability
- Safe and can be used in hazardous atmospheres
- Low cost of installation
- Good reliability and reproducibility
- Speed of response is relatively slow but steady
- Limited power capacity for large mass transfer

Limitations of pneumatic controllers

- Slow response
- Difficult to operate in sub-normal temperatures
- Pipe-couplings can give rise to leaks in certain ambient conditions
- Moving parts - more maintenance

Module 6: Pneumatic Systems
Lecture 6
Applications of pneumatic systems

In this section we will study the application of various pneumatic components in designing a pneumatic circuit. The graphical symbols of pneumatic components and equipments have already been discussed in lecture 7 of module 5.

1. Case study A

Consider a simple operation where a double-acting cylinder is used to transfer parts from a magazine. The cylinder is to be advanced either by operating a push button or by a foot pedal. Once the cylinder is fully advanced, it is to be retracted to its initial position. A 3/2-way roller lever valve is to be used to detect the full extension of the cylinder. Design a pneumatic circuit for the above-mentioned application.

1.1 Components used

The pneumatic components which can be used to implement the mentioned task are as follows:

- double acting cylinder
- 3/2 push button valve
- 3/2 roller valve
- shuttle valve
- 3/2 foot pedal actuated valve
- 5/3 pneumatic actuated direction control valve
- compressed air source and connecting piping

1.2 Working

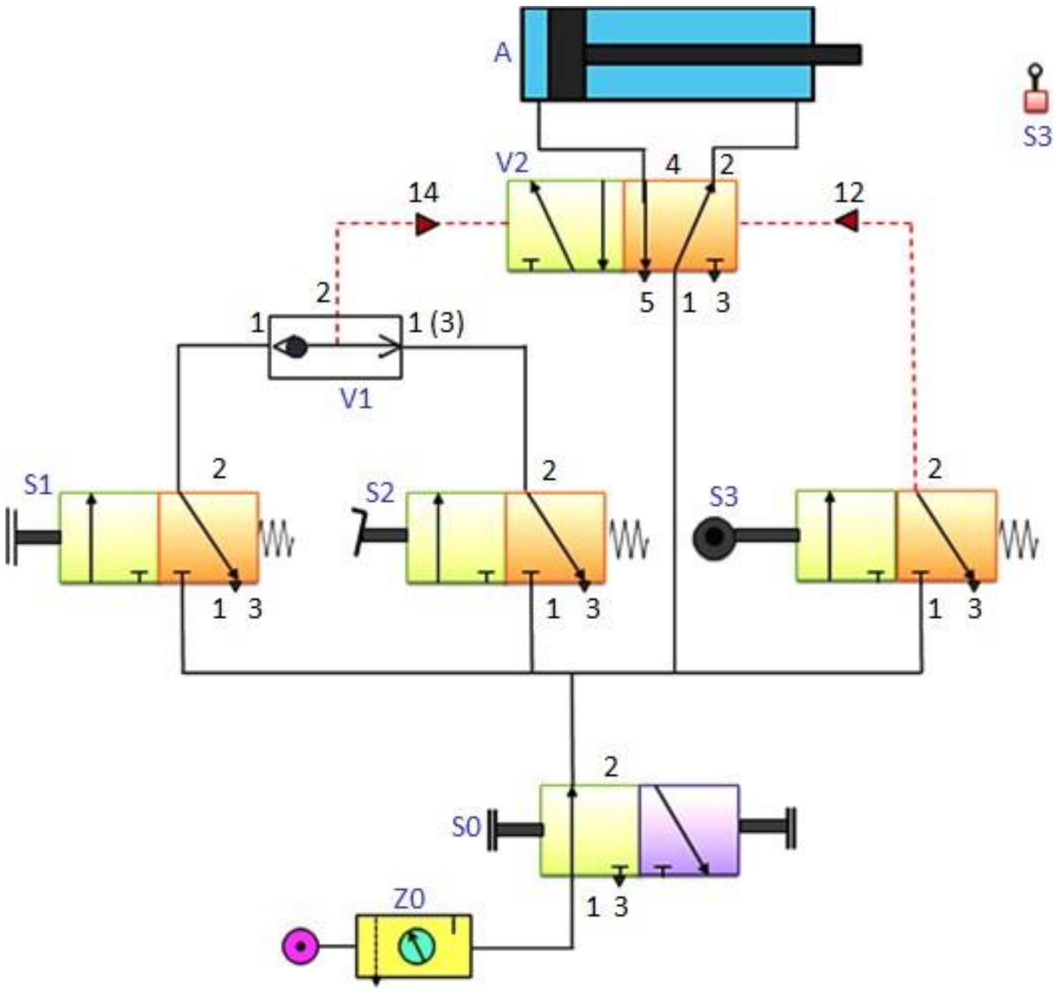

Fig. 6.6.1 Pneumatic circuit for shuttle valve operation

Figure 6.6.1 shows the proposed circuit diagram. As the problem stated, upon actuation of either the push button of valve (S1) or the foot pedal valve (S2), a signal is generated at 1 or 1(3) side of the shuttle valve. The OR condition is met and the signal is passed to the control port 14 of the direction control valve (V2). Due to this signal, the left position of V2 is actuated and the flow of air starts. Pressure is applied on the piston side of the cylinder (A) and the cylinder extends. If the push button or pedal valve is released, the signal at the direction control valve (V2) port is reset. Since DCV (V2) is a double pilot valve, it has a memory function which doesn't allow switching of positions. As the piston reaches the rod end position, the roller valve (S3) is actuated and a signal is applied to port 12 of the DCV (V2). This causes actuation of right side of DCV (V2). Due to this actuation, the flow enters at the rod-end side of the cylinder, which pushes the piston towards left and thus the cylinder retracts.

2. *Case study B*

A plastic component is to be embossed by using a die which is powered by a double acting cylinder. The return of the die is to be effected when the cylinder rod has fully extended to the embossing position and the preset pressure is reached. A roller lever valve is to be used to confirm full extension. The signal for retracting must only be generated when the piston rod has reached the embossing position. The pressure in the piston chamber is indicated by a pressure gauge.

2.1 Components used

The pneumatic components to be used to implement this task are:

- double acting cylinder
- 3/2 push button valve
- 3/2 roller valve
- shuttle valve
- 5/3 pneumatic actuated direction control valve
- pressure sequence valve
- compressed air source
- pressure gauge and connecting piping

2.2 Working

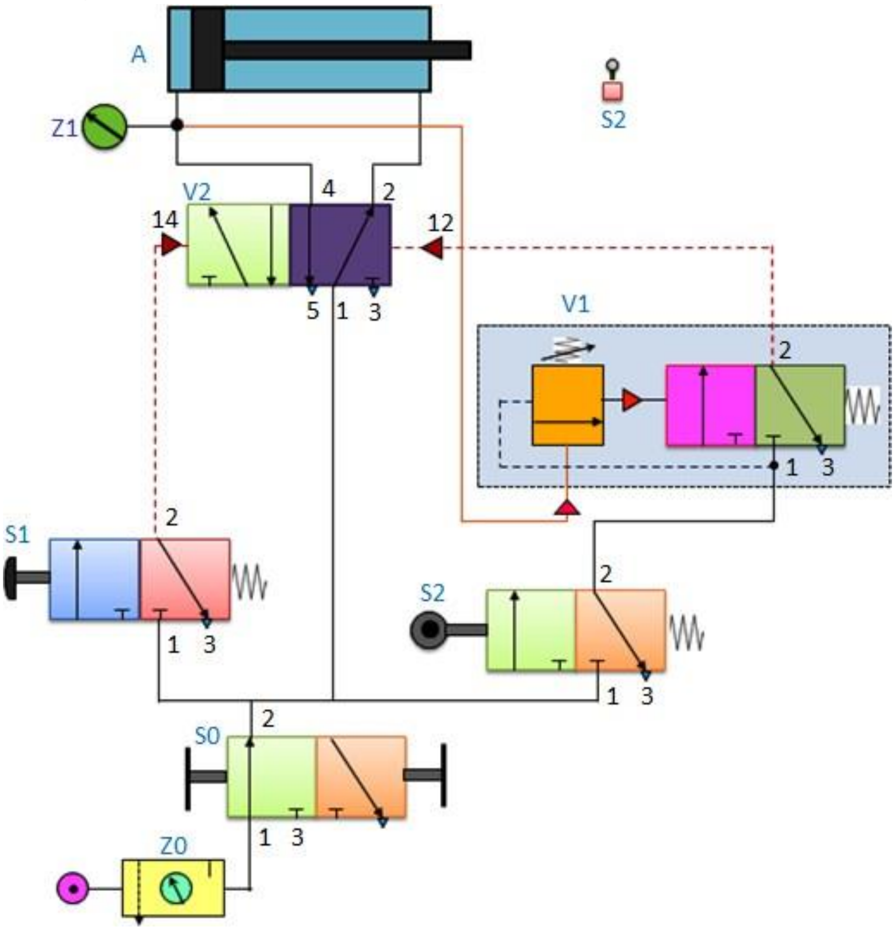

Fig. 6.6.2 Pneumatic circuit for embossing application

The proposed pneumatic circuit diagram for embossing application is shown in fig. 6.6.2. When the push button valve (S1) is pressed, the flow takes place through the valve and a signal is sent to the control port 14 of the direction control valve (V2). The left position of the direction control valve (V2) is switched-on and the flow enters at the piston-end of the cylinder (A). It causes the extension of the cylinder. Even if the push button is released the position of the DCV (V2) will not change due to its memory function. As the piston nears the end position, the roller valve (S2) is actuated and pressure line is connected to the pressure sequence valve (V1). During the embossing process the pressure at the piston-side of the cylinder (A) increases. This increase in pressure is indicated by the pressure regulator (Z1). When the pressure reaches to its pre-set value in the pressure sequence valve (V1), the 3/2 valve of pressure sequence valve switches and the signal is applied to port 12 of the DCV (V2). The right position of the DCV is actuated and the piston retracts. During the retracting movement, the roller valve (S2) is released and the signal at the control port 12 of the DCV (V2) is reset and the pressure sequence valve is also reset.

3. *Case study C*

Sequencing application

In process control applications such as sequencing, the Pneumatics systems are generally employed. Electrical components such as relays, programmable logic controllers are used to control the operations of Pneumatic systems. A simple example of a pneumatic sequencing is shown in Figure 6.6.3.

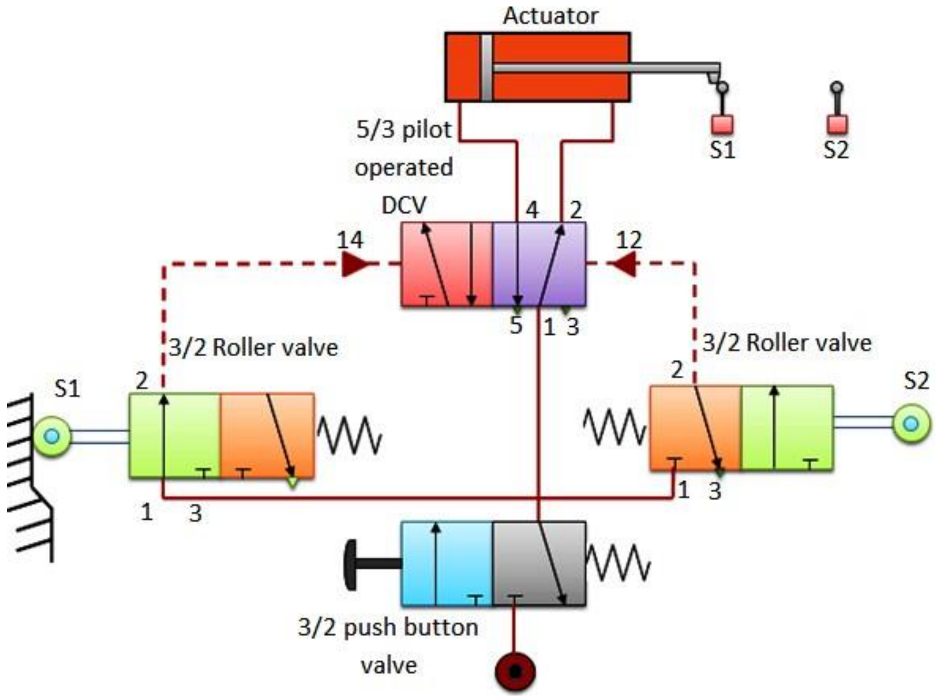

Fig. 6.6.3 Cylinder sequencing- Oscillating cylinder

3.1 Components used

The components used in the circuit are: double acting cylinder, 3/2 roller lever valve, 5/3 pilot operated direction control valve and a 3/2 push button valve. By using this circuit, a continuous to and fro motion of the actuator is obtained.

3.2 Working

When the 3/2 push button is actuated, the air flows from the source through the push button valve to the 3/2 roller valve (S1). The roller valve is already actuated by the cylinder when the piston rod hits the lever of S1. Therefore, there is continuous flow to the 5/3 pilot operated direction control valve (DCV). The flow given to the pilot line 14 actuates the first position of DCV. The air flows from port 1-4 pushes the piston head which causes the extension of the cylinder. As the cylinder fully extends it actuates the 3/2 roller lever valve (S2). The roller valve is actuated and air flows through the valve to the 5/3 DCV. The air enters the DCV through pilot port 12 actuating the second position. Hence the air flows from port 1-2 to the actuator rod end, causing its retraction. The cylinder reciprocates till the supply is stopped. In this way, we can achieve the sequencing operation by controlled actuation of various valves in a pneumatic system.

Module 4 Drives and Mechanisms

Lecture 1

Elements of CNC machine tools: electric motors

1. 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.

2. Power drives

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 stepless 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.

In CNC, usually AC, DC, servo and stepper electrical drives are used. The various drives used in CNC machines can be classified as:

a. Spindle drives to provide the main spindle power for cutting action
b. Feed drives to drive the axis

2.1 Spindle drives

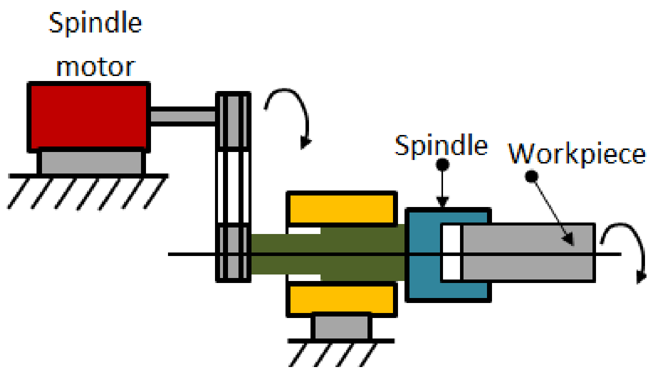

Fig. 4.1.1 Schematic of a spindle drive

The spindle drives are used to provide angular motion to the workpiece or a cutting tool. Figure 4.1.1 shows the components of a spindle drive. 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.

2.2Feed Drives

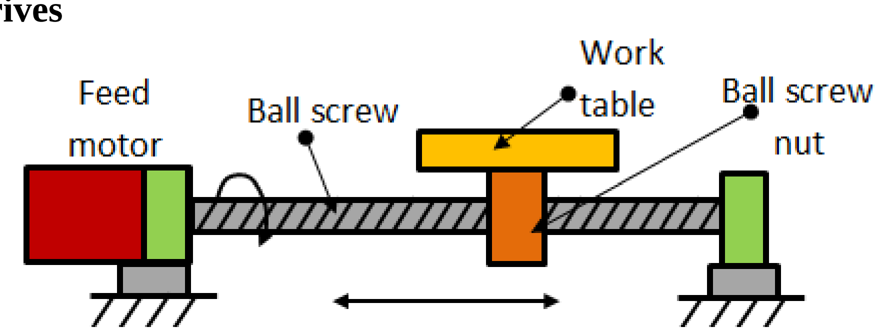

Fig. 4.1.2 Typical feed drive

These are used to drive the slide or a table. Figure 4.1.2 shows various elements of a feed drive. 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.

3. Electrical drives

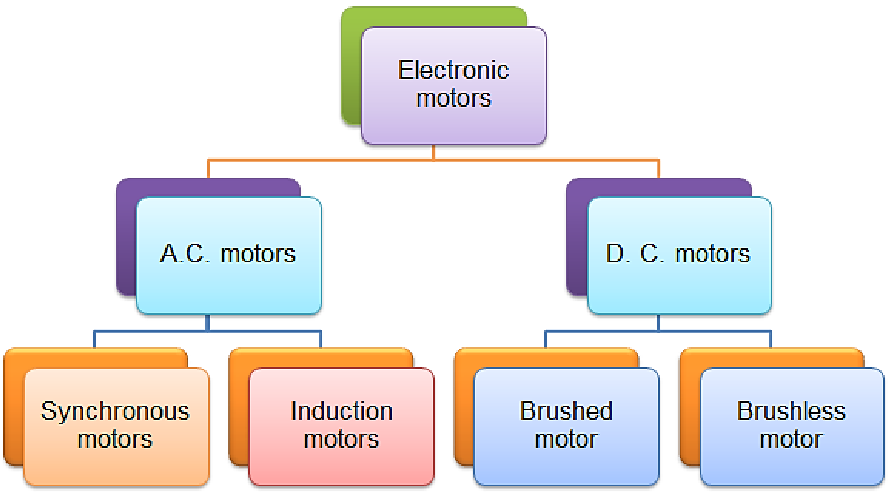

Fig. 4.1.3 Classification of motors

Electric drives are mostly used in position and speed control systems. The motors can be classified into two groups namely DC motors and AC motors (Fig. 4.1.3). In this session we shall study the operation, construction, advantages and limitations of DC and AC motors.

3.1. DC motors

A DC motor is a device that converts direct current (electrical energy) into rotation of an element (mechanical energy). These motors can further be classified into brushed DC motor and brushless DC motors.

3.1.1 Brush type DC motor

A typical brushed motor consists of an armature coil, slip rings divided into two parts, a pair of brushes and horse shoes electromagnet as shown in Fig. 4.1.4. A simple DC motor has two field poles namely a north pole and a south pole. The magnetic lines of force extend across the opening between the poles from north to south. The coil is wound around a soft iron core and is placed in between the magnet poles. These electromagnets receive electricity from an outside power source. The coil ends are connected to split rings. The carbon brushes are in contact with the split rings. The brushes are connected to a DC source. Here the split rings rotate with the coil while the brushes remain stationary.

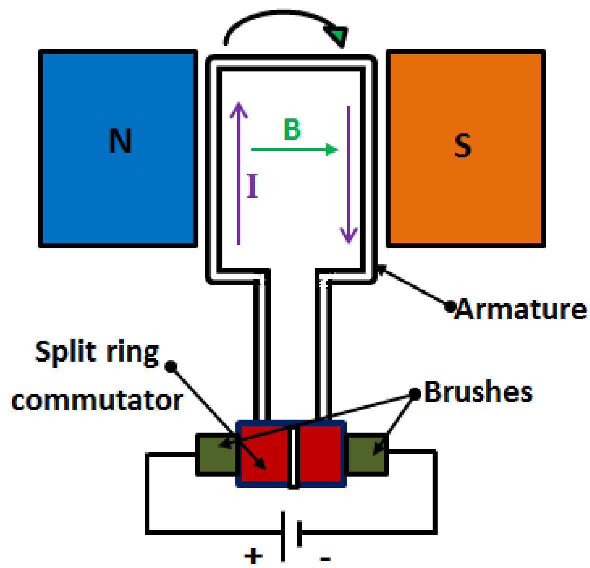

Fig. 4.1.4 Brushed DC motor

The working is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by Fleming's left-hand rule. The magnitude of the force is given by

$$F = BILsin\theta \qquad (4.1.1)$$

Where, *B* is magnetic field density in weber/m^2

I is the current in amperes and

L is the length of the conductor in meter

θ is the angle between the direction of the current in the conductor and the electric field

If the current and filed are perpendicular then θ=90°. The equation 4.1.1 becomes,

$$F = BIL \qquad (4.1.2)$$

A direct current in a set of windings creates a magnetic field. This field produces a force which turns the armature. This force is called torque. This torque will cause the armature to turn until its magnetic field is aligned with the external field. Once aligned the direction of the current in the windings on the armature reverses, thereby reversing the polarity of the rotor's electromagnetic field. A torque is once again exerted on the rotor, and it continues spinning. The change in direction of current is facilitated by the split ring commutator. The main purpose of the commutator is to overturn the direction of the electric current in the armature. The commutator also aids in the transmission of current between the armature and the power source. The brushes remain stationary, but they are in contact with the armature at the commutator, which rotates with the armature such that at every 180° of rotation, the current in the armature is reversed.

***Advantages of brushed DC motor*:**

- The design of the brushed DC motor is quite simple
- Controlling the speed of a Brush DC Motor is easy
- Very cost effective

***Disadvantages of brushed DC motor*:**

- High maintenance
- Performance decreases with dust particles
- Less reliable in control at lower speeds
- The brushes wear off with usage

3.1.2 <u>Brushless DC motor</u>

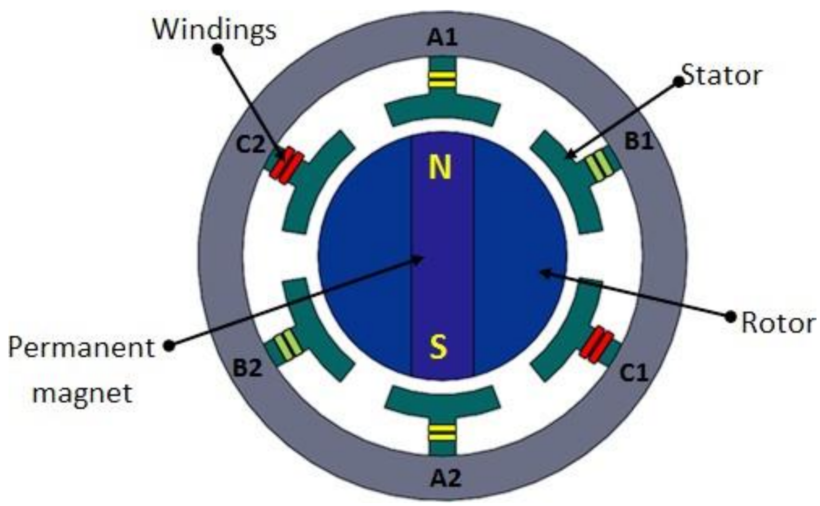

Fig. 4.1.5 Brushless DC motor

A brushless DC motor has a rotor with permanent magnets and a stator with windings. The rotor can be of ceramic permanent magnet type. The brushes and commutator are eliminated and the windings are connected to the control electronics. The control electronics replace the commutator and brushes and energize the stator sequentially. Here the conductor is fixed and the magnet moves (Fig. 4.1.5).

The current supplied to the stator is based on the position of rotor. It is switched in sequence using transistors. The position of the rotor is sensed by Hall effect sensors. Thus a continuous rotation is obtained.

***Advantages of brushless DC motor*:**

- More precise due to computer control
- More efficient
- No sparking due to absence of brushes
- Less electrical noise
- No brushes to wear out
- Electromagnets are situated on the stator hence easy to cool
- Motor can operate at speeds above 10,000 rpm under loaded and unloaded conditions
- Responsiveness and quick acceleration due to low rotor inertia

***Disadvantages of brushless DC motor*:**

- Higher initial cost
- Complex due to presence of computer controller
- Brushless DC motor also requires additional system wiring in order to power the electronic commutation circuitry

3.2 AC motors

AC motors convert AC current into the rotation of a mechanical element (mechanical energy). As in the case of DC motor, a current is passed through the coil, generating a torque on the coil. Typical components include a stator and a rotor. The armature of rotor is a magnet unlike DC motors and the stator is formed by electromagnets similar to DC motors. The main limitation of AC motors over DC motors is that speed is more difficult to control in AC motors. To overcome this limitation, AC motors are equipped with variable frequency drives but the improved speed control comes together with a reduced power quality.

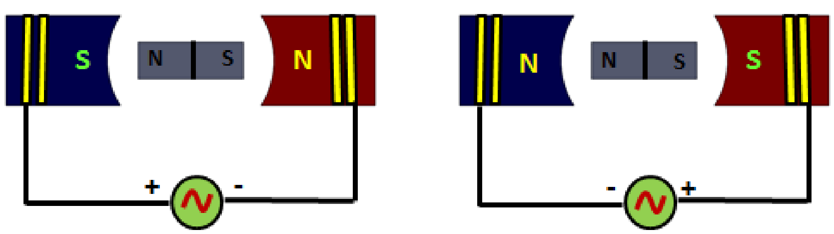

Fig. 4.1.6 AC motor working principle

The working principle of AC motor is shown in fig. 4.1.6. Consider the rotor to be a permanent magnet. Current flowing through conductors energizes the magnets and develops N and S poles. The strength of electromagnets depends on current. First half cycle current flows in one direction and in the second half cycle it flows in opposite direction. As AC voltage changes the poles alternate.

AC motors can be classified into synchronous motors and induction motors.

3.2.1 Synchronous motor

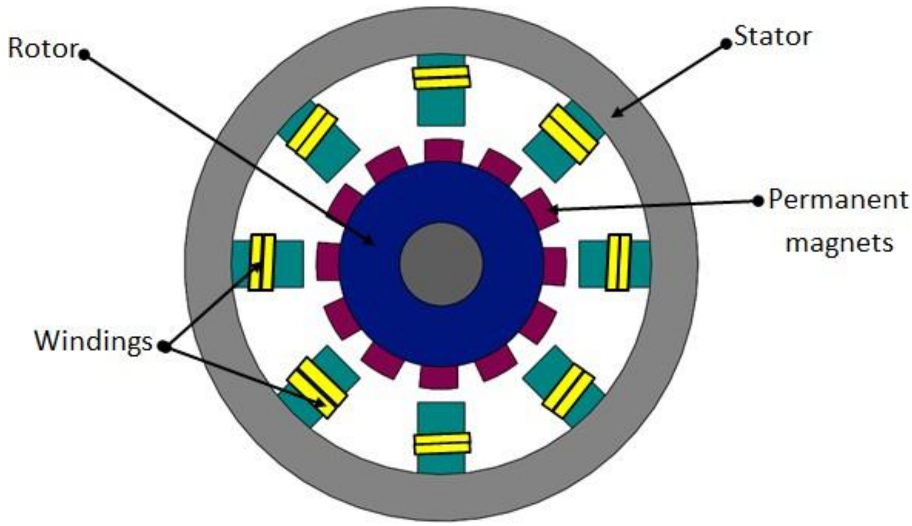

Fig. 4.1.7 Synchronous AC motor

A synchronous motor is an AC motor which runs at constant speed fixed by frequency of the system. It requires direct current (DC) for excitation and has low starting torque, and hence is suited for applications that start with a low load. It has two basic electrical parts namely stator and rotor as shown in fig. 4.1.7. The stator consists of a group of individual wounded electro-magnets arranged in such a way that they form a hollow cylinder. The stator produces a rotating magnetic field that is proportional to the frequency supplied. The rotor is the rotating electrical component. It also consists of a group of permanent magnets arranged around a cylinder, with the poles facing toward the stator poles. The rotor is mounted on the motor shaft. The main difference between the synchronous motor and the induction motor is that the rotor of the synchronous motor travels at the same speed as the rotating magnet.

The stator is given a three phase supply and as the polarity of the stator progressively change the magnetic field rotates, the rotor will follow and rotate with the magnetic field of the stator. If a synchronous motor loses lock with the line frequency it will stall. It cannot start by itself, hence has to be started by an auxiliary motor.

Synchronous speed of an AC motor is determined by the following formula:

$$N_s = \frac{120 * f}{P} \qquad (4.1.3)$$

N_s = Revolutions per minute
P = Number of pole pairs
f = Applied frequency

3.2.2 Induction motor

Induction motors are quite commonly used in industrial automation. In the synchronous motor the stator poles are wound with coils and rotor is permanent magnet and is supplied with current to create fixed polarity poles. In case of induction motor, the stator is similar to synchronous motor with windings but the rotors' construction is different.

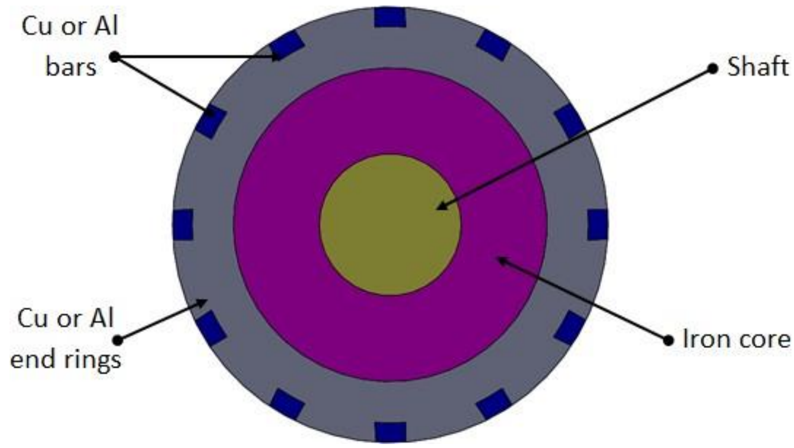

Fig. 4.1.8 Induction motor rotor

Rotor of an induction motor can be of two types:

- A squirrel-cage rotor consists of thick conducting bars embedded in parallel slots. The bars can be of copper or aluminum. These bars are fitted at both ends by means end rings as shown in figure 4.1.8.
- A wound rotor has a three-phase, double-layer, distributed winding. The rotor is wound for as many numbers of poles as the stator. The three phases are wired internally and the other ends are connected to slip-rings mounted on a shaft with brushes resting on them.

Induction motors can be classified into two types:

- *Single-phase induction motor*: It has one stator winding and a squirrel cage rotor. It operates with a single-phase power supply and requires a device to start the motor.
- *Three-phase induction motor*: The rotating magnetic field is produced by the balanced three-phase power supply. These motors can have squirrel cage or wound rotors and are self-starting.

In an induction motor there is no external power supply to rotor. It works on the principle of induction. When a conductor is moved through an existing magnetic field the relative motion of the two causes an electric current to flow in the conductor. In an induction motor the current flow in the rotor is not caused by any direct connection of the conductors to a voltage source, but rather by the influence of the rotor conductors cutting across the lines of flux produced by the stator magnetic fields. The induced current which is produced in the rotor results in a magnetic field around the rotor. The magnetic field around each rotor conductor will cause the rotor conductor to act like the permanent magnet. As the magnetic field of the stator rotates, due to the effect of the three-phase AC power supply, the induced magnetic field of the rotor will be attracted and will follow the rotation. However, to produce torque, an induction motor must suffer from slip. Slip is the result of the induced field in the rotor windings lagging behind the rotating magnetic field in the stator windings. The slip is given by,

$$S = \frac{Synchronous\ speed - Actual\ speed}{Synchronous\ speed} * 100\% \qquad (4.1.4)$$

Advantages of AC induction motors

- It has a simple design, low initial cost, rugged construction almost unbreakable
- The operation is simple with less maintenance (as there are no brushes)
- The efficiency of these motors is very high, as there are no frictional losses, with reasonably good power factor
- The control gear for the starting purpose of these motors is minimum and thus simple and reliable operation

Disadvantages of AC induction motors

- The speed control of these motors is at the expense of their efficiency
- As the load on the motor increases, the speed decreases
- The starting torque is inferior when compared to DC motors

Module 4 Drives and Mechanisms

Lecture 2

Stepper motors and Servo motors

1. Stepper motor

A stepper motor is a pulse-driven motor that changes the angular position of the rotor in steps. Due to this nature of a stepper motor, it is widely used in low cost, open loop position control systems.

Types of stepper motors:

- Permanent Magnet
  - Employ permanent magnet
  - Low speed, relatively high torque
- Variable Reluctance
  - Does not have permanent magnet
  - Low torque

1.1 Variable Reluctance Motor

Figure 4.2.1 shows the construction of Variable Reluctance motor. The cylindrical rotor is made of soft steel and has four poles as shown in Fig.4.2.1. It has four rotor teeth, 90^{0} apart and six stator poles, 60^{0} apart. Electromagnetic field is produced by activating the stator coils in sequence. It attracts the metal rotor. When the windings are energized in a reoccurring sequence of 2, 3, 1, and so on, the motor will rotate in a 30^{0} step angle. In the non-energized condition, there is no magnetic flux in the air gap, as the stator is an electromagnet and the rotor is a piece of soft iron; hence, there is no detent torque. This type of stepper motor is called a variable reluctance stepper.

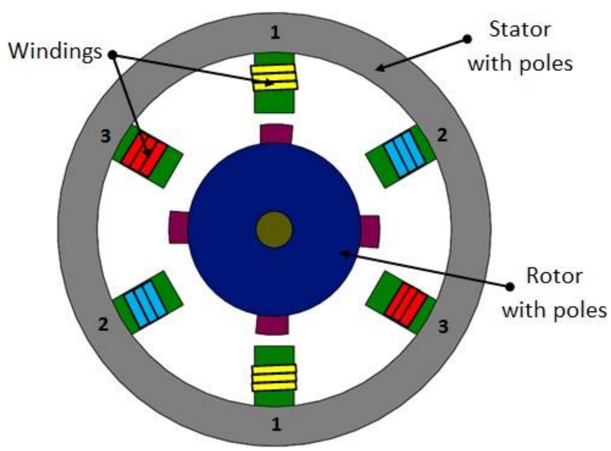

Fig. 4.2.1 Variable reluctance stepper motor

1.2 Permanent magnet (PM) stepper motor

In this type of motor, the rotor is a permanent magnet. Unlike the other stepping motors, the PM motor rotor has no teeth and is designed to be magnetized at a right angle to its axis. Figure 4.2.2 shows a simple, 90^0 PM motor with four phases (A-D). Applying current to each phase in sequence will cause the rotor to rotate by adjusting to the changing magnetic fields. Although it operates at fairly low speed, the PM motor has a relatively high torque characteristic. These are low cost motors with typical step angle ranging between 7.5^0 to 15^0.

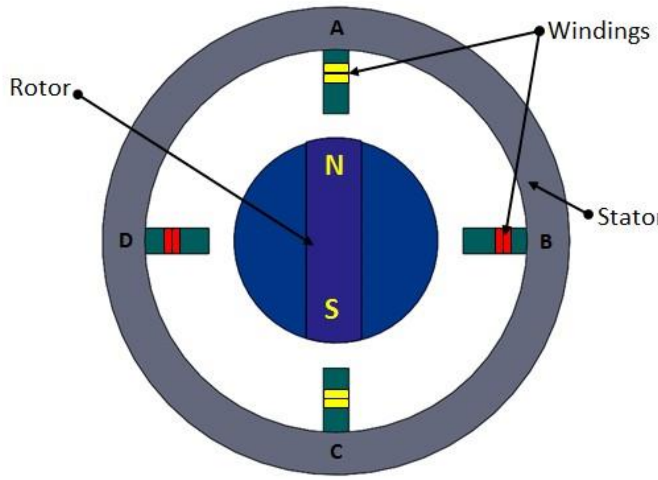

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Fig. 4.2.2 Permanent magnet stepper

1.3 Hybrid stepper motor

Hybrid stepping motors combine a permanent magnet and a rotor with metal teeth to provide features of the variable reluctance and permanent magnet motors together. The number of rotor pole pairs is equal to the number of teeth on one of the rotor's parts. The hybrid motor stator has teeth creating more poles than the main poles windings (Fig. 4.2.3).

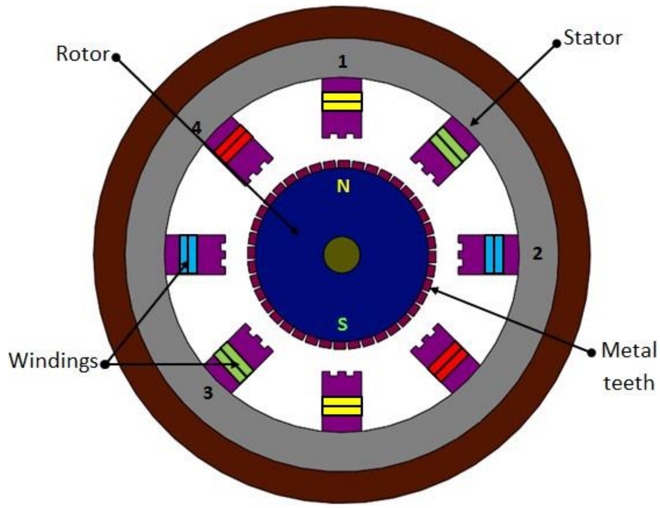

Fig. 3 Hybrid stepper motor

Rotation of a hybrid stepping motor is produced in the similar fashion as a permanent magnet stepping motor, by energizing individual windings in a positive or negative direction. When a winding is energized, north and south poles are created, depending on the polarity of the current flowing. These generated poles attract the permanent poles of the rotor and also the finer metal teeth present on rotor. The rotor moves one step to align the offset magnetized rotor teeth to the corresponding energized windings. Hybrid motors are more expensive than motors with permanent magnets, but they use smaller steps, have greater torque and maximum speed.

Step angle of a stepper motor is given by,

$$\text{Step angle} = \frac{360°}{\text{Number of poles}} \tag{4.2.1}$$

Advantages of stepper motors

- Low cost
- Ruggedness
- Simplicity of construction
- Low maintenance
- Less likely to stall or slip
- Will work in any environment
- Excellent start-stop and reversing responses

Disadvantages of stepper motors

- Low torque capacity compared to DC motors
- Limited speed
- During overloading, the synchronization will be broken. Vibration and noise occur when running at high speed.

2. Servomotor

Servomotors are special electromechanical devices that produce precise degrees of rotation. A servo motor is a DC or AC or brushless DC motor combined with a position sensing device. Servomotors are also called control motors as they are involved in controlling a mechanical system. The servomotors are used in a closed-loop servo system as shown in Figure 4.2.4. A reference input is sent to the servo amplifier, which controls the speed of the servomotor. A feedback device is mounted on the machine, which is either an encoder or resolver. This device changes mechanical motion into electrical signals and is used as a feedback. This feedback is sent to the error detector, which compares the actual operation with that of the reference input. If there is an error, that error is fed directly to the amplifier, which will be used to make necessary corrections in control action. In many servo systems, both velocity and position are monitored. Servomotors provide accurate speed, torque, and have ability of direction control.

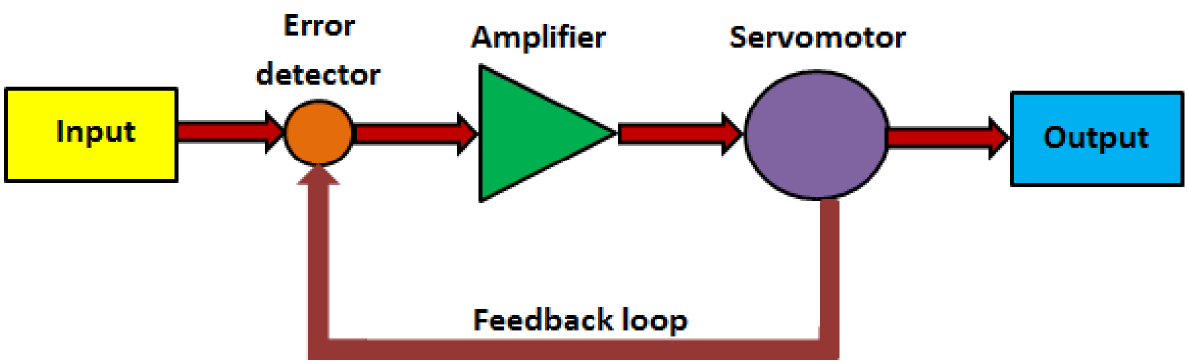

Fig. 4.2.4 Servo system block diagram

2.1 DC servomotors

DC operated servomotors are usually respond to error signal abruptly and accelerate the load quickly. A DC servo motor is actually an assembly of four separate components, namely:

- DC motor
- gear assembly
- position-sensing device
- control circuit

2.2. AC servo motor

In this type of motor, the magnetic force is generated by a permanent magnet and current which further produce the torque. It has no brushes so there is little noise/vibration. This motor provides high precision control with the help of high resolution encoder. The stator is composed of a core and a winding. The rotor part comprises of shaft, rotor core and a permanent magnet.

Digital encoder can be of optical or magnetic type. It gives digital signals, which are in proportion of rotation of the shaft. The details about optical encoder have already discussed in Lecture 3 of Module 2.

Advantages of servo motors

- Provides high intermittent torque, high torque to inertia ratio, and high speeds
- Work well for velocity control
- Available in all sizes
- Quiet in operation
- Smoother rotation at lower speeds

Disadvantages of servo motors

- More expensive than stepper motors
- Require tuning of control loop parameters
- Not suitable for hazardous environments or in vacuum
- Excessive current can result in partial demagnetization of DC type servo motor

Module 4 Drives and Mechanisms

Lecture 3

Cams

Cams are mechanical devices which are used to generate curvilinear or irregular motion of mechanical elements. They are used to convert rotary motion into oscillatory motion or oscillatory motion into rotary motion. There are two links namely the cam itself which acts as an input member. The other link that acts as an output member is called the follower. The cam transmits the motion to the follower by direct contact. In a cam-follower pair, the cam usually rotates while the follower translates or oscillates. Complicated output motions which are otherwise difficult to achieve can easily be produced with the help of cams. Cams are widely used in internal combustion engines, machine tools, printing control mechanisms, textile weaving industries, automated machines etc.

Necessary elements of a cam mechanism are shown in Figure 4.3.1.

- A driver member known as the cam
- A driven member called the follower
- A frame which supports the cam and guides the follower

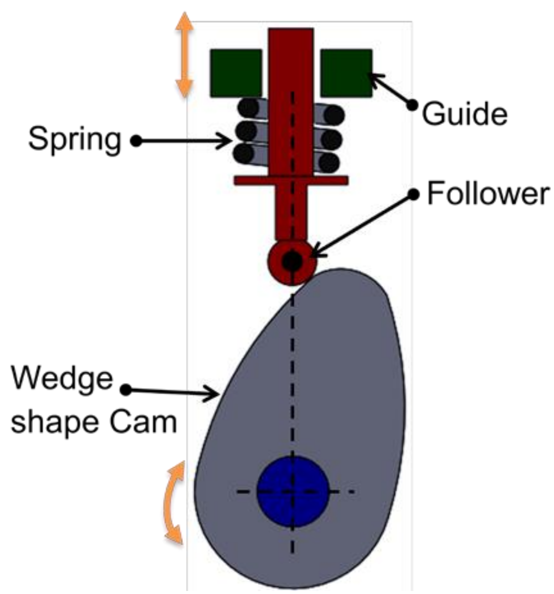

Figure 4.3.1 Cam mechanism.

1. Classification of cams

1.1 Wedge and Flat Cams

A wedge cam has a wedge of specified contour and has translational motion. The follower can either translate or oscillate. A spring is used to maintain the contact between the cam and the follower. Figure 4.3.2 shows the typical arrangement of Wedge cam.

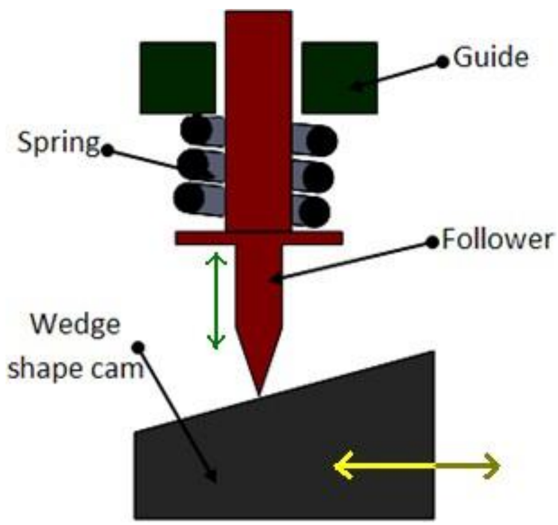

Figure 4.3.2 Wedge cam

1.2 Plate cam

In this type of cams, the follower moves in a radial direction from the centre of rotation of the cam (Figure 4.3.3). They are also known as radial or disc cam. The follower reciprocates or oscillates in a plane normal to the cam axis. Plate cams are very popular due to their simplicity and compactness.

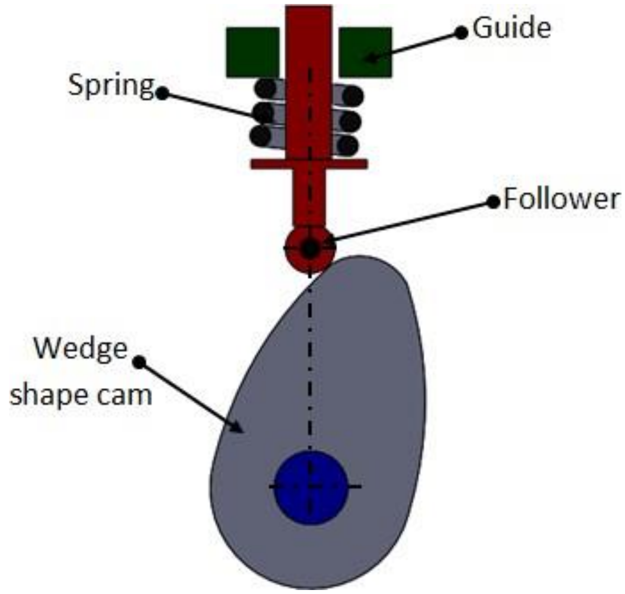

Figure 4.3.3 Plate cam

1.3 Cylindrical cam

Here a cylinder has a circumferential contour cut in the surface and the cam rotates about its axis (Figure 4.3.4). The follower motion is either oscillating or reciprocating type. These cams are also called drum or barrel cams.

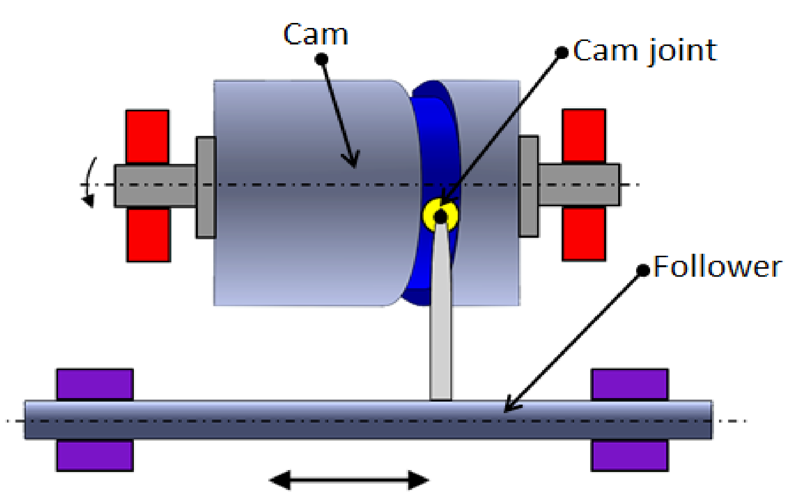

Figure 4.3.4 Cylindrical cam

2. Classification of followers:

Followers can be classified based on

- type of surface contact between cam and follower
- type of follower motion
- line of motion of followers

2.1 Classification based on type of surface contact between cam and follower

Figure 4.3.5 shows the schematics of various types of followers used cam mechanisms.

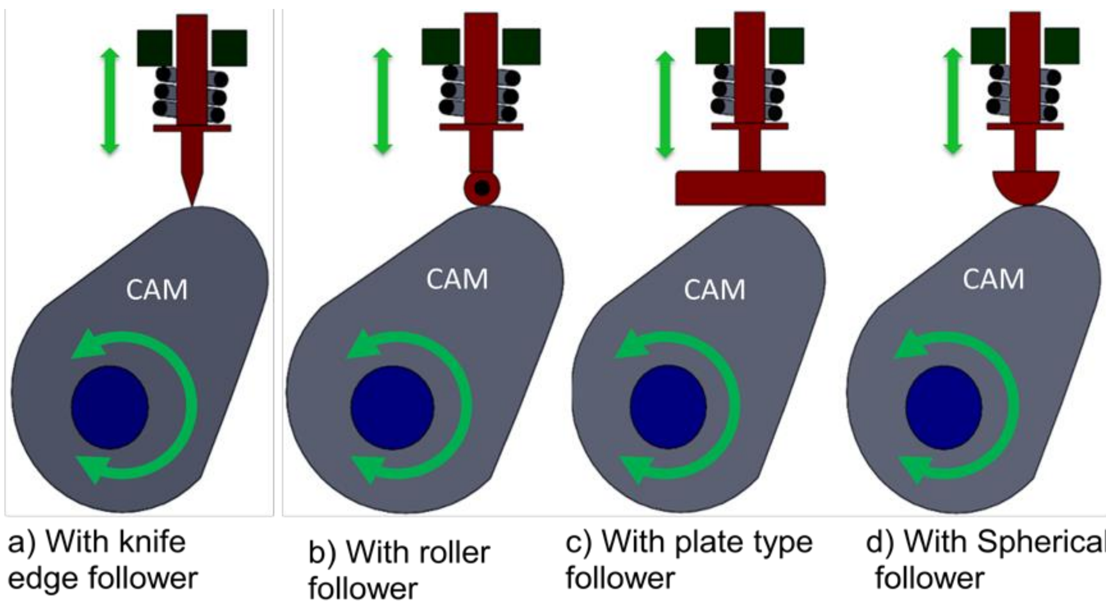

Figure 4.3.5 Types of follower based on the surface in contact

2.1.1 Knife edge follower

The contacting end of the follower has a sharp knife edge. A sliding motion exists between the contacting cam and follower surfaces. It is rarely used in practice because the small area of contacting surface results in excessive wear.

2.1.2 Roller follower

It consists of a cylindrical roller which rolls on cam surface. Because of the rolling motion between the contacting surfaces, the rate of wear is reduced in comparison with Knife edge follower. The roller followers are extensively used where more space is available such as gas and oil engines.

2.1.3 *Flat face follower*

The follower face is perfectly flat. It experiences a side thrust due to the friction between contact surfaces of follower and cam.

2.1.4 *Spherical face follower*

The contacting end of the follower is of spherical shape which overcomes the drawback of side thrust as experiences by flat face follower.

2.2 Classification based on followers' motion

Figure 4.3.6 shows the types of cams based followers' motion.

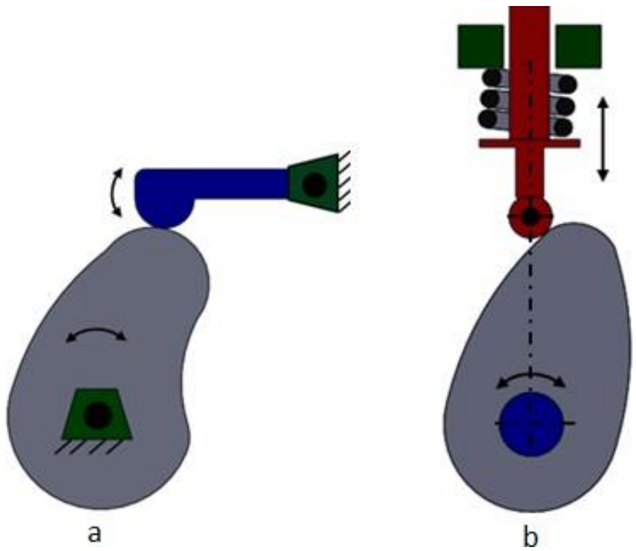

Figure 4.3.6 Classification of follower based on motion

2.2.1 *Oscillating follower*

In this configuration, the rotary motion of the cam is converted into predetermined oscillatory motion of the follower as shown in Figure 4.3.6 a).

2.2.2 *Translating follower*

These are also called as reciprocating follower. The follower reciprocates in the 'guide' as the cam rotates uniformly as shown in Figure 4.3.6 b).

2.3 Classification based on line of motion

Figure 4.3.7 shows the types of cams based followers' line of motion.

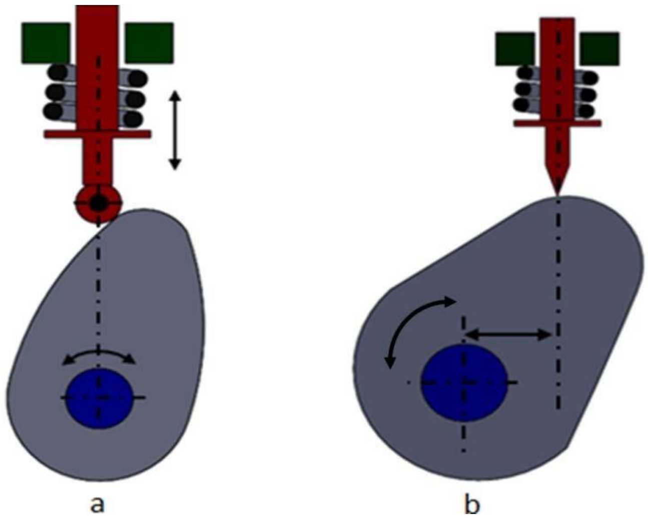

Figure 4.3.7 Classification of follower based on line of motion

4.3.1 *Radial follower*

The line of movement of the follower passes through the center of the camshaft (Figure 4.3.7 a).

4.3.2 *Offset follower*

The line of movement of the follower is offset from the center of the cam shaft (Figure 4.3.7 b).

3. *Force closed cam follower system*

In this type of cam-follwer system, an external force is needed to maintain the contact between cam and follower. Generally a spring maintains the contact between the two elements. The follower can be a oscillating type (Figure 4.3.8 a) or of translational type (Figure 4.3.8 b).

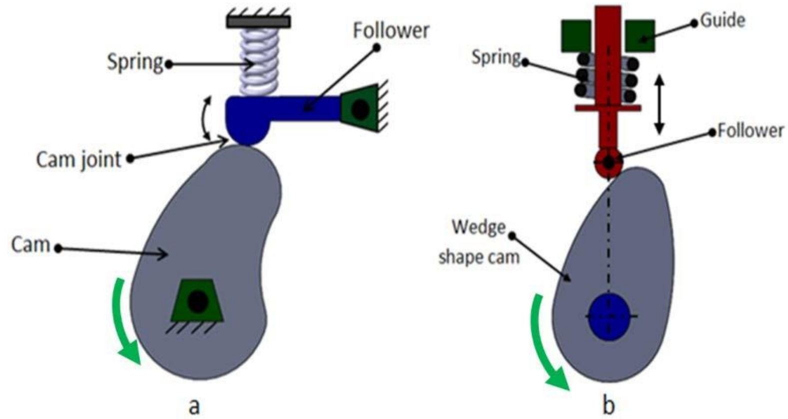

Figure 4.3.8 Force closed cam followers

4. *Form closed cam foller system*

In this system a slot or a groove profile is cut in the cam. The roller fits in the slot and follows the groove profile. These kind of systems do not require a spring. These are extensively used in machine tools and machinery. The follower can be a translating type (Figure 4.3.9 a) oscillating type (Figure 4.3.9 b).

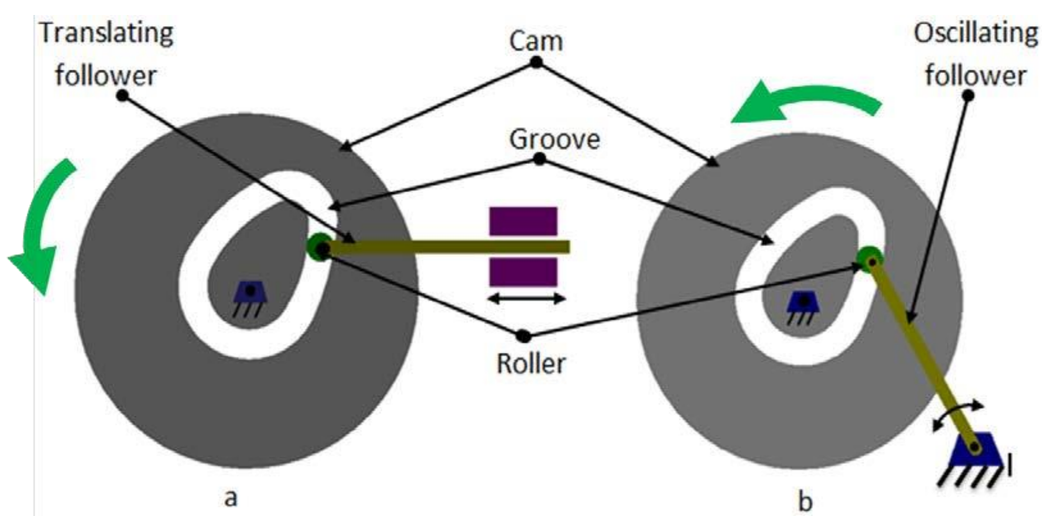

Figure 4.3.9 Form closed cam followers

5. Three-dimensional cam or Camoid

Camoid is a combination of radial and axial cams. It has three dimensional surface and two degrees-of-freedom. Two inputs are rotation of the cam about its axis and translation of the cam along its axis. Follower motion is based on both the inputs. Figure 4.3.10 shows a typical Camoid.

Figure 4.3.10 A Camoid

6. Applications of cams

Cams are widely used in automation of machinery, gear cutting machines, screw machines, printing press, textile industries, automobile engine valves, tool changers of machine centers, conveyors, pallet changers, sliding fork in wearhouses etc.

Cams are also used in I.C engines to operate the inlet valves and exhaust valves.The cam shaft rotates by using prime moveres. It causes the rotation of cam. This rotation produces translatory motion of tappet against the spring. This translatory motion is used to open or close the valve. The schematic of this operation is shown in Figure 4.3.11.

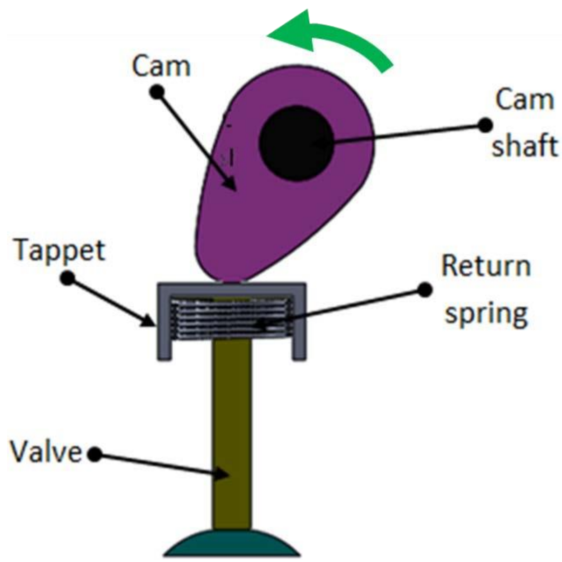

Figure 4.3.11 Cam in I.C engine

6.1 Cams in automatic lathes

The cam shaft is driven by a motor. The cutting tool mounted on the transverse slide travels to desired depth and at desired feed rate by a set of plate cams mounted on the cam shaft. The bar feeding through headstock at desired feed rate is carried out by a set of plate cams mounted on the camshaft.

6.2 Automatic copying machine

The cam profile can be transferred onto the work piece by using a roller follower as shown in Figure 4.3.12. The follower can be mounted with a cutting tool. As the cam traverses, the roller follows the cam profile. The required feature can be copied onto the workpiece by the movement of follower over the cam profile.

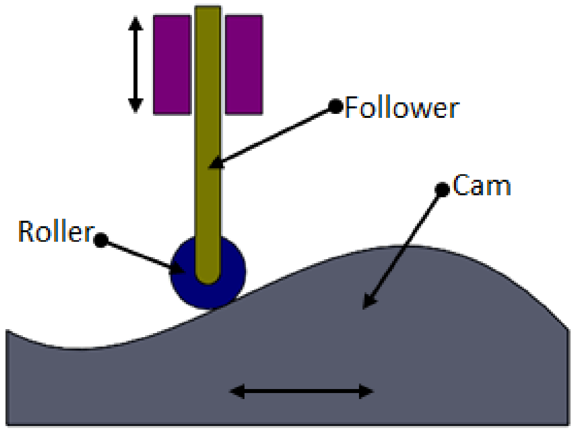

Figure 4.3.12 Automatic copying of cam profile

Module 4 Drives and Mechanisms

Lecture 4

Linear motion drives

Linear motion drives are mechanical transmission systems which are used to convert rotary motion into linear motion. The conventional thread forms like vee or square are not suitable in CNC because of their high wear and less efficiency. Therefore CNC machines generally employ ball screw for driving their workpiece carriages. These drives provide backlash free operation with low friction-wear characteristics. These are efficient and accurate in comparison with that of nut-and-screw drives. Most widely used linear motion drives are ball screws.

A **linear actuator** is an actuator that produces motion in a straight line. Linear actuators are extensively required in machine tools and industrial machinery. Hydraulic or pneumatic cylinders inherently produce linear motion. Many other mechanisms are used to generate linear motion from a rotating motor.

1. Mechanical actuators

These actuators convert rotary motion into linear motion. Conversion is made by using various types of mechanisms such as:

- Screw: This is a simple machine known as screw. By rotating the screw shaft, the actuator's nut moves in a line.
- Wheel and axle: Hoist, winch, rack and pinion, chain drive, belt drive, rigid chain and rigid belt actuators operate on the principle of the wheel and axle. A rotating wheel moves a cable, rack, chain or belt to produce linear motion.
- Cam: discussed in last lecture.
- Hydraulic actuators utilize pressurized fluid to produce a linear motion where as pneumatic systems employ compressed air for the same purpose. We will be discussing about these systems in Modules 4 and 5.

2. Piezoelectric actuators

These actuators work on the principle of Piezoelectricity which states that application of a voltage to a crystal material such as Quartz causes it to expand. However, very high voltages produce only tiny expansions. As a result, though the piezoelectric actuators achieve extremely fine positioning resolution, but also have a very short range of motion. In addition, piezoelectric materials exhibit hysteresis which makes it difficult to control their expansion in a repeatable manner.

3. Electro-mechanical actuators

Electro-mechanical actuators are similar to mechanical actuators except that the control knob or handle is replaced with an electric motor. Rotary motion of the motor is converted to linear displacement. In this type of actuators, an electric motor is mechanically connected to rotate a lead screw. A lead screw has a continuous helical thread machined on its circumference running along the length (similar to the thread on a bolt). Threaded onto the lead screw is a lead nut or ball nut with corresponding helical threads. The nut is prevented from rotating with the lead screw (typically the nut interlocks with a non-rotating part of the actuator body). Therefore, when the lead screw is rotated, the nut will be driven along the threads. The direction of motion of the nut depends on the direction of rotation of the lead screw. By connecting linkages to the nut, the motion can be converted to usable linear displacement.

There are many types of motors that can be used in a linear actuator system. These include dc brush, dc brushless, stepper, or in some cases, even induction motors. Electromechanical linear actuators find applications in robotics, optical and laser equipments, or X-Y tables with fine resolution in microns.

4. Linear motors

The working principle of a linear motor is similar to that of a rotary electric motor. It has a rotor and the stator circular magnetic field components are laid down in a straight line. Since the motor moves in a linear fashion, no lead screw is needed to convert rotary motion into linear. Linear motors can be used in outdoor or dirty environments; however the electromagnetic drive should be waterproofed and sealed against moisture and corrosion.

5. *Ball-screw based linear drives*

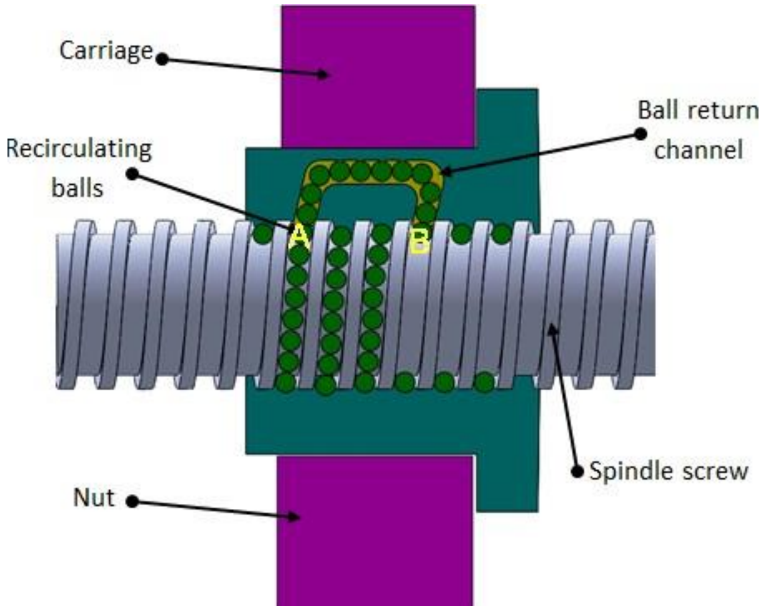

Fig.4.4.1 Ball-screw configuration

Ball screw is also called as ball bearing screw or recirculating ball-screw. It consists of a screw spindle, a nut, balls and integrated ball return mechanism a shown in Figure 4.4.1. The flanged nut is attached to the moving part of CNC machine tool. As the screw rotates, the nut translates the moving part along the guide ways. However, since the groove in the ball screw is helical, its steel balls roll along the helical groove, and, then, they may go out of the ball nut unless they are arrested at a certain spot. Thus, it is necessary to change their path after they have reached a certain spot by guiding them, one after another, back to their "starting point" (formation of a recirculation path). The recirculation parts play that role. When the screw shaft is rotating, as shown in Figure 4.4.1, a steel ball at point (A) travels 3 turns of screw groove, rolling along the grooves of the screw shaft and the ball nut, and eventually reaches point (B). Then, the ball is forced to change its pathway at the tip of the tube, passing back through the tube, until it finally returns to point (A). Whenever the nut strokes on the screw shaft, the balls repeat the same recirculation inside the return tube.

When debris or foreign matter enter the inside of the nut, it could affect smoothness in operation or cause premature wearing, either of which could adversely affect the ball screw's functions. To prevent such things from occurring, seals are provided to keep contaminants out. There are various types of seals viz. plastic seal or brush type of seal used in ball-screw drives.

5.1 Characteristics of ball screws:

5.1.1 High mechanical efficiency

In ball screws, about 90% or more of the force used to rotate the screw shaft can be converted to the force to move the ball nut. Since friction loss is extremely low, the amount of force used to rotate the screw shaft is as low as one third of that needed for the acme thread lead screw.

5.1.2 Low in wear

Because of rolling contact, wear is less than that of sliding contact. Thus, the accuracy is high. Ball screws move smoothly enough under very slow speed. They run smoothly even under a load.

5.2 Thread Form

The thread form used in these screws can either be gothic arc type (Fig. 4.4.2.a) or circular arc type (Fig. 4.4.2.b). The friction in this kind of arrangement is of rolling type. This reduces its wear as comparison with conventional sliding friction screws drives.

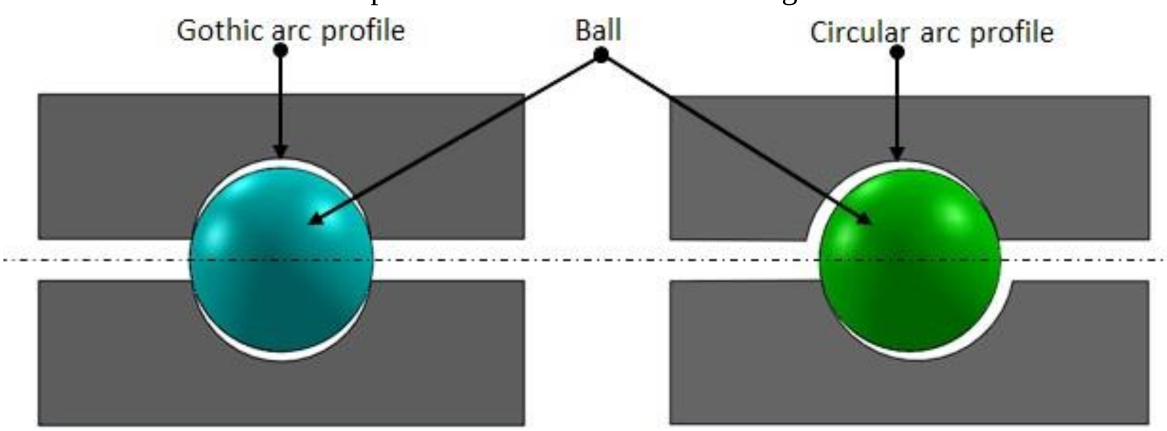

Fig. 2 Thread forms (a) Gothic arc (b) Circular arc

Recirculating ball screws are of two types. In one arrangement the balls are returned using an external tube. In the other arrangement the balls are returned to the start of the thread in the nut through a channel inside the nut.

5.3 Preloading

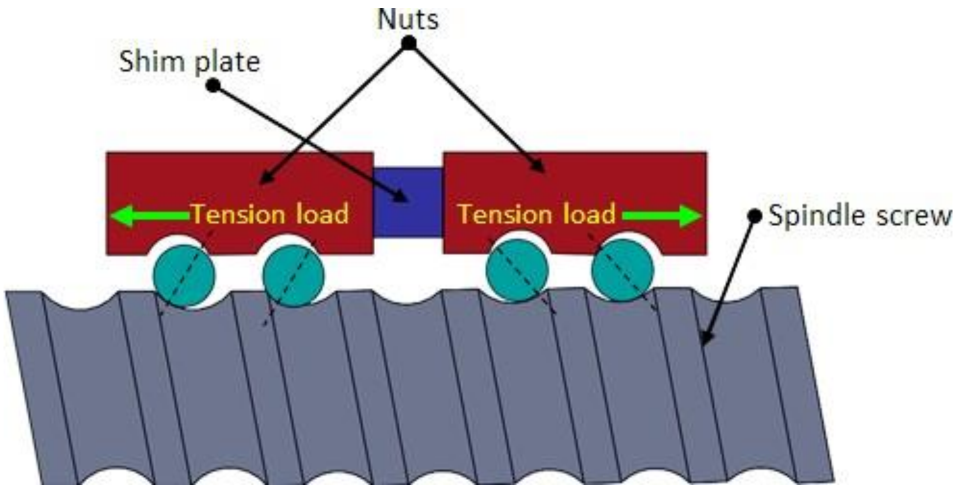

Fig. 4.4.3 Double nut preloading system

In order to obtain bidirectional motion of the carriage without any positional error, the backlash between the nut and screw should be minimum. Zero backlash can be obtained by fitting two nuts with preloading (tension or compression) or by applying a load which exceeds the maximum operating load. Figure 4.4.3 shows double nut preloading system. A shim plate (spacer) is inserted between two nuts for preloading. Preload is to create elastic deformations (deflections) in steel balls and ball grooves in the nut and the screw shaft in advance by providing an axial load. As a result the balls in one of the nuts contact the one side of the thread and balls in the other nut contact the opposite side.

5.3.1 Effects of preload

- Zero backlash: It eliminates axial play between a screw shaft and a ball nut.
- It minimizes elastic deformation caused by external force, thus the rigidity enhances.

In case mounting errors, misalignment between the screw shaft and the nut may occur this further generates distortion forces. This could lead to the problems such as,

- Shortened service life
- Adverse effect on smooth operation
- Reduced positioning accuracy
- Generation of noise or vibration
- Breakage of screw shaft

5.4 Advantages of ball screws

- Highly efficient and reliable.
- Less starting torque.
- Lower co efficient of friction compared to sliding type screws and run at cooler temperatures
- Power transmission efficiency is very high and is of the order of 95 %.
- Could be easily preloaded to eliminate backlash.
- The friction force is virtually independent of the travel velocity and the friction at rest is very small; consequently, the stick-slip phenomenon is practically absent, ensuring uniformity of motion.
- Has longer thread life hence need to be replaced less frequently.
- Ball screws are well -suited to high through output, high speed applications or those with continuous or long cycle times.
- Smooth movement over full range of travel.

5.5 Disadvantages of ball screws

- Tend to vibrate.
- Require periodic overhauling to maintain their efficiency.
- Inclusion of dirt or foreign particles reduces the life of the screws.
- Not as stiff as other power screws, thus deflection and critical speed can cause difficulties.
- They are not self-locking screws hence cannot be used in holding devices such as vices.
- Require high levels of lubrication.

5.6 Applications of ball screws:

- Ball screws are employed in cutting machines, such as machining center and NC lathe where accurate positioning of the table is desired
- Used in the equipments such as lithographic equipment or inspection apparatus where precise positioning is vital
- High precision ball screws are used in steppers for semiconductor manufacturing industries for precision assembly of micro parts.
- Used in robotics application where precision positioning is needed.
- Used in medical examination equipments since they are highly accurate and provide smooth motion.

Module 4 Drives and Mechanisms

Lecture 5

Indexing Mechanisms

Mechanism is a system of rigid elements arranged and connected to transmit motion in a predetermined fashion. Indexing mechanisms generally converts a rotating or oscillatory motion to a series of step movements of the output link or shaft. In machine tools the cutting tool has to be indexed in the tool turret after each operation. Also in production machines the product has to be indexed from station to station and need to be stopped if any operation is being performed in the station. Such motions can be accomplished by indexing mechanisms. Indexing mechanisms are also useful for machine tool feeds. There are several methods used to index but important types are ratchet and pawl, rack and pinion, Geneva mechanism and cam drive.

1. Ratchet and pawl mechanism

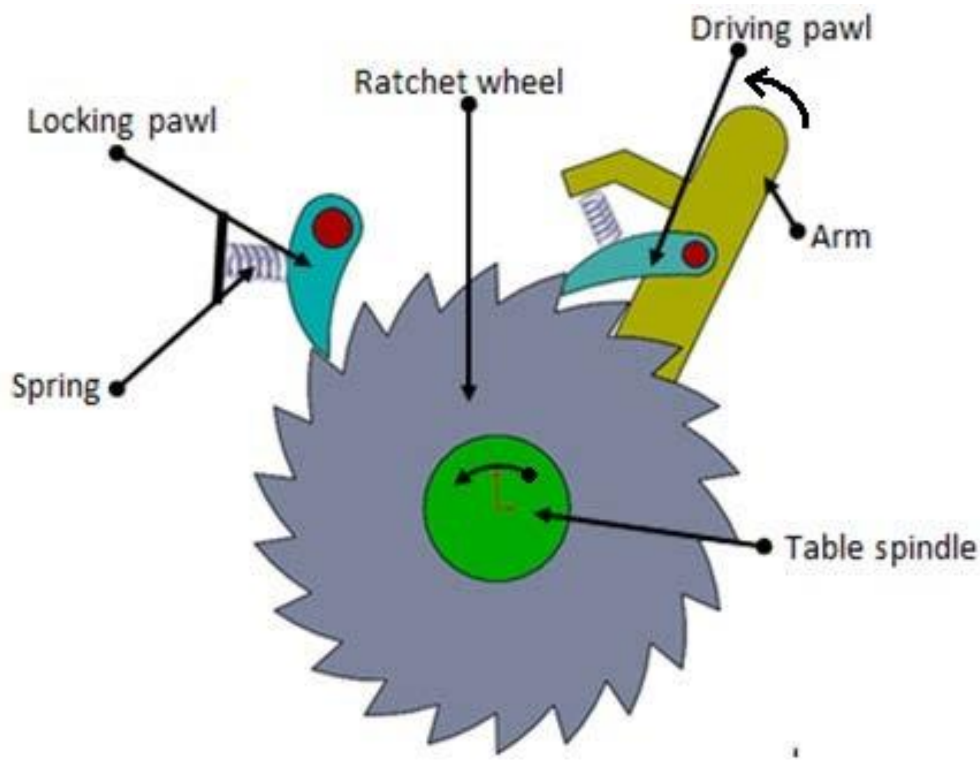

Fig. 4.5.1 Ratchet and pawl mechanism

A ratchet is a device that allows linear or rotary motion in only one direction. Figure 4.5.1 shows a schematic of the same. It is used in rotary machines to index air operated indexing tables. Ratchets consist of a gearwheel and a pivoting spring loaded pawl that engages the teeth. The teeth or the pawl, are at an angle so that when the teeth are moving in one direction the pawl slides in between the teeth. The spring forces the pawl back into the depression between the next teeth. The ratchet and pawl are not mechanically interlocked hence easy to set up. The table may over travel if the table is heavy when they are disengaged. Maintenance of this system is easy.

2. Rack and pinion mechanism

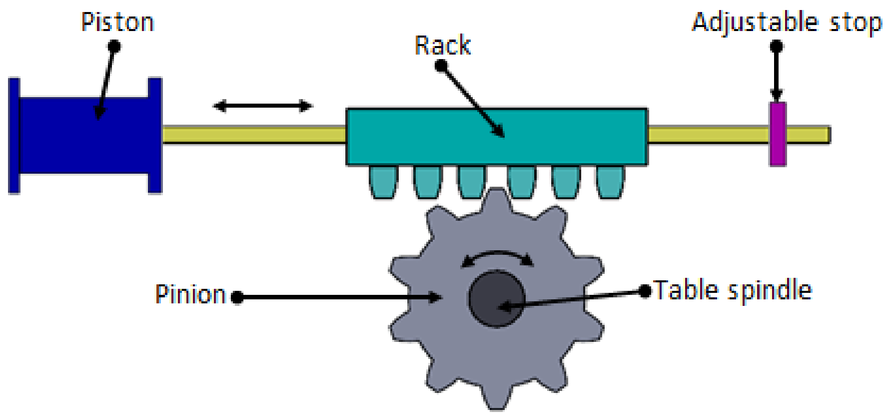

Fig. 4.5.2 Rack and pinion mechanism

A rack and pinion gear arrangement usually converts rotary motion from a pinion to linear motion of a rack. But in indexing mechanism the reverse case holds true. The device uses a piston to drive the rack, which causes the pinion gear and attached indexing table to rotate (Fig. 4.5.2). A clutch is used to provide rotation in the desired direction. This mechanism is simple but is not considered suitable for high-speed operation.

3. Geneva mechanism

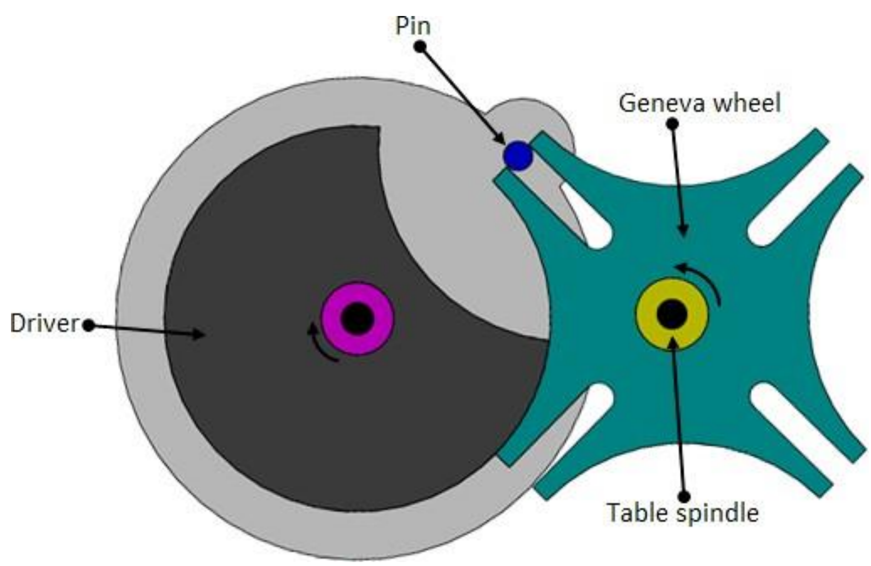

Fig. 4.5.3 Geneva mechanism

The Geneva drive is also commonly called a Maltese cross mechanism. The Geneva mechanism translates a continuous rotation into an intermittent rotary motion. The rotating drive wheel has a pin that reaches into a slot of the driven wheel. The drive wheel also has a raised circular blocking disc that locks the driven wheel in position between steps (Fig. 4.5.3). There are three basic types of Geneva motion mechanisms namely external, internal and spherical. The spherical Geneva mechanism is very rarely used. In the simplest form, the driven wheel has four slots and hence for each rotation of the drive wheel it advances by one step of 90°. If the driven wheel has n slots, it advances by 360°/n per full rotation of the drive wheel.

In an internal Geneva drive the axis of the drive wheel of the internal drive is supported on only one side (Fig. 4.5.4). The angle by which the drive wheel has to rotate to effect one step rotation of the driven wheel is always smaller than 180° in an external Geneva drive and is always greater than 180° in an internal one. The external form is the more common, as it can be built smaller and can withstand higher mechanical stresses.

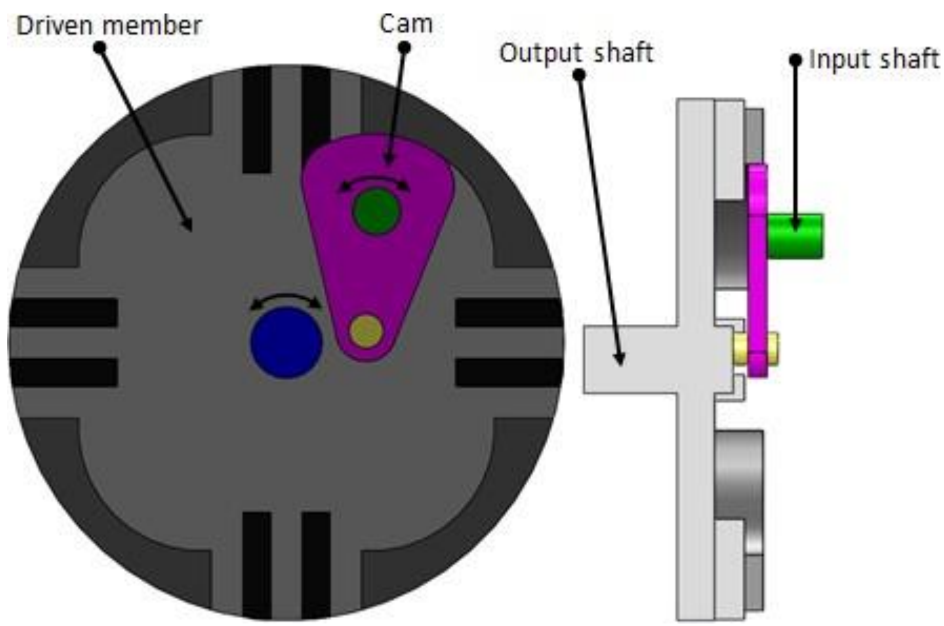

Fig. 4.5.4 Internal Geneva mechanism

Because the driven wheel always under full control of the driver, impact is a problem. It can be reduced by designing the pin in such a way that the pin picks up the driven member as slowly as possible. Both the Geneva mechanisms can be used for light and heavy duty applications. Generally, they are used in assembly machines.

Intermittent linear motion from rotary motion can also be obtained using Geneva mechanism (Fig. 4.5.5). This type of movement is basically required in packaging, assembly operations, stamping, embossing operations in manufacturing automation.

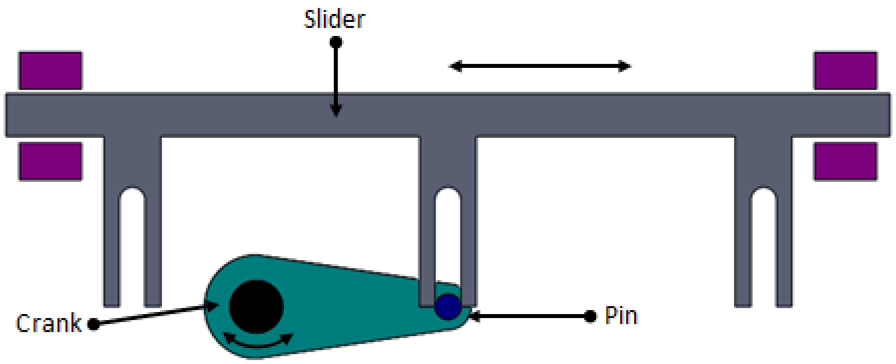

Fig. 4.5.5 Linear intermittent motion using Geneva mechanism

4. Cams mechanism

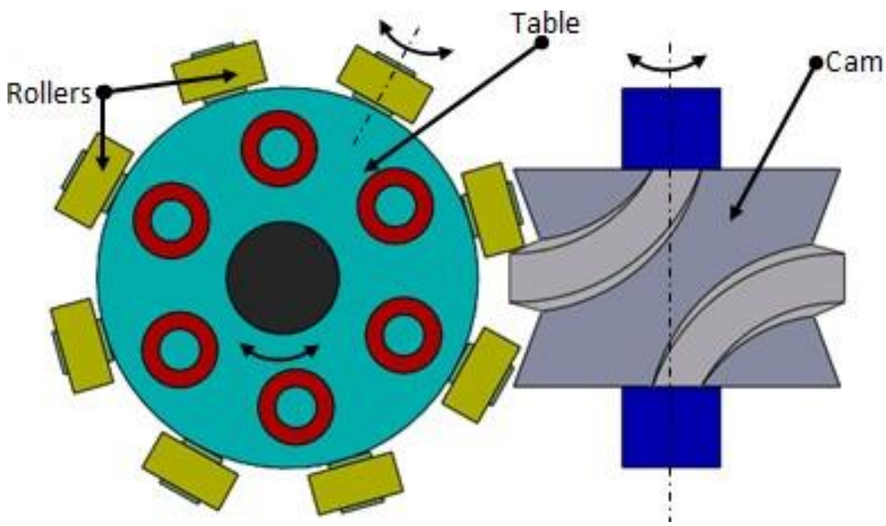

Fig. 4.5.6 Cam mechanism

Cam mechanism is one of the accurate and reliable methods of indexing. It is widely used in industry despite the fact that the cost is relatively high compared to alternative mechanisms. The cam can be designed to give a variety of velocity and dwell characteristics. The follower of the cams used in indexing mechanism has a unidirectional rotary motion rather than oscillating rotary motion which is usually the case of axial cams. The cam surface geometry is more complicated in a cross over indexing type of cam as shown in Figure 4.5.6.

5. Applications of indexing mechanisms

Some of the applications of indexing mechanism are discussed below.

5.1 Motion picture projectors

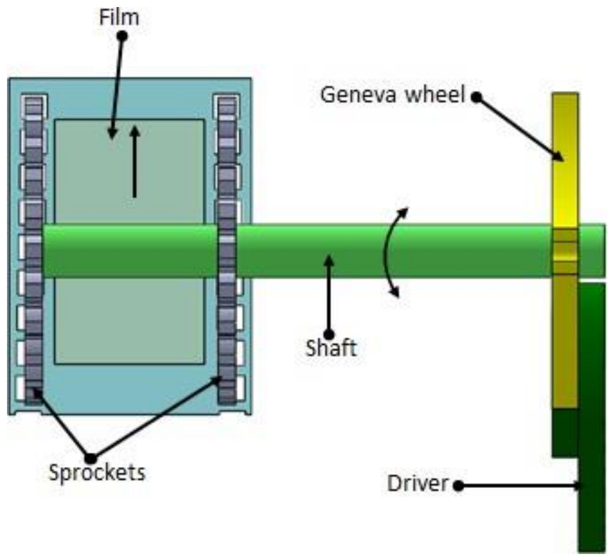

Fig. 4.5.7 Motion picture projector with Geneva mechanism

Geneva drive mechanism is used in conventional-mechanical type movie projectors. Figure 4.5.7 shows the schematic of movie projector with Geneva mechanism. The film does not run continuously through the projector. It is requited that the film should advance frame by frame and stands still in front of the lens for fraction of a second. Modern film projectors use an electronically controlled indexing mechanism which allows the fast-forwarding of the film.

5.2 Automated work assembly transfer lines

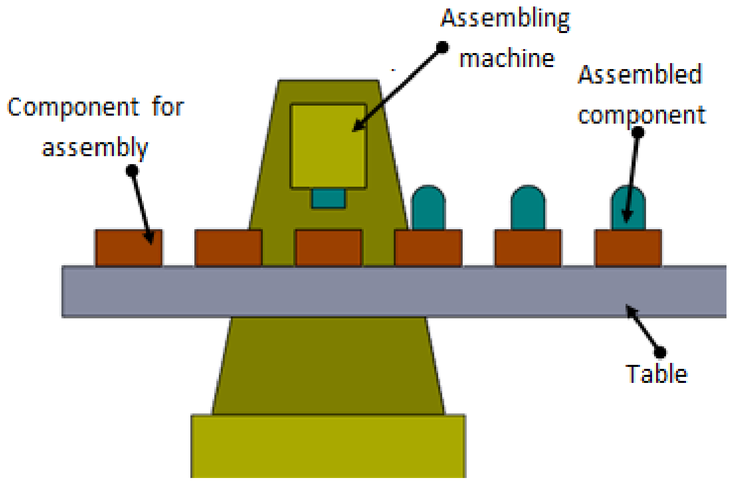

Fig. 4.5.8 Automated assembly line

In assembly lines, the parts to be assembled have to be moved over the assembling machine tool (Fig. 4.5.8). This is done using indexing mechanism. The part on the table is indexed to be in line with the assembly unit. Once the assembly is done the table is indexed to get the next part in line with the assembly.

5.3 CNC tool changers

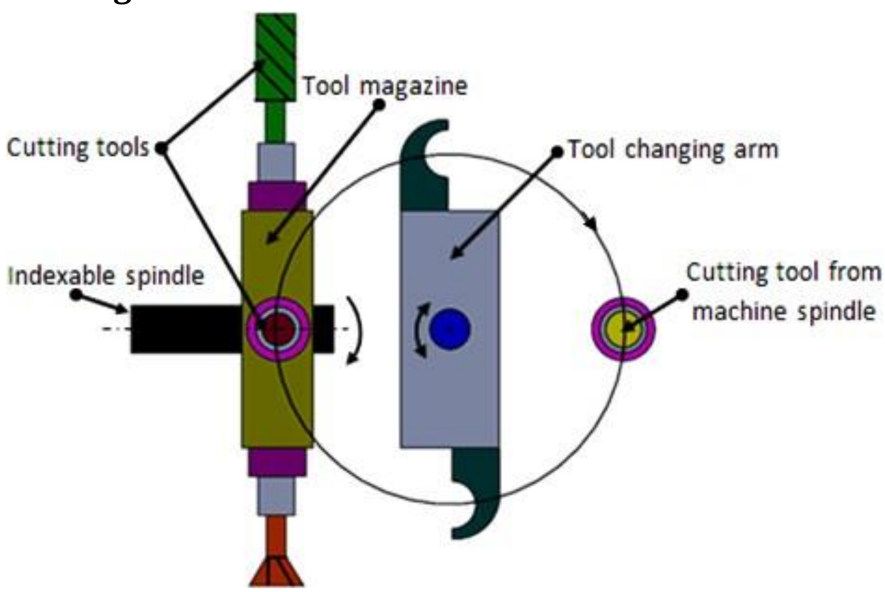

Fig. 4.5.9 CNC tool changer

In the CNC tool changing mechanism the tool magazine has to be indexed to bring the desired tool in line with the tool changing arm (Fig. 4.5.9). The tool changing arm picks the cutting tool from the spindle. Then it is indexed to reach the tool magazine. The tool is placed in the magazine. Then the magazine is indexed to bring the next cutting tool to be picked by the changing arm. Again the tool changing arm indexes to reach the spindle.

5.4 Material inspection station

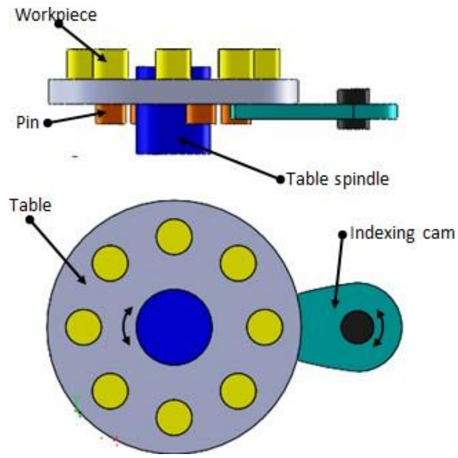

Fig. 4.5.10 Rotary table with cam indexing

Here a rotary index table is used to convey the parts for inspection operation. This index device conveys the parts in a rotary motion and stops intermittently for a fixed period of time for inspection. A cam mechanism is used to index the table (Fig. 4.5.10).

Module 4 Drives and Mechanisms

Lecture 6

Tool magazines and transfer systems

Machining centers are used to carry out multiple operations like drilling, milling, boring etc. in one set up on multiple faces of the workpiece. These operations require a number of different tools. Tool changing operation is time consuming which reduces the machine utilization. Hence the tools should be automatically changed to reduce the idle time. This can be achieved by using automatic tool changer (ATC) facility. It helps the workpiece to be machined in one setup which increases the machine utilization and productivity. Large numbers of tools can be stored in tool magazines. Tool magazines are specified by their storage capacity, tool change procedure and shape. The storage capacity ranges from 12 to 200. Some of the magazines are discuseed as follows.

1. Tool turret

It is the simplest form of tool magazine. Figure 4.6.1 the schematic of a turret with a capacity to hold twelve tools. It consists of a tool storage without any tool changer. The turret is indexed in the required position for desired machining operation. Advantage of the turret is that the tool can easily be identified, but the time consumed for tool change is more unless the tool is in the adjecent slot.

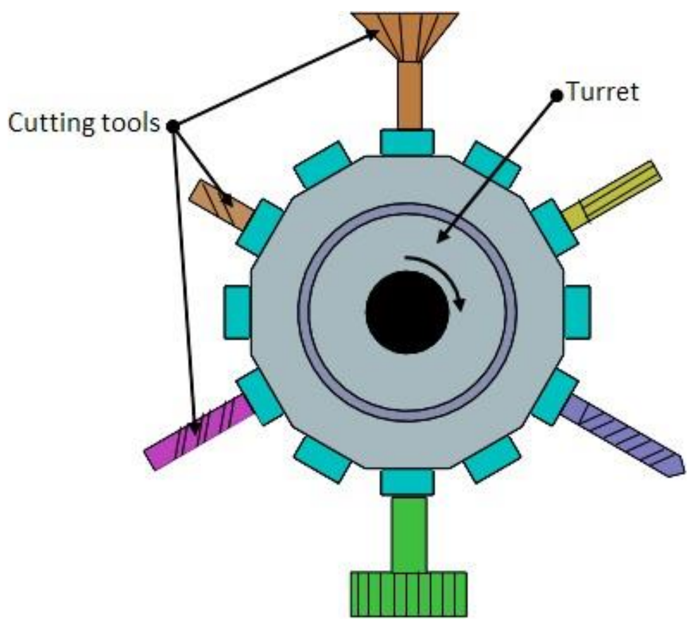

Fig. 4.6.1 Tool turret

2. Tool magazines

Tool magazines are generally employed in CNC drilling and milling machines. Compared to tool turrets the tool magazines can hold more number of tools therefore proper management of tools is essential. Duplication of the tools is possible and a new tool of same type may be selected when a particular tool is worn off. The power required to move the tools in a tool magazine is more in comparison with that required in tool turrets. The following are some of the tool magazines used in automation.

- **2.1** Disc or drum type
- **2.2** Chain type
- **2.3** Disk or drum type

2.1 Disc type magazine

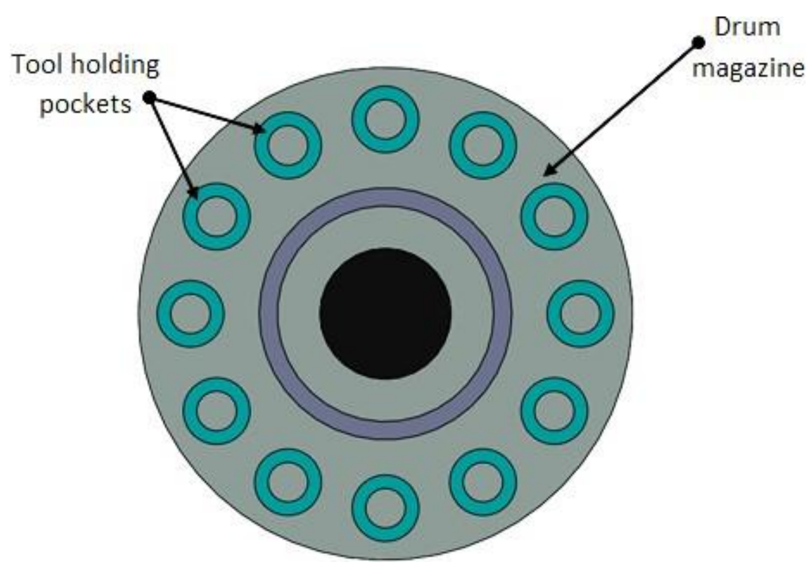

Fig. 4.6.2 Drum magazine

The disc type tool magazine rotates to get the desired tool in position with the tool change arm (Fig. 4.6.2). Larger the diameter of the disc/drum more the number of tools it can hold. It has pockets where tool can be inserted. In case of drum type magazine which can store large amount of tools, the pockets are on the surface along the length. It carries about 12 to 50 tools. If the number of tools are less the disc is mounted on top of the spindle to minimize the travel of tool between the spindle and the disc. If the tools are more then, the disc is wall mounted or mounted on the machining center column. If the disc is column mounted then, it needs an additional linear motion to move it to the loading station for tool change.

2.2 Chain type magazine

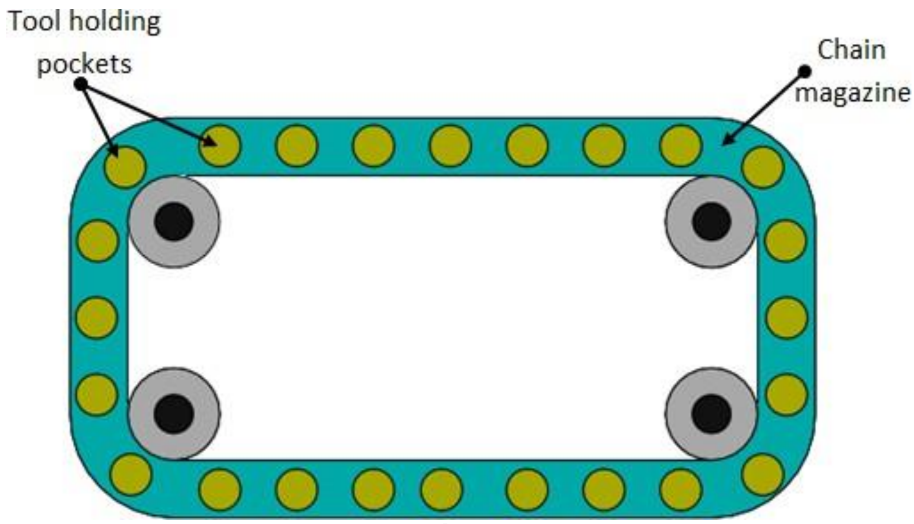

Fig. 4.6.3 Chain magazine

When the number of tools is more than 50, chain type of magazines are used (Fig. 4.6.3). The magazine is mounted overhead or as a separate column. In chain magazines the tools are identified either by their location in the tool holder or by means of some coding on the tool holder. These types of magazines can be duplicated. There can be two chain magazines: one is active for machining and the second magazine is used when the duplicate tool is needed since the active tool is worn out.

2.3 Rack type magazine

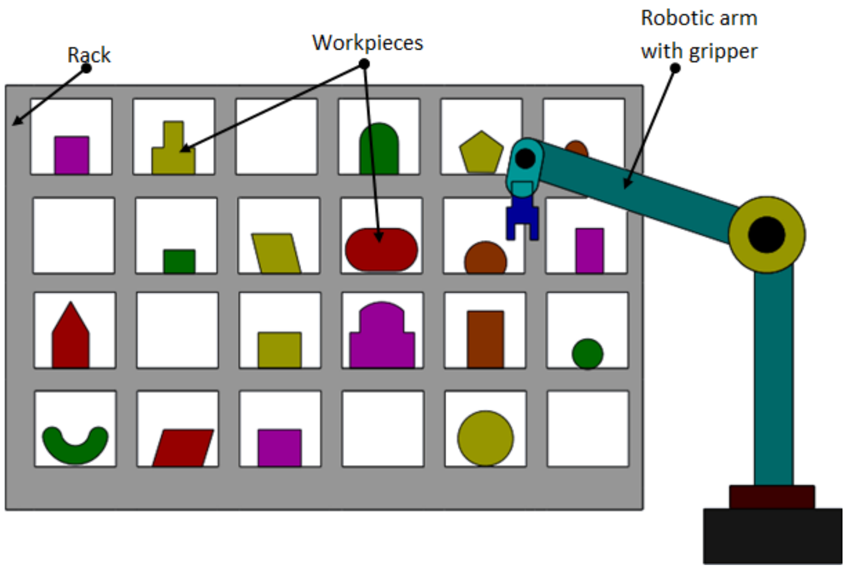

Fig. 4.6.4 Rack magazine

Rack magazines are cost-efficient alternative to usual tool magazine systems (Fig. 4.6.4). Set-up time can be optimized by utilizing the racks' capacity of up to 50 tools. The high storage capacity of up to 400 tools permits a large production capacity of varying work pieces without tool changes. They can also be used to store work pieces.

3. Automatic tool changing

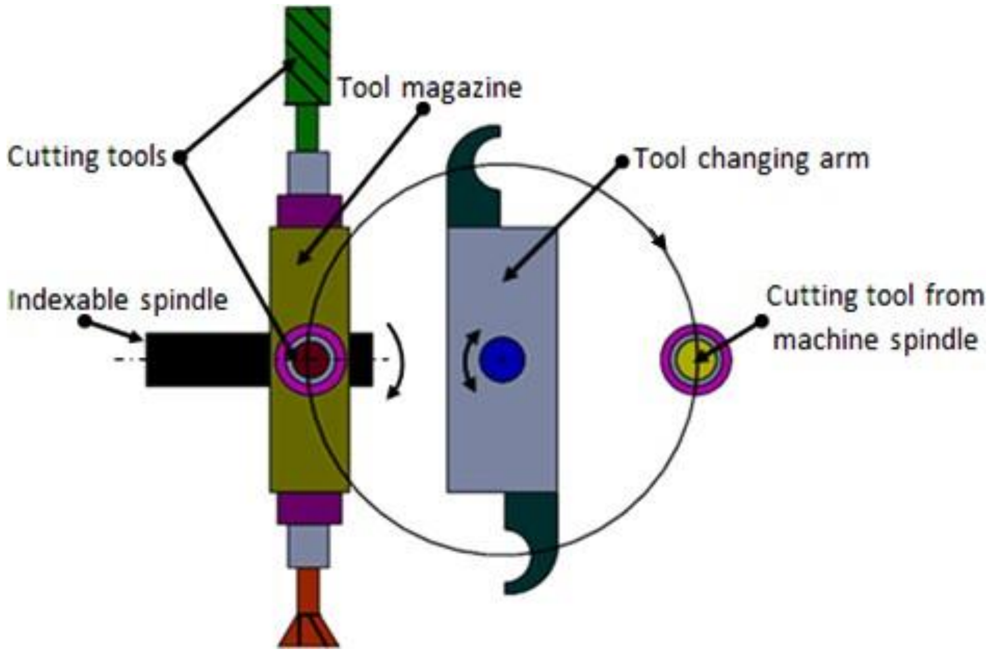

Fig. 4.6.5 Automatic tool changer

The tools from the magazines and spindle are exchanged by a tool changer arm (Fig. 4.6.5). The tool change activity requires the following motions:

a. The spindle stops at the correct orientation for the tool change arm to pick the tool from the spindle.
b. Tool change arm moves to the spindle.
c. Tool change arm picks the tool from the spindle.
d. Tool change arm indexes to reach the tool magazine.
e. Tool magazine indexes so that the tool from the spindle can be placed.
f. The tool is placed in the tool magazine.
g. The tool magazine indexes to bring the required tool to the tool change position.
h. Tool change arm picks the tool from the tool magazine.
i. Tool change arm indexes to reach the spindle.
j. New tool is placed in the spindle.
k. Tool change arm moves back to its parking position.

3.1 Advantages of automatic tool changer

- Increase in operator safety by changing tools automatically
- Changes the tools in seconds for maintenance and repair
- Increases flexibility
- Heavy and large multi-tools can easily be handled
- Decreases total production time

4. Cranes

Cranes are material handling equipments designed for lifting and moving heavy loads. Some of the important types of cranes are bridge cranes, gantry cranes and jib cranes. These are discussed as follows.

4.1 Bridge crane

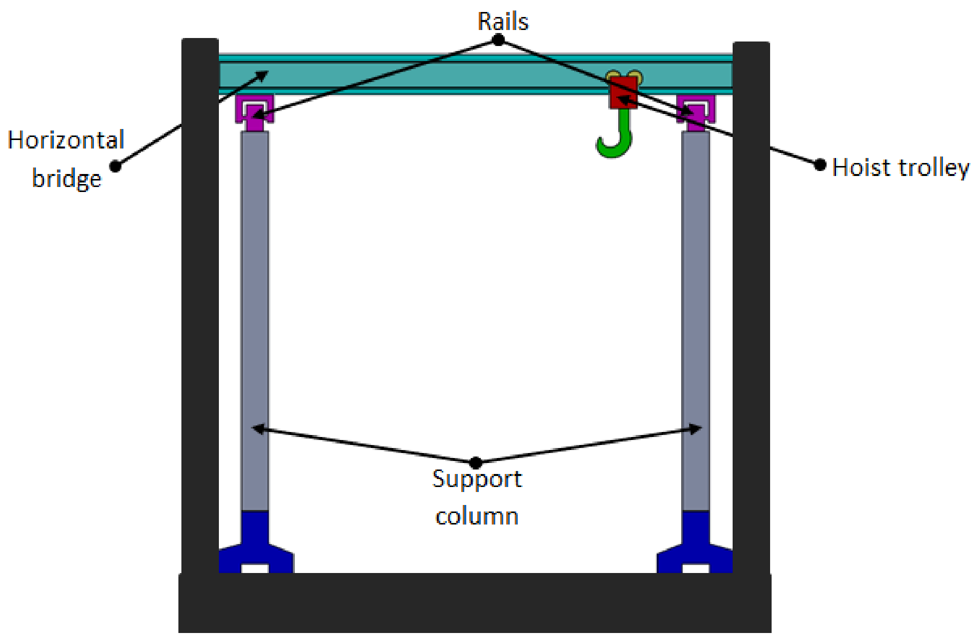

Fig. 4.6.6 Bridge crane

It consists of one or two horizontal beams supported between fixed rails on either end as shown in Fig. 4.6.6. The hoist moves along the length of the bridge, and the bridge moves along the rails. The x- and y-axes movements are provided by the above said movements and the hoist provides motion in the z-axis direction. In the bridge crane, vertical lifting is due to the hoist and horizontal movement of the material is due to the rail system. They are generally used in heavy machinery fabrication, steel mills, and power-generating stations.

4.2 Gantry crane

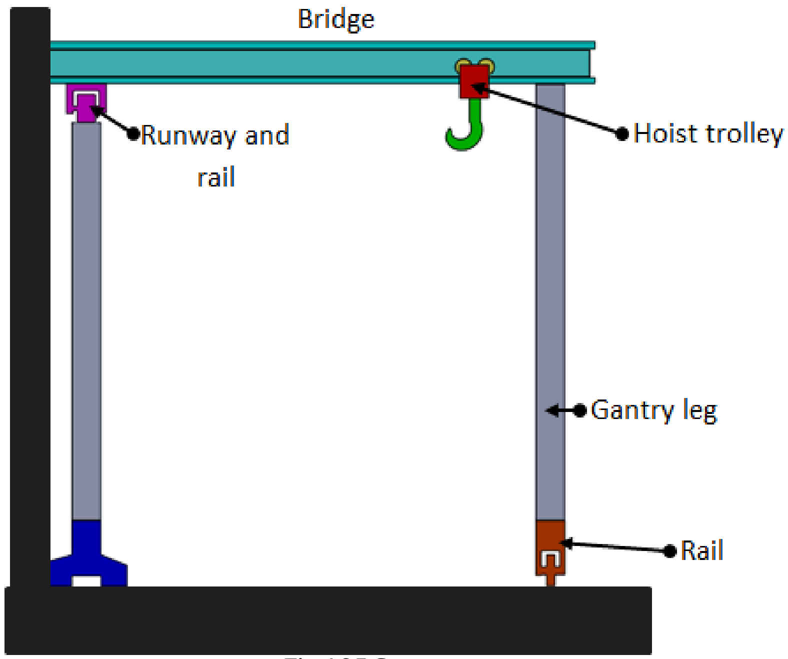

Fig. 4.6.7 Gantry crane

These types of cranes have one or two vertical legs which support the horizontal bridge. The bridge of the gantry crane has one or more hoists that help in vertical lifting as shwon in Fig. 4.6.7. Gantries are available in a variety of sizes. A double gantry crane has two legs. Other types of gantry cranes are half gantries and cantilever gantries. In a half gantry crane, there is a single leg on one end of the bridge, and the other end is supported by a rail mounted on the wall or other structural member. In a cantilever gantry crane the bridge extends beyond the length of support legs.

4.3 Jib crane

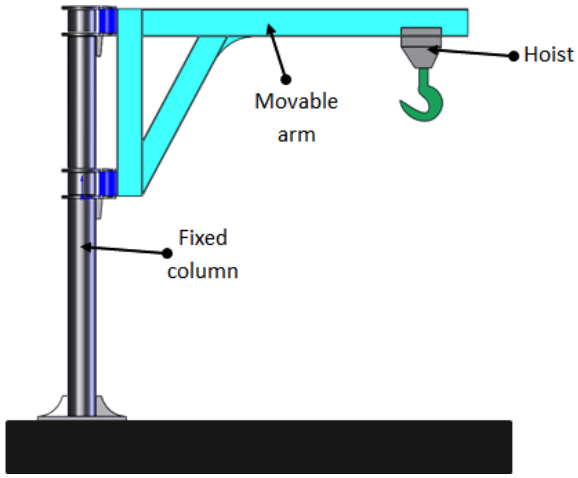

Fig. 4.6.8 Jib crane

It consists of a hoist mounted on a horizontal cantilever beam which is supported by a vertical column as shown in Fig. 4.6.8. The horizontal beam is pivoted about the vertical axis formed by the column to provide a horizontal sweep for the crane. The beam acts as a track for the hoist trolley to provide radial travel along the length of the beam. The horizontal sweep of a jib crane is circular or semicircular. The hoist provides vertical lifting and lowering movements.

5. Rail-Guided Vehicles

These are material transport equipments consisting of motorized vehicles that are guided by a fixed rail system. These are self-propelled vehicles that ride on a fixed-rail system. The vehicles operate independently and are driven by electric motors that pick up power from an electrified rail. The fixed rail system can be classified as,

- Overhead monorail
- On-floor parallel rails

Monorails are typically suspended overhead from the ceiling. In rail guided vehicle systems using parallel fixed rails on floor rails, the tracks generally protrude up from the floor. The vehicles operate asynchronously and are driven by an on-board electric motor. The rail guided vehicles pick up electrical power from an electrified rail. In such vehicles routing variations are possible.

6. Conveyors

These are of material transfer equipments designed to move materials over fixed paths, usually in large quantities or volumes. They can be classified as non-powered and powered systems. In non-powered systems, the materials are moved by human workers or by gravity whilst in powered systems, materials are transported by using automated systems. There are various types of conveyors such as roller, skate-wheel, belt, in-floor towline; overhead trolley conveyor and cart-on-track conveyor are used in industry.

6.1 Roller conveyor

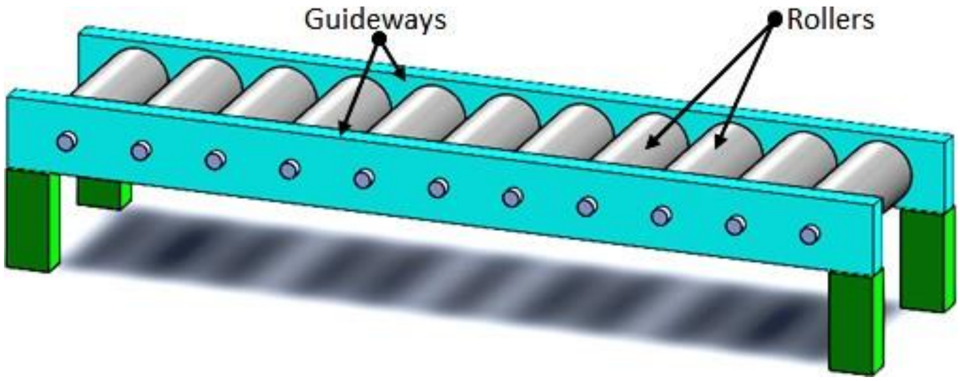

Fig. 4.6.9 Roller conveyor

In roller conveyors, the pathway consists of a series of rollers that are perpendicular to the direction of travel as shwon in Fig. 4.6.9. Loads must possess a flat bottom or placed in carts. Powered rollers rotate to drive the loads forward.

6.2 In-Floor Tow-Line Conveyor

It consists of a four wheel cart powered by moving chains or cables placed in trenches in the floor. Carts use steel pins which project below floor level and engage the chain for towing. The pins can be pulled out to allow the carts to be disengaged from towline for loading and unloading purpose.

6.3 Overhead Trolley Conveyor

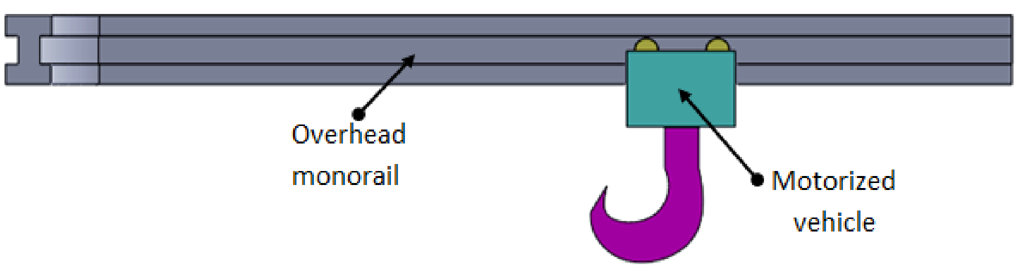

Fig. 4.6.10 Overhead trolley conveyor

In this equipment a motorized vehicle runs over an overhead track. By moving this trolley, loads can be conveyed with the help of hook as shown in Figure 4.6.10. Trolleys are connected and moved by a chain or cable that forms a complete loop. These are often used to move parts such heavy dies, molds, and assemblies of machine components.

6.4 Belt Conveyors

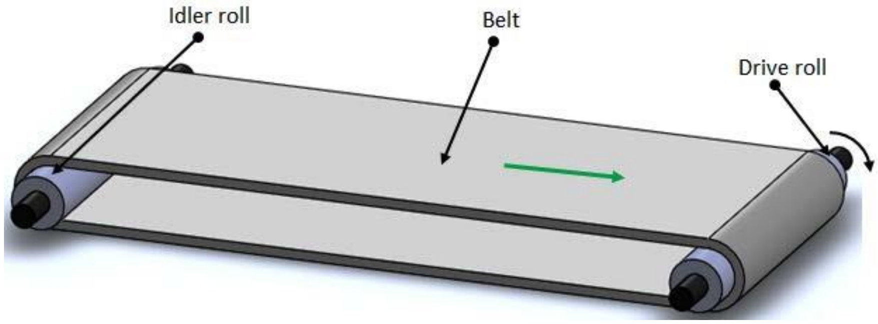

Fig. 4.6.11 Belt drive

Belt conveyors consist of a continuous loop of belt material (Fig.4.6.11). Half of the length is used to deliver the materials and the other half is for idle return. The drive roll powers the belt. The belt conveyors are of two types, namely flat belts and troughed belts. These are very commonly used in industry to convey light to heavy, solid, loose commodities such as food grains, sugar, cement bags, coal etc. They are also widely used to transfer small to large size cartons/boxes of products. Detail analysis and design of conveyors is out of the scope of this course.

7 Rotary indexing table

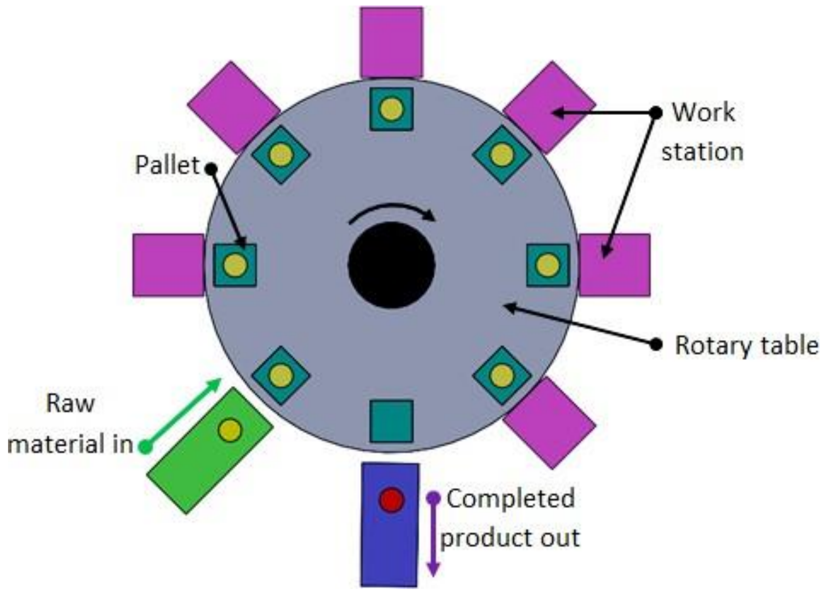

Fig. 4.6.12 Rotary indexing table

These are used for the synchronous transfer of small parts from one station to the other station at single work center. The workparts are indexed around a rotary table. The workstations are stationary and usually located around the outside periphery of the dial as shwon in Fig. 4.6.12. The parts riding on the rotating table are positioned at each station for their processing or assembly operation. This type of equipment is called as an indexing machine or dial index machine. These are generally used to carry out assembly operations of small sized products such as watches, jewelery, electronic circuits, small molds/dies, consumer appliances etc.

Module 4 Drives and Mechanisms

Lecture 1

Elements of CNC machine tools: electric motors

1. 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.

2. Power drives

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 stepless 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.

In CNC, usually AC, DC, servo and stepper electrical drives are used. The various drives used in CNC machines can be classified as:

a. Spindle drives to provide the main spindle power for cutting action
b. Feed drives to drive the axis

2.1 Spindle drives

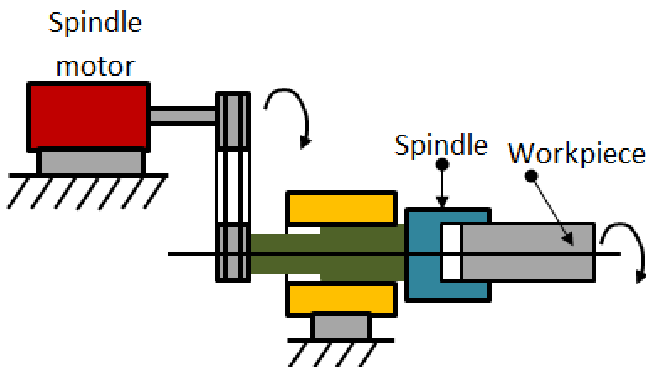

Fig. 4.1.1 Schematic of a spindle drive

The spindle drives are used to provide angular motion to the workpiece or a cutting tool. Figure 4.1.1 shows the components of a spindle drive. 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.

2.2Feed Drives

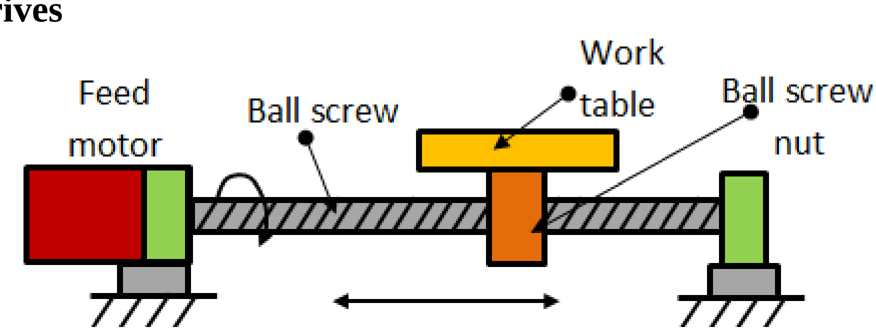

Fig. 4.1.2 Typical feed drive

These are used to drive the slide or a table. Figure 4.1.2 shows various elements of a feed drive. 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.

3. Electrical drives

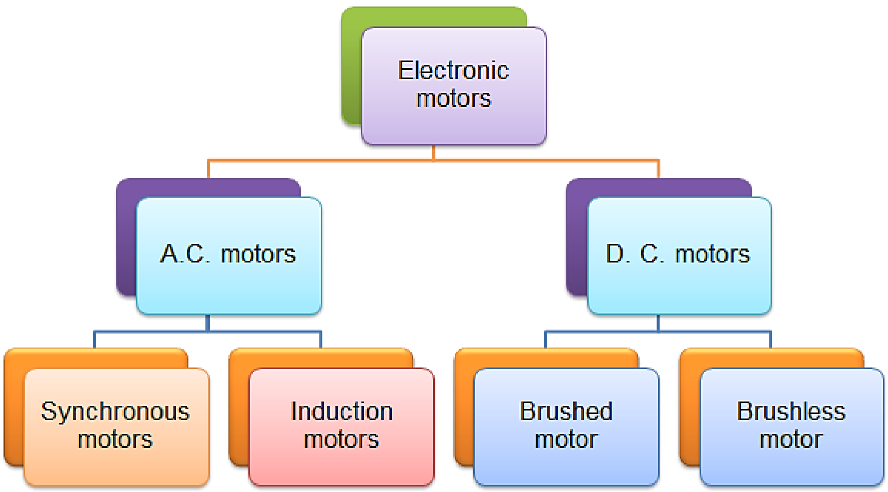

Fig. 4.1.3 Classification of motors

Electric drives are mostly used in position and speed control systems. The motors can be classified into two groups namely DC motors and AC motors (Fig. 4.1.3). In this session we shall study the operation, construction, advantages and limitations of DC and AC motors.

3.1. DC motors

A DC motor is a device that converts direct current (electrical energy) into rotation of an element (mechanical energy). These motors can further be classified into brushed DC motor and brushless DC motors.

3.1.1 Brush type DC motor

A typical brushed motor consists of an armature coil, slip rings divided into two parts, a pair of brushes and horse shoes electromagnet as shown in Fig. 4.1.4. A simple DC motor has two field poles namely a north pole and a south pole. The magnetic lines of force extend across the opening between the poles from north to south. The coil is wound around a soft iron core and is placed in between the magnet poles. These electromagnets receive electricity from an outside power source. The coil ends are connected to split rings. The carbon brushes are in contact with the split rings. The brushes are connected to a DC source. Here the split rings rotate with the coil while the brushes remain stationary.

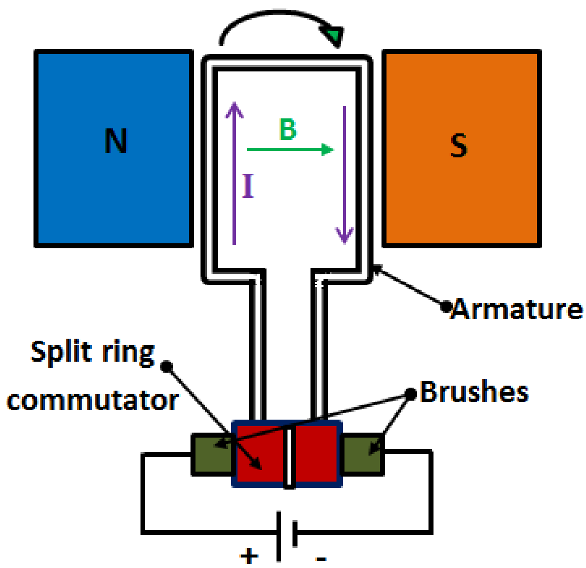

Fig. 4.1.4 Brushed DC motor

The working is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by Fleming's left-hand rule. The magnitude of the force is given by

$$F = BILsin\theta \qquad (4.1.1)$$

Where, B is magnetic field density in weber/m^2

I is the current in amperes and

L is the length of the conductor in meter

θ is the angle between the direction of the current in the conductor and the electric field

If the current and filed are perpendicular then θ=90°. The equation 4.1.1 becomes,

$$F = BIL \qquad (4.1.2)$$

A direct current in a set of windings creates a magnetic field. This field produces a force which turns the armature. This force is called torque. This torque will cause the armature to turn until its magnetic field is aligned with the external field. Once aligned the direction of the current in the windings on the armature reverses, thereby reversing the polarity of the rotor's electromagnetic field. A torque is once again exerted on the rotor, and it continues spinning. The change in direction of current is facilitated by the split ring commutator. The main purpose of the commutator is to overturn the direction of the electric current in the armature. The commutator also aids in the transmission of current between the armature and the power source. The brushes remain stationary, but they are in contact with the armature at the commutator, which rotates with the armature such that at every 180° of rotation, the current in the armature is reversed.

***Advantages of brushed DC motor*:**

- The design of the brushed DC motor is quite simple
- Controlling the speed of a Brush DC Motor is easy
- Very cost effective

***Disadvantages of brushed DC motor*:**

- High maintenance
- Performance decreases with dust particles
- Less reliable in control at lower speeds
- The brushes wear off with usage

3.1.2 Brushless DC motor

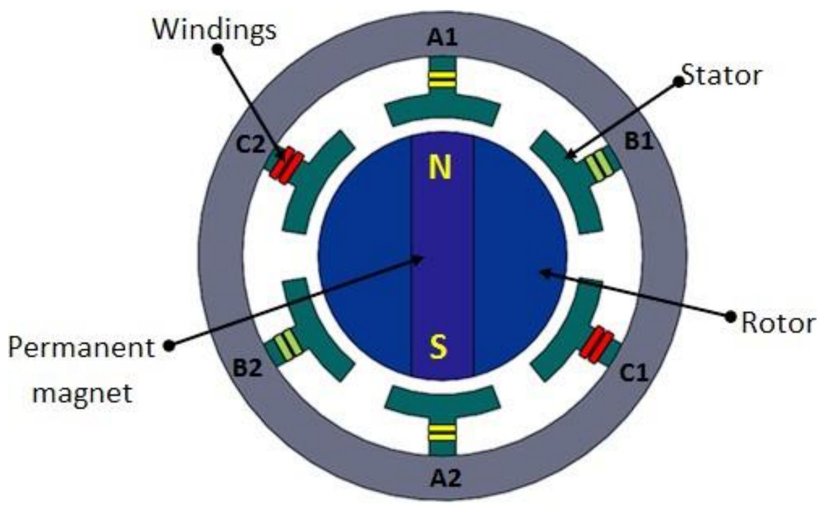

Fig. 4.1.5 Brushless DC motor

A brushless DC motor has a rotor with permanent magnets and a stator with windings. The rotor can be of ceramic permanent magnet type. The brushes and commutator are eliminated and the windings are connected to the control electronics. The control electronics replace the commutator and brushes and energize the stator sequentially. Here the conductor is fixed and the magnet moves (Fig. 4.1.5).

The current supplied to the stator is based on the position of rotor. It is switched in sequence using transistors. The position of the rotor is sensed by Hall effect sensors. Thus a continuous rotation is obtained.

***Advantages of brushless DC motor*:**

- More precise due to computer control
- More efficient
- No sparking due to absence of brushes
- Less electrical noise
- No brushes to wear out
- Electromagnets are situated on the stator hence easy to cool
- Motor can operate at speeds above 10,000 rpm under loaded and unloaded conditions
- Responsiveness and quick acceleration due to low rotor inertia

***Disadvantages of brushless DC motor*:**

- Higher initial cost
- Complex due to presence of computer controller
- Brushless DC motor also requires additional system wiring in order to power the electronic commutation circuitry

3.2 AC motors

AC motors convert AC current into the rotation of a mechanical element (mechanical energy). As in the case of DC motor, a current is passed through the coil, generating a torque on the coil. Typical components include a stator and a rotor. The armature of rotor is a magnet unlike DC motors and the stator is formed by electromagnets similar to DC motors. The main limitation of AC motors over DC motors is that speed is more difficult to control in AC motors. To overcome this limitation, AC motors are equipped with variable frequency drives but the improved speed control comes together with a reduced power quality.

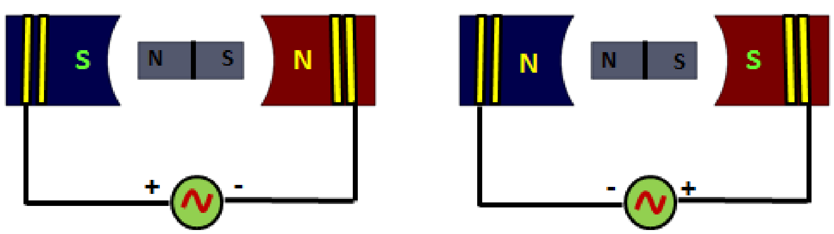

Fig. 4.1.6 AC motor working principle

The working principle of AC motor is shown in fig. 4.1.6. Consider the rotor to be a permanent magnet. Current flowing through conductors energizes the magnets and develops N and S poles. The strength of electromagnets depends on current. First half cycle current flows in one direction and in the second half cycle it flows in opposite direction. As AC voltage changes the poles alternate.

AC motors can be classified into synchronous motors and induction motors.

3.2.1 Synchronous motor

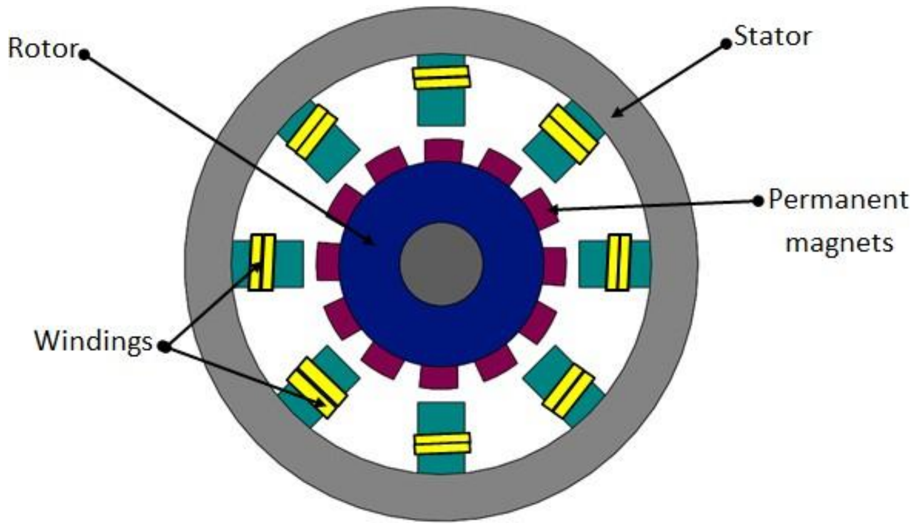

Fig. 4.1.7 Synchronous AC motor

A synchronous motor is an AC motor which runs at constant speed fixed by frequency of the system. It requires direct current (DC) for excitation and has low starting torque, and hence is suited for applications that start with a low load. It has two basic electrical parts namely stator and rotor as shown in fig. 4.1.7. The stator consists of a group of individual wounded electro-magnets arranged in such a way that they form a hollow cylinder. The stator produces a rotating magnetic field that is proportional to the frequency supplied. The rotor is the rotating electrical component. It also consists of a group of permanent magnets arranged around a cylinder, with the poles facing toward the stator poles. The rotor is mounted on the motor shaft. The main difference between the synchronous motor and the induction motor is that the rotor of the synchronous motor travels at the same speed as the rotating magnet.

The stator is given a three phase supply and as the polarity of the stator progressively change the magnetic field rotates, the rotor will follow and rotate with the magnetic field of the stator. If a synchronous motor loses lock with the line frequency it will stall. It cannot start by itself, hence has to be started by an auxiliary motor.

Synchronous speed of an AC motor is determined by the following formula:

$$N_s = \frac{120 * f}{P} \qquad (4.1.3)$$

N_s = Revolutions per minute
P = Number of pole pairs
f = Applied frequency

3.2.2 Induction motor

Induction motors are quite commonly used in industrial automation. In the synchronous motor the stator poles are wound with coils and rotor is permanent magnet and is supplied with current to create fixed polarity poles. In case of induction motor, the stator is similar to synchronous motor with windings but the rotors' construction is different.

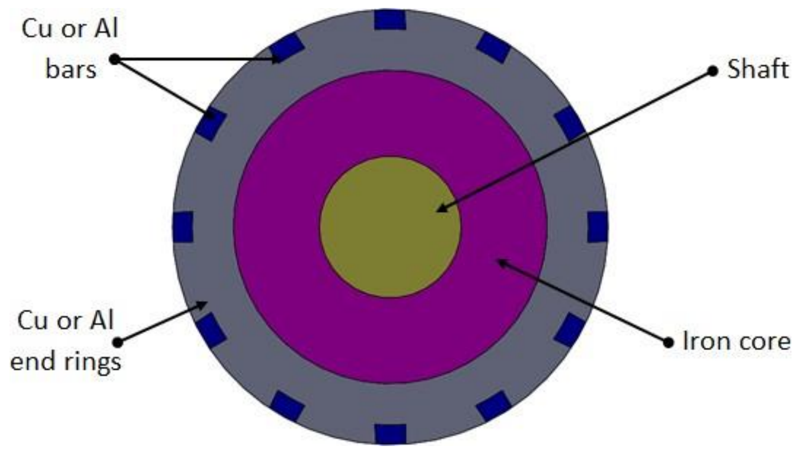

Fig. 4.1.8 Induction motor rotor

Rotor of an induction motor can be of two types:

- A squirrel-cage rotor consists of thick conducting bars embedded in parallel slots. The bars can be of copper or aluminum. These bars are fitted at both ends by means end rings as shown in figure 4.1.8.
- A wound rotor has a three-phase, double-layer, distributed winding. The rotor is wound for as many numbers of poles as the stator. The three phases are wired internally and the other ends are connected to slip-rings mounted on a shaft with brushes resting on them.

Induction motors can be classified into two types:

- *Single-phase induction motor*: It has one stator winding and a squirrel cage rotor. It operates with a single-phase power supply and requires a device to start the motor.
- *Three-phase induction motor*: The rotating magnetic field is produced by the balanced three-phase power supply. These motors can have squirrel cage or wound rotors and are self-starting.

In an induction motor there is no external power supply to rotor. It works on the principle of induction. When a conductor is moved through an existing magnetic field the relative motion of the two causes an electric current to flow in the conductor. In an induction motor the current flow in the rotor is not caused by any direct connection of the conductors to a voltage source, but rather by the influence of the rotor conductors cutting across the lines of flux produced by the stator magnetic fields. The induced current which is produced in the rotor results in a magnetic field around the rotor. The magnetic field around each rotor conductor will cause the rotor conductor to act like the permanent magnet. As the magnetic field of the stator rotates, due to the effect of the three-phase AC power supply, the induced magnetic field of the rotor will be attracted and will follow the rotation. However, to produce torque, an induction motor must suffer from slip. Slip is the result of the induced field in the rotor windings lagging behind the rotating magnetic field in the stator windings. The slip is given by,

$$S = \frac{Synchronous\ speed - Actual\ speed}{Synchronous\ speed} * 100\% \qquad (4.1.4)$$

Advantages of AC induction motors

- It has a simple design, low initial cost, rugged construction almost unbreakable
- The operation is simple with less maintenance (as there are no brushes)
- The efficiency of these motors is very high, as there are no frictional losses, with reasonably good power factor
- The control gear for the starting purpose of these motors is minimum and thus simple and reliable operation

Disadvantages of AC induction motors

- The speed control of these motors is at the expense of their efficiency
- As the load on the motor increases, the speed decreases
- The starting torque is inferior when compared to DC motors

Module 4 Drives and Mechanisms

Lecture 2

Stepper motors and Servo motors

1. Stepper motor

A stepper motor is a pulse-driven motor that changes the angular position of the rotor in steps. Due to this nature of a stepper motor, it is widely used in low cost, open loop position control systems.

Types of stepper motors:

- Permanent Magnet
  - Employ permanent magnet
  - Low speed, relatively high torque
- Variable Reluctance
  - Does not have permanent magnet
  - Low torque

1.1 Variable Reluctance Motor

Figure 4.2.1 shows the construction of Variable Reluctance motor. The cylindrical rotor is made of soft steel and has four poles as shown in Fig.4.2.1. It has four rotor teeth, 90^{0} apart and six stator poles, 60^{0} apart. Electromagnetic field is produced by activating the stator coils in sequence. It attracts the metal rotor. When the windings are energized in a reoccurring sequence of 2, 3, 1, and so on, the motor will rotate in a 30^{0} step angle. In the non-energized condition, there is no magnetic flux in the air gap, as the stator is an electromagnet and the rotor is a piece of soft iron; hence, there is no detent torque. This type of stepper motor is called a variable reluctance stepper.

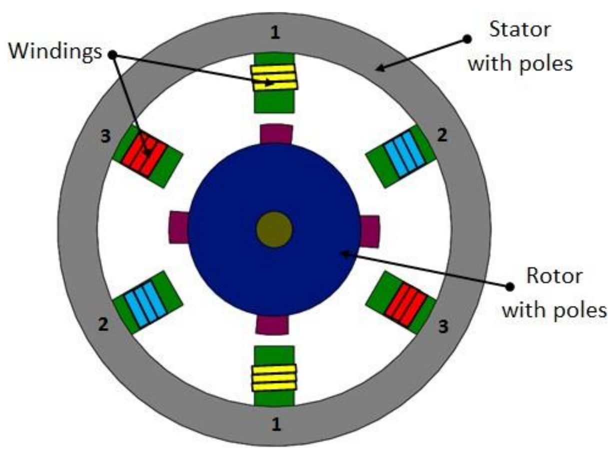

Fig. 4.2.1 Variable reluctance stepper motor

1.2 Permanent magnet (PM) stepper motor

In this type of motor, the rotor is a permanent magnet. Unlike the other stepping motors, the PM motor rotor has no teeth and is designed to be magnetized at a right angle to its axis. Figure 4.2.2 shows a simple, 90^0 PM motor with four phases (A-D). Applying current to each phase in sequence will cause the rotor to rotate by adjusting to the changing magnetic fields. Although it operates at fairly low speed, the PM motor has a relatively high torque characteristic. These are low cost motors with typical step angle ranging between 7.5^0 to 15^0.

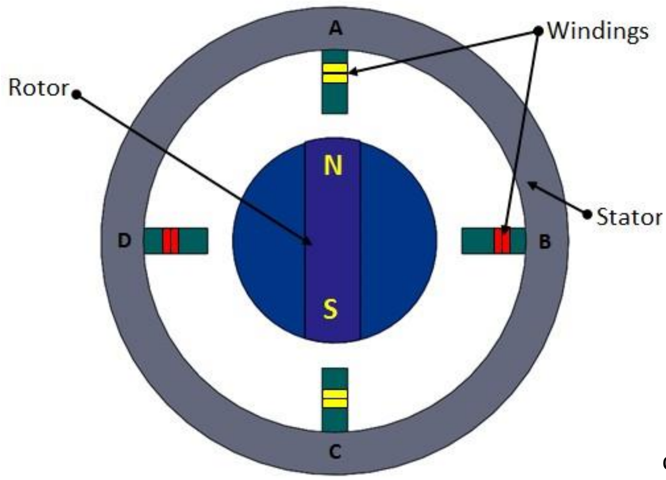

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Fig. 4.2.2 Permanent magnet stepper

1.3 Hybrid stepper motor

Hybrid stepping motors combine a permanent magnet and a rotor with metal teeth to provide features of the variable reluctance and permanent magnet motors together. The number of rotor pole pairs is equal to the number of teeth on one of the rotor's parts. The hybrid motor stator has teeth creating more poles than the main poles windings (Fig. 4.2.3).

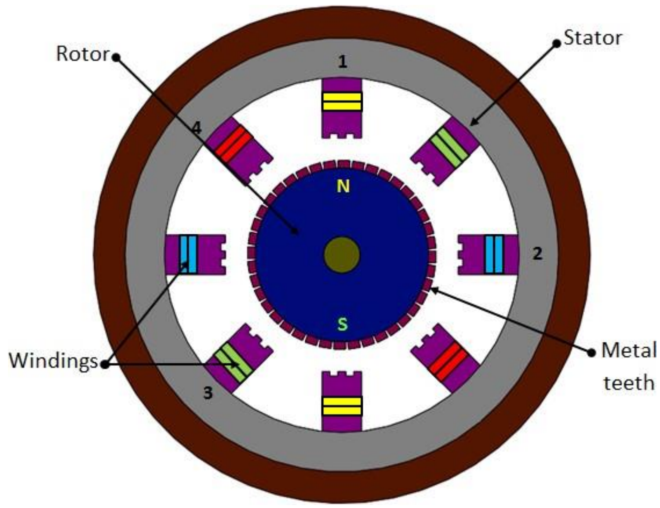


Fig. 3 Hybrid stepper motor

Rotation of a hybrid stepping motor is produced in the similar fashion as a permanent magnet stepping motor, by energizing individual windings in a positive or negative direction. When a winding is energized, north and south poles are created, depending on the polarity of the current flowing. These generated poles attract the permanent poles of the rotor and also the finer metal teeth present on rotor. The rotor moves one step to align the offset magnetized rotor teeth to the corresponding energized windings. Hybrid motors are more expensive than motors with permanent magnets, but they use smaller steps, have greater torque and maximum speed.

Step angle of a stepper motor is given by,

$$\text{Step angle} = \frac{360°}{\text{Number of poles}} \qquad (4.2.1)$$

Advantages of stepper motors

- Low cost
- Ruggedness
- Simplicity of construction
- Low maintenance
- Less likely to stall or slip
- Will work in any environment
- Excellent start-stop and reversing responses

Disadvantages of stepper motors

- Low torque capacity compared to DC motors
- Limited speed
- During overloading, the synchronization will be broken. Vibration and noise occur when running at high speed.

2. Servomotor

Servomotors are special electromechanical devices that produce precise degrees of rotation. A servo motor is a DC or AC or brushless DC motor combined with a position sensing device. Servomotors are also called control motors as they are involved in controlling a mechanical system. The servomotors are used in a closed-loop servo system as shown in Figure 4.2.4. A reference input is sent to the servo amplifier, which controls the speed of the servomotor. A feedback device is mounted on the machine, which is either an encoder or resolver. This device changes mechanical motion into electrical signals and is used as a feedback. This feedback is sent to the error detector, which compares the actual operation with that of the reference input. If there is an error, that error is fed directly to the amplifier, which will be used to make necessary corrections in control action. In many servo systems, both velocity and position are monitored. Servomotors provide accurate speed, torque, and have ability of direction control.

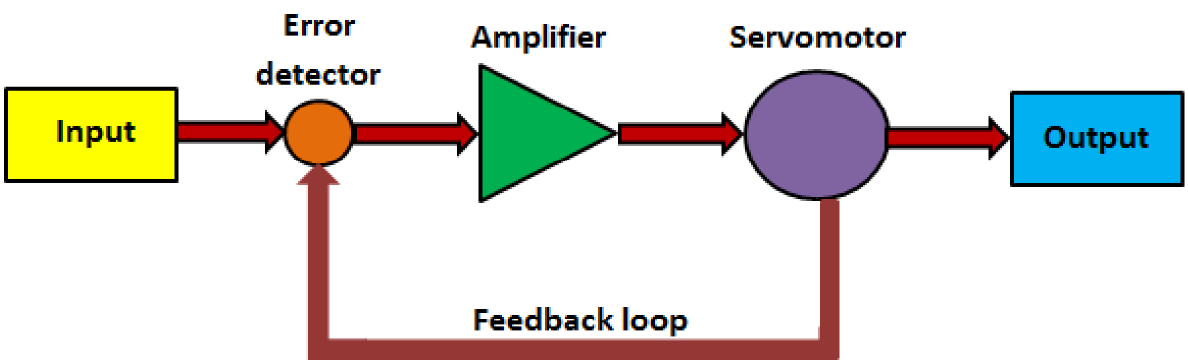


Fig. 4.2.4 Servo system block diagram

2.1 DC servomotors

DC operated servomotors are usually respond to error signal abruptly and accelerate the load quickly. A DC servo motor is actually an assembly of four separate components, namely:

- DC motor
- gear assembly
- position-sensing device
- control circuit

2.2. AC servo motor

In this type of motor, the magnetic force is generated by a permanent magnet and current which further produce the torque. It has no brushes so there is little noise/vibration. This motor provides high precision control with the help of high resolution encoder. The stator is composed of a core and a winding. The rotor part comprises of shaft, rotor core and a permanent magnet.

Digital encoder can be of optical or magnetic type. It gives digital signals, which are in proportion of rotation of the shaft. The details about optical encoder have already discussed in Lecture 3 of Module 2.

Advantages of servo motors

- Provides high intermittent torque, high torque to inertia ratio, and high speeds
- Work well for velocity control
- Available in all sizes
- Quiet in operation
- Smoother rotation at lower speeds

Disadvantages of servo motors

- More expensive than stepper motors
- Require tuning of control loop parameters
- Not suitable for hazardous environments or in vacuum
- Excessive current can result in partial demagnetization of DC type servo motor

Module 4 Drives and Mechanisms

Lecture 3

Cams

Cams are mechanical devices which are used to generate curvilinear or irregular motion of mechanical elements. They are used to convert rotary motion into oscillatory motion or oscillatory motion into rotary motion. There are two links namely the cam itself which acts as an input member. The other link that acts as an output member is called the follower. The cam transmits the motion to the follower by direct contact. In a cam-follower pair, the cam usually rotates while the follower translates or oscillates. Complicated output motions which are otherwise difficult to achieve can easily be produced with the help of cams. Cams are widely used in internal combustion engines, machine tools, printing control mechanisms, textile weaving industries, automated machines etc.

Necessary elements of a cam mechanism are shown in Figure 4.3.1.

- A driver member known as the cam
- A driven member called the follower
- A frame which supports the cam and guides the follower

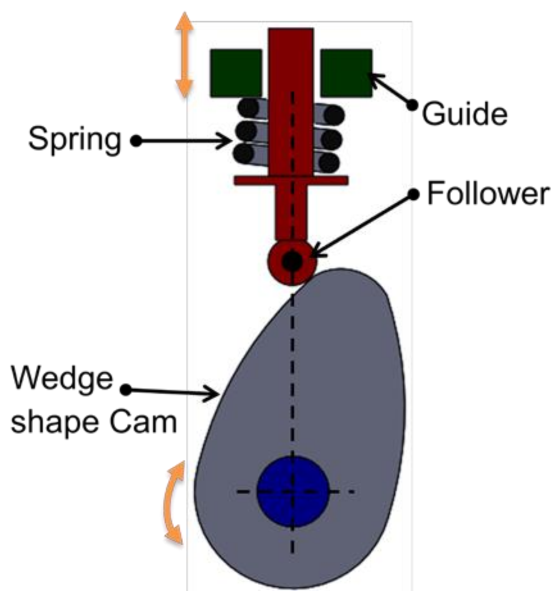


Figure 4.3.1 Cam mechanism.

1. Classification of cams

1.1 Wedge and Flat Cams

A wedge cam has a wedge of specified contour and has translational motion. The follower can either translate or oscillate. A spring is used to maintain the contact between the cam and the follower. Figure 4.3.2 shows the typical arrangement of Wedge cam.

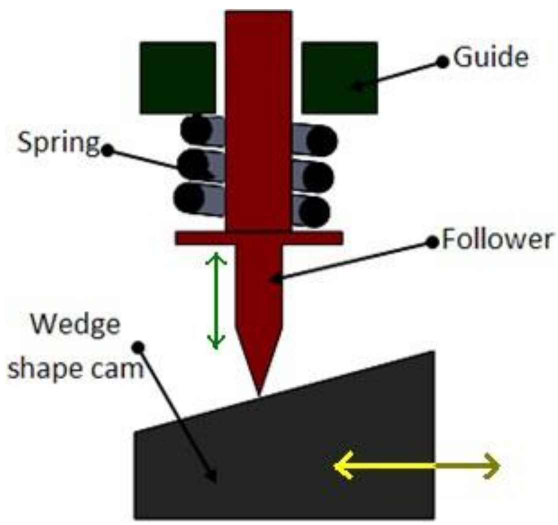


Figure 4.3.2 Wedge cam

1.2 Plate cam

In this type of cams, the follower moves in a radial direction from the centre of rotation of the cam (Figure 4.3.3). They are also known as radial or disc cam. The follower reciprocates or oscillates in a plane normal to the cam axis. Plate cams are very popular due to their simplicity and compactness.

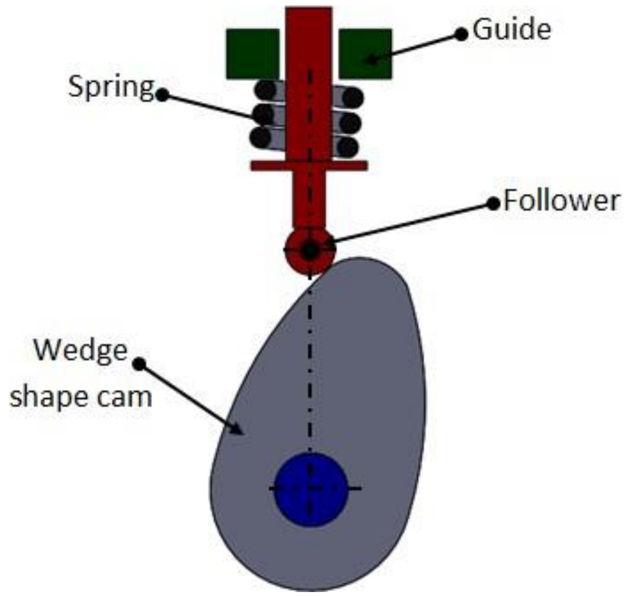


Figure 4.3.3 Plate cam

1.3 Cylindrical cam

Here a cylinder has a circumferential contour cut in the surface and the cam rotates about its axis (Figure 4.3.4). The follower motion is either oscillating or reciprocating type. These cams are also called drum or barrel cams.

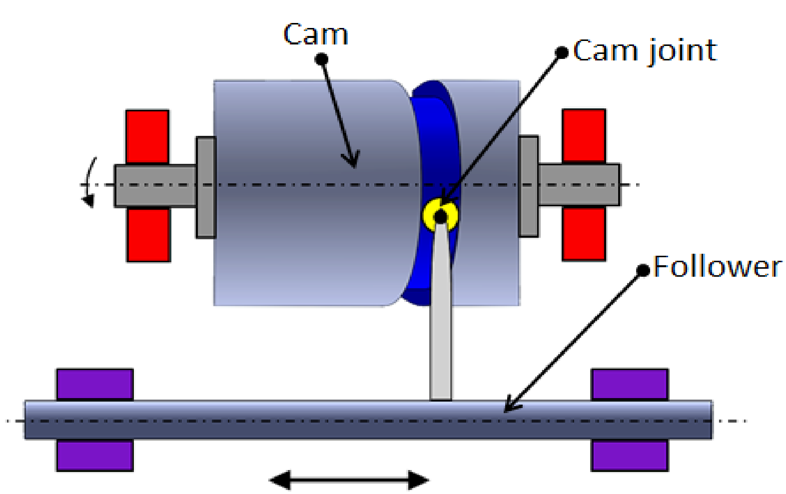


Figure 4.3.4 Cylindrical cam

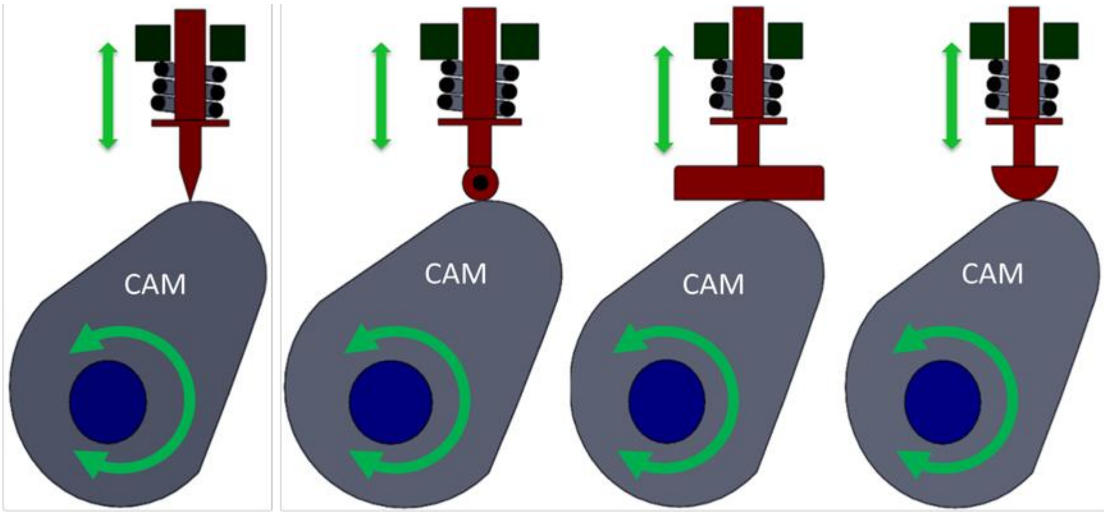
2. Classification of followers:

Followers can be classified based on

- type of surface contact between cam and follower
- type of follower motion
- line of motion of followers

2.1 Classification based on type of surface contact between cam and follower

Figure 4.3.5 shows the schematics of various types of followers used cam mechanisms.



a) With knife edge follower b) With roller follower c) With plate type follower d) With Spherical follower

Figure 4.3.5 Types of follower based on the surface in contact

2.1.1 <u>Knife edge follower</u>

The contacting end of the follower has a sharp knife edge. A sliding motion exists between the contacting cam and follower surfaces. It is rarely used in practice because the small area of contacting surface results in excessive wear.

2.1.2 <u>Roller follower</u>

It consists of a cylindrical roller which rolls on cam surface. Because of the rolling motion between the contacting surfaces, the rate of wear is reduced in comparison with Knife edge follower. The roller followers are extensively used where more space is available such as gas and oil engines.

2.1.3 Flat face follower

The follower face is perfectly flat. It experiences a side thrust due to the friction between contact surfaces of follower and cam.

2.1.4 Spherical face follower

The contacting end of the follower is of spherical shape which overcomes the drawback of side thrust as experiences by flat face follower.

2.2 Classification based on followers' motion

Figure 4.3.6 shows the types of cams based followers' motion.

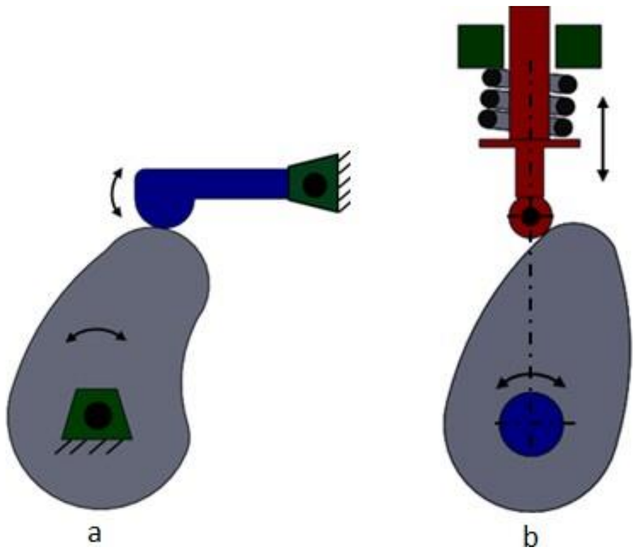


Figure 4.3.6 Classification of follower based on motion

2.2.1 Oscillating follower

In this configuration, the rotary motion of the cam is converted into predetermined oscillatory motion of the follower as shown in Figure 4.3.6 a).

2.2.2 Translating follower

These are also called as reciprocating follower. The follower reciprocates in the 'guide' as the cam rotates uniformly as shown in Figure 4.3.6 b).

2.3 Classification based on line of motion

Figure 4.3.7 shows the types of cams based followers' line of motion.

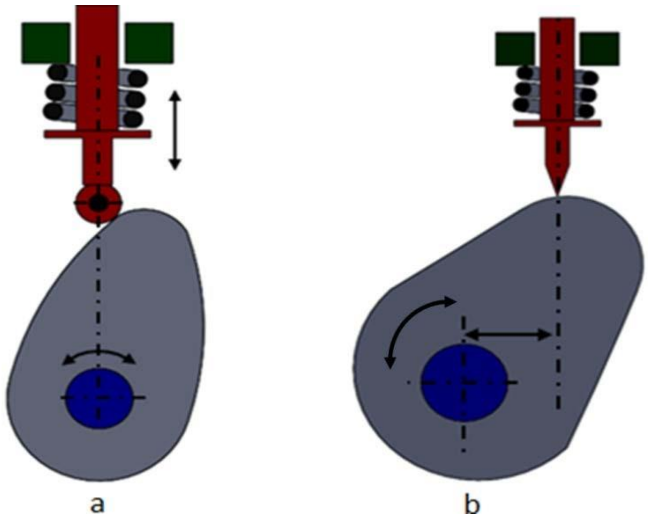


Figure 4.3.7 Classification of follower based on line of motion

4.3.1 Radial follower

The line of movement of the follower passes through the center of the camshaft (Figure 4.3.7 a).

4.3.2 Offset follower

The line of movement of the follower is offset from the center of the cam shaft (Figure 4.3.7 b).

3. *Force closed cam follower system*

In this type of cam-follwer system, an external force is needed to maintain the contact between cam and follower. Generally a spring maintains the contact between the two elements. The follower can be a oscillating type (Figure 4.3.8 a) or of translational type (Figure 4.3.8 b).

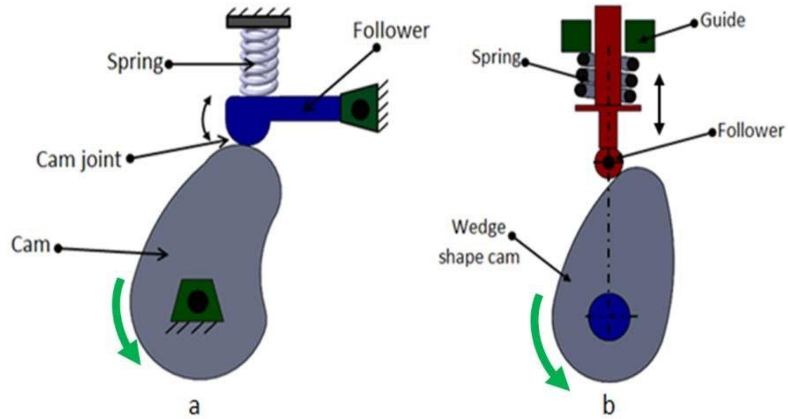


Figure 4.3.8 Force closed cam followers

4. *Form closed cam foller system*

In this system a slot or a groove profile is cut in the cam. The roller fits in the slot and follows the groove profile. These kind of systems do not require a spring. These are extensively used in machine tools and machinery. The follower can be a translating type (Figure 4.3.9 a) oscillating type (Figure 4.3.9 b).

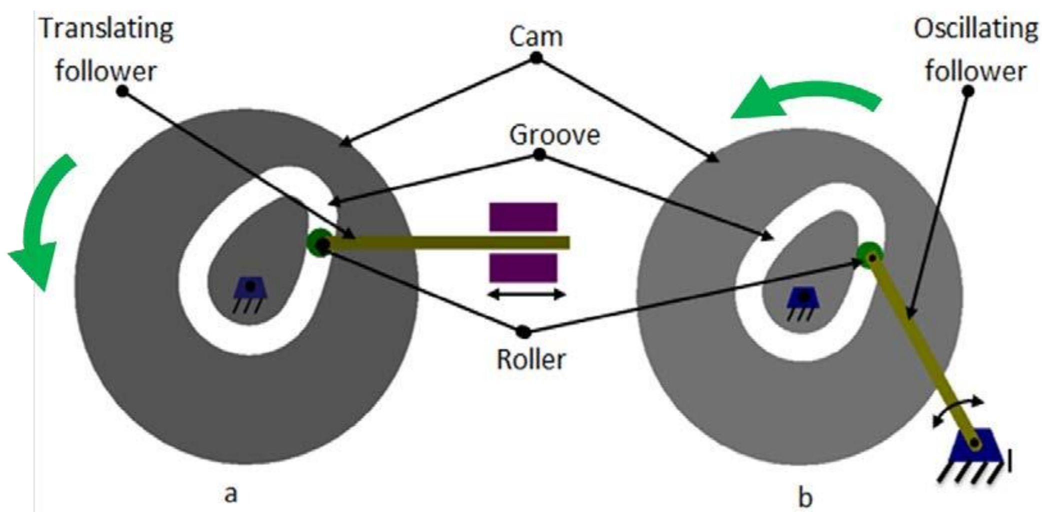


Figure 4.3.9 Form closed cam followers

5. Three-dimensional cam or Camoid

Camoid is a combination of radial and axial cams. It has three dimensional surface and two degrees-of-freedom. Two inputs are rotation of the cam about its axis and translation of the cam along its axis. Follower motion is based on both the inputs. Figure 4.3.10 shows a typical Camoid.

Figure 4.3.10 A Camoid

6. *Applications of cams*

Cams are widely used in automation of machinery, gear cutting machines, screw machines, printing press, textile industries, automobile engine valves, tool changers of machine centers, conveyors, pallet changers, sliding fork in wearhouses etc.

Cams are also used in I.C engines to operate the inlet valves and exhaust valves.The cam shaft rotates by using prime moveres. It causes the rotation of cam. This rotation produces translatory motion of tappet against the spring. This translatory motion is used to open or close the valve. The schematic of this operation is shown in Figure 4.3.11.

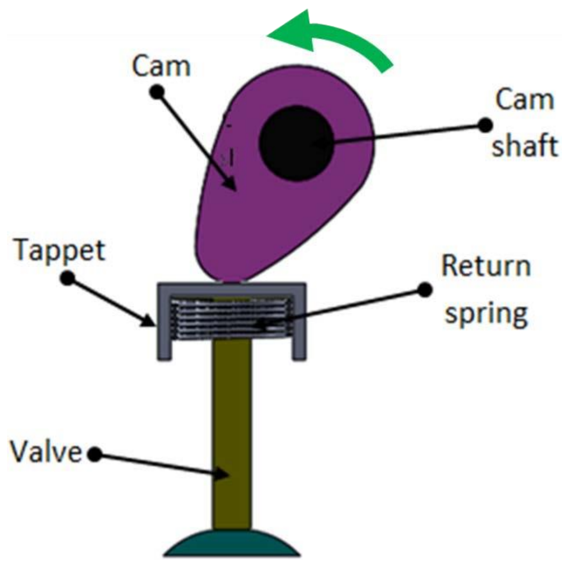


Figure 4.3.11 Cam in I.C engine

6.1 Cams in automatic lathes

The cam shaft is driven by a motor. The cutting tool mounted on the transverse slide travels to desired depth and at desired feed rate by a set of plate cams mounted on the cam shaft. The bar feeding through headstock at desired feed rate is carried out by a set of plate cams mounted on the camshaft.

6.2 Automatic copying machine

The cam profile can be transferred onto the work piece by using a roller follower as shown in Figure 4.3.12. The follower can be mounted with a cutting tool. As the cam traverses, the roller follows the cam profile. The required feature can be copied onto the workpiece by the movement of follower over the cam profile.

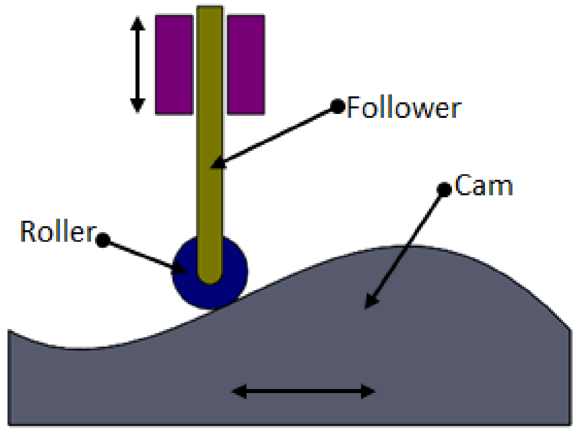


Figure 4.3.12 Automatic copying of cam profile

Module 4 Drives and Mechanisms

Lecture 4

Linear motion drives

Linear motion drives are mechanical transmission systems which are used to convert rotary motion into linear motion. The conventional thread forms like vee or square are not suitable in CNC because of their high wear and less efficiency. Therefore CNC machines generally employ ball screw for driving their workpiece carriages. These drives provide backlash free operation with low friction-wear characteristics. These are efficient and accurate in comparison with that of nut-and-screw drives. Most widely used linear motion drives are ball screws.

A **linear actuator** is an actuator that produces motion in a straight line. Linear actuators are extensively required in machine tools and industrial machinery. Hydraulic or pneumatic cylinders inherently produce linear motion. Many other mechanisms are used to generate linear motion from a rotating motor.

1. Mechanical actuators

These actuators convert rotary motion into linear motion. Conversion is made by using various types of mechanisms such as:

- Screw: This is a simple machine known as screw. By rotating the screw shaft, the actuator's nut moves in a line.
- Wheel and axle: Hoist, winch, rack and pinion, chain drive, belt drive, rigid chain and rigid belt actuators operate on the principle of the wheel and axle. A rotating wheel moves a cable, rack, chain or belt to produce linear motion.
- Cam: discussed in last lecture.
- Hydraulic actuators utilize pressurized fluid to produce a linear motion where as pneumatic systems employ compressed air for the same purpose. We will be discussing about these systems in Modules 4 and 5.

2. Piezoelectric actuators

These actuators work on the principle of Piezoelectricity which states that application of a voltage to a crystal material such as Quartz causes it to expand. However, very high voltages produce only tiny expansions. As a result, though the piezoelectric actuators achieve extremely fine positioning resolution, but also have a very short range of motion. In addition, piezoelectric materials exhibit hysteresis which makes it difficult to control their expansion in a repeatable manner.

3. Electro-mechanical actuators

Electro-mechanical actuators are similar to mechanical actuators except that the control knob or handle is replaced with an electric motor. Rotary motion of the motor is converted to linear displacement. In this type of actuators, an electric motor is mechanically connected to rotate a lead screw. A lead screw has a continuous helical thread machined on its circumference running along the length (similar to the thread on a bolt). Threaded onto the lead screw is a lead nut or ball nut with corresponding helical threads. The nut is prevented from rotating with the lead screw (typically the nut interlocks with a non-rotating part of the actuator body). Therefore, when the lead screw is rotated, the nut will be driven along the threads. The direction of motion of the nut depends on the direction of rotation of the lead screw. By connecting linkages to the nut, the motion can be converted to usable linear displacement.

There are many types of motors that can be used in a linear actuator system. These include dc brush, dc brushless, stepper, or in some cases, even induction motors. Electromechanical linear actuators find applications in robotics, optical and laser equipments, or X-Y tables with fine resolution in microns.

4. Linear motors

The working principle of a linear motor is similar to that of a rotary electric motor. It has a rotor and the stator circular magnetic field components are laid down in a straight line. Since the motor moves in a linear fashion, no lead screw is needed to convert rotary motion into linear. Linear motors can be used in outdoor or dirty environments; however the electromagnetic drive should be waterproofed and sealed against moisture and corrosion.

5. *Ball-screw based linear drives*

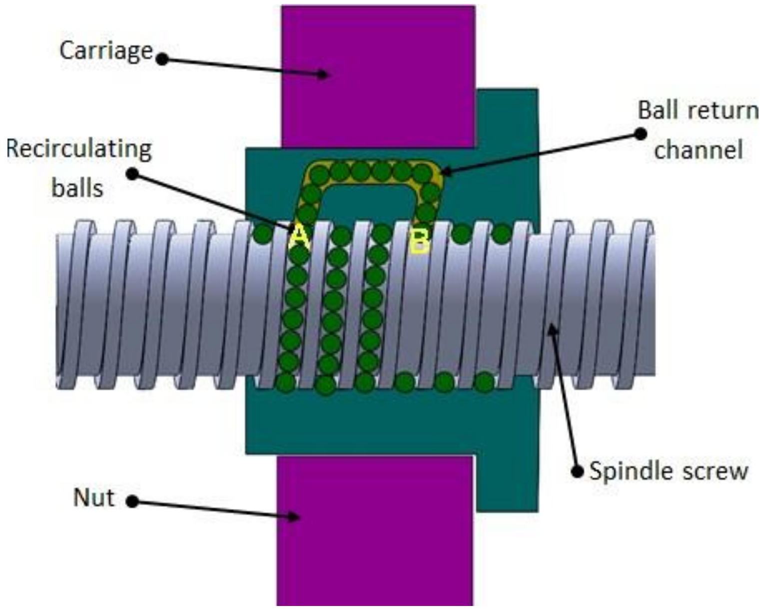


Fig.4.4.1 Ball-screw configuration

Ball screw is also called as ball bearing screw or recirculating ball-screw. It consists of a screw spindle, a nut, balls and integrated ball return mechanism a shown in Figure 4.4.1. The flanged nut is attached to the moving part of CNC machine tool. As the screw rotates, the nut translates the moving part along the guide ways. However, since the groove in the ball screw is helical, its steel balls roll along the helical groove, and, then, they may go out of the ball nut unless they are arrested at a certain spot. Thus, it is necessary to change their path after they have reached a certain spot by guiding them, one after another, back to their "starting point" (formation of a recirculation path). The recirculation parts play that role. When the screw shaft is rotating, as shown in Figure 4.4.1, a steel ball at point (A) travels 3 turns of screw groove, rolling along the grooves of the screw shaft and the ball nut, and eventually reaches point (B). Then, the ball is forced to change its pathway at the tip of the tube, passing back through the tube, until it finally returns to point (A). Whenever the nut strokes on the screw shaft, the balls repeat the same recirculation inside the return tube.

When debris or foreign matter enter the inside of the nut, it could affect smoothness in operation or cause premature wearing, either of which could adversely affect the ball screw's functions. To prevent such things from occurring, seals are provided to keep contaminants out. There are various types of seals viz. plastic seal or brush type of seal used in ball-screw drives.

5.1 Characteristics of ball screws:

5.1.1 High mechanical efficiency

In ball screws, about 90% or more of the force used to rotate the screw shaft can be converted to the force to move the ball nut. Since friction loss is extremely low, the amount of force used to rotate the screw shaft is as low as one third of that needed for the acme thread lead screw.

5.1.2 Low in wear

Because of rolling contact, wear is less than that of sliding contact. Thus, the accuracy is high. Ball screws move smoothly enough under very slow speed. They run smoothly even under a load.

5.2 Thread Form

The thread form used in these screws can either be gothic arc type (Fig. 4.4.2.a) or circular arc type (Fig. 4.4.2.b). The friction in this kind of arrangement is of rolling type. This reduces its wear as comparison with conventional sliding friction screws drives.

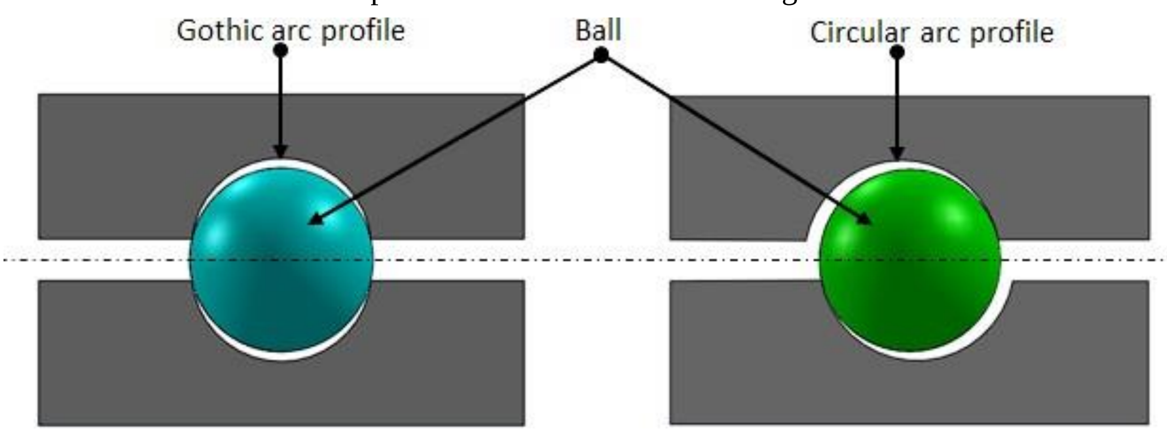


Fig. 2 Thread forms (a) Gothic arc (b) Circular arc

Recirculating ball screws are of two types. In one arrangement the balls are returned using an external tube. In the other arrangement the balls are returned to the start of the thread in the nut through a channel inside the nut.

5.3 Preloading

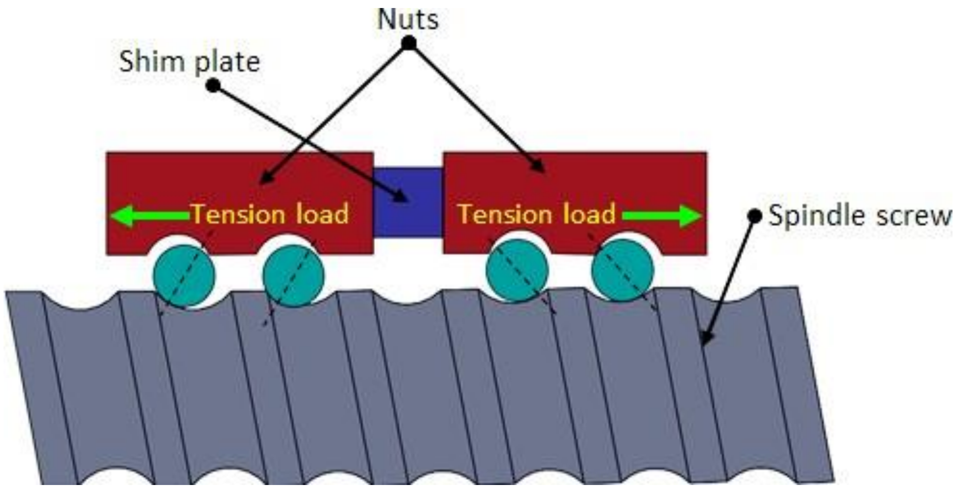


Fig. 4.4.3 Double nut preloading system

In order to obtain bidirectional motion of the carriage without any positional error, the backlash between the nut and screw should be minimum. Zero backlash can be obtained by fitting two nuts with preloading (tension or compression) or by applying a load which exceeds the maximum operating load. Figure 4.4.3 shows double nut preloading system. A shim plate (spacer) is inserted between two nuts for preloading. Preload is to create elastic deformations (deflections) in steel balls and ball grooves in the nut and the screw shaft in advance by providing an axial load. As a result the balls in one of the nuts contact the one side of the thread and balls in the other nut contact the opposite side.

5.3.1 Effects of preload

- Zero backlash: It eliminates axial play between a screw shaft and a ball nut.
- It minimizes elastic deformation caused by external force, thus the rigidity enhances.

In case mounting errors, misalignment between the screw shaft and the nut may occur this further generates distortion forces. This could lead to the problems such as,

- Shortened service life
- Adverse effect on smooth operation
- Reduced positioning accuracy
- Generation of noise or vibration
- Breakage of screw shaft

5.4 Advantages of ball screws

- Highly efficient and reliable.
- Less starting torque.
- Lower co efficient of friction compared to sliding type screws and run at cooler temperatures
- Power transmission efficiency is very high and is of the order of 95 %.
- Could be easily preloaded to eliminate backlash.
- The friction force is virtually independent of the travel velocity and the friction at rest is very small; consequently, the stick-slip phenomenon is practically absent, ensuring uniformity of motion.
- Has longer thread life hence need to be replaced less frequently.
- Ball screws are well -suited to high through output, high speed applications or those with continuous or long cycle times.
- Smooth movement over full range of travel.

5.5 Disadvantages of ball screws

- Tend to vibrate.
- Require periodic overhauling to maintain their efficiency.
- Inclusion of dirt or foreign particles reduces the life of the screws.
- Not as stiff as other power screws, thus deflection and critical speed can cause difficulties.
- They are not self-locking screws hence cannot be used in holding devices such as vices.
- Require high levels of lubrication.

5.6 Applications of ball screws:

- Ball screws are employed in cutting machines, such as machining center and NC lathe where accurate positioning of the table is desired
- Used in the equipments such as lithographic equipment or inspection apparatus where precise positioning is vital
- High precision ball screws are used in steppers for semiconductor manufacturing industries for precision assembly of micro parts.
- Used in robotics application where precision positioning is needed.
- Used in medical examination equipments since they are highly accurate and provide smooth motion.

Module 4 Drives and Mechanisms

Lecture 5

Indexing Mechanisms

Mechanism is a system of rigid elements arranged and connected to transmit motion in a predetermined fashion. Indexing mechanisms generally converts a rotating or oscillatory motion to a series of step movements of the output link or shaft. In machine tools the cutting tool has to be indexed in the tool turret after each operation. Also in production machines the product has to be indexed from station to station and need to be stopped if any operation is being performed in the station. Such motions can be accomplished by indexing mechanisms. Indexing mechanisms are also useful for machine tool feeds. There are several methods used to index but important types are ratchet and pawl, rack and pinion, Geneva mechanism and cam drive.

1. Ratchet and pawl mechanism

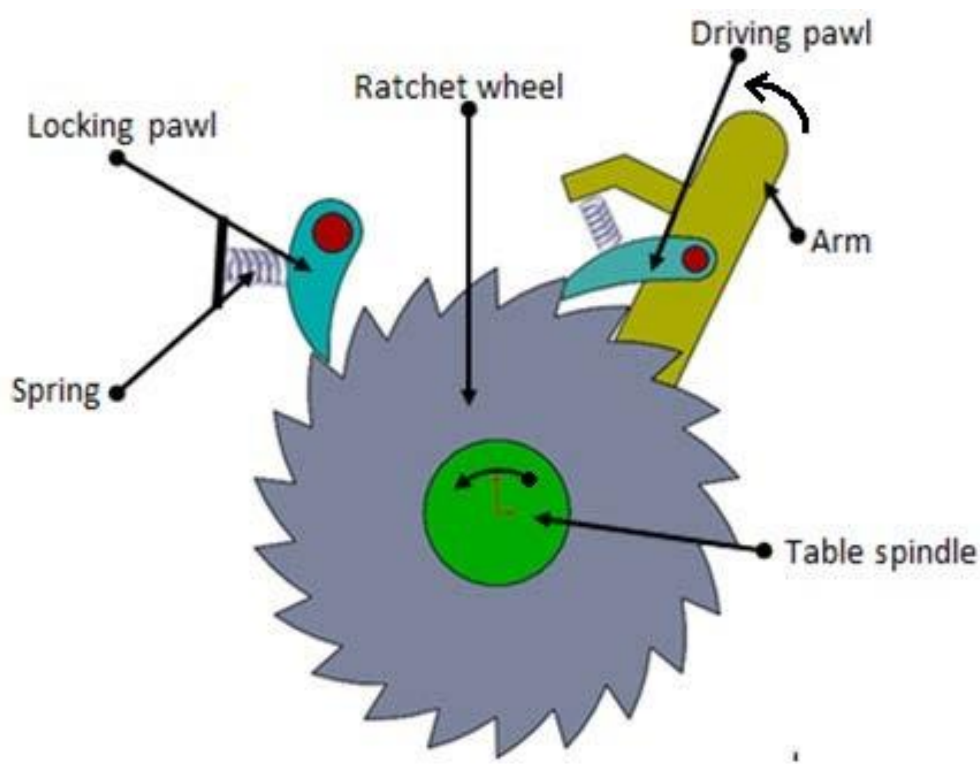


Fig. 4.5.1 Ratchet and pawl mechanism

A ratchet is a device that allows linear or rotary motion in only one direction. Figure 4.5.1 shows a schematic of the same. It is used in rotary machines to index air operated indexing tables. Ratchets consist of a gearwheel and a pivoting spring loaded pawl that engages the teeth. The teeth or the pawl, are at an angle so that when the teeth are moving in one direction the pawl slides in between the teeth. The spring forces the pawl back into the depression between the next teeth. The ratchet and pawl are not mechanically interlocked hence easy to set up. The table may over travel if the table is heavy when they are disengaged. Maintenance of this system is easy.

2. Rack and pinion mechanism

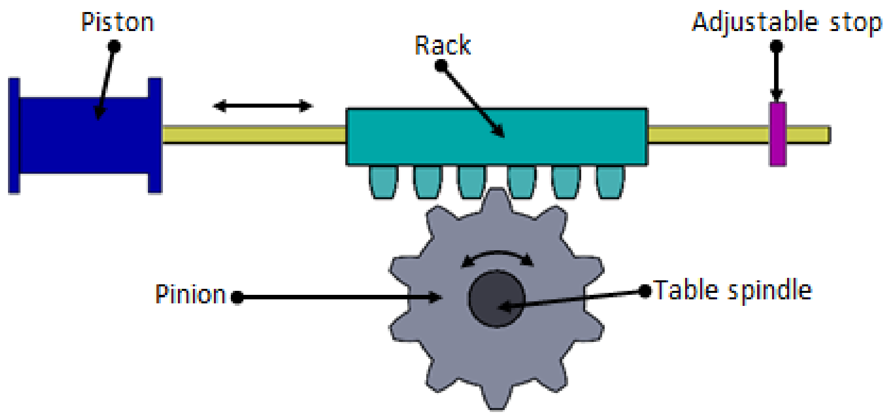


Fig. 4.5.2 Rack and pinion mechanism

A rack and pinion gear arrangement usually converts rotary motion from a pinion to linear motion of a rack. But in indexing mechanism the reverse case holds true. The device uses a piston to drive the rack, which causes the pinion gear and attached indexing table to rotate (Fig. 4.5.2). A clutch is used to provide rotation in the desired direction. This mechanism is simple but is not considered suitable for high-speed operation.

3. Geneva mechanism

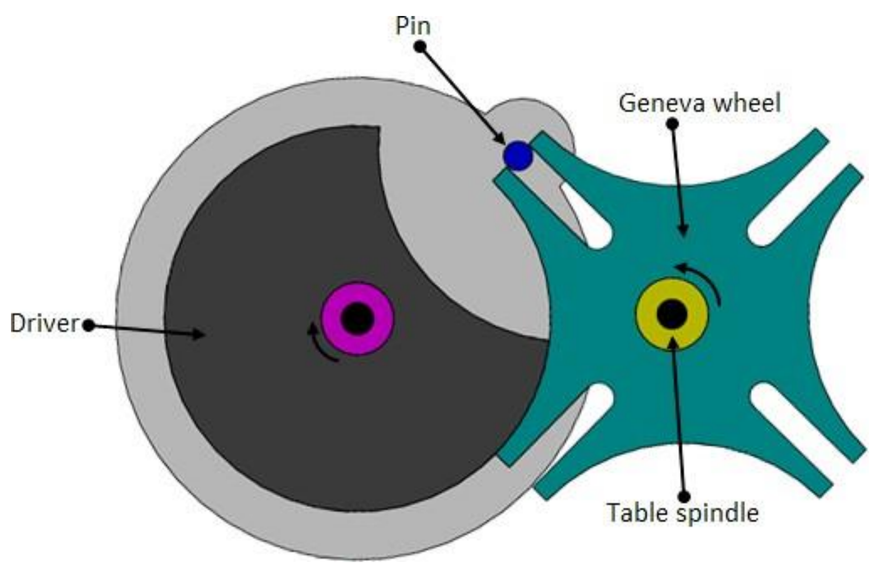


Fig. 4.5.3 Geneva mechanism

The Geneva drive is also commonly called a Maltese cross mechanism. The Geneva mechanism translates a continuous rotation into an intermittent rotary motion. The rotating drive wheel has a pin that reaches into a slot of the driven wheel. The drive wheel also has a raised circular blocking disc that locks the driven wheel in position between steps (Fig. 4.5.3). There are three basic types of Geneva motion mechanisms namely external, internal and spherical. The spherical Geneva mechanism is very rarely used. In the simplest form, the driven wheel has four slots and hence for each rotation of the drive wheel it advances by one step of 90°. If the driven wheel has n slots, it advances by 360°/n per full rotation of the drive wheel.

In an internal Geneva drive the axis of the drive wheel of the internal drive is supported on only one side (Fig. 4.5.4). The angle by which the drive wheel has to rotate to effect one step rotation of the driven wheel is always smaller than 180° in an external Geneva drive and is always greater than 180° in an internal one. The external form is the more common, as it can be built smaller and can withstand higher mechanical stresses.

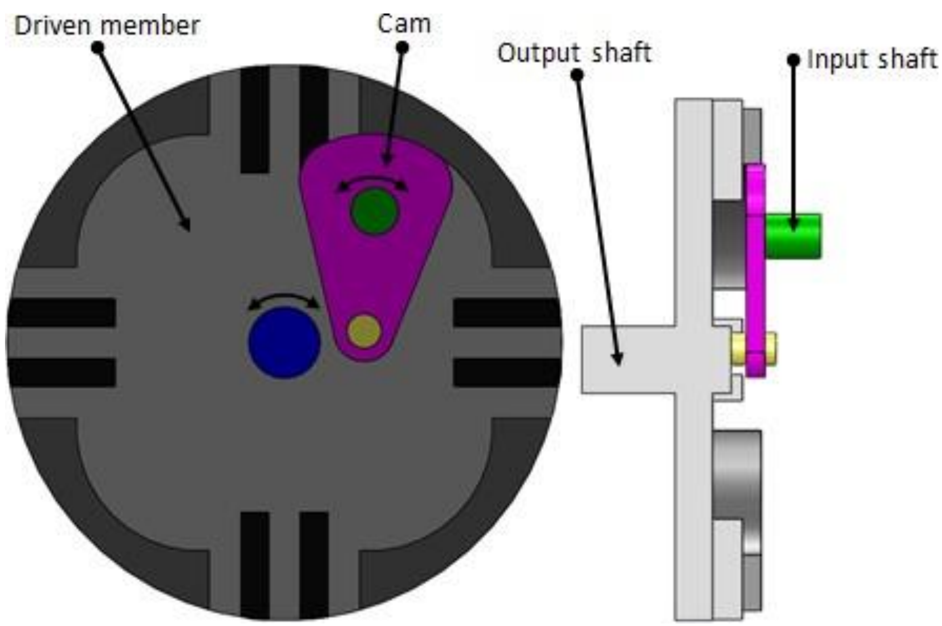


Fig. 4.5.4 Internal Geneva mechanism

Because the driven wheel always under full control of the driver, impact is a problem. It can be reduced by designing the pin in such a way that the pin picks up the driven member as slowly as possible. Both the Geneva mechanisms can be used for light and heavy duty applications. Generally, they are used in assembly machines.

Intermittent linear motion from rotary motion can also be obtained using Geneva mechanism (Fig. 4.5.5). This type of movement is basically required in packaging, assembly operations, stamping, embossing operations in manufacturing automation.

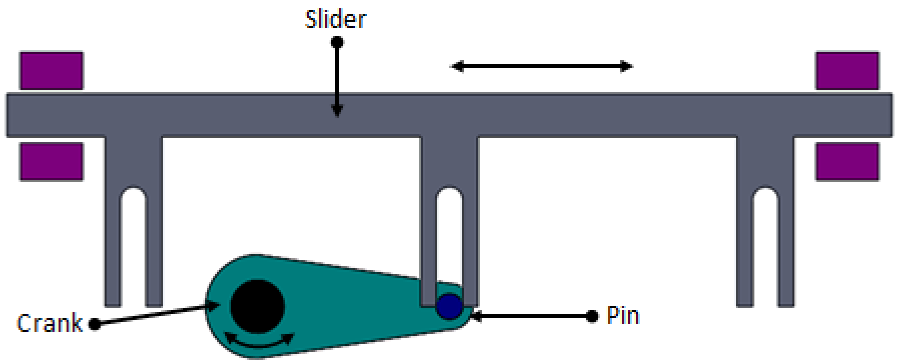


Fig. 4.5.5 Linear intermittent motion using Geneva mechanism

4. Cams mechanism

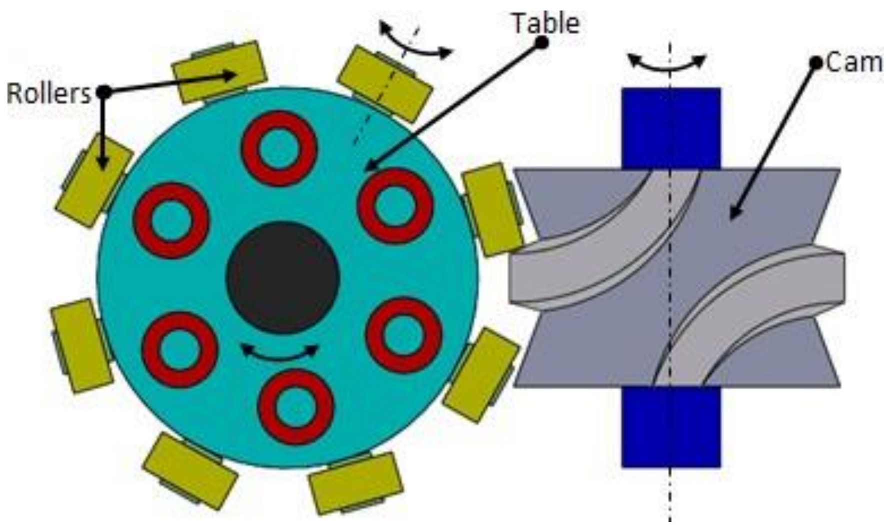


Fig. 4.5.6 Cam mechanism

Cam mechanism is one of the accurate and reliable methods of indexing. It is widely used in industry despite the fact that the cost is relatively high compared to alternative mechanisms. The cam can be designed to give a variety of velocity and dwell characteristics. The follower of the cams used in indexing mechanism has a unidirectional rotary motion rather than oscillating rotary motion which is usually the case of axial cams. The cam surface geometry is more complicated in a cross over indexing type of cam as shown in Figure 4.5.6.

5. Applications of indexing mechanisms

Some of the applications of indexing mechanism are discussed below.

5.1 Motion picture projectors

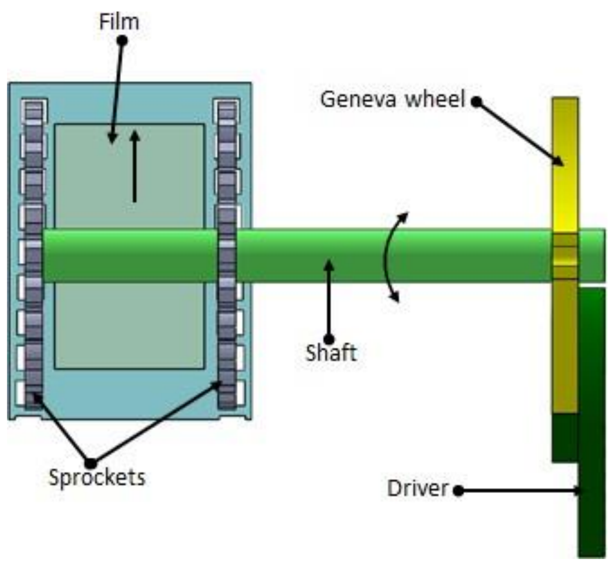


Fig. 4.5.7 Motion picture projector with Geneva mechanism

Geneva drive mechanism is used in conventional-mechanical type movie projectors. Figure 4.5.7 shows the schematic of movie projector with Geneva mechanism. The film does not run continuously through the projector. It is requited that the film should advance frame by frame and stands still in front of the lens for fraction of a second. Modern film projectors use an electronically controlled indexing mechanism which allows the fast-forwarding of the film.

5.2 Automated work assembly transfer lines

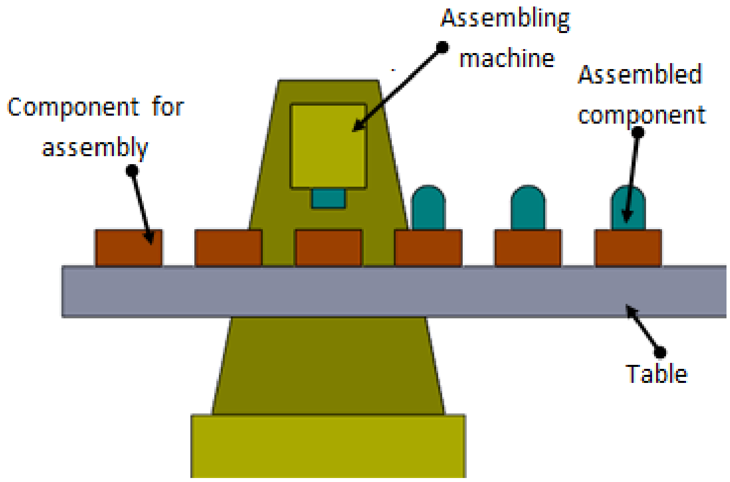


Fig. 4.5.8 Automated assembly line

In assembly lines, the parts to be assembled have to be moved over the assembling machine tool (Fig. 4.5.8). This is done using indexing mechanism. The part on the table is indexed to be in line with the assembly unit. Once the assembly is done the table is indexed to get the next part in line with the assembly.

5.3 CNC tool changers

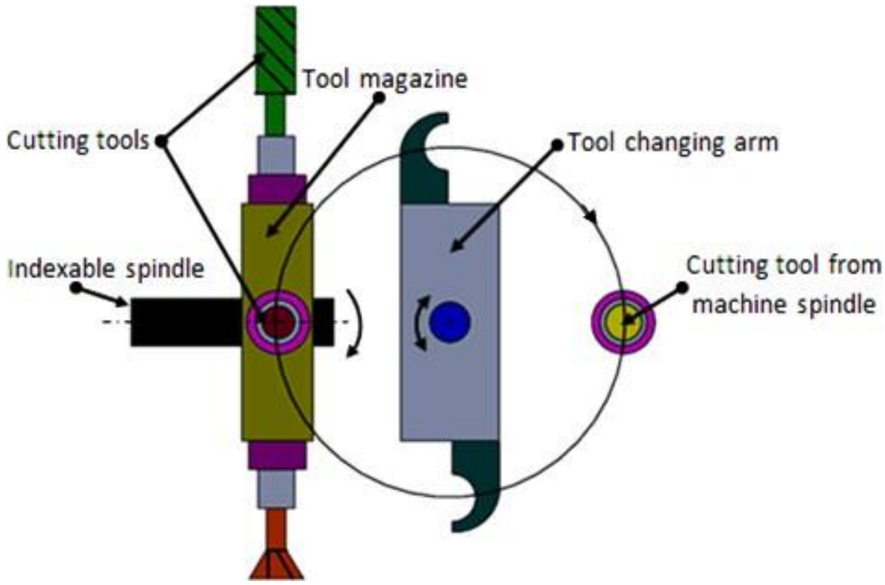


Fig. 4.5.9 CNC tool changer

In the CNC tool changing mechanism the tool magazine has to be indexed to bring the desired tool in line with the tool changing arm (Fig. 4.5.9). The tool changing arm picks the cutting tool from the spindle. Then it is indexed to reach the tool magazine. The tool is placed in the magazine. Then the magazine is indexed to bring the next cutting tool to be picked by the changing arm. Again the tool changing arm indexes to reach the spindle.

5.4 Material inspection station

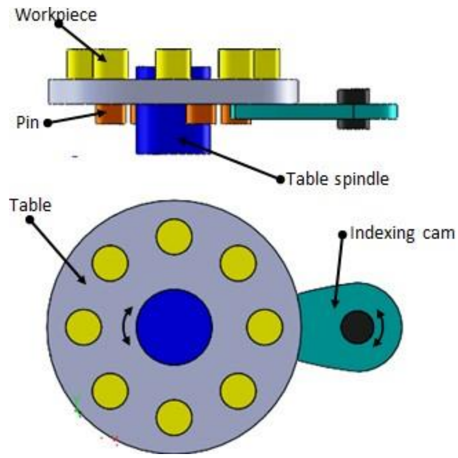


Fig. 4.5.10 Rotary table with cam indexing

Here a rotary index table is used to convey the parts for inspection operation. This index device conveys the parts in a rotary motion and stops intermittently for a fixed period of time for inspection. A cam mechanism is used to index the table (Fig. 4.5.10).

Module 4 Drives and Mechanisms

Lecture 6

Tool magazines and transfer systems

Machining centers are used to carry out multiple operations like drilling, milling, boring etc. in one set up on multiple faces of the workpiece. These operations require a number of different tools. Tool changing operation is time consuming which reduces the machine utilization. Hence the tools should be automatically changed to reduce the idle time. This can be achieved by using automatic tool changer (ATC) facility. It helps the workpiece to be machined in one setup which increases the machine utilization and productivity. Large numbers of tools can be stored in tool magazines. Tool magazines are specified by their storage capacity, tool change procedure and shape. The storage capacity ranges from 12 to 200. Some of the magazines are discuseed as follows.

1. Tool turret

It is the simplest form of tool magazine. Figure 4.6.1 the schematic of a turret with a capacity to hold twelve tools. It consists of a tool storage without any tool changer. The turret is indexed in the required position for desired machining operation. Advantage of the turret is that the tool can easily be identified, but the time consumed for tool change is more unless the tool is in the adjecent slot.

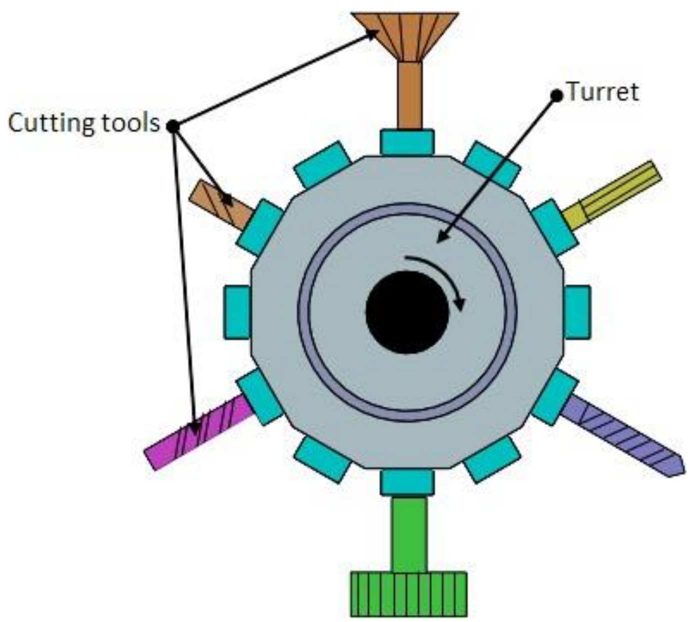


Fig. 4.6.1 Tool turret

2. Tool magazines

Tool magazines are generally employed in CNC drilling and milling machines. Compared to tool turrets the tool magazines can hold more number of tools therefore proper management of tools is essential. Duplication of the tools is possible and a new tool of same type may be selected when a particular tool is worn off. The power required to move the tools in a tool magazine is more in comparison with that required in tool turrets. The following are some of the tool magazines used in automation.

2.1 Disc or drum type
2.2 Chain type
2.3 Disk or drum type

2.1 Disc type magazine

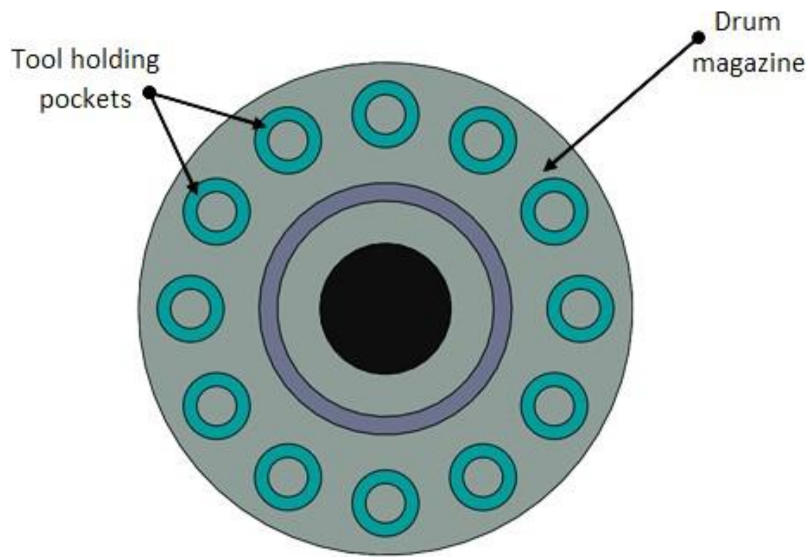


Fig. 4.6.2 Drum magazine

The disc type tool magazine rotates to get the desired tool in position with the tool change arm (Fig. 4.6.2). Larger the diameter of the disc/drum more the number of tools it can hold. It has pockets where tool can be inserted. In case of drum type magazine which can store large amount of tools, the pockets are on the surface along the length. It carries about 12 to 50 tools. If the number of tools are less the disc is mounted on top of the spindle to minimize the travel of tool between the spindle and the disc. If the tools are more then, the disc is wall mounted or mounted on the machining center column. If the disc is column mounted then, it needs an additional linear motion to move it to the loading station for tool change.

2.2 Chain type magazine

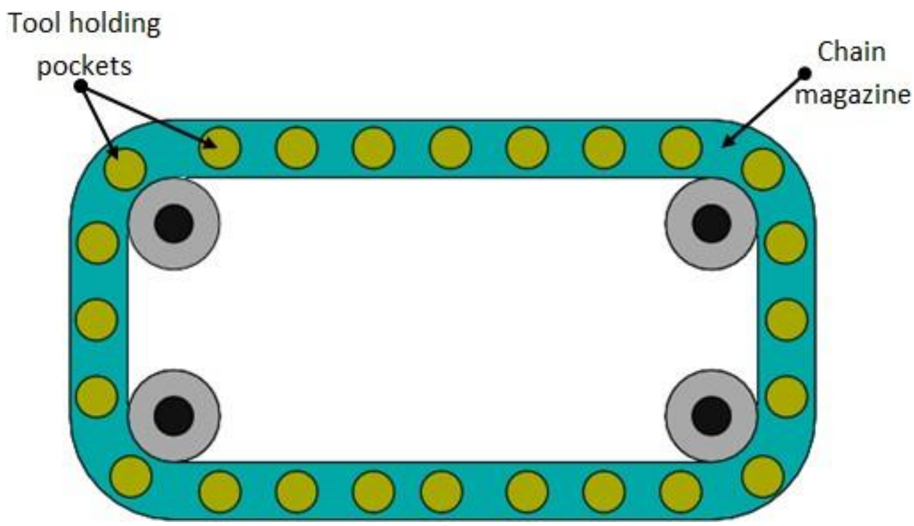


Fig. 4.6.3 Chain magazine

When the number of tools is more than 50, chain type of magazines are used (Fig. 4.6.3). The magazine is mounted overhead or as a separate column. In chain magazines the tools are identified either by their location in the tool holder or by means of some coding on the tool holder. These types of magazines can be duplicated. There can be two chain magazines: one is active for machining and the second magazine is used when the duplicate tool is needed since the active tool is worn out.

2.3 Rack type magazine

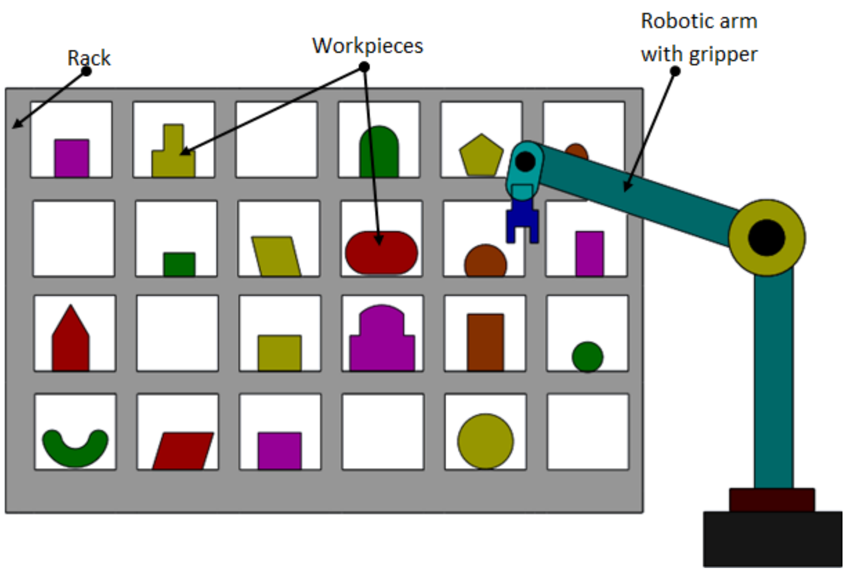


Fig. 4.6.4 Rack magazine

Rack magazines are cost-efficient alternative to usual tool magazine systems (Fig. 4.6.4). Set-up time can be optimized by utilizing the racks' capacity of up to 50 tools. The high storage capacity of up to 400 tools permits a large production capacity of varying work pieces without tool changes. They can also be used to store work pieces.

3. Automatic tool changing

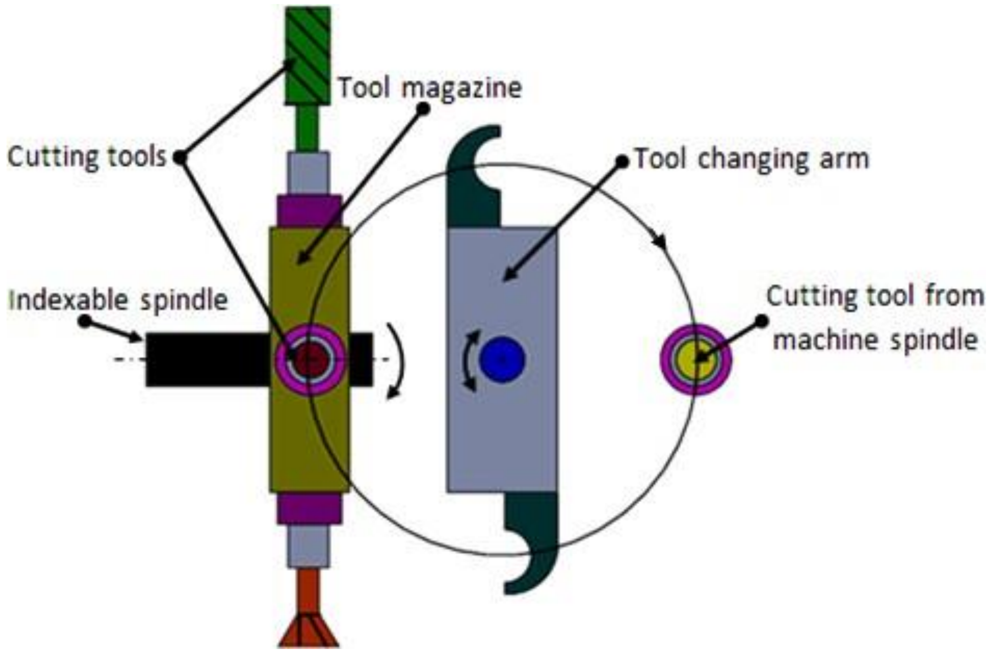


Fig. 4.6.5 Automatic tool changer

The tools from the magazines and spindle are exchanged by a tool changer arm (Fig. 4.6.5). The tool change activity requires the following motions:

a. The spindle stops at the correct orientation for the tool change arm to pick the tool from the spindle.
b. Tool change arm moves to the spindle.
c. Tool change arm picks the tool from the spindle.
d. Tool change arm indexes to reach the tool magazine.
e. Tool magazine indexes so that the tool from the spindle can be placed.
f. The tool is placed in the tool magazine.
g. The tool magazine indexes to bring the required tool to the tool change position.
h. Tool change arm picks the tool from the tool magazine.
i. Tool change arm indexes to reach the spindle.
j. New tool is placed in the spindle.
k. Tool change arm moves back to its parking position.

3.1 Advantages of automatic tool changer

- Increase in operator safety by changing tools automatically
- Changes the tools in seconds for maintenance and repair
- Increases flexibility
- Heavy and large multi-tools can easily be handled
- Decreases total production time

4. Cranes

Cranes are material handling equipments designed for lifting and moving heavy loads. Some of the important types of cranes are bridge cranes, gantry cranes and jib cranes. These are discussed as follows.

4.1 Bridge crane

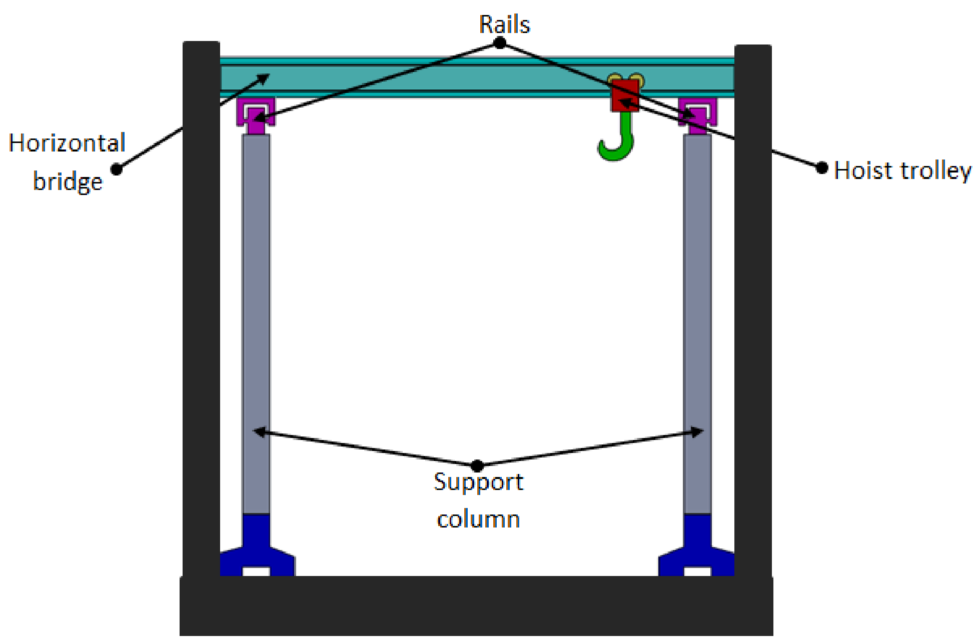


Fig. 4.6.6 Bridge crane

It consists of one or two horizontal beams supported between fixed rails on either end as shown in Fig. 4.6.6. The hoist moves along the length of the bridge, and the bridge moves along the rails. The x- and y-axes movements are provided by the above said movements and the hoist provides motion in the z-axis direction. In the bridge crane, vertical lifting is due to the hoist and horizontal movement of the material is due to the rail system. They are generally used in heavy machinery fabrication, steel mills, and power-generating stations.

4.2 Gantry crane

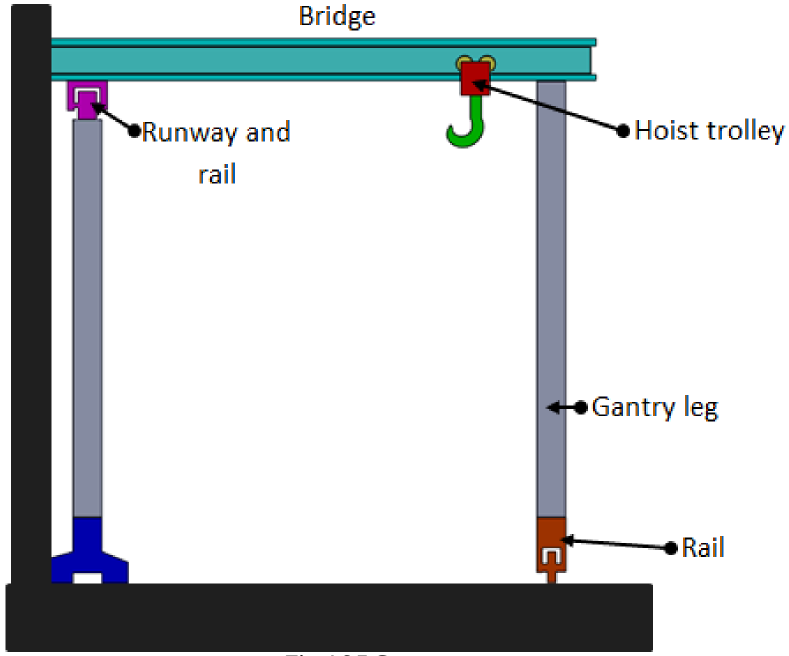


Fig. 4.6.7 Gantry crane

These types of cranes have one or two vertical legs which support the horizontal bridge. The bridge of the gantry crane has one or more hoists that help in vertical lifting as shwon in Fig. 4.6.7. Gantries are available in a variety of sizes. A double gantry crane has two legs. Other types of gantry cranes are half gantries and cantilever gantries. In a half gantry crane, there is a single leg on one end of the bridge, and the other end is supported by a rail mounted on the wall or other structural member. In a cantilever gantry crane the bridge extends beyond the length of support legs.

4.3 Jib crane

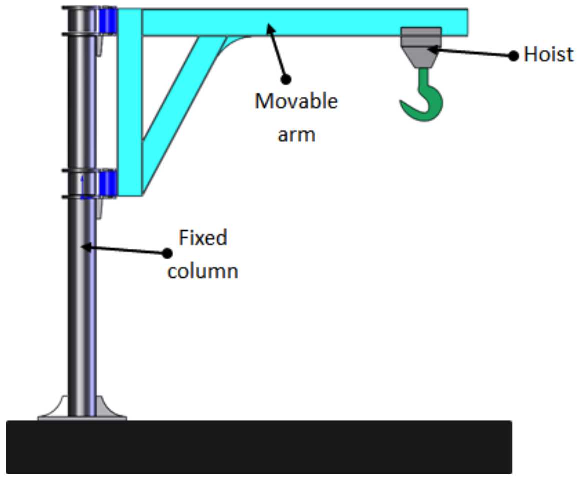


Fig. 4.6.8 Jib crane

It consists of a hoist mounted on a horizontal cantilever beam which is supported by a vertical column as shown in Fig. 4.6.8. The horizontal beam is pivoted about the vertical axis formed by the column to provide a horizontal sweep for the crane. The beam acts as a track for the hoist trolley to provide radial travel along the length of the beam. The horizontal sweep of a jib crane is circular or semicircular. The hoist provides vertical lifting and lowering movements.

5. Rail-Guided Vehicles

These are material transport equipments consisting of motorized vehicles that are guided by a fixed rail system. These are self-propelled vehicles that ride on a fixed-rail system. The vehicles operate independently and are driven by electric motors that pick up power from an electrified rail. The fixed rail system can be classified as,

- Overhead monorail
- On-floor parallel rails

Monorails are typically suspended overhead from the ceiling. In rail guided vehicle systems using parallel fixed rails on floor rails, the tracks generally protrude up from the floor. The vehicles operate asynchronously and are driven by an on-board electric motor. The rail guided vehicles pick up electrical power from an electrified rail. In such vehicles routing variations are possible.

6. Conveyors

These are of material transfer equipments designed to move materials over fixed paths, usually in large quantities or volumes. They can be classified as non-powered and powered systems. In non-powered systems, the materials are moved by human workers or by gravity whilst in powered systems, materials are transported by using automated systems. There are various types of conveyors such as roller, skate-wheel, belt, in-floor towline; overhead trolley conveyor and cart-on-track conveyor are used in industry.

6.1 Roller conveyor

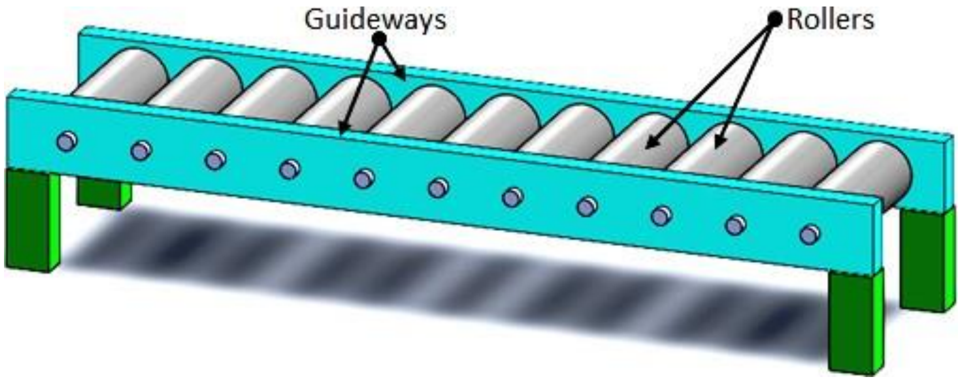


Fig. 4.6.9 Roller conveyor

In roller conveyors, the pathway consists of a series of rollers that are perpendicular to the direction of travel as shwon in Fig. 4.6.9. Loads must possess a flat bottom or placed in carts. Powered rollers rotate to drive the loads forward.

6.2 In-Floor Tow-Line Conveyor

It consists of a four wheel cart powered by moving chains or cables placed in trenches in the floor. Carts use steel pins which project below floor level and engage the chain for towing. The pins can be pulled out to allow the carts to be disengaged from towline for loading and unloading purpose.

6.3 Overhead Trolley Conveyor

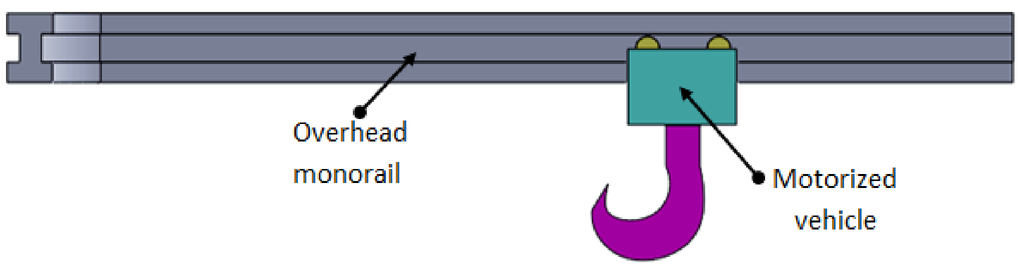


Fig. 4.6.10 Overhead trolley conveyor

In this equipment a motorized vehicle runs over an overhead track. By moving this trolley, loads can be conveyed with the help of hook as shown in Figure 4.6.10. Trolleys are connected and moved by a chain or cable that forms a complete loop. These are often used to move parts such heavy dies, molds, and assemblies of machine components.

6.4 Belt Conveyors

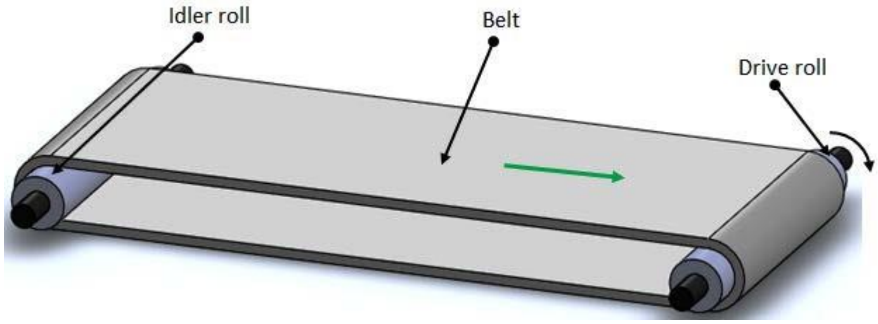


Fig. 4.6.11 Belt drive

Belt conveyors consist of a continuous loop of belt material (Fig.4.6.11). Half of the length is used to deliver the materials and the other half is for idle return. The drive roll powers the belt. The belt conveyors are of two types, namely flat belts and troughed belts. These are very commonly used in industry to convey light to heavy, solid, loose commodities such as food grains, sugar, cement bags, coal etc. They are also widely used to transfer small to large size cartons/boxes of products. Detail analysis and design of conveyors is out of the scope of this course.

7 *Rotary indexing table*

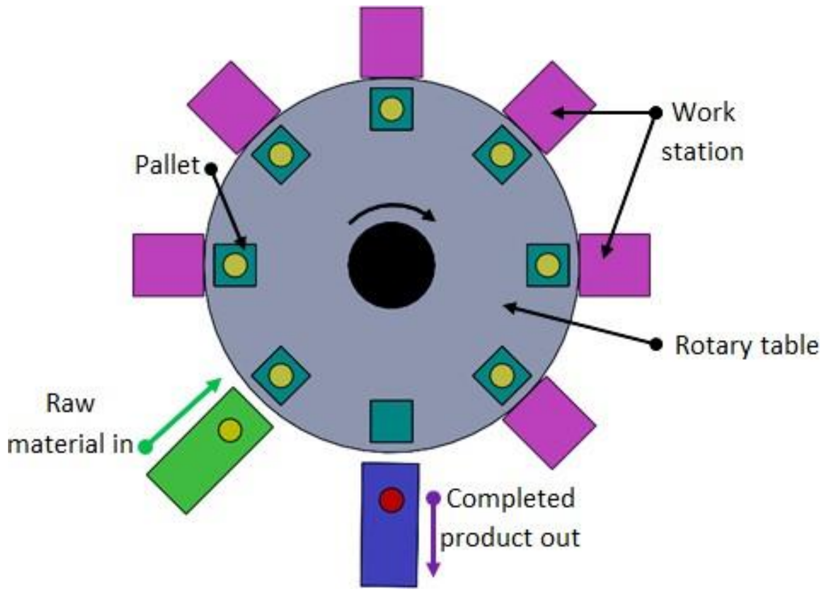


Fig. 4.6.12 Rotary indexing table

These are used for the synchronous transfer of small parts from one station to the other station at single work center. The workparts are indexed around a rotary table. The workstations are stationary and usually located around the outside periphery of the dial as shwon in Fig. 4.6.12. The parts riding on the rotating table are positioned at each station for their processing or assembly operation. This type of equipment is called as an indexing machine or dial index machine. These are generally used to carry out assembly operations of small sized products such as watches, jewelery, electronic circuits, small molds/dies, consumer appliances etc.

Module 5: Hydraulic Systems

Lecture 1

Introduction

1. Introduction

The controlled movement of parts or a controlled application of force is a common requirement in the industries. These operations are performed mainly by using electrical machines or diesel, petrol and steam engines as a prime mover. These prime movers can provide various movements to the objects by using some mechanical attachments like screw jack, lever, rack and pinions etc. However, these are not the only prime movers. The enclosed fluids (liquids and gases) can also be used as prime movers to provide controlled motion and force to the objects or substances. The specially designed enclosed fluid systems can provide both linear as well as rotary motion. The high magnitude controlled force can also be applied by using these systems. This kind of enclosed fluid based systems using pressurized incompressible liquids as transmission media are called as hydraulic systems. The hydraulic system works on the principle of Pascal's law which says that the pressure in an enclosed fluid is uniform in all the directions. The Pascal's law is illustrated in figure 5.1.1. The force given by fluid is given by the multiplication of pressure and area of cross section. As the pressure is same in all the direction, the smaller piston feels a smaller force and a large piston feels a large force. Therefore, a large force can be generated with smaller force input by using hydraulic systems.

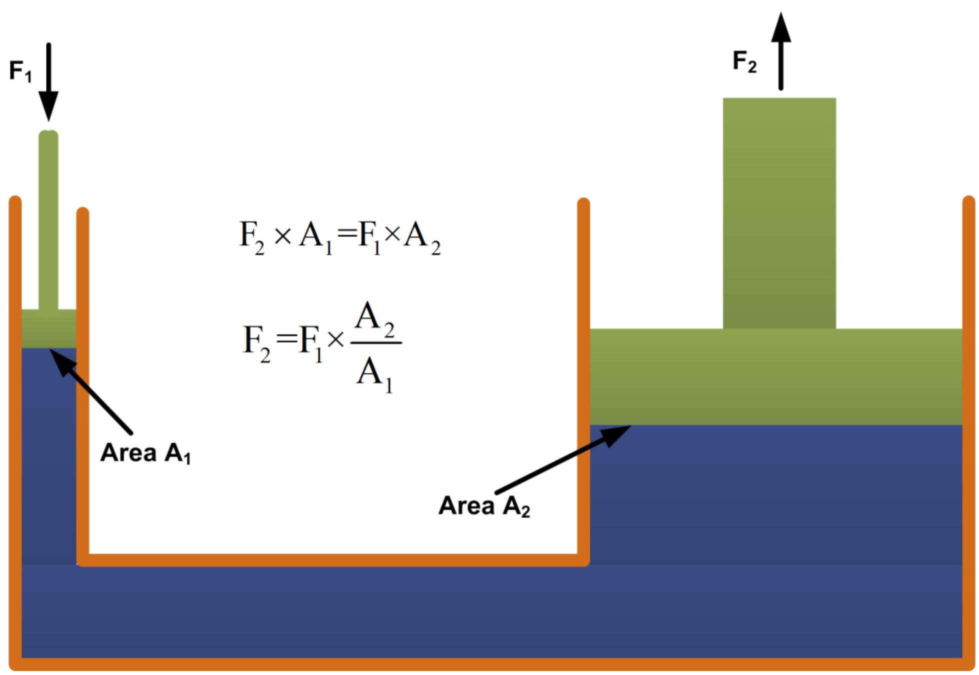


Figure 5.1.1 Principle of hydraulic system

The hydraulic systems consists a number of parts for its proper functioning. These include storage tank, filter, hydraulic pump, pressure regulator, control valve, hydraulic cylinder, piston and leak proof fluid flow pipelines. The schematic of a simple hydraulic system is shown in figure 5.1.2. It consists of:

- a movable piston connected to the output shaft in an enclosed cylinder
- storage tank
- filter
- electric pump
- pressure regulator
- control valve
- leak proof closed loop piping.

The output shaft transfers the motion or force however all other parts help to control the system. The storage/fluid tank is a reservoir for the liquid used as a transmission media. The liquid used is generally high density incompressible oil. It is filtered to remove dust or any other unwanted particles and then pumped by the hydraulic pump. The capacity of pump depends on the hydraulic system design. These pumps generally deliver constant volume in each revolution of the pump shaft. Therefore, the fluid pressure can increase indefinitely at the dead end of the piston until the system fails. The pressure regulator is used to avoid such circumstances which redirect the excess fluid back to the storage tank. The movement of piston is controlled by changing liquid flow from port A and port B. The cylinder movement is controlled by using control valve which directs the fluid flow. The fluid pressure line is connected to the port B to raise the piston and it is connected to port A to lower down the piston. The valve can also stop the fluid flow in any of the port. The leak proof piping is also important due to safety, environmental hazards and economical aspects. Some accessories such as flow control system, travel limit control, electric motor starter and overload protection may also be used in the hydraulic systems which are not shown in figure 5.1.2.

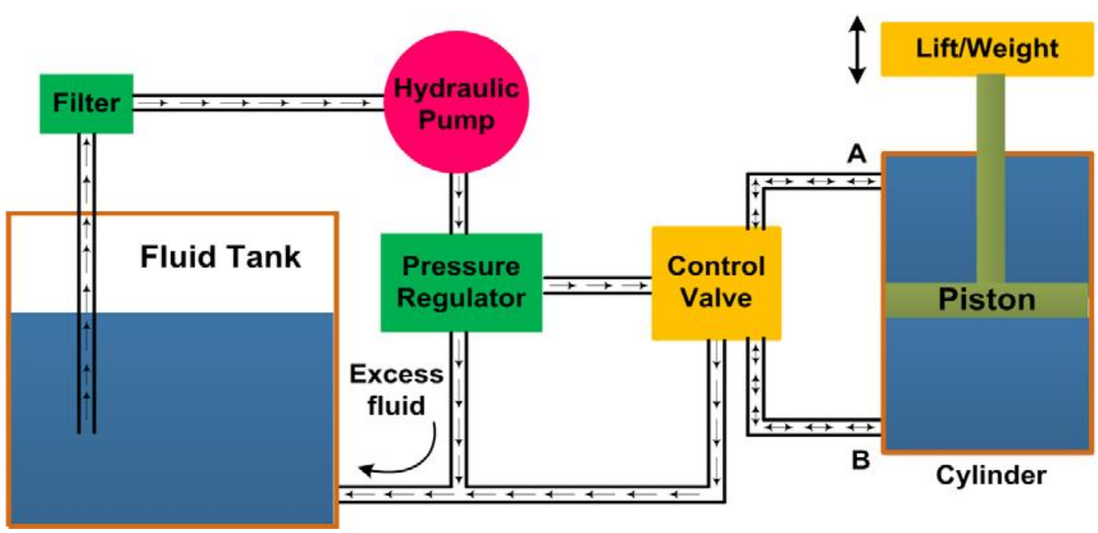


Figure 5.1.2 Schematic of hydraulic system

2. *Applications of hydraulic systems*

The hydraulic systems are mainly used for precise control of larger forces. The main applications of hydraulic system can be classified in five categories:

2.1 Industrial: Plastic processing machineries, steel making and primary metal extraction applications, automated production lines, machine tool industries, paper industries, loaders, crushes, textile machineries, R & D equipment and robotic systems etc.

2.2 Mobile hydraulics: Tractors, irrigation system, earthmoving equipment, material handling equipment, commercial vehicles, tunnel boring equipment, rail equipment, building and construction machineries and drilling rigs etc.

2.3 Automobiles: It is used in the systems like breaks, shock absorbers, steering system, wind shield, lift and cleaning etc.

2.4 Marine applications: It mostly covers ocean going vessels, fishing boats and navel equipment.

2.5 Aerospace equipment: There are equipment and systems used for rudder control, landing gear, breaks, flight control and transmission etc. which are used in airplanes, rockets and spaceships.

3. *Hydraulic Pump*

The combined pumping and driving motor unit is known as hydraulic pump. The hydraulic pump takes hydraulic fluid (mostly some oil) from the storage tank and delivers it to the rest of the hydraulic circuit. In general, the speed of pump is constant and the pump delivers an equal volume of oil in each revolution. The amount and direction of fluid flow is controlled by some external mechanisms. In some cases, the hydraulic pump itself is operated by a servo controlled motor but it makes the system complex. The hydraulic pumps are characterized by its flow rate capacity, power consumption, drive speed, pressure delivered at the outlet and efficiency of the pump. The pumps are not 100% efficient. The efficiency of a pump can be specified by two ways. One is the volumetric efficiency which is the ratio of actual volume of fluid delivered to the maximum theoretical volume possible. Second is power efficiency which is the ratio of output hydraulic power to the input mechanical/electrical power. The typical efficiency of pumps varies from 90-98%.

The hydraulic pumps can be of two types:

- centrifugal pump
- reciprocating pump

Centrifugal pump uses rotational kinetic energy to deliver the fluid. The rotational energy typically comes from an engine or electric motor. The fluid enters the pump impeller along or near to the rotating axis, accelerates in the propeller and flung out to the periphery by centrifugal force as shown in figure 5.1.3. In centrifugal pump the delivery is not constant and varies according to the outlet pressure. These pumps are not suitable for high pressure applications and are generally used for low-pressure and high-volume flow applications. The maximum pressure capacity is limited to 20-30 bars and the specific speed ranges from 500 to 10000. Most of the centrifugal pumps are not self-priming and the pump casing needs to be filled with liquid before the pump is started.

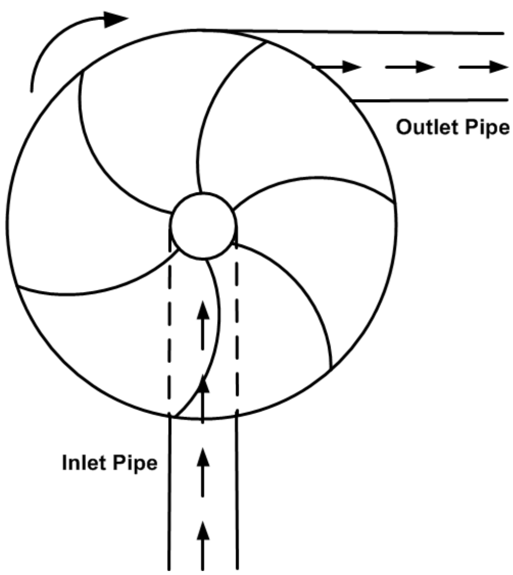


Figure 5.1.3 Centrifugal pump

The reciprocating pump is a positive plunger pump. It is also known as positive displacement pump or piston pump. It is often used where relatively small quantity is to be handled and the delivery pressure is quite large. The construction of these pumps is similar to the four stroke engine as shown in figure 5.1.4. The crank is driven by some external rotating motor. The piston of pump reciprocates due to crank rotation. The piston moves down in one half of crank rotation, the inlet valve opens and fluid enters into the cylinder. In second half crank rotation the piston moves up, the outlet valve opens and the fluid moves out from the outlet. At a time, only one valve is opened and another is closed so there is no fluid leakage. Depending on the area of cylinder the pump delivers constant volume of fluid in each cycle independent to the pressure at the output port.

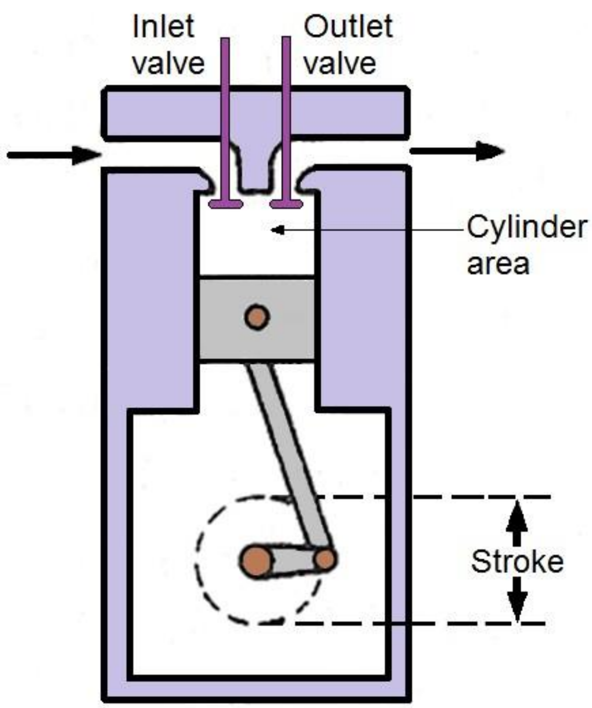


Figure 5.1.4 Reciprocating or positive displacement pump

4. Pump Lift

In general, the pump is placed over the fluid storage tank as shown in figure 5.1.5. The pump creates a negative pressure at the inlet which causes fluid to be pushed up in the inlet pipe by atmospheric pressure. It results in the fluid lift in the pump suction. The maximum pump lift can be determined by atmospheric pressure and is given by pressure head as given below:

$$\text{Pressure Head, } P = \rho g h \qquad (5.1.1)$$

Theoretically, a pump lift of 8 m is possible but it is always lesser due to undesirable effects such as cavitation. The cavitation is the formation of vapor cavities in a liquid. The cavities can be small liquid-free zones ("bubbles" or "voids") formed due to partial vaporization of fluid (liquid). These are usually generated when a liquid is subjected to rapid changes of pressure and the pressure is relatively low. At higher pressure, the voids implode and can generate an intense shockwave. Therefore, the cavitation should always be avoided. The cavitation can be reduced by maintaining lower flow velocity at the inlet and therefore the inlet pipes have larger diameter than the outlet pipes in a pump. The pump lift should be as small as possible to decrease the cavitation and to increase the efficiency of the pump.

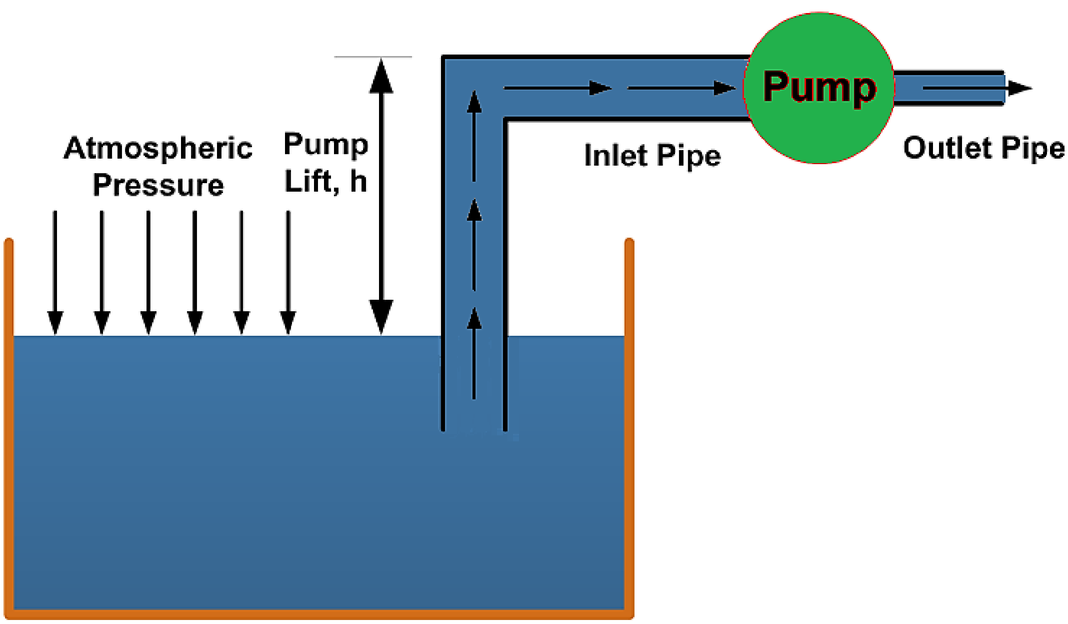


Figure 5.1.5 Pump lift

5. *Pressure Regulation*

The pressure regulation is the process of reduction of high source pressure to a lower working pressure suitable for the application. It is an attempt to maintain the outlet pressure within acceptable limits. The pressure regulation is performed by using pressure regulator. The primary function of a pressure regulator is to match the fluid flow with demand. At the same time, the regulator must maintain the outlet pressure within certain acceptable limits.

The schematic of pressure regulator and various valves placement is shown in figure 5.1.6. When the valve V_1 is closed and V_2 is opened then the load moves down and fluid returns to the tank but the pump is dead ended and it leads to a continuous increase in pressure at pump delivery. Finally, it may lead to permanent failure of the pump. Therefore some method is needed to keep the delivery pressure P_1 within the safe level. It can be achieved by placing pressure regulating valve V_3 as shown in figure 5.1.6. This valve is closed in normal conditions and when the pressure exceeds a certain limit, it opens and fluid from pump outlet returns to the tank via pressure regulating valve V_3. As the pressure falls in a limiting range, the valve V_3 closes again.

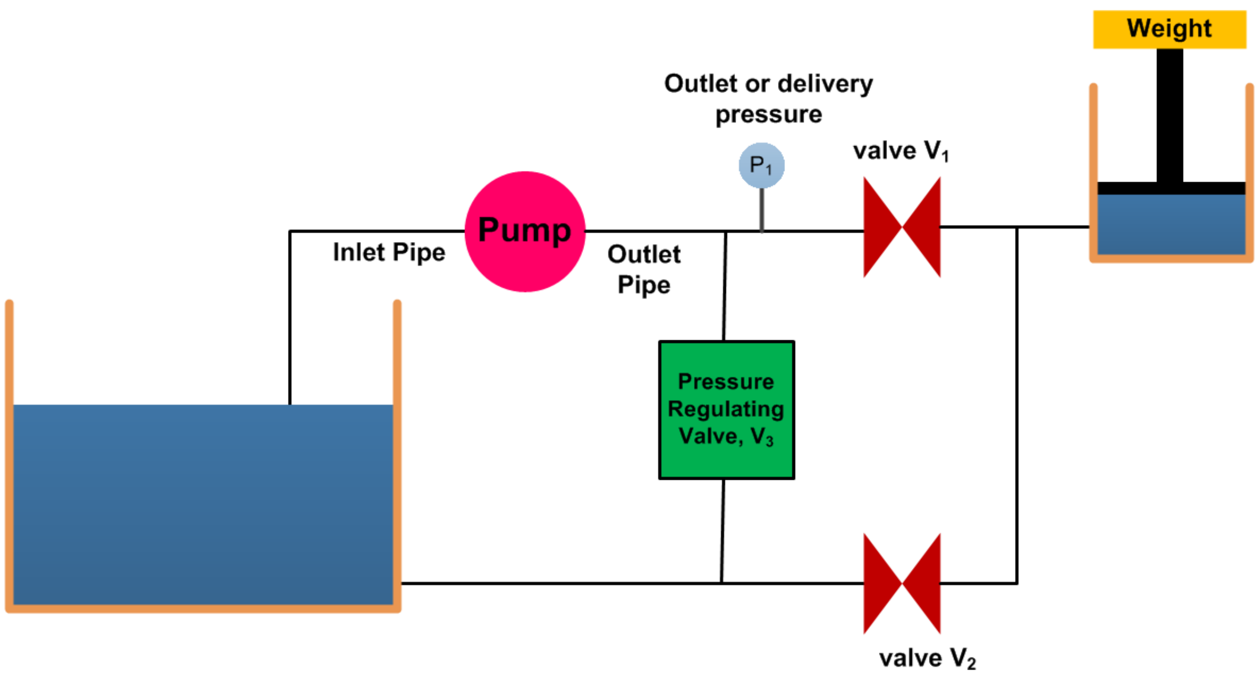


Figure 5.1.6 Schematic of pressure regulation

When valve V_1 is closed, the whole fluid is dumped back to the tank through the pressure regulating valve. This leads to the substantial loss of power because the fluid is circulating from tank to pump and then pump to tank without performing any useful work. This may lead to increase in fluid temperature because the energy input into fluid leads to the increase in fluid temperature. This may need to the installation of heat exchanger in to the storage tank to extract the excess heat. Interestingly, the motor power consumption is more in such condition because the outlet pressure is higher than the working pressure.

6. Advantages and Disadvantages of Hydraulic system

6.1 Advantages

- The hydraulic system uses incompressible fluid which results in higher efficiency.
- It delivers consistent power output which is difficult in pneumatic or mechanical drive systems.
- Hydraulic systems employ high density incompressible fluid. Possibility of leakage is less in hydraulic system as compared to that in pneumatic system. The maintenance cost is less.
- These systems perform well in hot environment conditions.

6.2 Disadvantages

- The material of storage tank, piping, cylinder and piston can be corroded with the hydraulic fluid. Therefore one must be careful while selecting materials and hydraulic fluid.
- The structural weight and size of the system is more which makes it unsuitable for the smaller instruments.
- The small impurities in the hydraulic fluid can permanently damage the complete system, therefore one should be careful and suitable filter must be installed.
- The leakage of hydraulic fluid is also a critical issue and suitable prevention method and seals must be adopted.
- The hydraulic fluids, if not disposed properly, can be harmful to the environment.

Module 5: Hydraulic Systems

Lecture 2

Hydraulic Pumps

1. Classification of Hydraulic Pumps

These are mainly classified into two categories:

A. Non-positive displacement pumps
B. Positive displacement pumps.

A. Non-Positive Displacement Pumps

These pumps are also known as hydro-dynamic pumps. In these pumps the fluid is pressurized by the rotation of the propeller and the fluid pressure is proportional to the rotor speed. These pumps can not withstanding high pressures and generally used for low-pressure and high-volume flow applications. The fluid pressure and flow generated due to inertia effect of the fluid. The fluid motion is generated due to rotating propeller. These pumps provide a smooth and continuous flow but the flow output decreases with increase in system resistance (load). The flow output decreases because some of the fluid slip back at higher resistance. The fluid flow is completely stopped at very large system resistance and thus the volumetric efficiency will become zero. Therefore, the flow rate not only depends on the rotational speed but also on the resistance provided by the system. The important advantages of non-positive displacement pumps are lower initial cost, less operating maintenance because of less moving parts, simplicity of operation, higher reliability and suitability with wide range of fluid etc. These pumps are primarily used for transporting fluids and find little use in the hydraulic or fluid power industries. Centrifugal pump is the common example of non-positive displacement pumps. Details have already discussed in the previous lecture.

B. Positive displacement pump

These pumps deliver a constant volume of fluid in a cycle. The discharge quantity per revolution is fixed in these pumps and they produce fluid flow proportional to their displacement and rotor speed. These pumps are used in most of the industrial fluid power applications. The output fluid flow is constant and is independent of the system pressure (load). The important advantage associated with these pumps is that the high-pressure and low-pressure areas (means input and output region) are separated and hence the fluid cannot leak back due to higher pressure at the outlets. These features make the positive displacement pump most suited and universally accepted for hydraulic systems. The important advantages of positive displacement pumps over non-positive displacement pumps include capability to generate high pressures, high volumetric efficiency, high power to weight ratio, change in efficiency throughout the pressure range is small and wider operating range pressure and speed. The fluid flow rate of these pumps ranges from 0.1 and 15,000 gpm, the pressure head ranges between 10 and 100,000 psi and specific speed is less than 500.

It is important to note that the positive displacement pumps do not produce pressure but they only produce fluid flow. The resistance to output fluid flow generates the pressure. It means that if the discharge port (output) of a positive displacement pump is opened to the atmosphere, then fluid flow will not generate any output pressure above atmospheric pressure. But, if the discharge port is partially blocked, then the pressure will rise due to the increase in fluid flow resistance. If the discharge port of the pump is completely blocked, then an infinite resistance will be generated. This will result in the breakage of the weakest component in the circuit. Therefore, the safety valves are provided in the hydraulic circuits along with positive displacement pumps. Important positive displacement pumps are gears pumps, vane pumps and piston pumps. The details of these pumps are discussed in the following sections.

2. Gear Pumps

Gear pump is a robust and simple positive displacement pump. It has two meshed gears revolving about their respective axes. These gears are the only moving parts in the pump. They are compact, relatively inexpensive and have few moving parts. The rigid design of the gears and houses allow for very high pressures and the ability to pump highly viscous fluids. They are suitable for a wide range of fluids and offer self-priming performance. Sometimes gear pumps are designed to function as either a motor or a pump. These pump includes helical and herringbone gear sets (instead of spur gears), lobe shaped rotors similar to Roots blowers (commonly used as superchargers), and mechanical designs that allow the stacking of pumps. Based upon the design, the gear pumps are classified as:

- External gear pumps
- Lobe pumps
- Internal gear pumps
- Gerotor pumps

Generally gear pumps are used to pump:

- Petrochemicals: Pure or filled bitumen, pitch, diesel oil, crude oil, lube oil etc.
- Chemicals: Sodium silicate, acids, plastics, mixed chemicals, isocyanates etc.
- Paint and ink
- Resins and adhesives
- Pulp and paper: acid, soap, lye, black liquor, kaolin, lime, latex, sludge etc.
- Food: Chocolate, cacao butter, fillers, sugar, vegetable fats and oils, molasses, animal food etc.

2.1 External gear pump

The external gear pump consists of externally meshed two gears housed in a pump case as shown in figure 5.2.1. One of the gears is coupled with a prime mover and is called as driving gear and another is called as driven gear. The rotating gear carries the fluid from the tank to the outlet pipe. The suction side is towards the portion whereas the gear teeth come out of the mesh. When the gears rotate, volume of the chamber expands leading to pressure drop below atmospheric value. Therefore the vacuum is created and the fluid is pushed into the void due to atmospheric pressure. The fluid is trapped between housing and rotating teeth of the gears. The discharge side of pump is towards the portion where the gear teeth run into the mesh and the volume decreases between meshing teeth. The pump has a positive internal seal against leakage; therefore, the fluid is forced into the outlet port. The gear pumps are often equipped with the side wear plate to avoid the leakage. The clearance between gear teeth and housing and between side plate and gear face is very important and plays an important role in preventing leakage. In general, the gap distance is less than 10 micrometers. The amount of fluid discharge is determined by the number of gear teeth, the volume of fluid between each pair of teeth and the speed of rotation. The important drawback of external gear pump is the unbalanced side load on its bearings. It is caused due to high pressure at the outlet and low pressure at the inlet which results in slower speeds and lower pressure ratings in addition to reducing the bearing life. Gear pumps are most commonly used for the hydraulic fluid power applications and are widely used in chemical installations to pump fluid with a certain viscosity.

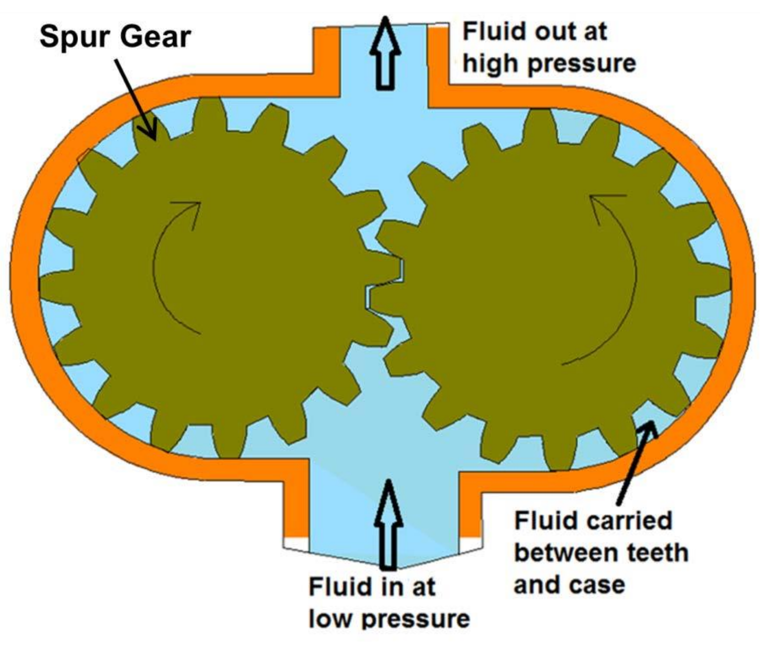


Figure 5.2.1 Gear pump

2.2 Lobe Pump

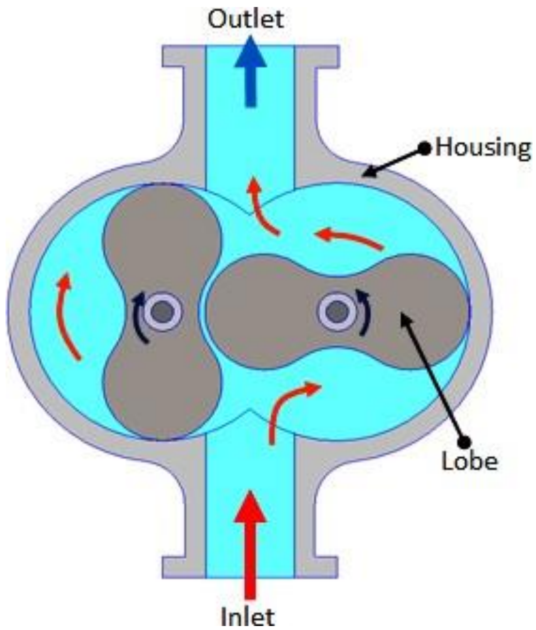


Figure 5.2.3 Lobe pump

Lobe pumps work on the similar principle of working as that of external gear pumps. However in Lobe pumps, the lobes do not make any contact like external gear pump (see Figure 5.2.3). Lobe contact is prevented by external timing gears located in the gearbox. Similar to the external gear pump, the lobes rotate to create expanding volume at the inlet. Now, the fluid flows into the cavity and is trapped by the lobes. Fluid travels around the interior of casing in the pockets between the lobes and the casing. Finally, the meshing of the lobes forces liquid to pass through the outlet port. The bearings are placed out of the pumped liquid. Therefore the pressure is limited by the bearing location and shaft deflection.

Because of superb sanitary qualities, high efficiency, reliability, corrosion resistance and good clean-in-place and steam-in-place (CIP/SIP) characteristics, Lobe pumps are widely used in industries such as pulp and paper, chemical, food, beverage, pharmaceutical and biotechnology etc. These pumps can handle solids (e.g., cherries and olives), slurries, pastes, and a variety of liquids. A gentle pumping action minimizes product degradation. They also offer continuous and intermittent reversible flows. Flow is relatively independent of changes in process pressure and therefore, the output is constant and continuous.

Lobe pumps are frequently used in food applications because they handle solids without damaging the product. Large sized particles can be pumped much effectively than in other positive displacement types. As the lobes do not make any direct contact therefore, the clearance is not as close as in other Positive displacement pumps. This specific design of pump makes it suitable to handle low viscosity fluids with diminished performance.

Loading characteristics are not as good as other designs, and suction ability is low. High-viscosity liquids require reduced speeds to achieve satisfactory performance. The reduction in speed can be 25% or more in case of high viscosity fluid.

2.3 Internal Gear Pump

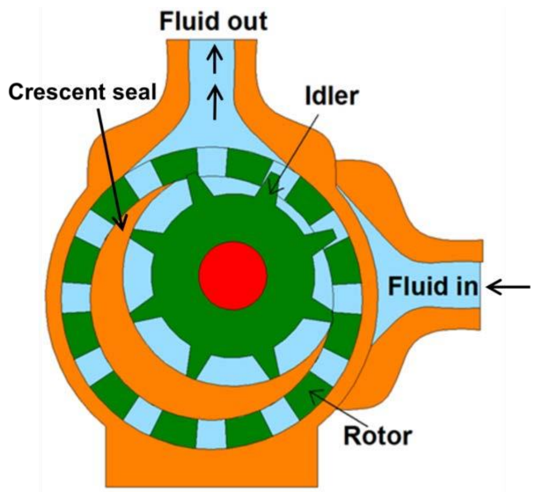


Figure 5.2.4 Internal gear pump

Internal gear pumps are exceptionally versatile. They are often used for low or medium viscosity fluids such as solvents and fuel oil and wide range of temperature. This is non-pulsing, self-priming and can run dry for short periods. It is a variation of the basic gear pump.

It comprises of an internal gear, a regular spur gear, a crescent-shaped seal and an external housing. The schematic of internal gear pump is shown in figure 5.2.4. Liquid enters the suction port between the rotor (large exterior gear) and idler (small interior gear) teeth. Liquid travels through the pump between the teeth and crescent. Crescent divides the liquid and acts as a seal between the suction and discharge ports. When the teeth mesh on the side opposite to the crescent seal, the fluid is forced out through the discharge port of the pump. This clearance between gears can be adjusted to accommodate high temperature, to handle high viscosity fluids and to accommodate the wear. These pumps are bi-rotational so that they can be used to load and unload the vessels. As these pumps have only two moving parts and one stuffing box, therefore they are reliable, simple to operate and easy to maintain. However, these pumps are not suitable for high speed and high pressure applications. Only one bearing is used in the pump therefore overhung load on shaft bearing reduces the life of the bearing.

Applications

Some common internal gear pump applications are:

- All varieties of fuel oil and lube oil
- Resins and Polymers
- Alcohols and solvents
- Asphalt, Bitumen, and Tar
- Polyurethane foam (Isocyanate and polyol)
- Food products such as corn syrup, chocolate, and peanut butter
- Paint, inks, and pigments
- Soaps and surfactants
- Glycol

2.4 Gerotor Pump

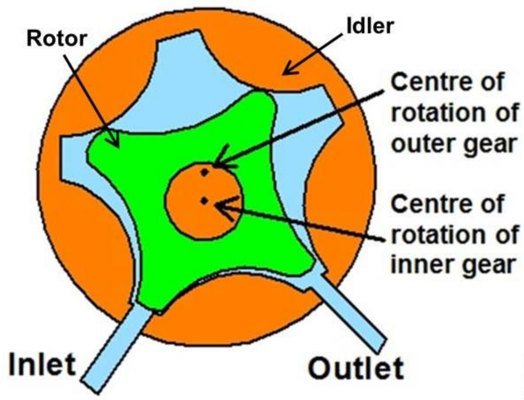


Figure 5.2.5 Gerotor pump

Gerotor is a positive displacement pump. The name Gerotor is derived from "Generated Rotor". At the most basic level, a Gerotor is essentially one that is moved via fluid power. Originally this fluid was water, today the wider use is in hydraulic devices. The schematic of Gerotor pump is shown in figure 5.2.5. Gerotor pump is an internal gear pump without the crescent. It consists of two rotors viz. inner and outer rotor. The inner rotor has N teeth, and the outer rotor has N+1 teeth. The inner rotor is located off-center and both rotors rotate. The geometry of the two rotors partitions the volume between them into N different dynamically-changing volumes. During the rotation, volume of each partition changes continuously. Therefore, any given volume first increases, and then decreases. An increase in volume creates vacuum. This vacuum creates suction, and thus, this part of the cycle sucks the fluid. As the volume decreases, compression occurs. During this compression period, fluids can be pumped, or compressed (if they are gaseous fluids).

The close tolerance between the gears acts as a seal between the suction and discharge ports. Rotor and idler teeth mesh completely to form a seal equidistant from the discharge and suction ports. This seal forces the liquid out of the discharge port. The flow output is uniform and constant at the outlets.

The important advantages of the pumps are high speed operation, constant discharge in all pressure conditions, bidirectional operation, less sound in running condition and less maintenance due to only two moving parts and one stuffing box etc. However, the pump is having some limitations such as medium pressure operating range, clearance is fixed, solids can’t be pumped and overhung load on the shaft bearing etc.

Applications

Gerotors are widely used in industries and are produced in variety of shapes and sizes by a number of different methods. These pumps are primarily suitable for low pressure applications such as lubrication systems or hot oil filtration systems, but can also be found in low to moderate pressure hydraulic applications. However common applications are as follows:

- Light fuel oils
- Lube oil
- Cooking oils
- Hydraulic fluid

Module 5: Hydraulic Systems

Lecture 3

Hydraulic Pumps -2

1. Vane Pumps

In the previous lecture we have studied the gear pumps. These pumps have a disadvantage of small leakage due to gap between gear teeth and the pump housing. This limitation is overcome in vane pumps. The leakage is reduced by using spring or hydraulically loaded vanes placed in the slots of driven rotor. Capacity and pressure ratings of a vane pump are generally lower than the gear pumps, but reduced leakage gives an improved volumetric efficiency of around 95%.

Vane pumps are available in a number of vane configurations including sliding vane, flexible vane, swinging vane, rolling vane, and external vane etc. Each type of vane pump has its own advantages. For example, external vane pumps can handle large solids. Flexible vane pumps can handle only the small solids but create good vacuum. Sliding vane pumps can run dry for short periods of time and can handle small amounts of vapor. The vane pumps are known for their dry priming, ease of maintenance, and good suction characteristics. The operating range of these pumps varies from -32 °C to 260 °C.

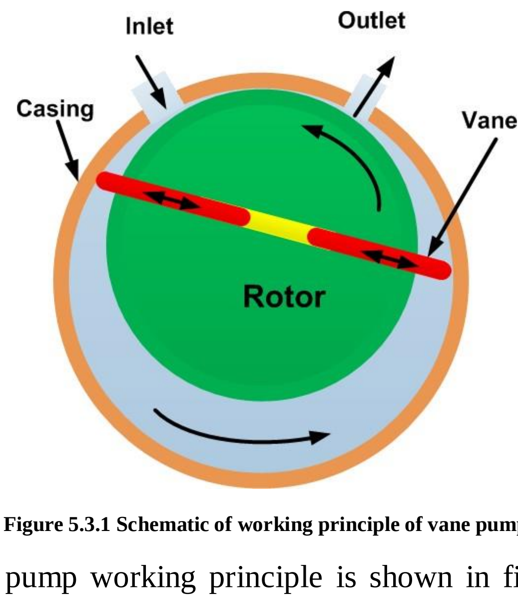


Figure 5.3.1 Schematic of working principle of vane pump

The schematic of vane pump working principle is shown in figure 5.3.1. Vane pumps generate a pumping action by tracking of vanes along the casing wall. The vane pumps generally consist of a rotor, vanes, ring and a port plate with inlet and outlet ports. The rotor in a vane pump is connected to the prime mover through a shaft. The vanes are located on the slotted rotor. The rotor is eccentrically placed inside a cam ring as shown in the figure. The rotor is sealed into the cam by two side plates. When the prime mover rotates the rotor, the vanes are thrown outward due to centrifugal force. The vanes track along the ring. It provides a tight hydraulic seal to the fluid which is more at the higher rotation speed due to higher centrifugal force. This produces a suction cavity in the ring as the rotor rotates. It creates vacuum at the inlet and therefore, the fluid is pushed into the pump through the inlet. The fluid is carried around to the outlet by the vanes whose retraction causes the fluid to be expelled. The capacity of the pump depends upon the eccentricity, expansion of vanes, width of vanes and speed of the rotor. It can be noted that the fluid flow will not occur when the eccentricity is zero. These pumps can handle thin liquids (low viscosity) at relatively higher pressure. These pumps can be run dry for a small duration without any failure. These pumps develop good vacuum due to negligible leakage. However, these pumps are not suitable for high speed applications and for the high viscosity fluids or fluids carrying some abrasive particles. The maintenance cost is also higher due to many moving parts. These pumps have various applications for the pumping of following fluids:

- Aerosol and Propellants
- Aviation Service - Fuel Transfer, Deicing
- Auto Industry - Fuels, Lubes, Refrigeration Coolants
- Bulk Transfer of LPG and NH3
- LPG Cylinder Filling
- Alcohols
- Refrigeration - Freons, Ammonia
- Solvents
- Aqueous solutions

1.1 Unbalanced Vane pump

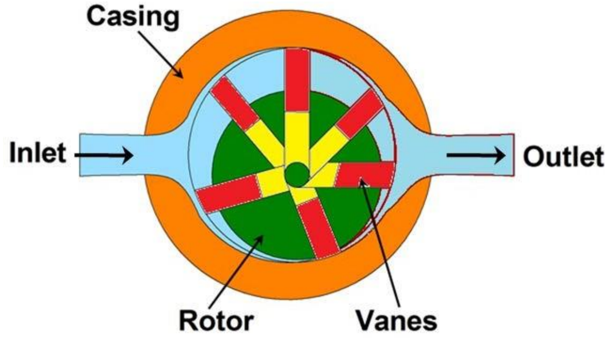


Figure 5.3.2 Unbalanced vane pump

In practice, the vane pumps have more than one vane as shown in figure 5.3.2. The rotor is offset within the housing, and the vanes are constrained by a cam ring as they cross inlet and outlet ports. Although the vane tips are held against the housing, still a small amount of leakage exists between rotor faces and body sides. Also, the vanes compensate to a large degree for wear at the vane tips or in the housing itself. The pressure difference between outlet and inlet ports creates a large amount of load on the vanes and a significant amount of side load on the rotor shaft which can lead to bearing failure. This type of pump is called as unbalanced vane pump.

1.2 Balanced vane pump

Figure 5.3.3 shows the schematic of a balanced vane pump. This pump has an elliptical cam ring with two inlet and two outlet ports. Pressure loading still occurs in the vanes but the two identical pump halves create equal but opposite forces on the rotor. It leads to the zero net force on the shaft and bearings. Thus, lives of pump and bearing increase significantly. Also the sounds and vibrations decrease in the running mode of the pump.

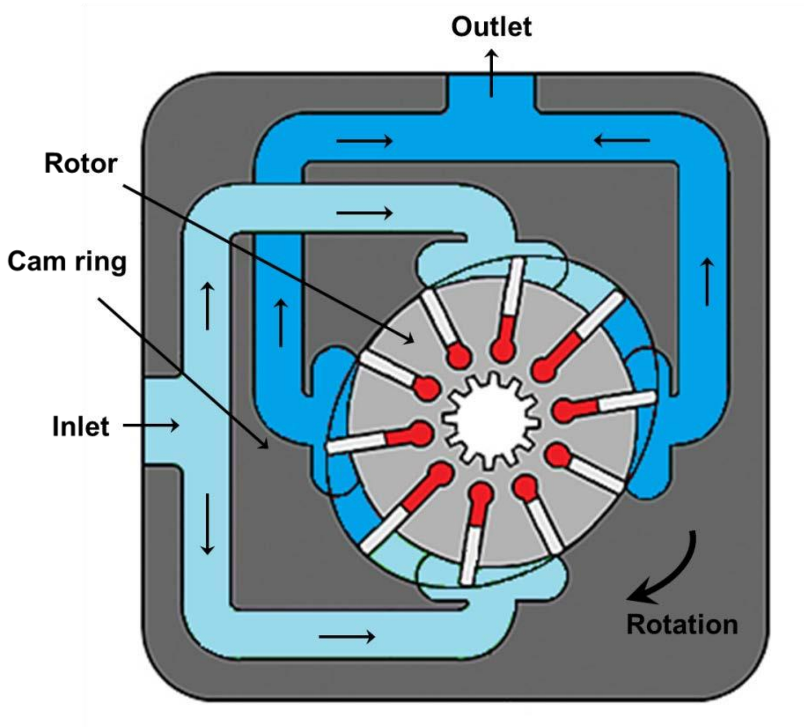


Figure 5.3.3 Balanced Vane Pump

1.3 Adjustable vane pump

The proper design of pump is important and a challenging task. In ideal condition, the capacity of a pump should be exactly same to load requirements. A pump with larger capacity wastes energy as the excess fluid will pass through the pressure relief valve. It also leads to a rise in fluid temperature due to energy conversion to the heat instead of useful work and therefore it needs some external cooling arrangement. Therefore, the higher capacity pump increases the power consumption and makes the system bulky and costly. Pumps are generally available with certain standard capacities and the user has to choose the next available capacity of the pump. Also, the flow rate from the pump in most hydraulic applications needs to be varying as per the requirements. Therefore, some vane pumps are also available with adjustable capacity as shown in figure 5.3.4. This can be achieved by adjusting a positional relationship between rotor and the inner casing by the help of an external controlling screw. These pumps basically consist of a rotor, vanes, cam ring, port plate, thrust bearing for guiding the cam ring and a discharge control screw by which the position of the cam ring relative to the rotor can be varied. In general, the adjustable vane pumps are unbalanced pump type.

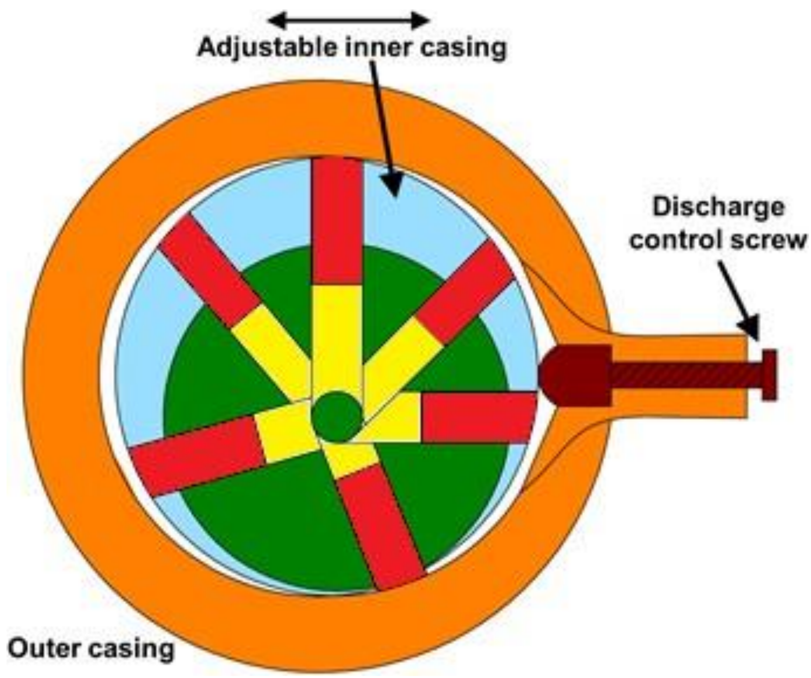


Figure 5.3.4 Adjustable vane pump

The amount of fluid that is displaced by a vane pump running at a constant speed is determined by the maximum extension of the vanes and the vanes width. However, for a pump running in operation, the width of vanes cannot be changed but the distance by which the vanes are extended can be varied. This is possible by making a provision for changing the position of the cam ring (adjustable inner casing) relative to the rotor as shown in figure 5.3.4. The eccentricity of rotor with respect to the cam ring is adjusted by the movement of the screw. The delivery volume increases with increase in the eccentricity. This kind of arrangement can be used to achieve a variable volume from the pump and is known as variable displacement vane pump.

In general, the adjusted vane pumps are pressure compensated. It means that the discharge is controlled by pre-adjusted value and when the discharge pressure reaches a certain (adjusted) value; the pumping action ceases. This mechanism is accomplished by using a compensating spring to offset the cam ring. Initially, the eccentricity is maximum because the discharge pressure is zero and spring force keeps the cam ring at the extreme right position. As the discharge pressure increases, it acts on the inner contour of the cam ring. It pushes the cam ring towards the left against the spring force and hence the eccentricity reduces and hence the discharge through the pump reduces. When the discharge pressure becomes high enough to overcome the entire spring force; the compensator spring will compress until the zero eccentricity is achieved. In this condition, the pumping action ceases and the fluid flow (except small leakages) does not occur. Therefore, the system pressure can be adjusted by setting the compensator spring. These pumps ensure their own protection against excessive system pressure and do not rely on the safety control devices of the hydraulic system. These pumps are used as energy savings devices and have been used in many applications, including automotive transmissions.

2. Piston pumps

Piston pumps are meant for the high-pressure applications. These pumps have high-efficiency and simple design and needs lower maintenance. These pumps convert the rotary motion of the input shaft to the reciprocating motion of the piston. These pumps work similar to the four stroke engines. They work on the principle that a reciprocating piston draws fluid inside the cylinder when the piston retracts in a cylinder bore and discharge the fluid when it extends. Generally, these pumps have fixed inclined plate or variable degree of angle plate known as swash plate (shown in Figure 5.3.5 and Figure 5.3.6). When the piston barrel assembly rotates, the swash plate in contact with the piston slippers slides along its surface. The stroke length (axial displacement) depends on the inclination angle of the swash plate. When the swash plate is vertical, the reciprocating motion does not occur and hence pumping of the fluid does not take place. As the swash plate angle increases, the piston reciprocates inside the cylinder barrel. The stroke length increases with increase in the swash plate angle and therefore volume of pumping fluid increases. During one half of the rotation cycle, the pistons move out of the cylinder barrel and the volume of the barrel increases. During another half of the rotation, the pistons move into the cylinder barrel and the barrel volume decreases. This phenomenon is responsible for drawing the fluid in and pumping it out. These pumps are positive displacement pump and can be used for both liquids and gases. Piston pumps are basically of two types:

i. Axial piston pumps
ii. Radial piston pumps

2.1 Axial Piston Pump

Axial piston pumps are positive displacement pumps which converts rotary motion of the input shaft into an axial reciprocating motion of the pistons. These pumps have a number of pistons (usually an odd number) in a circular array within a housing which is commonly referred to as a cylinder block, rotor or barrel. These pumps are used in jet aircraft. They are also used in small earthmoving plants such as skid loader machines. Another use is to drive the screws of torpedoes. In general, these systems have a maximum operating temperature of about 120 °C. Therefore, the leakage between cylinder housing and body block is used for cooling and lubrication of the rotating parts. This cylinder block rotates by an integral shaft aligned with the pistons. These pumps have sub-types as:

a. Bent axis piston pumps
b. Swash plate axial piston pump

2.1.1 Bent-Axis Piston Pumps

Figure 5.3.5 shows the schematic of bent axis piston pump. In these pumps, the reciprocating action of the pistons is obtained by bending the axis of the cylinder block. The cylinder block rotates at an angle which is inclined to the drive shaft. The cylinder block is turned by the drive shaft through a universal link. The cylinder block is set at an offset angle with the drive shaft. The cylinder block contains a number of pistons along its periphery. These piston rods are connected with the drive shaft flange by ball-and-socket joints. These pistons are forced in and out of their bores as the distance between the drive shaft flange and the cylinder block changes. A universal link connects the block to the drive shaft, to provide alignment and a positive drive.

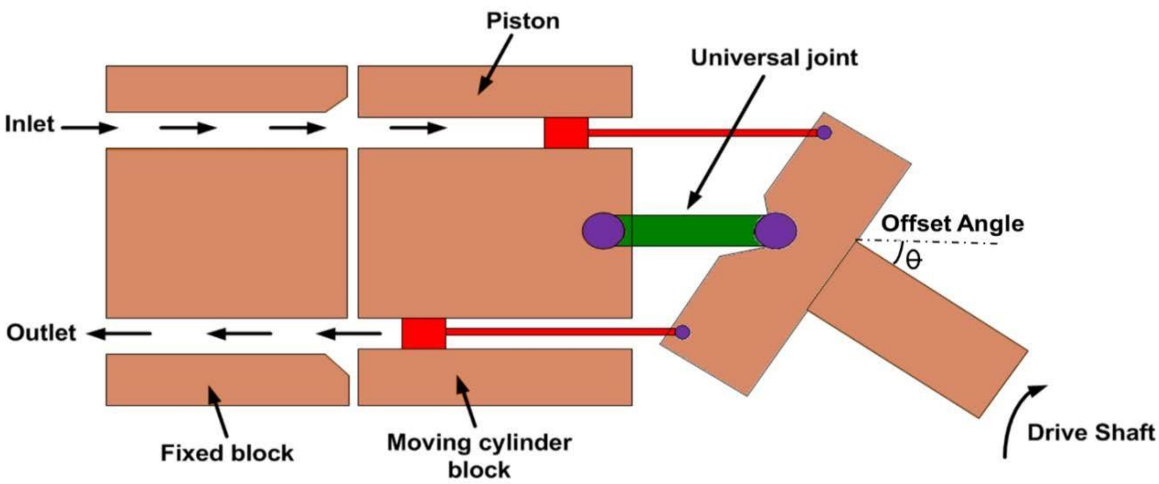


Figure 5.3.5 Bent axis piston pump

The volumetric displacement (discharge) of the pump is controlled by changing the offset angle. It makes the system simple and inexpensive. The discharge does not occur when the cylinder block is parallel to the drive shaft. The offset angle can vary from 0° to 40°. The fixed displacement units are usually provided with 23° or 30° offset angles while the variable displacement units are provided with a yoke and an external control mechanism to change the offset angle. Some designs have arrangement of moving the yoke over the center position to reverse the fluid flow direction. The flow rate of the pump varies with the offset angle θ . There is no flow when the cylinder block centerline is parallel to the drive shaft centerline (offset angle is 0°). The total fluid flow per stroke can be given as:

$$V_d = nADtan\theta \tag{5.3.1}$$

The flow rate of the pump can be given as:

$$V_d = nADN\, tan\theta \tag{5.3.2}$$

here, $tan\theta = \frac{S}{D}$ (5.3.3)

where S is the piston stroke, D is piston diameter, n is the number of pistons, N is the speed of pump and A is the area of piston.

2.1.2 Swash Plate Axial Piston Pump

A swash plate is a device that translates the rotary motion of a shaft into the reciprocating motion. It consists of a disk attached to a shaft as shown in Figure 5.3.6. If the disk is aligned perpendicular to the shaft; the disk will turn along with the rotating shaft without any reciprocating effect. Similarly, the edge of the inclined shaft will appear to oscillate along the shaft's length. This apparent linear motion increases with increase in the angle between disk and the shaft (offset angle). The apparent linear motion can be converted into an actual reciprocating motion by means of a follower that does not turn with the swash plate.

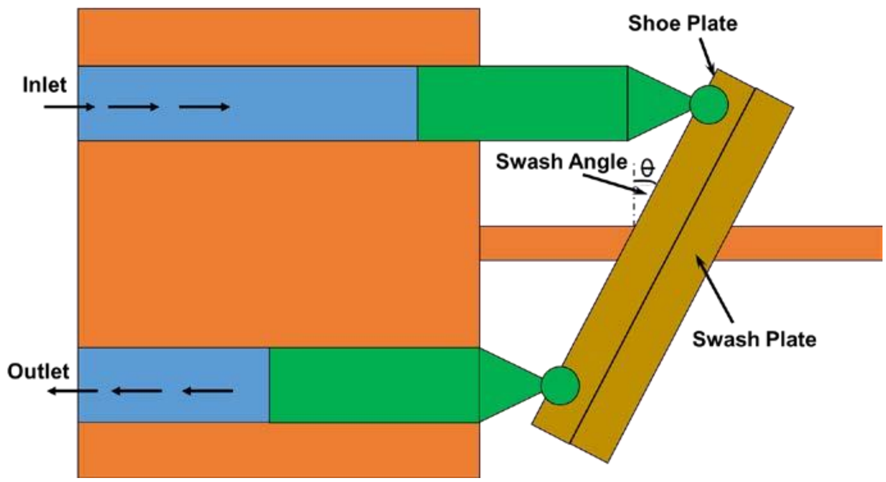


Figure 5.3.6 Swash plate piston pump

In swash plate axial piston pump a series of pistons are aligned coaxially with a shaft through a swash plate to pump a fluid. The schematic of swash plate piston pump is shown in Figure 5.3.6. The axial reciprocating motion of pistons is obtained by a swash plate that is either fixed or has variable degree of angle. As the piston barrel assembly rotates, the piston rotates around the shaft with the piston shoes in contact with the swash plate. The piston shoes follow the angled surface of the swash plate and the rotational motion of the shaft is converted into the reciprocating motion of the pistons. When the swash plate is perpendicular to the shaft; the reciprocating motion to the piston does not occur. As the swash plate angle increases, the piston follows the angle of the swash plate surface and hence it moves in and out of the barrel. The piston moves out of the cylinder barrel during one half of the cycle of rotation thereby generating an increasing volume, while during other half of the rotating cycle, the pistons move into the cylinder barrel generating a decreasing volume. This reciprocating motion of the piston results in the drawing in and pumping out of the fluid. Pump capacity can be controlled by varying the swash plate angle with the help of a separate hydraulic cylinder. The pump capacity (discharge) increases with increase in the swash plate angle and vice-versa. The cylinder block and the drive shaft in this pump are located on the same centerline. The pistons are connected through shoes and a shoe plate that bears against the swash plate. These pumps can be designed to have a variable displacement capability. It can be done by mounting the swash plate in a movable yoke. The swash plate angle can be changed by pivoting the yoke on pintles.

2.2 Radial Piston Pump

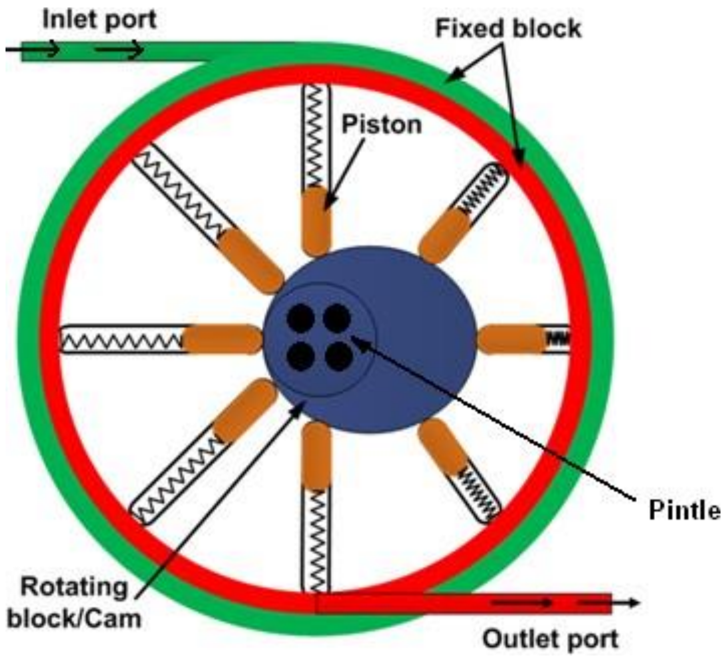


Figure 5.3.7 Radial piston pump

The typical construction of radial piston pump is shown in Figure 5.3.7. The piston pump has pistons aligned radially in a cylindrical block. It consists of a pintle, a cylinder barrel with pistons and a rotor containing a reaction ring. The pintle directs the fluid in and out of the cylinder. Pistons are placed in radial bores around the rotor. The piston shoes ride on an eccentric ring which causes them to reciprocate as they rotate. The eccentricity determines the stroke of the pumping piston. Each piston is connected to inlet port when it starts extending while it is connected to the outlet port when start retracting. This connection to the inlet and outlet port is performed by the timed porting arrangement in the pintle. For initiating a pumping action, the reaction ring is moved eccentrically with respect to the pintle or shaft axis. As the cylinder barrel rotates, the pistons on one side travel outward. This draws the fluid in as the cylinder passes the suction port of the pintle. It is continued till the maximum eccentricity is reached. When the piston passes the maximum eccentricity, pintle is forced inwards by the reaction ring. This forces the fluid to flow out of the cylinder and enter in the discharge (outlet) port of the pintle.

The radial piston pump works on high pressure (up to 1000 bar). It is possible to use the pump with various hydraulic fluids like mineral oil, biodegradable oil, HFA (oil in water), HFC (water-glycol), HFD (synthetic ester) or cutting emulsion. This is because the parts are hydrostatically balanced. It makes the pump suitable for the many applications such as machine tools (displace of cutting emulsion, supply for hydraulic equipment like cylinders), high pressure units (overload protection of presses), test rigs, automotive sector (automatic transmission, hydraulic suspension control in upper-class cars), plastic (powder injection molding) and wind energy etc.

3. *Combination Pump*

There are two basic requirements for load lifting or load applying by a hydraulic ram. First, there is a need of large volume of fluid at a low pressure when the cylinder extends or retracts. The low pressure is required to overcome the frictional resistance. The second requirement is that a high pressure is needed, when the load is gripped.

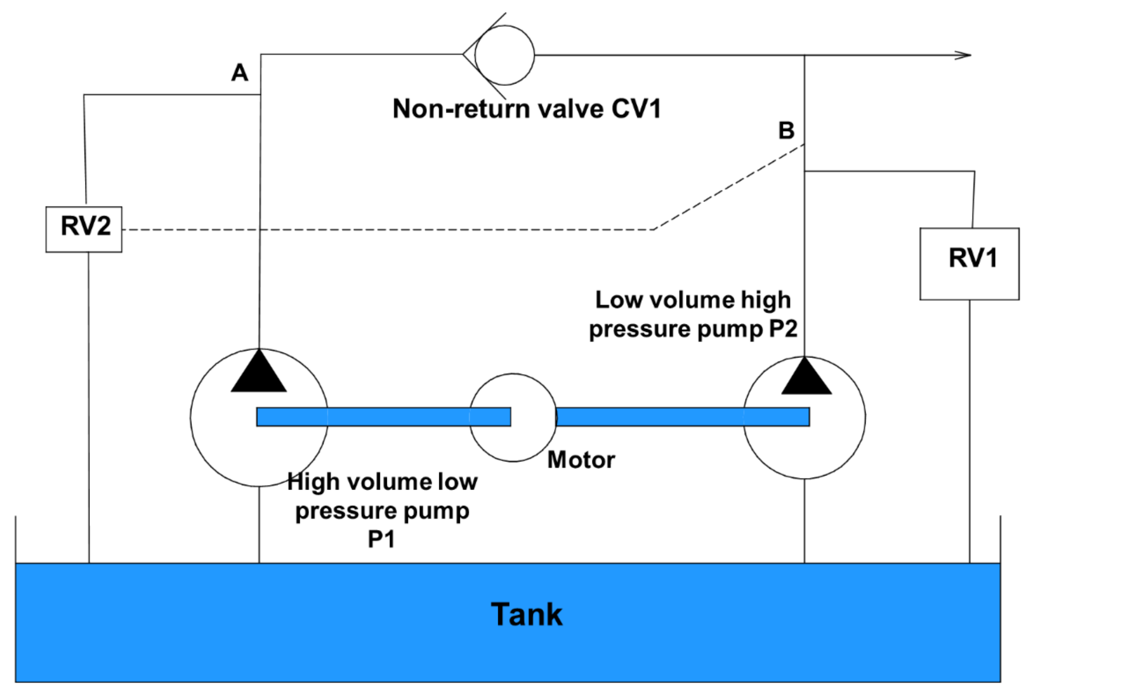


Figure 5.3.8 Combination pump

This type of requirements can be fulfilled by an arrangement as shown in figure 5.3.8. In this system two separate pumps are driven by a common electrical motor. Pump P1 is a high pressure low volume pump and pump P2 is a high volume low pressure pump. The hydraulic system is associated with relief valves RV1 and RV2 and a one-way check valve CV1. This kind of arrangement allows the fluid flow from left to right, but blocks in the reverse direction.

The pressure relief valve RV1 is a normal high pressure valve. The pressure relief valve RV2 is not operated by the pressure at point A, however, it is remotely operated by the pressure at point B. This can be achieved with the balanced piston valve. In low pressure mode both relief valves are closed and both pumps P1 and P2 deliver fluid to the load but the majority comes from the pump P2 as its capacity is higher.

When the load is in the holding mode, the pressure at B rises and relief valve RV2 opens. It results in all the fluid from pump P2 to return straight to the tank directly and the pressure at A to fall to a low value. The check valve CV1 stops the fluid from pump P1 pass it back to the tank via relief valve RV2, consequently pressure at B rises to the level set by relief valve RV1.

This kind of arrangement saves energy as the large volume of fluid from pump P2 is returned to the tank at a very low pressure, and only a small volume of fluid from pump P1 is returned at a high pressure.

In general the applications of Hydraulic Pumps can be summarized as,

- Hydraulic pumps are used to transfer power via hydraulic liquid. These pumps have a number of applications in automobiles, material handling systems, automatic transmissions, controllers, compressors and household items.
- The hand operated hydraulic pump is used in a hydraulic jack where many strokes of the pump apply hydraulic pressure to lift the ram.
- A backhoe uses an engine driven hydraulic pump to drive the articulating parts of the mechanical hoe.
- The hydraulic pumps are commonly used in the automotive vehicles especially in power steering systems.
- The lift system of tractor is operated by the hydraulic pumps. These are used in automatic transmissions and material handling systems in industries.
- Many precise controllers are developed by using hydraulic pumps. The commonly used compressor is operated by reciprocating pumps.
- The hydraulic pumps are also used in routine household systems like power lift and air-conditions. Therefore, it can be said that the hydraulic pumps have significant applications in industries as well as ones routine life.

Module 5: Hydraulic Systems

Lecture 4

Control Valves -1

In a hydraulic system, the hydraulic energy available from a pump is converted into motion and force by means of an actuator. The control of these mechanical outputs (motion and force) is one of the most important functions in a hydraulic system. The proper selection of control selection ensures the desired output and safe function of the system. In order to control the hydraulic outputs, different types of control valves are required. It is important to know various types of control valves and their functions. This not only helps to design a proper hydraulic system but also helps to discover the innovative ways to improve the existing systems. In this lecture and next few lectures, various types of valves will be discussed.

There are basically three types of valves employed in hydraulic systems:

1. Directional control valves
2. Flow control valves
3. Pressure control valves

1. Direction control valve

Directional control valves are used to control the distribution of energy in a fluid power system. They provide the direction to the fluid and allow the flow in a particular direction. These valves are used to control the start, stop and change in direction of the fluid flow. These valves regulate the flow direction in the hydraulic circuit. These control valves contain ports that are external openings for the fluid to enter and leave. The number of ports is usually identified by the term 'way'. For example, a valve with four ports is named as four-way valve. The fluid flow rate is responsible for the speed of actuator (motion of the output) and should controlled in a hydraulic system. This operation can be performed by using flow control valves. The pressure may increase gradually when the system is under operation. The pressure control valves protect the system by maintaining the system pressure within the desired range. Also, the output force is directly proportional to the pressure and hence, the pressure control valves ensure the desired force output at the actuator.

Directional control valves can be classified in the following manner:

1. Type of construction:

- Poppet valves
- Spool valves

2. Number of ports:

- Two- way valves
- Three – way valves
- Four- way valves.

3. Number of switching position:

- Two – position
- Three - position

4. Actuating mechanism:

- Manual actuation
- Mechanical actuation
- Solenoid actuation
- Hydraulic actuation
- Pneumatic actuation
- Indirect actuation

1.1 Type of construction

1.1.1 Check Valves

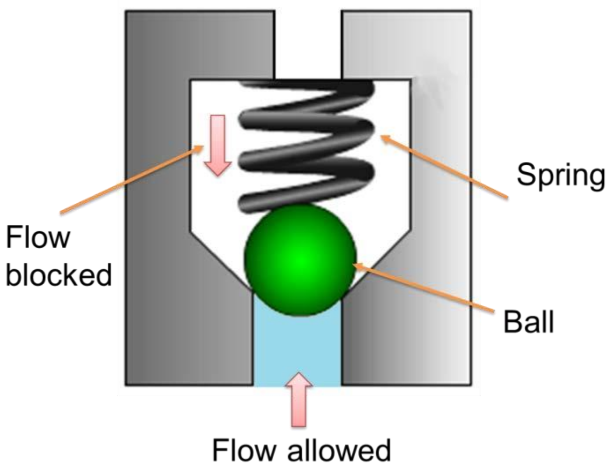


Figure 5.4.1 Inline check valve

These are unidirectional valves and permit the free flow in one direction only. These valves have two ports: one for the entry of fluid and the other for the discharge. They are consists of a housing bore in which ball or poppet is held by a small spring force. The valve having ball as a closing member is known as ball check valve. The various types of check valves are available for a range of applications. These valves are generally small sized, simple in construction and inexpensive. Generally, the check valves are automatically operated. Human intervention or any external control system is not required. These valves can wear out or can generate the cracks after prolonged usage and therefore they are mostly made of plastics for easy repair and replacements.

An important concept in check valves is the cracking pressure. The check valve is designed for a specific cracking pressure which is the minimum upstream pressure at which the valve operates. The simplest check valve is an inline check valve as shown in Figure 5.4.1. The ball is held against the valve seat by a spring force. It can be observed from the figure that the fluid flow is not possible from the spring side but the fluid from opposite side can pass by lifting the ball against. However, there is some pressure drop across the valve due to restriction by the spring force. Therefore these valves are not suitable for the application of high flow rate. When the operating pressure increases the valve becomes more tightly seated in this design.

The advantages of the poppet valves include no leakage, long life and suitability with high pressure applications. These valves are commonly used in liquid or gel mini-pump dispenser spigots, spray devices, some rubber bulbs for pumping air, manual air pumps, and refillable dispensing syringes. Sometimes, the right angle check valve as shown in Figure 5.4.2 is used for the high flow rate applications. The pressure drop is comparatively less in right angle check valve.

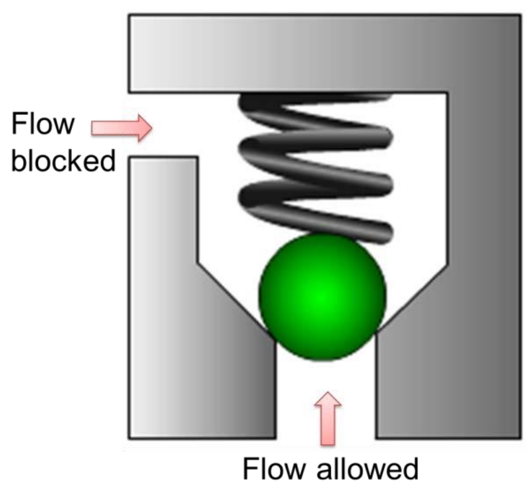


Figure 5.4.2 Right angle check valve

When the closing member is not a ball but a poppet energized by a spring is known as poppet valve. The typical poppet valve is shown in Figure 5.4.3. Some valves are meant for an application where free flow is required in one direction and restricted flow required in another direction. These types of valves are called as restriction check valve (see Figure 5.4.3). These valves are used when a direction sensitive flow rate is required. For example, the different actuator speeds are required in both the directions. The flow adjustment screw can be used to set the discharge (flow rate) in the restricted direction.

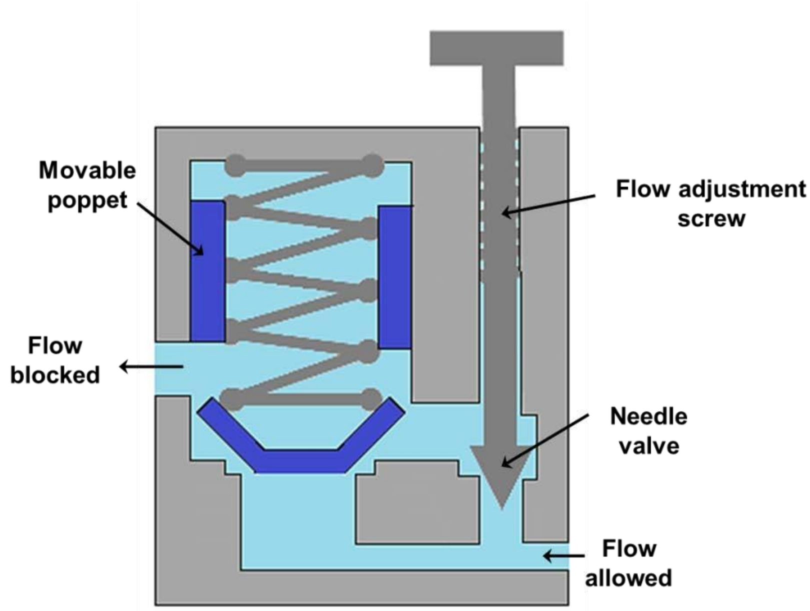


Figure 5.4.3 Restriction check valve

Another important type of check valve known as pilot operated check valve which is shown in figure 5.4.4. The function of the pilot operated check valve is similar to a normal check valve unless it gets an extra pressure signal through a pilot line. Pilot allows free flow in one direction and prevents the flow in another direction until the pilot pressure is applied. But when pilot pressure acts, the poppet opens and the flow is blocked from both the sides. These valves are used to stop the fluid suddenly.

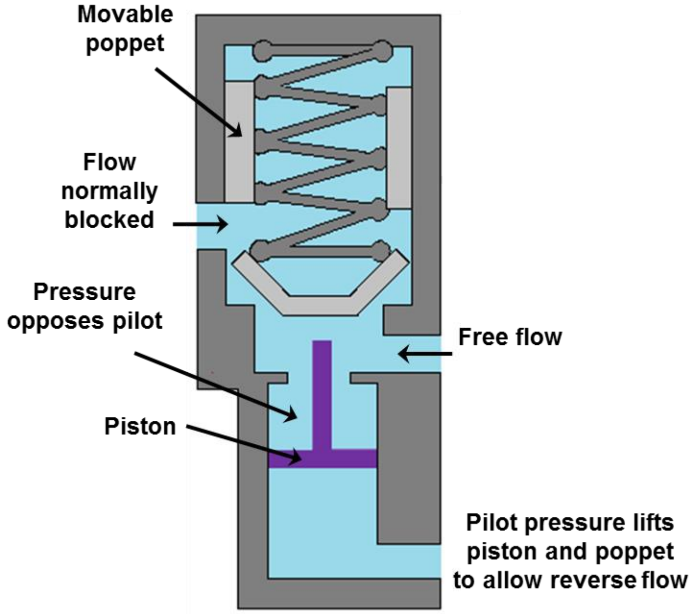


Figure 5.4.4 Pilot operated check valve

1.1.2 Spool valve

The spool valves derive their name from their appearance. It consists of a shaft sliding in a bore which has large groove around the circumference. This type of construction makes it look like a spool. The spool is sealed along the clearance between moving spool and housing (valve body). The quality of seal or the amount of leakage depends on the amount of clearance, viscosity of fluid and the level of the pressure. The grooves guide the fluid flow by interconnecting or blocking the holes (ports). The spool valves are categorized according to the number of operating positions and the way hydraulic lines interconnections. One of the simplest two way spool valve is shown in Figure 5.4.5. The standard terms are referred as Port 'P' is pressure port, Port 'T' is tank port and Port 'A' and Port 'B' are the actuator (or working) ports. The actuators can move in forward or backward direction depending on the connectivity of the pressure and tank port with the actuators port.

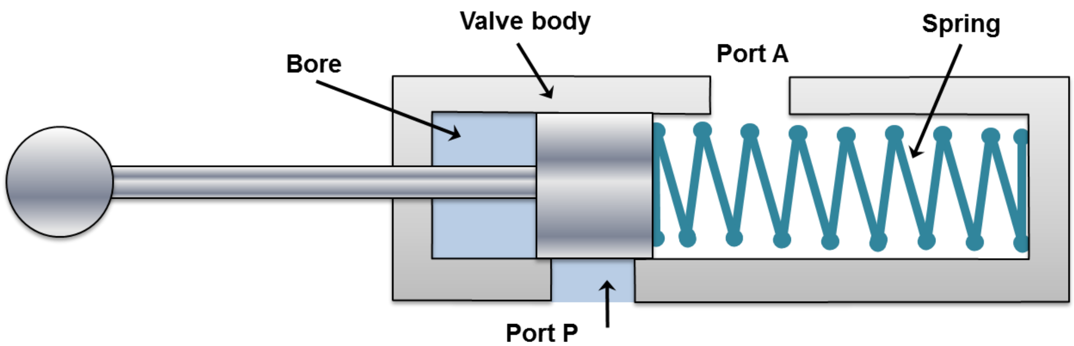


Figure 5.4.5 Valve closed

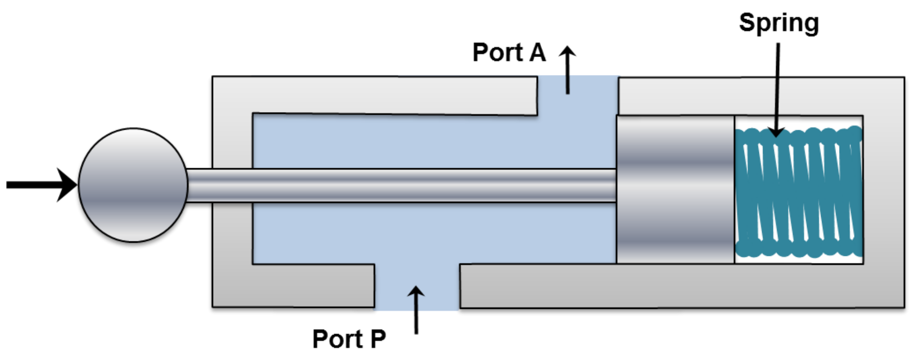


Figure 5.4.6 Valve opened by actuation

1.2 Number of ports

1.2.1 Two way valves

Two way valves have only two ports as shown in Figure 5.4.5 and Figure 5.4.6. These valves are also known as on-off valves because they allow the fluid flow only in direction. Normally, the valve is closed. These valves are available as normally open and normally closed function. These are the simplest type of spool valves. When actuating force is not applied to the right, the port P is not connected with port A as shown in figure 5.4.5. Therefore, the actuation does not take place. Similarly, Figure 5.4.6 shows the two-way spool valve in the open condition. Here, the pressure port P is connected with the actuator port A.

1.2.2 Three way valves

When a valve has one pressure port, one tank port and one actuating port as shown in Figures 5.4.7 and 5.4.8, it is known as three way valve. In this valve, the pressure port pressurizes one port and exhausts another one. As shown in figures, only one actuator port is opened at a time. In some cases a neutral position is also available when both the ports are blocked. Generally, these valves are used to operate single acting cylinders.

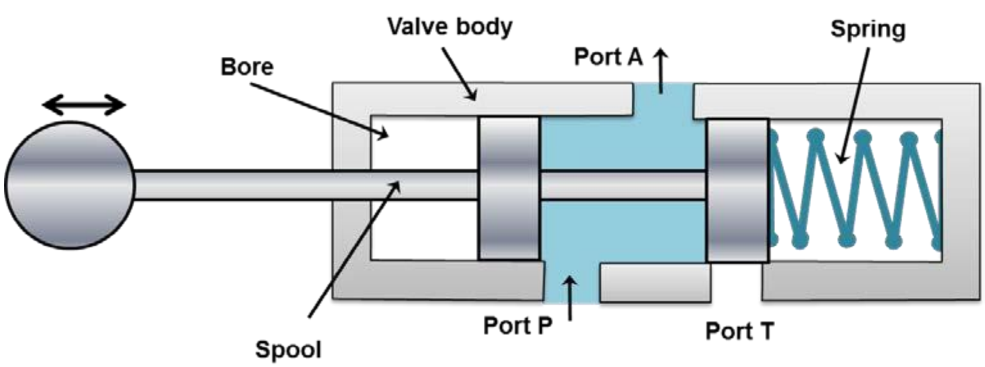


Figure 5.4.7 Three way valve: P to A connected and T is blocked

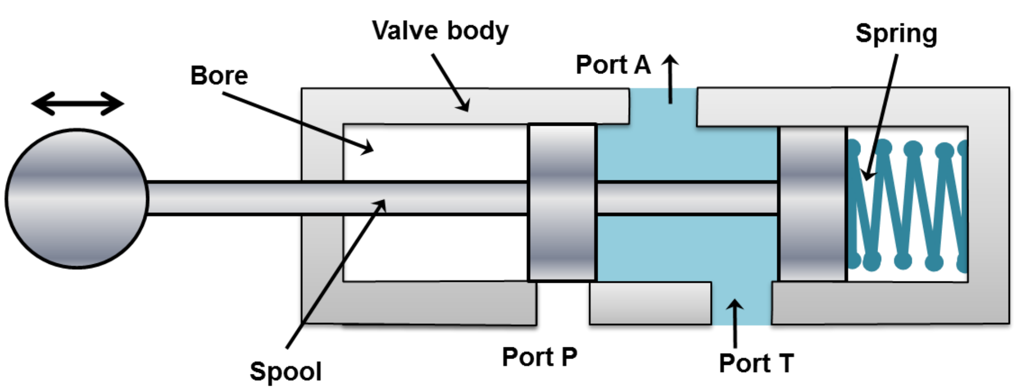


Figure 5.4.8 Three way valve in closed position

1.2.3 Four way valves

Figure 5.4.9 shows a four-way valve. It is generally used to operate the cylinders and fluid motors in both the directions. The four ways are: pump port P, tank port T, and two working ports A and B connected to the actuator. The primary function of a four way valve is to pressurize and exhaust two working ports A and B alternatively.

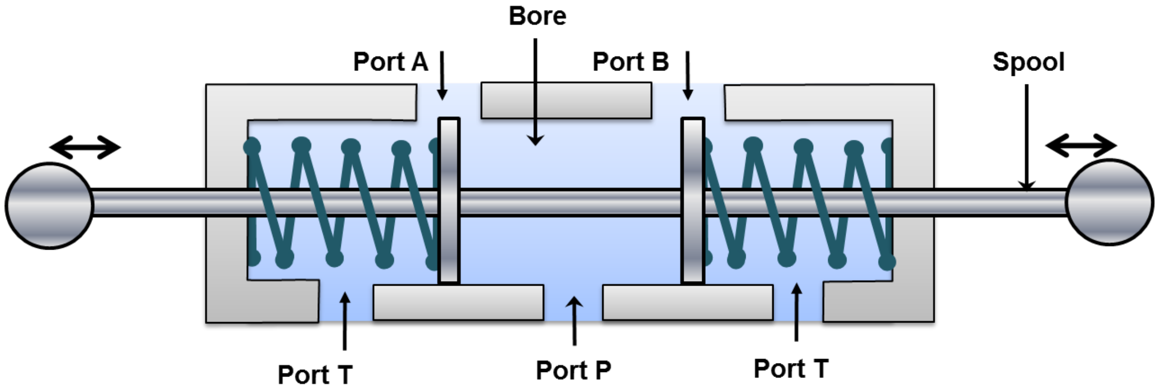


Figure 5.4.9 Three position four way valve in open center mode

Module 5: Hydraulic Systems

Lecture 5

Control valves -2

1. Classification of control valve according to number/ways of switching position

1.1 Three position four way (3/4) valves

Three position four way (3/4) valves are used in double-acting cylinders to perform advance, hold and return operation to the piston. Figures 5.5.1 and 5.5.2 show three position four way valves. These types of valves have three switching positions. They have a variety of possible flow path configurations but have identical flow path configuration. When the centered path is actuated, port A and B are connected with both the ports P and T respectively. In this case, valve is not active because all the ports are open to each other. The fluid flows to the tank at atmospheric pressure. In this position work cannot be done by any part of the system. This configuration helps to prevent heat buildup.

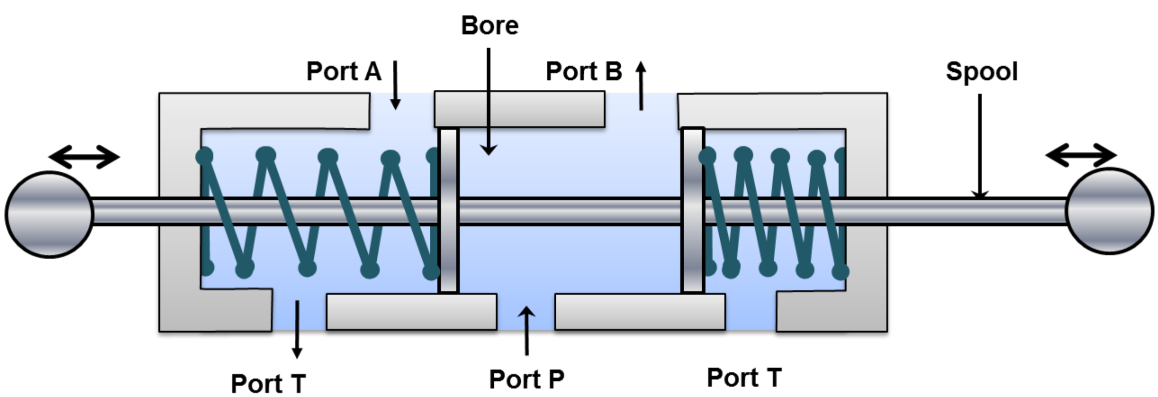


Figure 5.5.1 Three position four way valve: P to B and A to T

When left end (port B) is actuated, the port P is connected with ports B and T is connected with port A as shown in Figure 5.5.1. Similarly, when the right end is actuated the port P is connected to A and working port B is connected to port T as shown in Figure 5.5.2. The three position valves are used when the actuator is needed to stop or hold at some intermediate position. It can also be used when the multiple circuits or functions are accomplished from one hydraulic power source.

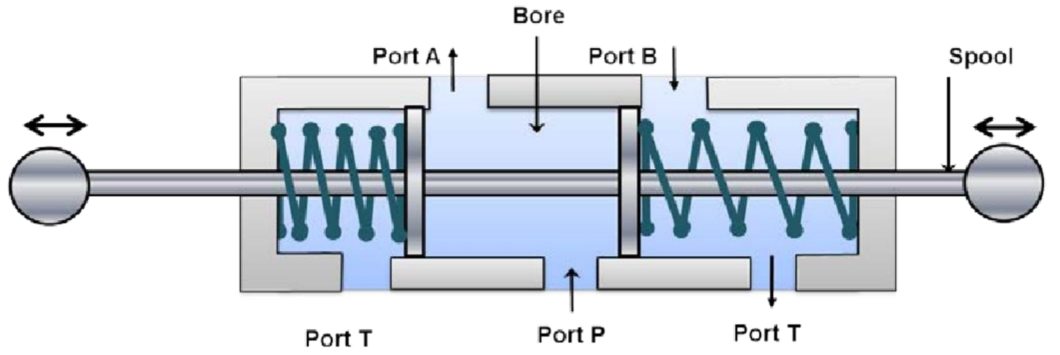


Figure 5.5.2 Three position four way valve: P to A and B to T

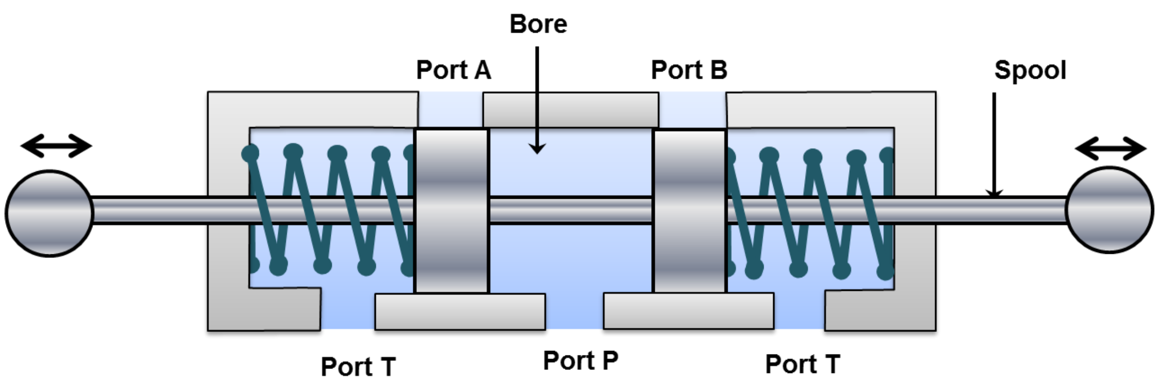


Figure 5.5.3 Three position four way valve: closed center

Figure 5.5.3 shows a three position four way valve in the closed center position. The working of the valve is similar to open center DCV. In closed center DCV all user ports (port A and port B) are closed. Therefore, these ports are hydraulically locked and the actuator cannot be moved by the external load. The pumped fluid flows through the relief valve. The pump works under the high pressure condition which not only wastes the pump power but also causes wear of the pump parts. The fluid temperature also rises due to heat generation by the pump energy transformation. The increase in fluid temperature may lead to the oxidation and viscosity drop of the fluid. The oxidation and viscosity drop reduces the pump life and leakage in the system.

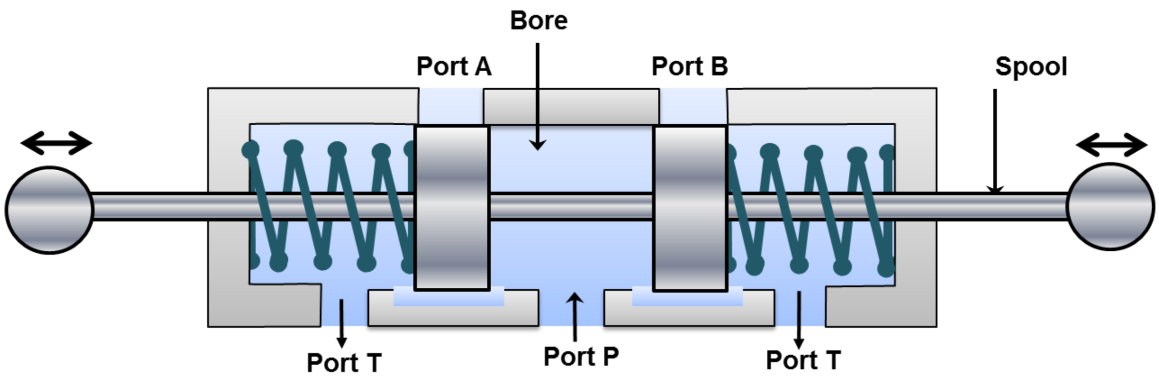


Figure 5.5.4 Tandem centered valve

Figure 5.5.4 shows a tandem center three position four way direction control valve. In this configuration, the working ports A and B are blocked and the pump port P is connected to the tank port T. Tandem center results in the locked actuator. However, pump to tank flow takes place at the atmospheric temperature. This kind of configuration can be used when the load is needed to hold. Disadvantages of high pressure pumping in case of closed center (shown in Figure 5.5.3) can be removed by using this configuration.

The regenerative center is another important type of common center configuration used in hydraulic circuits. Regenerative means the flow is generated from the system itself. Regenerative center is used when the actuator movement in one direction requires two different speeds. For example, the half-length of the stroke requires fast movement during no-load condition and remaining half-length requires slow motion during load conditions. The regenerative center saves the pump power.

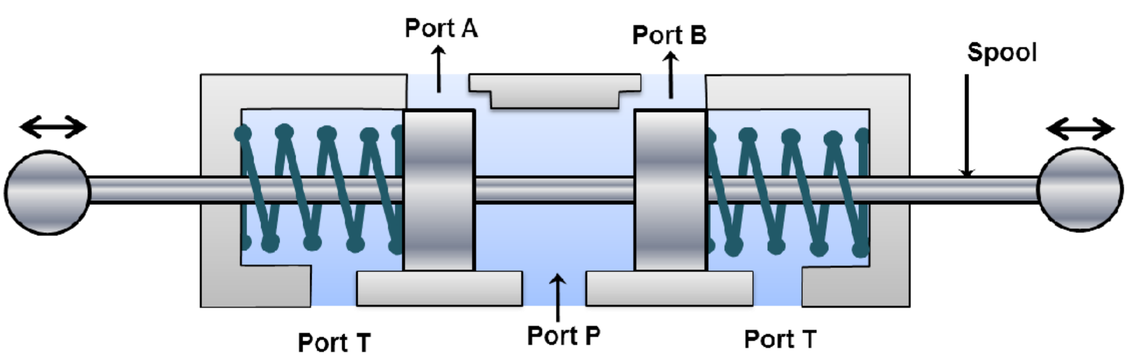


Figure 5.5.5 Regenerative Center

Figure 5.5.5 shows the regenerative configuration for the three position four way (3/4) DCV in its mid position. This configuration increases the piston speed. In the mid position pump Port P is connected to A and B, and tank port T is blocked.

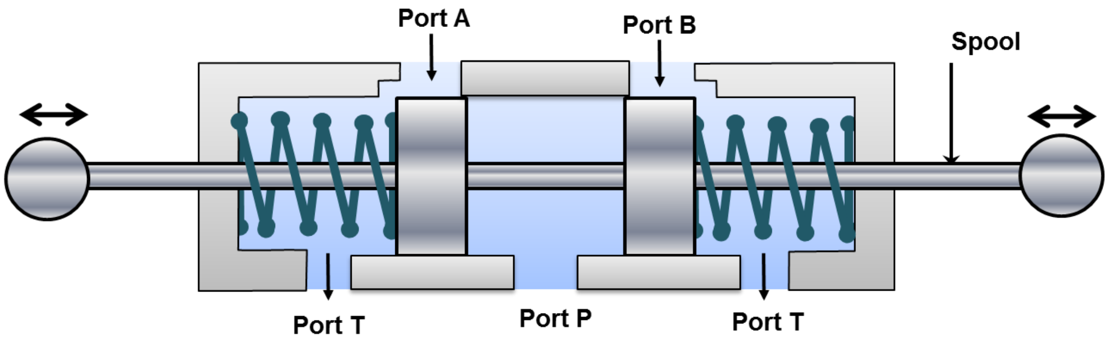


Figure 5.5.6 Floating Center

Figure 5.5.6 shows the floating center 3/4 DCV in its mid position. In this configuration, the pump port is blocked and both the working ports A and B are connected to the tank port T. Therefore, the working ports A and B can be moved freely which is reason they are called as floating center. The pumped fluid passes through the relief valve. Therefore, pump works in the high pressure condition. This configuration is used only in some special cases.

1.2 Two position four way (2/4) valves

The two position four way valves have only two switching positions and do not have any mid position. Therefore, they are also known as impulse valves. The typical connections of 2/4 valves is shown in Figures 5.5.7 and 5.5.8. These valves can be used to operate double acting cylinders. These are also used to reciprocate or hold an actuator. The operation is faster because the distance between ports of these valves is smaller. Hence, these valves are used on machines where fast reciprocation cycles are needed such as punching and stamping etc.

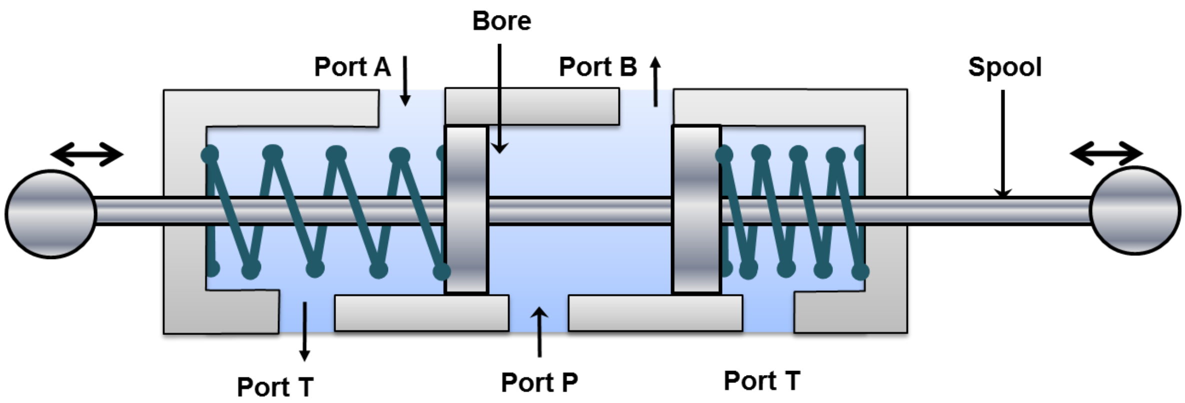


Figure 5.5.7 Two position four way DCV: P to B and A to T

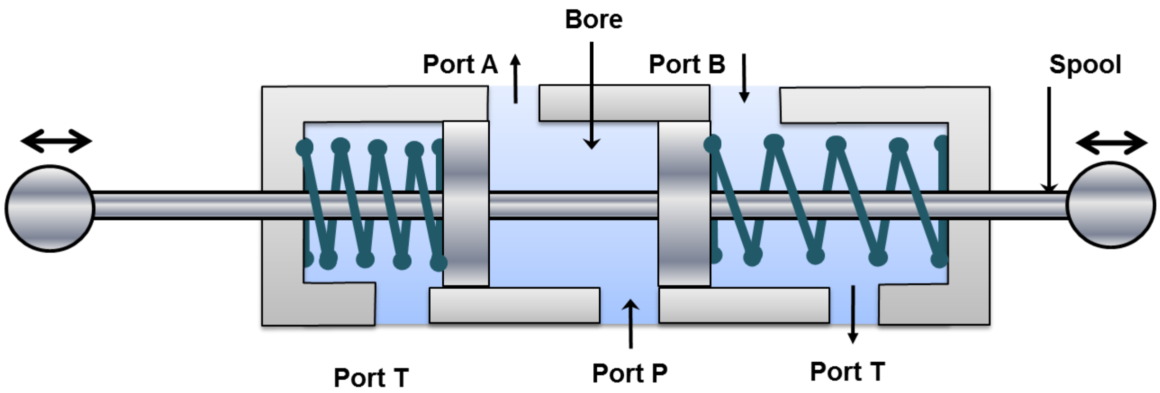


Figure 5.5.8 Two position four way DCV: P to A and B to T

2. Classification based on actuation mechanism

2.1 Manual actuation

In this type, the spool is operated manually. Manual actuators are hand lever, push button and pedals etc.

2.2 Mechanical actuation

The DCV spool can be operated by using mechanical elements such as roller and cam, roller and plunger and rack and pinion etc. In these arrangements, the spool end is of roller or a pinion gear type. The plunger or cam or rack gear is attached to the actuator. Thus, the mechanical elements gain some motion relative to the actuator (cylinder piston) which can be used for the actuation.

2.3 Solenoid actuation

The solenoid actuation is also known as electrical actuation. The schematic of solenoid actuation is shown in Figure 5.5.9. The energized solenoid coil creates a magnetic force which pulls the armature into the coil. This movement of armature controls the spool position. The main advantage of solenoid actuation is its less switching time.

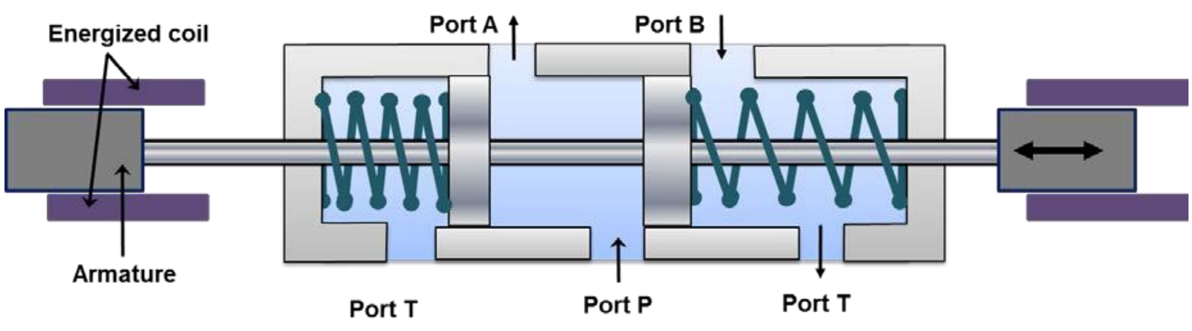


Figure 5.5.9 Working of solenoid to shift spool of valve

2.4 Hydraulic actuation

This type actuation is usually known as pilot-actuated valve and a schematic is shown in Figure 5.5.10. In this type of actuation, the hydraulic pressure is directly applied on the spool. The pilot port is located on one end of the valve. Fluid entering from pilot port operates against the piston and forces the spool to move forward. The needle valve is used to control the speed of the actuation.

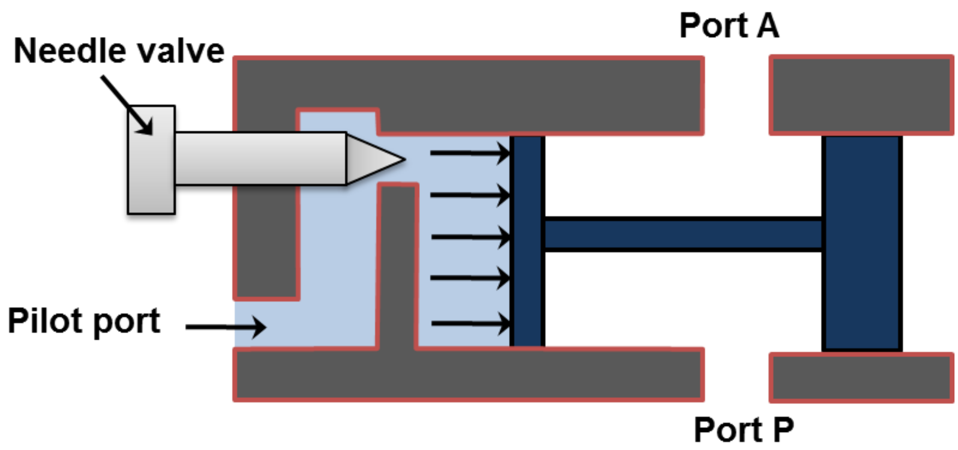


Figure 5.5.10 Pilot actuated DCV

2.5 Pneumatic actuation

DCV can also be operated by applying compressed air against a piston at either end of the valve spool. The construction of the system is similar to the hydraulic actuation as shown in Figure 5.5.10. The only difference would be the actuation medium. The actuation medium is the compressed air in pneumatic actuation system.

2.6 Indirect actuation of directional control valve

The direction control valve can be operated by manual, mechanical, solenoidal (electrical), hydraulic (pilot) and pneumatic actuations. The mode of actuation does not have any influence on the basic operation of the hydraulic circuits. Mostly, the direct actuation is restricted to use with smaller valves only because usually lot of force is not available. The availability of limited force is the greatest disadvantage of the direct actuation systems. In practice, the force required to shift the spool is quiet higher. Therefore, the larger valves are often indirectly actuated in sequence. First, the smaller valve is actuated directly and the flow from the smaller valve is directed to either side of the larger valve. The control fluid can be supplied by the same circuit or by a separate circuit. The pilot valve pressure is usually supplied internally. These two valves are often incorporated as a single unit. These valves are also called as Electro-hydraulic operated DCV.

3. *Flow Control Valves*

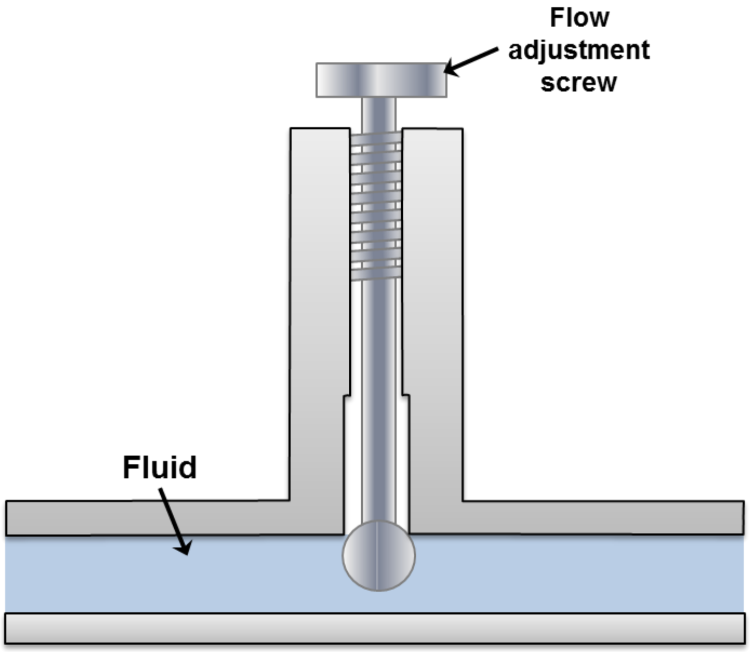


Figure 5.5.11 Flow Control Valve

In practice, the speed of actuator is very important in terms of the desired output and needs to be controlled. The speed of actuator can be controlled by regulating the fluid flow. A flow control valve can regulate the flow or pressure of the fluid. The fluid flow is controlled by varying area of the valve opening through which fluid passes. The fluid flow can be decreased by reducing the area of the valve opening and it can be increased by increasing the area of the valve opening. A very common example to the fluid flow control valve is the household tap. Figure 5.5.11 shows the schematic diagram of a flow control valve. The pressure adjustment screw varies the fluid flow area in the pipe to control the discharge rate.

The pressure drop across the valve may keep on fluctuating. In general, the hydraulic systems have a pressure compensating pump. The inlet pressure remains almost constant but the outlet pressure keeps on fluctuating depending on the external load. It creates fluctuating pressure drop. Thus, the ordinary flow control valve will not be able to maintain a constant fluid flow. A pressure compensated flow control valve maintains the constant flow throughout the movement of a spool, which shifts its position depending on the pressure. Flow control valves can also be affected by temperature changes. It is because the viscosity of the fluid changes with temperature. Therefore, the advanced flow control valves often have the temperature compensation. The temperature compensation is achieved by the thermal expansion of a rod, which compensates for the increased coefficient of discharge due to decreasing viscosity with temperature.

4. Types of Flow Control Valves

The flow control valves work on applying a variable restriction in the flow path. Based on the construction; there are mainly four types viz. plug valve, butterfly valve, ball valve and balanced valve.

4.1Plug or glove valve

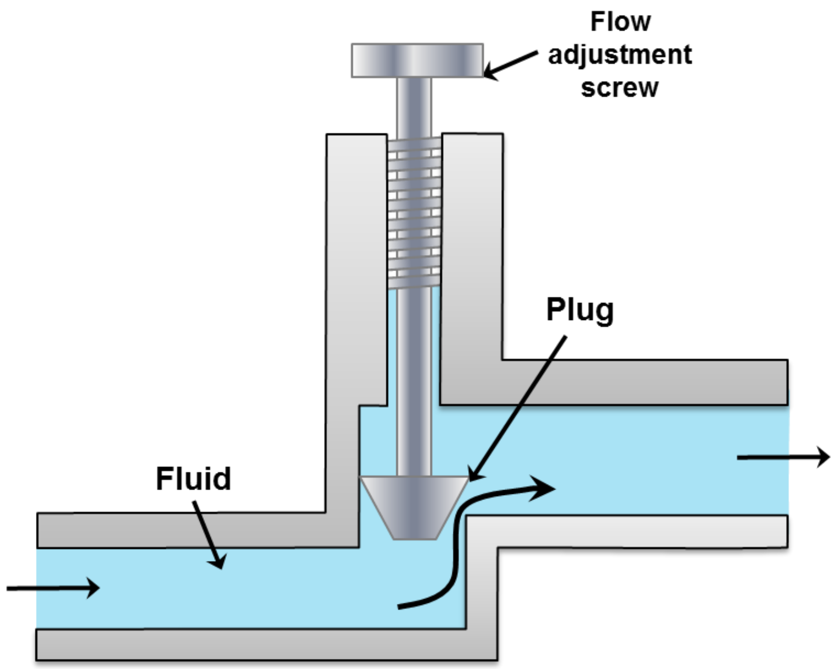


Figure 5.5.12 Plug or glove valve

The plug valve is quite commonly used valve. It is also termed as glove valve. Schematic of plug or glove valve is shown in Figure 5.5.12. This valve has a plug which can be adjusted in vertical direction by setting flow adjustment screw. The adjustment of plug alters the orifice size between plug and valve seat. Thus the adjustment of plug controls the fluid flow in the pipeline. The characteristics of these valves can be accurately predetermined by machining the taper of the plug. The typical example of plug valve is stopcock that is used in laboratory glassware. The valve body is made of glass or teflon. The plug can be made of plastic or glass. Special glass stopcocks are made for vacuum applications. Stopcock grease is used in high vacuum applications to make the stopcock air-tight.

4.2 Butterfly valve

A butterfly valve is shown in Figure 5.5.13. It consists of a disc which can rotate inside the pipe. The angle of disc determines the restriction. Butterfly valve can be made to any size and is widely used to control the flow of gas. These valves have many types which have for different pressure ranges and applications. The resilient butterfly valve uses the flexibility of rubber and has the lowest pressure rating. The high performance butterfly valves have a slight offset in the way the disc is positioned. It increases its sealing ability and decreases the wear. For high-pressure systems, the triple offset butterfly valve is suitable which makes use of a metal seat and is therefore able to withstand high pressure. It has higher risk of leakage on the shut-off position and suffer from the dynamic torque effect. Butterfly valves are favored because of their lower cost and lighter weight. The disc is always present in the flow therefore a pressure drop is induced regardless of the valve position.

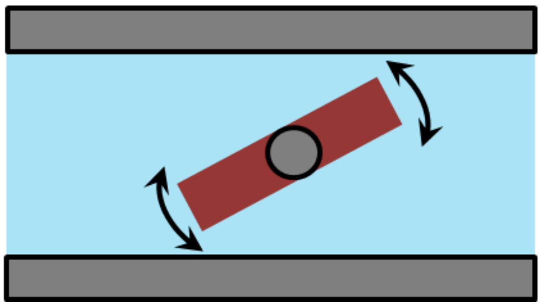


Figure 5.5.13 Butterfly valve

4.3 Ball Valve

The ball valve is shown in Figure 5.5.14. This type of flow control valve uses a ball rotated inside a machined seat. The ball has a through hole as shown in Figure 5.5.14. It has very less leakage in its shut-off condition. These valves are durable and usually work perfectly for many years. They are excellent choice for shutoff applications. They do not offer fine control which may be necessary in throttling applications. These valves are widely used in industries because of their versatility, high supporting pressures (up to 1000 bar) and temperatures (up to 250°C). They are easy to repair and operate.

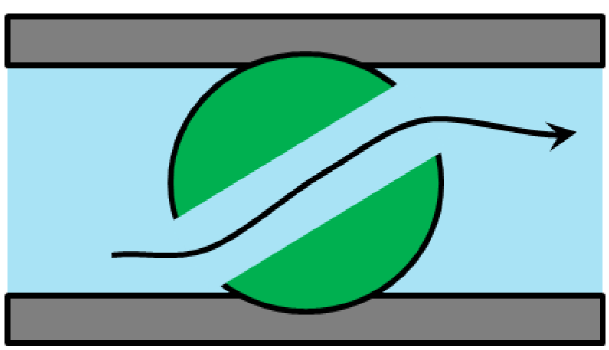


Figure 5.5.14 Ball valve

4.4 Balanced valve

Schematic of a balanced valve is shown in figure 5.5.15. It comprises of two plugs and two seats. The opposite flow gives little dynamic reaction onto the actuator shaft. It results in the negligible dynamic torque effect. However, the leakage is more in these kind of valves because the manufacturing tolerance can cause one plug to seat before the other. The pressure-balanced valves are used in the houses. They provide water at nearly constant temperature to a shower or bathtub despite of pressure fluctuations in either the hot or cold supply lines.

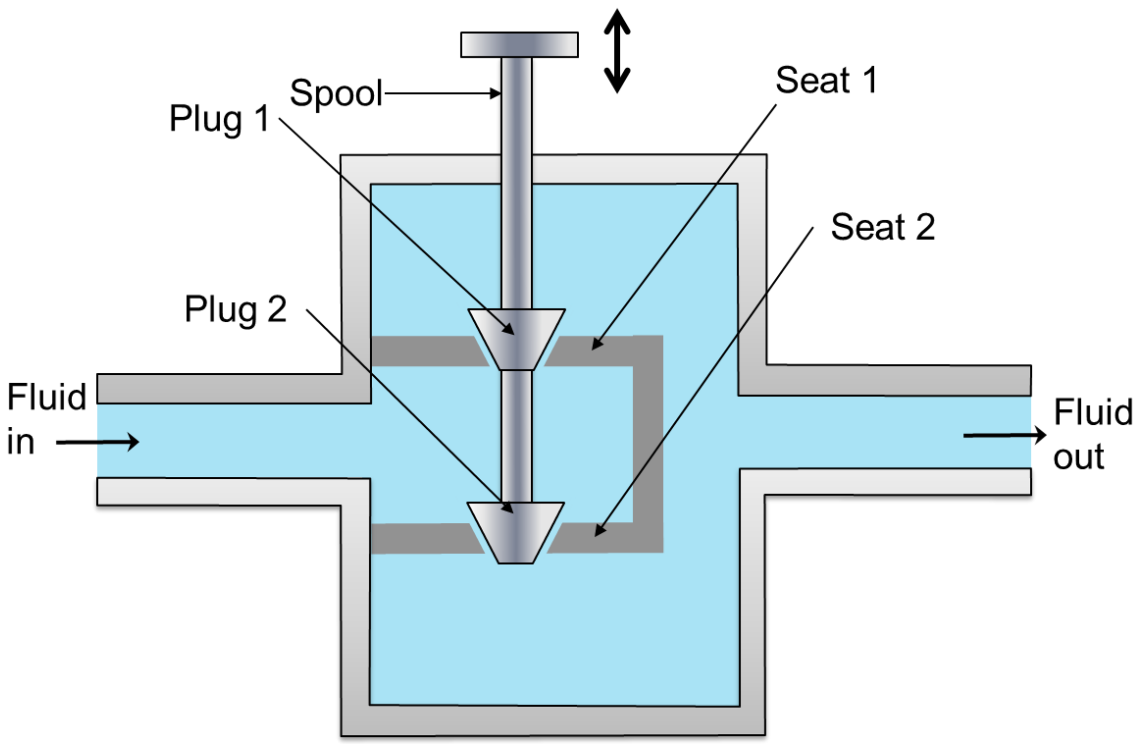


Figure 5.5.15 Balanced valve

Module 5: Hydraulic systems

Lecture 6

Pressure relief valves

The pressure relief valves are used to protect the hydraulic components from excessive pressure. This is one of the most important components of a hydraulic system and is essentially required for safe operation of the system. Its primary function is to limit the system pressure within a specified range. It is normally a closed type and it opens when the pressure exceeds a specified maximum value by diverting pump flow back to the tank. The simplest type valve contains a poppet held in a seat against the spring force as shown in Figure 5.6.1. The fluid enters from the opposite side of the poppet. When the system pressure exceeds the preset value, the poppet lifts and the fluid is escaped through the orifice to the storage tank directly. It reduces the system pressure and as the pressure reduces to the set limit again the valve closes. This valve does not provide a flat cut-off pressure limit with flow rate because the spring must be deflected more when the flow rate is higher. Various types of pressure control valves are discussed in the following sections:

1. *Direct type of relief valve*

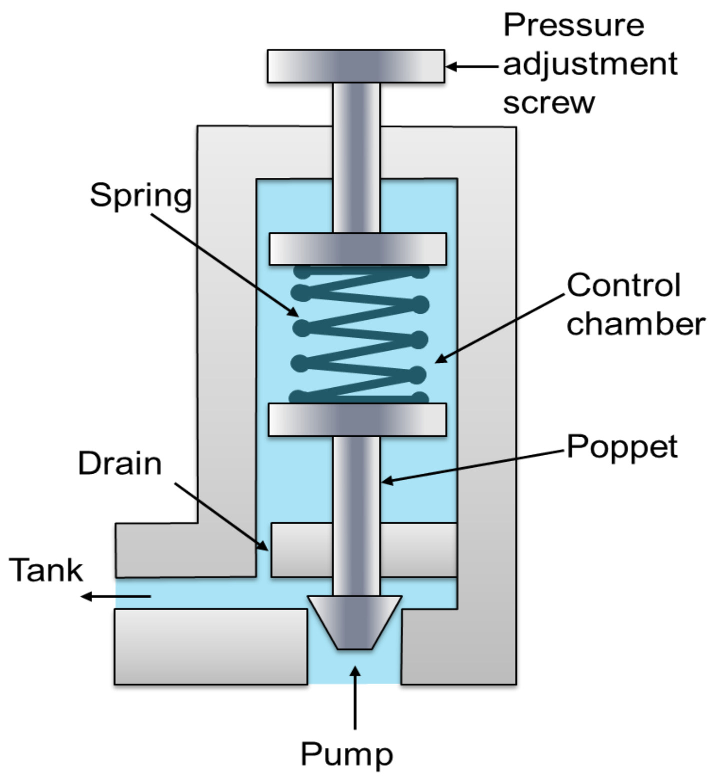


Figure 5.6.1 Pressure Relief Valve

Schematic of direct pressure relief valve is shown in figure 5.6.1. This type of valves has two ports; one of which is connected to the pump and another is connected to the tank. It consists of a spring chamber where poppet is placed with a spring force. Generally, the spring is adjustable to set the maximum pressure limit of the system. The poppet is held in position by combined effect of spring force and dead weight of spool. As the pressure exceeds this combined force, the poppet raises and excess fluid bypassed to the reservoir (tank). The poppet again reseats as the pressure drops below the pre-set value. A drain is also provided in the control chamber. It sends the fluid collected due to small leakage to the tank and thereby prevents the failure of the valve.

2. *Unloading Valve*

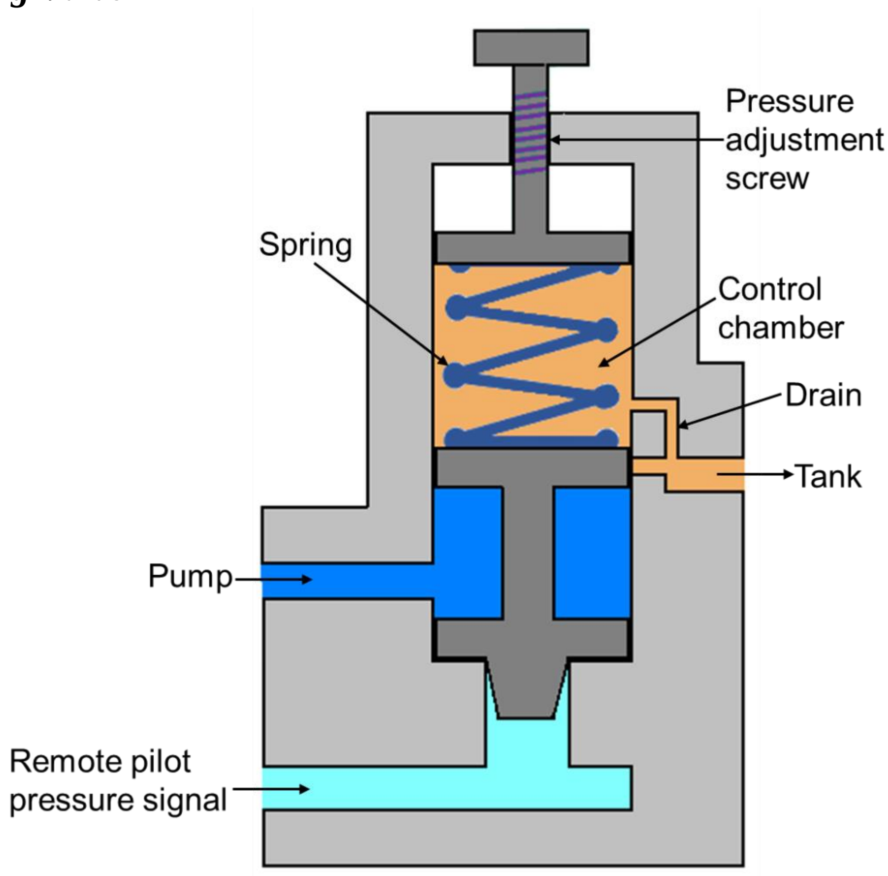


Figure 5.6.2 Unloading Valve

The construction of unloading valve is shown in Figure 5.6.2. This valve consists of a control chamber with an adjustable spring which pushes the spool down. The valve has two ports: one is connected to the tank and another is connected to the pump. The valve is operated by movement of the spool. Normally, the valve is closed and the tank port is also closed. These valves are used to permit a pump to operate at the minimum load. It works on the same principle as direct control valve that the pump delivery is diverted to the tank when sufficient pilot pressure is applied to move the spool. The pilot pressure maintains a static pressure to hold the valve opened. The pilot pressure holds the valve until the pump delivery is needed in the system. As the pressure is needed in the hydraulic circuit; the pilot pressure is relaxed and the spool moves down due to the self-weight and the spring force. Now, the flow is diverted to the hydraulic circuit. The drain is provided to remove the leaked oil collected in the control chamber to prevent the valve failure. The unloading valve reduces the heat buildup due to fluid discharge at a preset pressure value.

3. Sequence valve

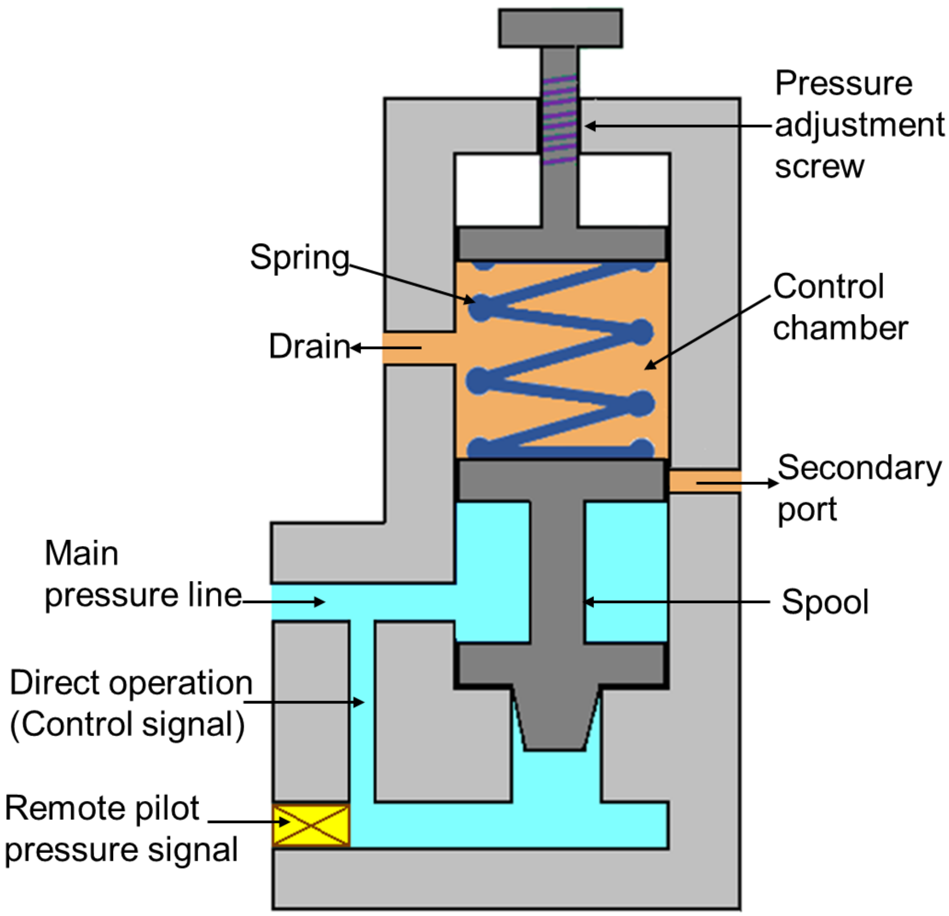


Figure 5.6.3 Sequence valve

The primary function of this type of valve is to divert flow in a predetermined sequence. It is used to operate the cycle of a machine automatically. A sequence valve may be of direct-pilot or remote-pilot operated type.

Schematic of the sequence valve is shown in Figure 5.6.3. Its construction is similar to the direct relief valve. It consists of the two ports; one main port connecting the main pressure line and another port (secondary port) is connected to the secondary circuit. The secondary port is usually closed by the spool. The pressure on the spool works against the spring force. When the pressure exceeds the preset value of the spring; the spool lifts and the fluid flows from the primary port to the secondary port. For remote operation; the passage used for the direct operation is closed and a separate pressure source for the spool operation is provided in the remote operation mode.

4. Counterbalance Valve

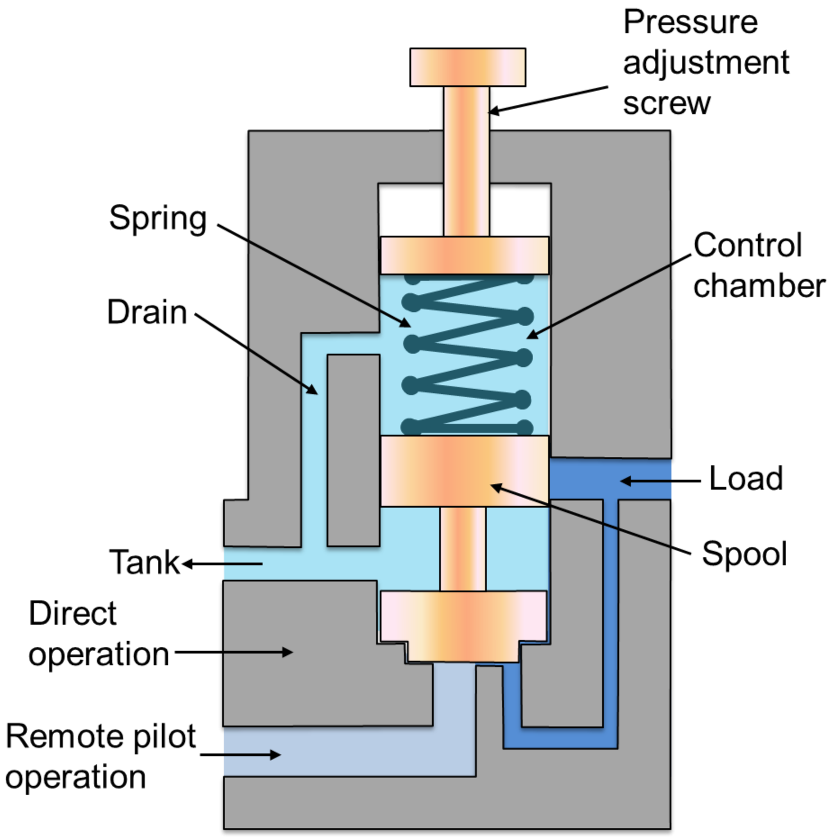


Figure 5.6.4 Counter Balance Valve

The schematic of counterbalance valve is shown in Figure 5.6.4. It is used to maintain the back pressure and to prevent a load from failing. The counterbalance valves can be used as breaking valves for decelerating heavy loads. These valves are used in vertical presses, lift trucks, loaders and other machine tools where position or hold suspended loads are important. Counterbalance valves work on the principle that the fluid is trapped under pressure until pilot pressure overcomes the pre-set value of spring force. Fluid is then allowed to escape, letting the load to descend under control. This valve is normally closed until it is acted upon by a remote pilot pressure source. Therefore, a lower spring force is sufficient. It leads to the valve operation at the lower pilot pressure and hence the power consumption reduces, pump life increases and the fluid temperature decreases.

5. *Pressure Reducing Valve*

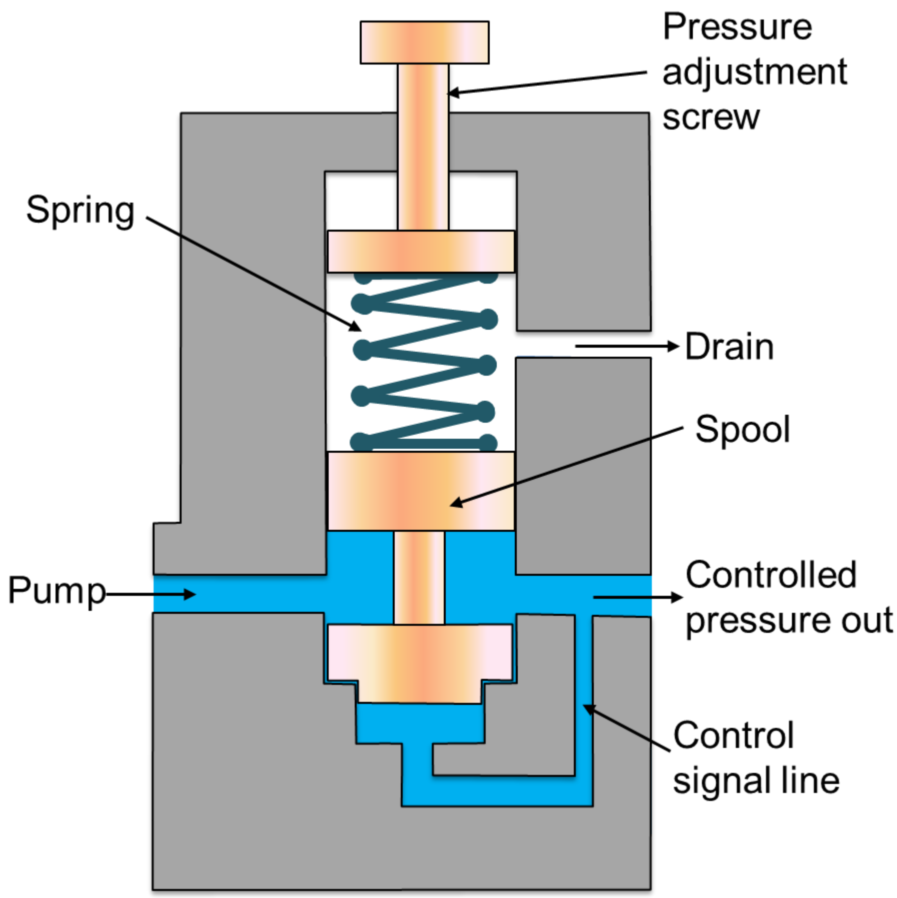


Figure 5.6.5 Pressure Reducing Valve

Sometimes a part of the system may need a lower pressure. This can be made possible by using pressure reducing valve as shown in Figure 5.6.5. These valves are used to limit the outlet pressure. Generally, they are used for the operation of branch circuits where the pressure may vary from the main hydraulic pressure lines. These are open type valve and have a spring chamber with an adjustable spring, a movable spool as shown in figure. A drain is provided to return the leaked fluid in the spring (control) chamber. A free flow passage is provided from inlet port to the outlet port until a signal from the outlet port tends to throttle the passage through the valve. The pilot pressure opposes the spring force and when both are balanced, the downstream is controlled at the pressure setting. When the pressure in the reduced pressure line exceeds the valve setting, the spool moves to reduce the flow passage area by compressing the spring. It can be seen from the figure that if the spring force is more, the valve opens wider and if the controlled pressure has greater force, the valves moves towards the spring and throttles the flow.

Module 5: Hydraulic systems
Lecture 7
Graphical representation of hydraulic and pneumatic elements

The hydraulic and pneumatic elements such as cylinders and valves are connected through pipelines to form a hydraulic or a pneumatic circuit. It is difficult to represent the complex functioning of these elements using sketches. Therefore graphical symbols are used to indicate these elements. The symbols only specify the function of the element without indicating the design of the element. Symbols also indicate the actuation method, direction of flow of air and designation of the ports. Symbols are described in various documents like DIN24300, BS2917, ISO1219 and the new ISO5599, CETOP RP3 and the original American JIC and ANSI symbols.

The symbol used to represent an individual element display the following characteristics:

- Function
- Actuation and return actuation methods
- Number of connections
- Number of switching positions
- General operating principle
- Simplified representation of the flow path

The symbol does not represent the following characteristics:

- Size or dimensions of the component
- Particular manufacturer, methods of construction or costs
- Operation of the ports
- Any physical details of the elements
- Any unions or connections other than junctions

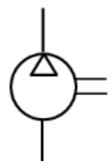
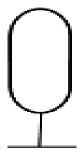
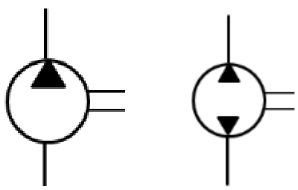
Earlier the ports were designated with letter system. Now as per ISO5599 the ports are designated based on number system. The port designations are shown in table 5.7.1

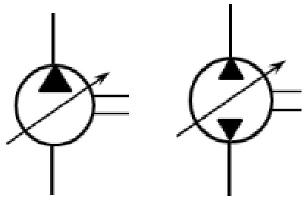
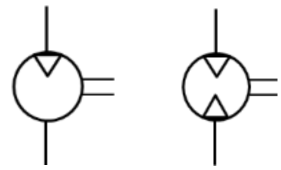
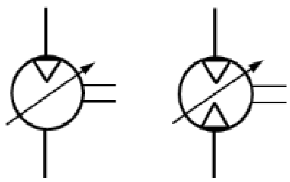
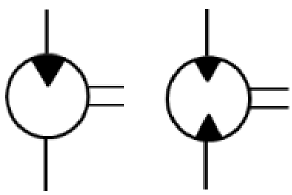
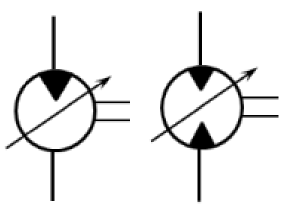
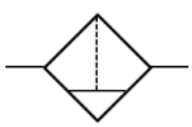
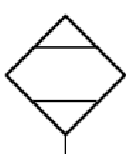
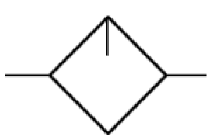
Table 5.7.1 Symbols for ports

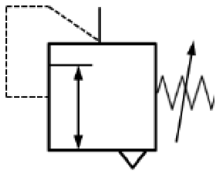
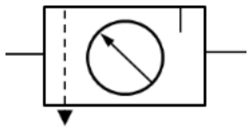
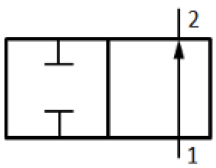
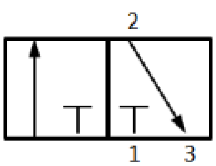
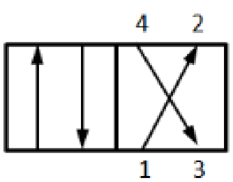
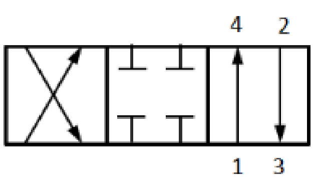
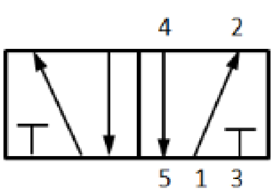
Port	Letter system	Number system
Pressure port	P	1
Working port	A	4
Working port	B	2
Exhaust port	R	5
Exhaust port	S	3
Pilot port	Z	14
Pilot port	Y	12

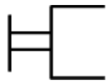
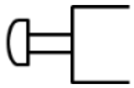
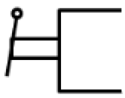
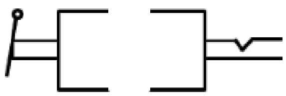
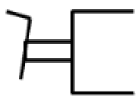
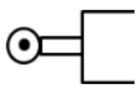
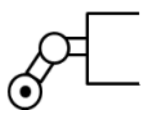
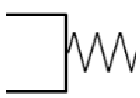
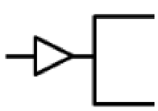
The graphical representation, designation and explanation of various components and equipments used in hydraulic and pneumatic system are given in table 5.7.2. Readers are suggested to study these representations carefully.

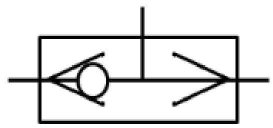
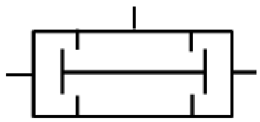
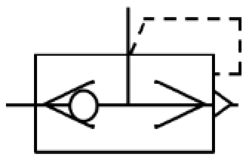
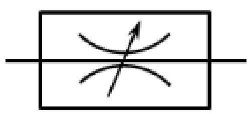
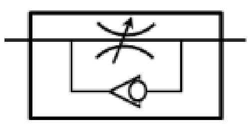
Table 5.7.2 Graphical symbols of hydraulic / pneumatic elements and equipments

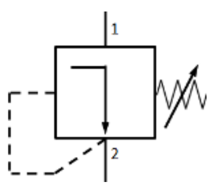
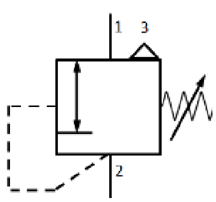
SYMBOL	DESIGNATION	EXPLANATION
Energy supply		
	Air compressor	One direction of rotation only with constant displacement volume
	Air receiver	Compressed air from the compressor is stored and diverted to the system when required
		One direction and two direction of rotation with constant displacement volume

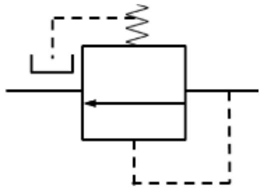
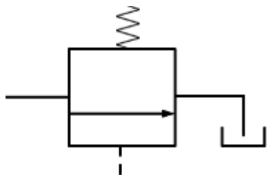
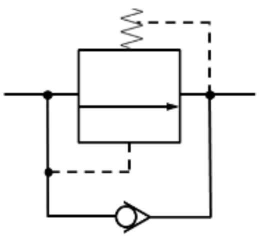
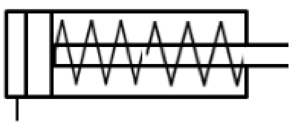
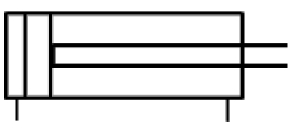
	Hydraulic pump	One direction and two direction of rotation with variable displacement
Rotary actuators		
	Pneumatic motor	One direction and two direction of rotation with constant displacement volume
		One direction and two direction of rotation with variable displacement
	Hydraulic motor	One direction and two direction of rotation with constant displacement volume
		One direction and two direction of rotation with variable displacement
Service units		
	Air filter	This device is a combination of filter and water separator
	Dryer	For drying the air
	Lubricator	For lubrication of connected devices, small amount of oil is added to

		the air flowing through this device
	Regulator	To regulate the air pressure
	FRL unit	Combined filter, regulator and lubricator system
Direction control valves (DCVs)		
	2/2 way valve	Two closed ports in the closed neutral position and flow during actuated position
	3/2 way valve	In the first position flow takes place to the cylinder In the second position flow takes out of the cylinder to the exhaust (Single acting cylinder)
	4/2 way valve	For double acting cylinder all the ports are open
	4/3 way valve	Two open positions and one closed neutral position
	5/2 way valve	Two open positions with two exhaust ports

Direction control valve actuation methods		
	General manual actuation	Manual operation of DCV
	Push button actuation	
	Lever actuation	
	Detent lever actuation	
	Foot pedal actuation	Mechanical actuation of DCV
	Roller lever actuation	
	Idle return roller actuation	
	Spring actuation	
	Direct pneumatic actuation	Pneumatic actuation of DCV
Non return valves		
	Check valve	Allows flow in one direction and blocks flow in other direction
	Spring loaded check valve	

	Shuttle/ OR valve	When any one of the input is given the output is produced
	AND valve	Only when both the inputs are given output is produced
	Quick exhaust valve	For quick exhaust of air to cause rapid extension/ retraction of cylinder
Flow control valves		
	Flow control valve	To allow controlled flow
	Flow control valve with one way adjustment	To allow controlled flow in one direction and free flow in other

Pressure control valves		
	Pressure relieving valve	Non relieving type
		Relieving type with overload being vented out

	Pressure reducing valve	Maintains the reduced pressure at specified location in hydraulic system
	Unloading valve	Allows pump to build pressure to an adjustable pressure setting and then allow it to be discharged to tank
	Counter balance valve	Controls the movement of vertical hydraulic cylinder and prevents its descend due to external load weight
Actuators		
	Single acting cylinder	Spring loaded cylinder with retraction taking place by spring force
	Double acting cylinder	Both extension and retraction by pneumatic/hydraulic force

Module 5: Hydraulic systems
Lecture 8
Design of Hydraulic Circuit

Case study 1

1.1 Problem Definition: Package lifting device

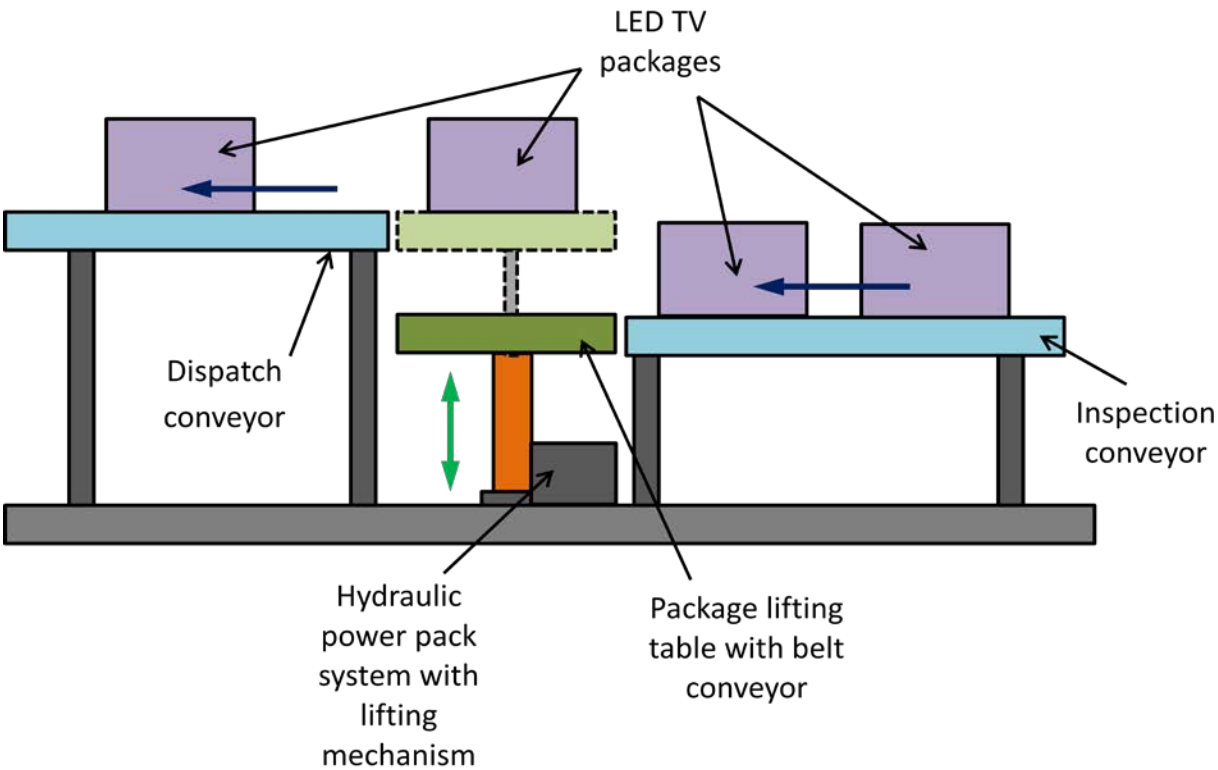


Figure 5.8.1 Schematic of a Package lifting system for LED TVs

For a dispatch station of a LED TV production house, design a package lifting device to lift packages containing 21” to 51” LED TVs from the inspection conveyor to the dispatch conveyor. Draw the hydraulic circuit diagram. List the components. Readers are requested to assume suitable data.

1.2Solution

By applying the principle of hydraulics and after studying the various sensors, pumps, valves and hydraulic actuators, the proposed hydraulic circuit is shown in Figure 5.8.1. Components required are listed in table 5.8.1.

Table 5.8.1 List of Components

S. No.	Item No.	Quantity	Description
1	1A	1	Two direction Hydraulic Motor with constant displacement volume
2	0Z1	1	Hydraulic Power Pack
3	0Z2	1	Pressure gauge
4	1V1	1	Shut-off valve
5	1V2	1	Pressure relief valve
6	1S	1	Flow sensor
7		5	Hose line
8		2	Branch tee

1.3 Proposed hydraulic circuit and its operation

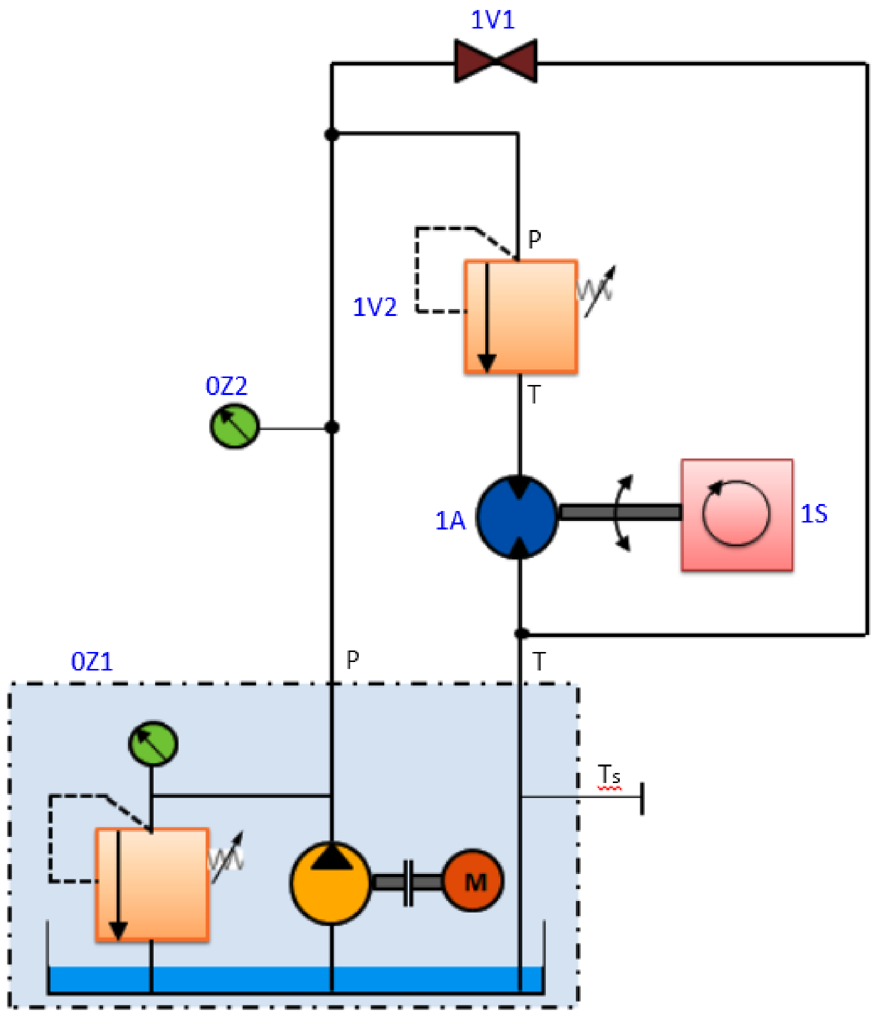


Figure 5.8.2 Hydraulic circuit design for package lifting device

Figure 5.8.2 shows the circuit design for package lifting device. The two direction hydraulic motor is run by using a hydraulic power pack. Required valves and pressure sensors are also included for desired control action. Readers are requested to carefully read the circuit and comprehend the circuit.

Once the hydraulic circuit has been assembled and checked, valve 1V1 and pressure relief valve 1V2 can be operated in sequence to obtain the rotary motion of hydraulic motor in required direction (clockwise/counter clockwise). This rotary motion can further be converted into linear motion by using suitable motion converter mechanism viz. Rack and pinion mechanism. Linear motion is used to lift the packages. It is required to develop a PID based controller to control the operation of the valves. The pressure gauge and flow sensor are used to monitor the operation continuously.

Case Study 2

2.1 Problem Definition: Furnace door control

Design a hydraulic circuit for a furnace door to be opened and closed. Figure 5.8.3 shows the schematic of the furnace and its door that to be controlled. Propose a suitable hydraulic technology. List the components. Draw the hydraulic circuit diagram. Compute stroke speeds and stroke times by assuming assume suitable data.

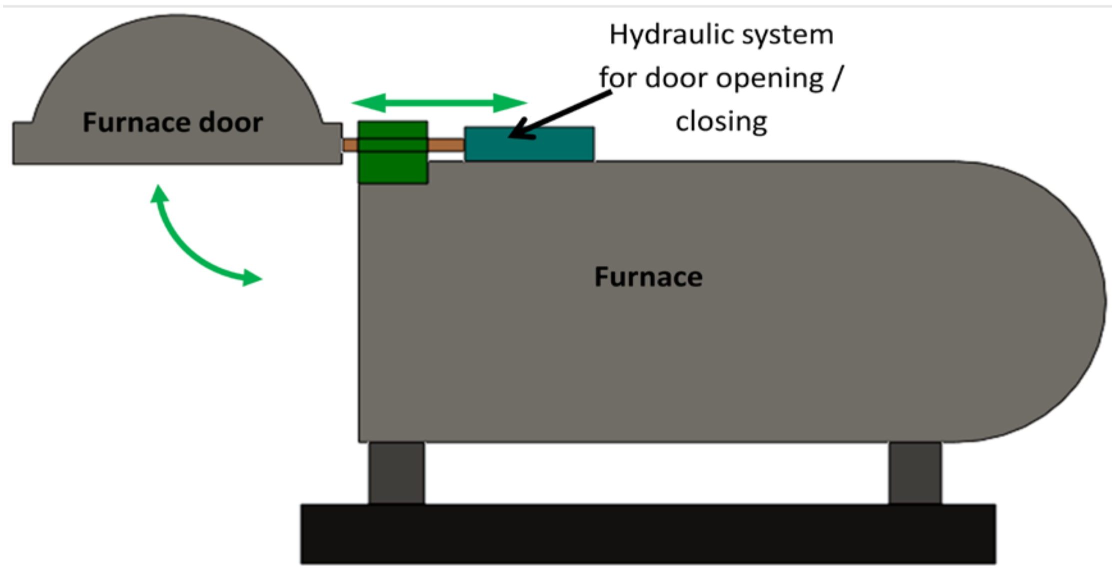


Figure 5.8.3 Furnace and its door

2.2 Solution

A double-acting cylinder can be used to control the movements of furnace door. The cylinder is to be activated by a 4/2-way valve with spring return. This will ensure that the door opens only as long as the valve is actuated. When the valve actuating lever is released, the door closes again. Table 5.8.2 lists the required hydraulic and mechanical components. Figure 5.8.4 shows the proposed hydraulic circuit.

Table 5.8.2 List of components

S. No.	Item No.	Quantity	Description
1	0Z1	1	Hydraulic Power Pack
2	0Z2	1	Pressure gauge
3	1S1, 1S2	2	Pressure sensor
4	0V	1	Pressure relief valve
5	1V	1	4/2 way valve, manually operated
6	1A	1	Cylinder
7		6	Hose line
8		2	Branch tee
9		1	Stop watch

2.3 Calculations

Let us assume the following data that required for the calculations:

Piston area, A_{PN} = 200 mm^2

Piston annular area, A_{PR} = 120 mm^2

Stroke length, S = 200 mm

Pump output, $Q = 3.333 \times 10^4 mm^3/sec$

Now,

Area ration, $\alpha = \frac{A_{PN}}{A_{PR}} = 1.667$

Advance-stroke speed, $V_{adv} = \frac{Q}{A_{PN}} = 166.665$ mm/sec

Return stroke speed, $V_{ret} = \frac{Q}{A_{PR}} = 277.775$ mm/sec

Advance-stroke time, $T_{adv} = \frac{S}{V_{adv}} = 1.2$ sec

Return-stroke time, $T_{ret} = \frac{S}{V_{ret}} = 0.72$ sec

Travel speed ration, $\frac{V_{adv}}{V_{ret}} = 0.6$

Travel time ratio, $\frac{T_{adv}}{T_{ret}} = 1.667$

2.4 Proposed hydraulic circuit and its operation

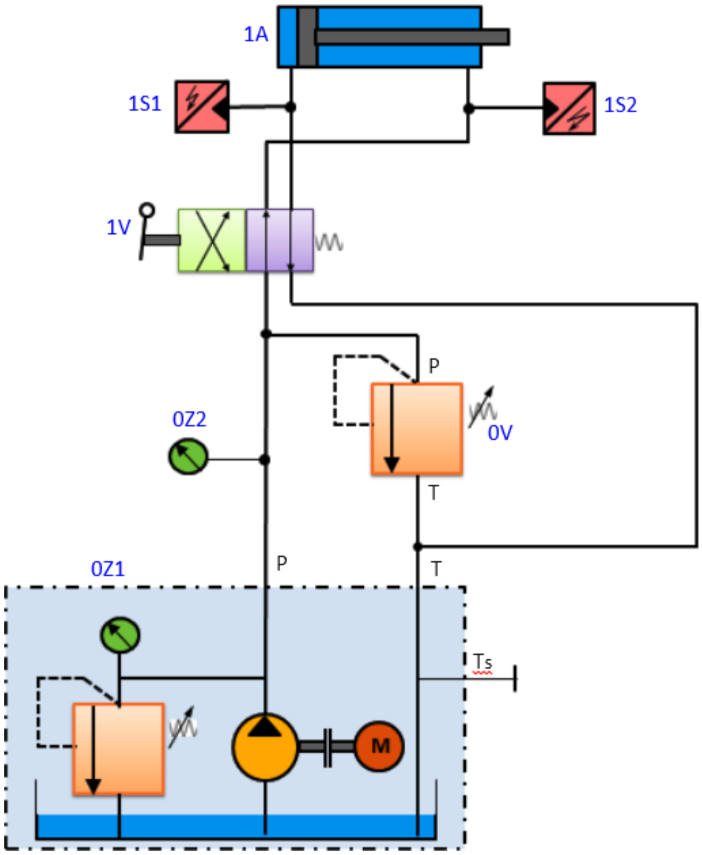


Figure 5.8.4 Hydraulic circuit for furnace door control

Figure 5.8.4 shows the hydraulic circuit for furnace door control. Once the circuit has been assembled and checked, the hydraulic power pack should be switched on and the system pressure set on the pressure relief valve 0V to a pre-set value. By operating the hand lever of valve 1V the opening and closing of the furnace can easily be carried out. When this 4/2-way valve is actuated, the piston rod of the cylinder will advance until the lever is released or the piston rod runs against the stop. When the lever is released, the piston rod will immediately return to its retracted end position. The hand lever can also be remotely operated by using suitable mechanism. Pressure sensors should be used to measure the travel and back pressures.