COURSE MATERIAL

IV Year B. Tech I- Semester

MECHANICAL ENGINEERING

AY: 2022-23

AUTOMATION AND CONTROL ENGINEERING

R18A0324

Prepared by:
Dr. T. Lokeswara Rao
Associate Professor

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

DEPARTMENT OF MECHANICAL ENGINEERING

(Autonomous Institution-UGC, Govt. of India)
Secunderabad-500100, Telangana State, India.
www.mrcet.ac.in

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY
(Autonomous Institution – UGC, Govt. of India)
DEPARTMENT OF MECHANICAL ENGINEERING

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MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

(Autonomous Institution – UGC, Govt. of India)

VISION

- To establish a pedestal for the integral innovation, team spirit, originality and competence in the students, expose them to face the global challenges and become technology leaders of Indian vision of modern society.

MISSION

- To become a model institution in the fields of Engineering, Technology and Management.
- To impart holistic education to the students to render them as industry ready engineers.
- To ensure synchronization of MRCET ideologies with challenging demands of International Pioneering Organizations.

QUALITY POLICY

- To implement best practices in Teaching and Learning process for both UG and PG courses meticulously.
- To provide state of art infrastructure and expertise to impart quality education.
- To groom the students to become intellectually creative and professionally competitive.
- To channelize the activities and tune them in heights of commitment and sincerity, the requisites to claim the never - ending ladder of **SUCCESS** year after year.

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Department of Mechanical Engineering

VISION

To become an innovative knowledge center in mechanical engineering through state-of-the-art teaching-learning and research practices, promoting creative thinking professionals.

MISSION

The Department of Mechanical Engineering is dedicated for transforming the students into highly competent Mechanical engineers to meet the needs of the industry, in a changing and challenging technical environment, by strongly focusing in the fundamentals of engineering sciences for achieving excellent results in their professional pursuits.

Quality Policy

- ✓ To pursuit global Standards of excellence in all our endeavors namely teaching, research and continuing education and to remain accountable in our core and support functions, through processes of self-evaluation and continuous improvement.
- ✓ To create a midst of excellence for imparting state of art education, industry-oriented training research in the field of technical education.

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Department of Mechanical Engineering

PROGRAM OUTCOMES

Engineering Graduates will be able to:

1. **Engineering knowledge:** Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
2. **Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
3. **Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
4. **Conduct investigations of complex problems**: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
5. **Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
6. **The engineer and society**: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
7. **Environment and sustainability**: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
8. **Ethics**: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
9. **Individual and teamwork**: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.
10. **Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.
11. **Project management and finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one’s own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

12. **Life-long learning**: Recognize the need for and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.
13.

PROGRAM SPECIFIC OUTCOMES (PSOs)

PSO1 Ability to analyze, design and develop Mechanical systems to solve the Engineering problems by integrating thermal, design and manufacturing Domains.

PSO2 Ability to succeed in competitive examinations or to pursue higher studies or research.

PSO3 Ability to apply the learned Mechanical Engineering knowledge for the Development of society and self.

Program Educational Objectives (PEOs)

The Program Educational Objectives of the program offered by the department are broadly listed below:

PEO1: PREPARATION

To provide sound foundation in mathematical, scientific and engineering fundamentals necessary to analyze, formulate and solve engineering problems.

PEO2: CORE COMPETANCE

To provide thorough knowledge in Mechanical Engineering subjects including theoretical knowledge and practical training for preparing physical models pertaining to Thermodynamics, Hydraulics, Heat and Mass Transfer, Dynamics of Machinery, Jet Propulsion, Automobile Engineering, Element Analysis, Production Technology, Mechatronics etc.

PEO3: INVENTION, INNOVATION AND CREATIVITY

To make the students to design, experiment, analyze, interpret in the core field with the help of other inter disciplinary concepts wherever applicable.

PEO4: CAREER DEVELOPMENT

To inculcate the habit of lifelong learning for career development through successful completion of advanced degrees, professional development courses, industrial training etc.

PEO5: PROFESSIONALISM

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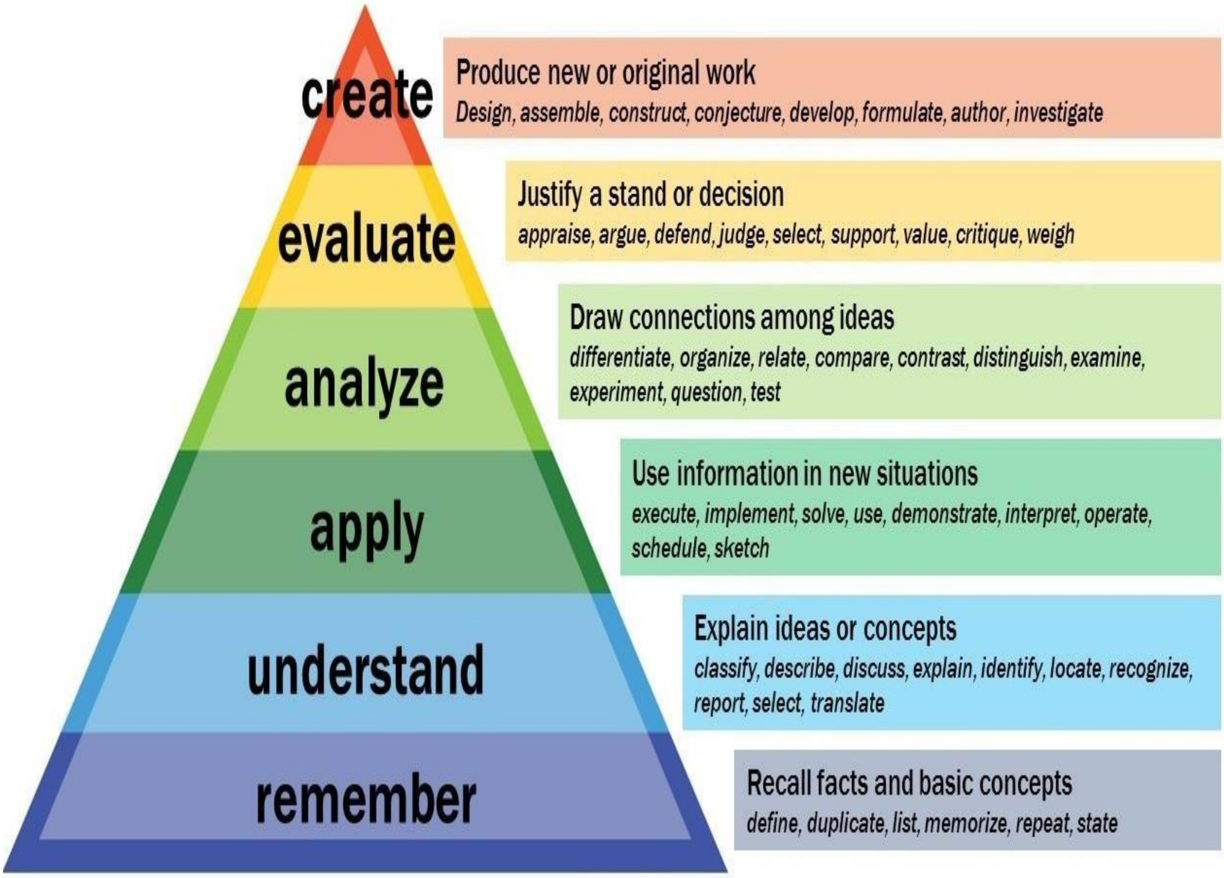
Department of Mechanical Engineering

To impart technical knowledge, ethical values for professional development of the student to solve complex problems and to work in multi-disciplinary ambience, whose solutions lead to significant societal benefits.

Blooms Taxonomy

Bloom's Taxonomy is a classification of the different objectives and skills that educators set for their students (learning objectives). The terminology has been updated to include the following six levels of learning. These 6 levels can be used to structure the learning objectives, lessons, and assessments of a course.

1. **Remembering**: Retrieving, recognizing, and recalling relevant knowledge from long- term memory.
2. **Understanding**: Constructing meaning from oral, written, and graphic messages through interpreting, exemplifying, classifying, summarizing, inferring, comparing, and explaining.
3. **Applying**: Carrying out or using a procedure for executing or implementing.
4. **Analyzing**: Breaking material into constituent parts, determining how the parts relate to one another and to an overall structure or purpose through differentiating, organizing, and attributing.
5. **Evaluating**: Making judgments based on criteria and standard through checking and critiquing.
6. **Creating**: Putting elements together to form a coherent or functional whole; reorganizing elements into a new pattern or structure through generating, planning, or producing.



create
Produce new or original work
Design, assemble, construct, conjecture, develop, formulate, author, investigate
evaluate
Justify a stand or decision
appraise, argue, defend, judge, select, support, value, critique, weigh
analyze
Draw connections among ideas
differentiate, organize, relate, compare, contrast, distinguish, examine, experiment, question, test
apply
Use information in new situations
execute, implement, solve, use, demonstrate, interpret, operate, schedule, sketch
understand
Explain ideas or concepts
classify, describe, discuss, explain, identify, locate, recognize, report, select, translate
remember
Recall facts and basic concepts
define, duplicate, list, memorize, repeat, state

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AUTOMATION AND CONTROL ENGINEERING

Course objectives

The general objectives of the course are to enable the students to

1. Understand the basics of automation and the need of Mechatronics systems
2. Learn the constructions and working principle of different types of sensors and transducers.
3. Understand the constructions and working principle of different types of Actuators and drive systems.
4. To impart knowledge on the control elements
5. To understand the different control schemes generally used to get best output.

Unit -1

Introduction to Automation: Types and strategies of automation, pneumatic and hydraulic components circuits, Mechanical Feeding and machine tool control to transfer the automation.

Introduction to Mechatronics: Role of various engineering disciplines in Mechatronics, Mechatronics design elements, Scope of Mechatronics, Applications of Mechatronics.

Unit -2

Sensors and Transducers: Sensors and transducers, performance terminology, displacement, position and proximity, velocity and motion, force, fluid pressure, liquid flow, liquid level, temperature, light sensors, selection of sensors.

Unit -3

Actuators and drive systems: Mechanical, Electrical, Hydraulic drive systems, Characteristics of mechanical, Electrical, Hydraulic and pneumatic actuators and their limitations.

Unit -4

Control system components: Introduction, classification of control system- classification of control systems on the basis of control signal used, Adaptive control system, Process control systems

Unit -5

Process control: Introduction, concept of process control, Automatic controllers- digital controller, Electronic controllers, Pneumatic controllers, P-I controller, PD controller, P-I-D controller, Hydraulic controllers.

Text Book(s):

1. Mechatronics, W.Bolton, Pearson Education, Asia.
2. Mechatronics, M.D. Singh and J.G. Joshi, PHI.

Reference Book(s):

1. Mechatronics, D.A. Bradley, D. Dawson, N.C. Buru and A.J. Loader, Chapman Hall.
2. Microprocessor Architecture, Programming & Applications, S. Ramesh, Gaonkar, Wiley Eastern.
3. The Mechatronics Handbook with ISA– The Instrumentation, Systems, Automation, Robert H. Bishop. Ed.-in-chief., CRC Press.

Course outcomes

At the end of the course the students shall be able to

1. The importance of automation in industries and Identification of key elements of mechatronics system
2. Identify different types of sensors and transducers required for specific applications
3. handle different types of controller like Electronic, Pneumatic and Hydraulic, Mechanical actuators and drives for specific applications
4. Describe and analyze working principles of various types of motors, differences, characteristics and selection criteria, control methods.
5. Identify different types of process control required for specific applications

AUTOMATION AND CONTROL ENGINEERING (R17A0327)

COURSE OBJECTIVES

UNIT - 1	CO1: To Understand the basics of automation & To understand theneed of Mechatronics systems
UNIT - 2	CO2: Learn the constructions and working principle of different types ofsensors and transducers
UNIT - 3	CO3: Understand the fundamental concepts of electro mechanics andfluid mechanics (hydraulics and pneumatics) of Actuators and drive systems.
UNIT - 4	CO4: To impart knowledge on the control elements
UNIT - 5	CO5: To understand the different control schemes generally used to getbest output.

COURSE OUTLINE

UNIT – 1

NO OF LECTURE HOURS:

LECTURE	LECTURE TOPIC	KEY ELEMENTS	LEARNING OBJECTIVES
1.	INTRODUCTION TO AUTOMATION	Definition of force.	Understanding the basics of Automation (B2)
2.	Types and strategies of automation	Define types of automation	Understanding the types of automation (B2)
3.	Pneumatic and Hydraulic components circuits	Working principle of pneumatic and hydraulic components circuits	Understanding and Analyze the Working principle of pneumatic and hydraulic components circuits. (B2, B4)
4.	Mechanical Feeding and machine tool control to transfer the automation	Transformation of materials	How the material is transferred inbetween the machines (B1)
5.	Introduction to Mechatronics	Definition of Mechatronics	Understanding of basics of Mechatronics (B2)
6.	Role of various engineering disciplines in Mechatronics	Importance of mechatronics	Understanding the role of mechatronics in variousapplications (B2)
7.	Mechatronics design elements	Mechatronics elements	What are the major elements inmechatronics

8.	Scope of Mechatronics, Applications of Mechatronics	Applications of Mechatronics	Analyze the working of the washing machine, water level controller (B4)

UNIT – 2

NO OF LECTURE HOURS:

LECTURE	LECTURE TOPIC	KEY ELEMENTS	LEARNING OBJECTIVES
1.	Introduction to Sensors and transducers, performance terminology	Definition of Sensors and transducers	Understanding the basics of Sensors andtransducers (B2)
2.	Displacement sensors	Working principle of Displacement sensors	Understand the applications of sensors in various systems and to know the functions of each element(B2)
3.	Position and proximity sensors	Working principle of Position and proximity sensors	
4.	Velocity and motion sensors	Working principle of Velocity and motion sensors	
5.	Force, fluid pressure sensors	Working principle of Force, fluid pressure sensors	
6.	Liquid flow, liquid level sensors	Working principle of Liquid flow, liquid level sensors	
7.	Temperature, light sensors, selection of sensors.	Working principle of Temperature, light sensors, selection of sensors.	

UNIT – 3

NO OF LECTURE HOURS:

LECTURE	LECTURE TOPIC	KEY ELEMENTS	LEARNING OBJECTIVES
1.	Actuators and drive systems	Definition of Sensors and transducers	Understanding the basics of Sensors andtransducers (B2)
2.	Mechanical, Electrical, Hydraulic drive systems	Working principle of Types of Actuators and drive systems	Understand the applications of actuators in various systems and to know the functions of each element(B2)
3.	Mechanical actuators		
4.	Electrical actuators		
5.	Hydraulic actuators		
6.	Pneumatic actuators		

UNIT – 4

NO OF LECTURE HOURS:

LECTURE	LECTURE TOPIC	KEY ELEMENTS	LEARNING OBJECTIVES
1.	Introduction to control system	Define control system	Understanding the basics of control system (B2)
2.	Classification of control system - Open and closed loop control system - Linear and Non-linear control system - Continuous time and discrete time control system - Lumped and distributed parameter control system	Types of control system	Understanding the types of control systems (B2)
3.	Adaptive control system	Working principle of Types of control systems	• Understand the applications of control systems in various systems and to know the functions of each element(B2) • Analyze the control system in machines (B4)
4.	Process control systems		

UNIT – 5

NO OF LECTURE HOURS:

LECTURE	LECTURE TOPIC	KEY ELEMENTS	LEARNING OBJECTIVES
1.	Introduction to Process control	Define the Process control	Understanding the basics of process control (B2)
2.	Automatic controllers - digital controller - Analog controller	Working principle of Types of process control systems	• Understand the applications of process control systems in various systems and to know the functions of each element(B2) • Able to analyze the which control is used in real time (B4)
3.	Electronic controllers - Control models - Composites mode electronic controllers		
4.	Pneumatic controllers - P-I controller - PD controller - P-I-D controller		
5.	Hydraulic controllers - Hydraulic integral controller - Hydraulic proportional controller		

(R17A0327) AUTOMATION AND CONTROL ENGINEERING

COURSE OBJECTIVES AND PO's PSO's MAPPING

CO /PO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PO13	PO14	PSO1	PSO2	PSO3
CO1	X			X	X										X	X	X
CO2	X	x	x	X	X										X	X	X
CO3	X	x	x	X	X										X	X	X
CO4	X	x	x	X	X										X	X	X
CO5	X	x	x	X	X										X	X	X

UNIT 1

Introduction to Automation and Mechatronics

UNIT-1

COURSE OBJECTIVE

- **Understand the basics of automation and the need of Mechatronics systems**

COURSE OUTCOME

- **The importance of automation in industries and Identification of key elements of mechatronics system**

Automation

Definition: It is technology concerned with the application of Mechanical, electronic & computer-based systems to operate and control production in order to improves productions.

If Includes:

1) Automated machine tools.
2) Automated assembly machines
3) Industrial robots.
4) Automated material handling & storages system
5) Automated inspection system for quality control
6) Feedback control & computer process control
7) Computer integrated system for planning, data collection decision making.

Examples: Automotive, Electronics, Applications, Aircraft manufacturing industries.

Type of Automation:

Automated production systems are classified into three basic types:

1) Fixed Automation
2) Programmable Automation
3) Flexible Automation

Fixed Automation

- ✓ Fixed automation is a system in which the sequence of processing (or assembly) operations is fixed by the equipment configuration.
- ✓ The operations in the sequence are usually simple.
- ✓ It is the integration and coordination of many such operations into one piece of equipment that makes the system complex.
- ✓ The typical features of fixed automation are:
  - High initial investment for custom-engineered equipment
  - High production rates
  - Relatively inflexible in accommodating product changes
- ✓ The economic justification for fixed automation is found in products with very high demand rates and volumes.
- ✓ The high initial cost of the equipment can be spread over a very large number of units, thus making the unit cost attractive compared to alternative methods of production.

Example: Automated material handling & transfer lines & assembly equipment's.

Programmable Automation

- ✓ In programmable automation, the production equipment is designed with the capability to change the sequence of operations to accommodate different product configurations.
- ✓ The operation sequence is controlled by a program, which is a set of instructions coded so that the system can read and interpret them.
- ✓ New programs can be prepared and entered into the equipment to produce new products.
- ✓ The typical features of programmable automation are:
  - High investment in general-purpose equipment
  - Low production rates relative to fixed automation
  - Flexibility to deal with changes in product configuration
  - Most suitable for batch production
- ✓ Automated production systems that are programmable are used in low and medium-volume production.

Example: Numerically Controlled (NC) machine tools, industrial robots, and programmable logic controllers

Flexible Automation

- ✓ Flexible automation is an extension of programmable automation.
- ✓ The concept of flexible automation has developed only over the last 15 to 20 years, and the principles are still evolving.
- ✓ A flexible automated system is one that is capable of producing a variety of products (or parts) with virtually no time lost for changeovers from one product to the next.
- ✓ There is no production time lost while reprogramming the system and altering the physical setup (tooling, fixtures and machine settings).
- ✓ Consequently, the system can produce various combinations and schedules of products, instead of requiring that they be made in separate batches.
- ✓ The features of flexible automation can be summarized as follows:
  - High investment for a custom-engineered system
  - Continuous production of variable mixtures of products
  - Medium production rates
  - Flexibility to deal with product design variations

Example: CNC m/c tools, reprogrammable Industrial robots and flexible manufacturing systems for performing machining operations

Diagraph:

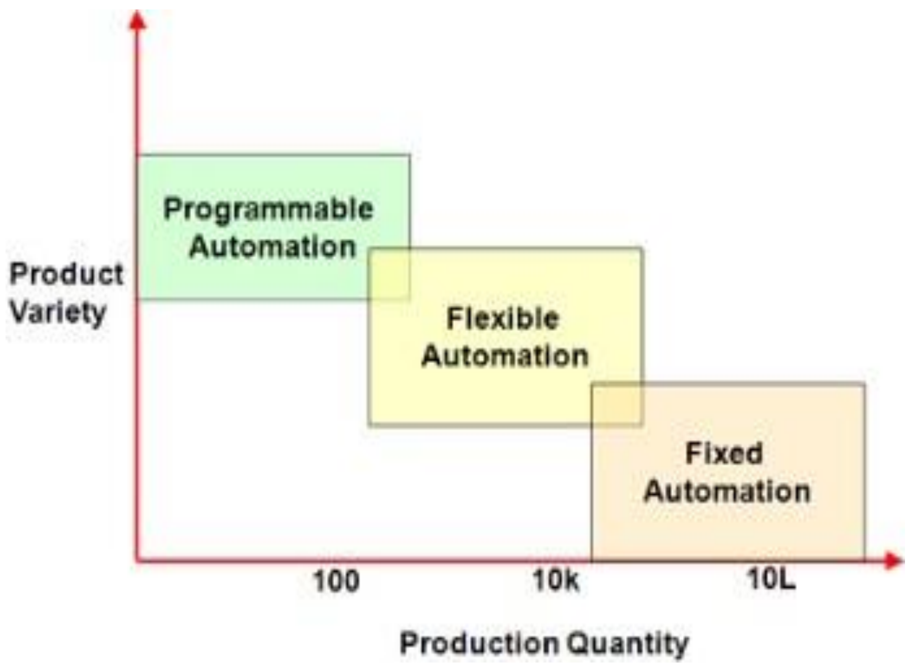


Fig1 Types of Automation

Reasons for Automation:

1. **Increased productivity due competition**
   - ✓ Due to Industrialization and globalization the global competition escalates which causes
   - ✓ increase the demand the stoner of productivity & quality.
   - ✓ Automation of manufacturing operations promise to in erasing the productivity of labour.
   - ✓ Automation causes higher output to lesser input.
   - ✓ Higher production rates are achieved with automation as compare to manual operations.
2. **High cost of Labour**
   - ✓ Automation system required less Labour hence increasing cost of Labour don't of heat on it.
   - ✓ Higher cost of Labour is forcing businesses to substitute m/c's for human Labour.
   - ✓ Machines can produce higher rates of output the use of automation results in a lower cost per unit of product.

3. **Labour shortage**
    - ✓ Many Advanced nations, there has been a shortage of Labour.
    - ✓ Labour shortages stimulate the development of automation as a substitute of Labour.
4. **Trend of Labour toward the sector**
    - ✓ There are some social & institutional forces Labour toward the service sector.
    - ✓ There has been a tendency for people to view factory work as tedious, demeaning & dirty.
    - ✓ This view has caused them to seek employment in the service sector of the economy.
5. **Safety**
    - ✓ Automation delaminates the human role, work is made safer.
    - ✓ The safety and physical wellbeing of the worker is main objective of today's industries.
6. **High cost of raw materials**
    - ✓ The high cost of raw materials in manufacturing results in the need for greater efficiency in using their materials.
    - ✓ The reduction of scrap is one of the benefits of automation.
7. **Improved Product Quality**
    - ✓ Automated operation not only produces parts of faster rates but they produce parts with greater consistency and conformity to quality.
8. **Reduced manufacturing Lead time**
    - ✓ For automation allows the manufacturer to reduce the time between custom order and product delivery.
9. **Reduction of in process inventory**
    - ✓ Holiday large inventories of work in process represent a significant cost to the manufacturer because it ties up capital.
    - ✓ In process inventory is of no value.
    - ✓ It is to the manufacturer's advantage to reduce work in progress to a minimum.
    - ✓ Automation play big role to reducing time a work part spends in the factory.
10. **High cost of not automation**
    - ✓ The benefits of automation often show up in intangible and unexpected ways. Such as improved quality, higher sales, better Labour relations and better company image.
    - ✓ Companies that do not automate are likely to final themselves of a competitive disadvantage with their customers, their employees & the general public.

Automation Strategies:

If automation seems a feasible solution to improving productivity, quality, or other measure of performance, then the following ten strategies provide a road map to search for these improvements.

1. **Specialization of operations**
   - ✓ It is strategies which involves use of specialized purpose equipment's designed to perform one operation with greatest efficiency.
   - ✓ It is strategy which involves used of specialized Labour to handle automation for improving the productivity.
2. **Combined operations**
   - ✓ It is the strategy of combined operations on some complex parts reducing the number of distinct production m/c‟s or workstations through which the part must be routed.
3. **Simultaneous operations**
   - ✓ It is an extension of combined operation strategy to perform same operations with less time simultaneously.
   - ✓ In effect, two or more processing operations are being performed simultaneous on same work part reducing processing time.
4. **Integration of operations**
   - ✓ It is link several workstations into a single integrated mechanism using automated work handling devices.
5. **Increased flexibility:**
   - ✓ It attempts to use maximum utilizations of equipment's for productions.
   - ✓ By using the one equipment for variety of products. There by reducing set up time and programming time for production m/c's.
6. **Improved material handling and storage**
   - ✓ It is useful for reducing lots of non-operative time hence reduction in lead time.
7. **On- line inspection**
   - ✓ Inspection for quality of work is performed after the process traditionally.
   - ✓ On line inspection into the manufacturing process permits corrections to the process as product is being made.
   - ✓ This reduces scrap and brings the overall quantity of product closer to the nominal specifications intended by the designer.
8. **Process control & optimization**

- ✓ It is included a wide range of control schemes intended to operate the individual process and associated equipment move efficiently.

9. **Plan operations control**
    - ✓ This strategy is concerned with control at the plant – Level.
    - ✓ It is to manage and co-ordinate the aggregate equipment more efficiently.

10. **Computer-integrated manufacturing (CIM)**
    - ✓ Taking the previous strategy one level higher, we have the integration of factory operations with engineering design and the business functions of the firm.
    - ✓ CIM involves extensive use of computer applications, computer data bases, and computer networking throughout the enterprise.

Hydraulic System

Hydraulic systems are power-transmitting assemblies employing pressurized liquid as a fluid for transmitting energy from an energy-generating source to an energy-using point to accomplish useful work. Figure 2 shows a simple circuit of a hydraulic system with basic components.

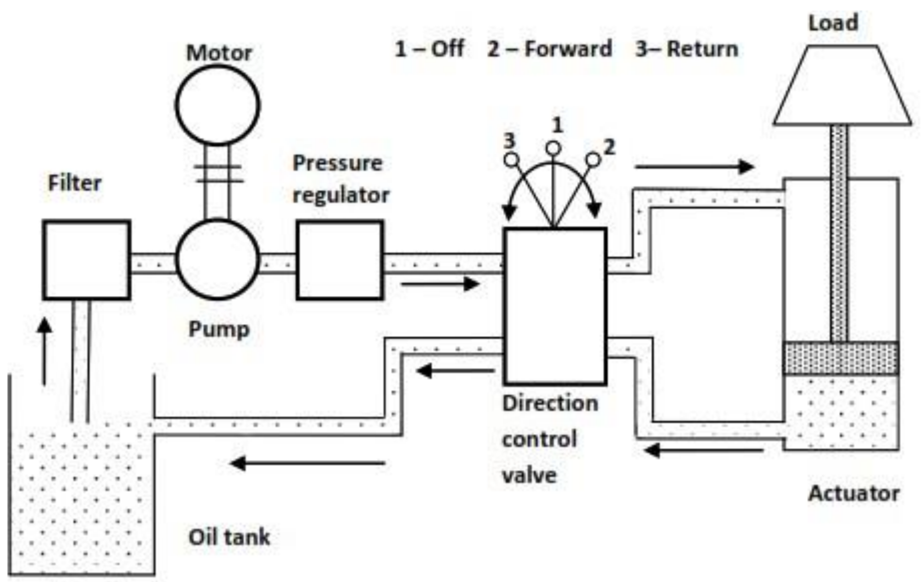


Fig 2 Components of a Hydraulic System.

Basic Components of a Hydraulic System

The functions of various components shown in Fig. 3 are as follows:

1. The hydraulic actuator is a device used to convert the fluid power into mechanical power to do useful work. The actuator may be of the linear type (e.g., hydraulic cylinder) or rotary type (e.g., hydraulic motor) to provide linear or rotary motion, respectively.

2. The hydraulic pump is used to force the fluid from the reservoir to rest of the hydraulic circuit by converting mechanical energy into hydraulic energy.
3. Valves are used to control the direction, pressure and flow rate of a fluid flowing through the circuit.
4. External power supply (motor) is required to drive the pump.
5. Reservoir is used to hold the hydraulic liquid, usually hydraulic oil.
6. Piping system carries the hydraulic oil from one place to another.
7. Filters are used to remove any foreign particles so as keep the fluid system clean and efficient, as well as avoid damage to the actuator and valves.
8. Pressure regulator regulates (i.e., maintains) the required level of pressure in the hydraulic fluid.

The piping shown in Fig. 2 is of closed-loop type with fluid transferred from the storage tank to one side of the piston and returned back from the other side of the piston to the tank. Fluid is drawn from the tank by a pump that produces fluid flow at the required level of pressure. If the fluid pressure exceeds the required level, then the excess fluid returns back to the reservoir and remains there until the pressure acquires the required level.

Cylinder movement is controlled by a three-position change over a control valve.

1. When the piston of the valve is changed to upper position, the pipe pressure line is connected to port A and thus the load is raised.
2. When the position of the valve is changed to lower position, the pipe pressure line is connected to port B and thus the load is lowered.
3. When the valve is at center position, it locks the fluid into the cylinder (thereby holding it in position) and dead-ends the fluid line (causing all the pump output fluid to return to tank via the pressure relief).

In industry, a machine designer conveys the design of hydraulic systems using a circuit diagram. Figure 3 shows the components of the hydraulic system using symbols. The working fluid, which is the hydraulic oil, is stored in a reservoir. When the electric motor is switched ON, it runs a positive displacement pump that draws hydraulic oil through a filter and delivers at high pressure. The pressurized oil passes through the regulating valve and does work on actuator. Oil from the other end of the actuator goes back to the tank via return line. To and fro motion of the cylinder is controlled using directional control valve.

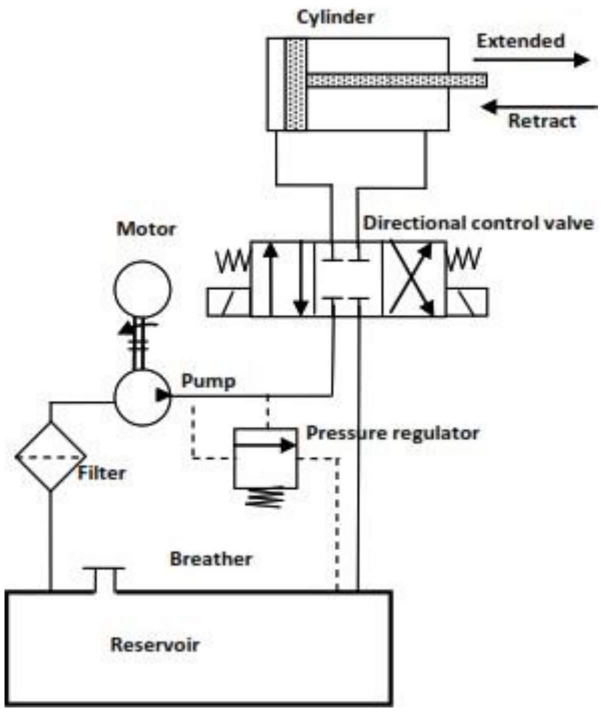


Fig 3 Components of a hydraulic system (shown using symbols).

The hydraulic system discussed above can be broken down into four main divisions that are analogous to the four main divisions in an electrical system.

1. The power device parallels the electrical generating station.
2. The control valves parallel the switches, resistors, timers, pressure switches, relays, etc.
3. The lines in which the fluid power flows parallel the electrical lines.
4. The fluid power motor (whether it is a rotating or a non-rotating cylinder or a fluid power motor) parallels the solenoids and electrical motors.

Pneumatic System

A pneumatic system carries power by employing compressed gas, generally air, as a fluid for transmitting energy from an energy-generating source to an energy-using point to accomplish useful work. Figure 4 shows a simple circuit of a pneumatic system with basic components.

Basic Components of a Pneumatic System

The functions of various components shown in Fig. 4 are as follows:

1. The pneumatic actuator converts the fluid power into mechanical power to perform useful work.
2. The compressor is used to compress the fresh air drawn from the atmosphere.
3. The storage reservoir is used to store a given volume of compressed air.

4. The valves are used to control the direction, flow rate and pressure of compressed air.
5. External power supply (motor) is used to drive the compressor.
6. The piping system carries the pressurized air from one location to another.

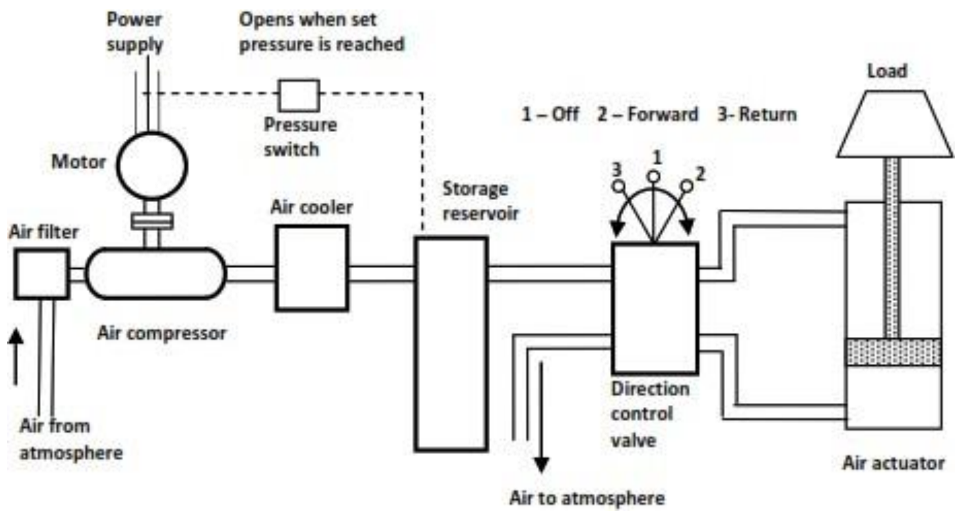


Fig 3 Components of a pneumatic system.

Air is drawn from the atmosphere through an air filter and raised to required pressure by an air compressor. As the pressure rises, the temperature also rises; hence, an air cooler is provided to cool the air with some preliminary treatment to remove the moisture. The treated pressurized air then needs to get stored to maintain the pressure. With the storage reservoir, a pressure switch is fitted to start and stop the electric motor when pressure falls and reaches the required level, respectively.

The three-position change over the valve delivering air to the cylinder operates in a way similar to its hydraulic circuit.

Comparison between Hydraulic and Pneumatic Systems

Usually hydraulic and pneumatic systems and equipment do not compete. They are so dissimilar that there are few problems in selecting any of them that cannot be readily resolved. Certainly, availability is one of the important factors of selection but this may be outweighed by other factors. In numerous instances, for example, air is preferred to meet certain unalterable conditions, that is, in “hot spots” where there is an open furnace or other potential ignition hazard or in operations where motion is required at extremely high speeds. It is often found more efficient to use a combined circuit in which oil is used in one part and air in another on the same machine or process. Table 1 shows a brief comparison of hydraulic and pneumatic systems.

S. No.	Hydraulic System	Pneumatic System
1	It employs a pressurized liquid as a fluid	It employs a compressed gas, usually air, as a fluid
2	An oil hydraulic system operates at pressures up to 700 bar	A pneumatic system usually operates at 5–10 bar
3	Generally designed as closed system	Usually designed as open system
4	The system slows down when leakage occurs	Leakage does not affect the system much
5	Valve operations are difficult	Valve operations are easy
6	Heavier in weight	Lighter in weight
7	Pumps are used to provide pressurized liquids	Compressors are used to provide compressed gases
8	The system is unsafe to fire hazards	The system is free from fire hazards
9	Automatic lubrication is provided	Special arrangements for lubrication are needed

AUTOMATED FLOW LINES

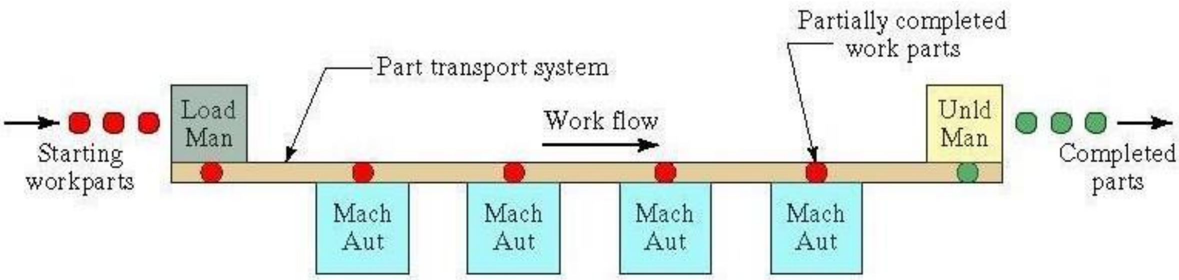
An automated flow line consists of several machines or workstations which are linked together by work handling devices that transfer parts between the stations. The transfer of work parts occurs automatically and the workstations carry out their specialized functions automatically.

The objectives of the use of flow line automation are, therefore:

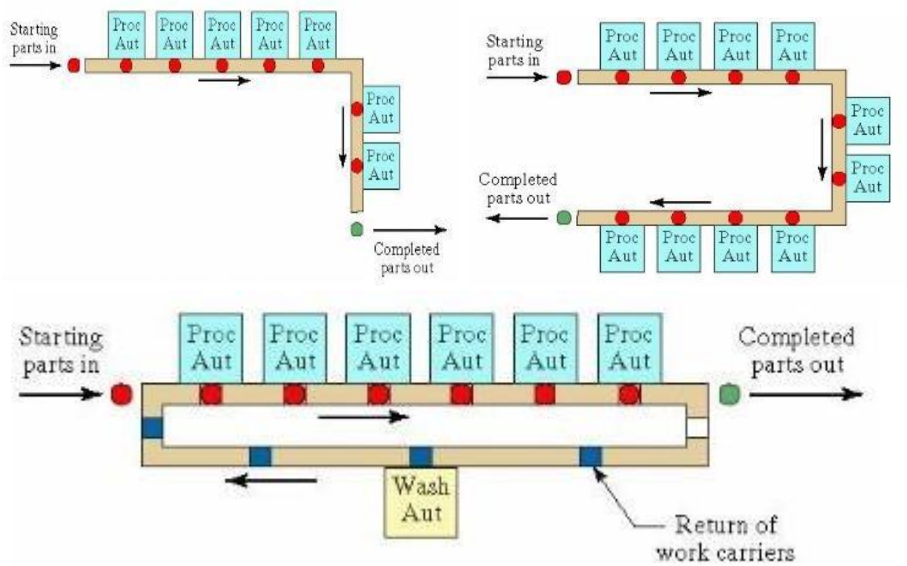
- ✓ To reduce labor costs
- ✓ To increase production rates
- ✓ To reduce work-in-process
- ✓ To minimize distances moved between operations
- ✓ To achieve specialization of operations
- ✓ To achieve integration of operations

Configurations of automated flow line.

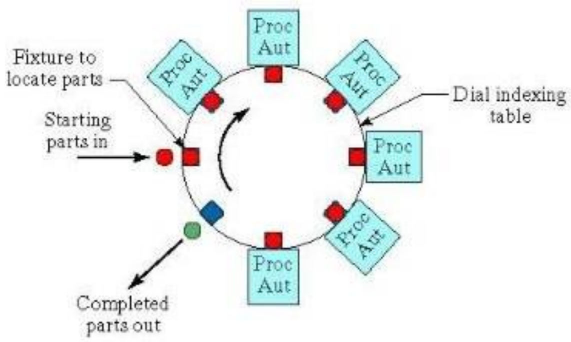
1) **In-line type:** The in-line configuration consists of a sequence of workstations in a more or less straight-line arrangement as shown in below Figure. An example of an in-line transfer machine used for metal cutting operations.



2) **Segmented In-Line Type:** The segmented in-line configuration consists of two or more straight line arrangement which are usually perpendicular to each other with L shaped or U shaped or rectangular shaped as shown in below Figure. The flow of work can take a few 90°turns, either for workpiece reorientation, factory layout limitations, or other reasons, and still qualify as a straight-line configuration.



3) **Rotary type:** In the rotary configuration, the work parts are indexed around a circular table or dial. The workstations are stationary and usually located around the outside periphery of the dial. The parts ride on the rotating table and arc registered or positioned, in turn, at each station for its processing or assembly operation. This type of equipment is often referred to as an indexing machine or dial index machine and the configuration is shown in below



Methods of work part transport

The transfer mechanism of the automated flow line must not only move the partially completed workparts or assemblies between adjacent stations, it must also orient and locate the parts in the correct position for processing at each station. The general methods of transporting workpieces on flow lines can be classified into the following three categories:

1. Continuous transfer
2. Intermittent or synchronous transfer
3. Asynchronous or power-and-free transfer

The most appropriate type of transport system for a given application depends on such factors as:

- The types of operation to be performed
- The number of stations on the line
- The weight and size of the work parts
- Whether manual stations are included on the line
- Production rate requirements
- Balancing the various process times on the line

1) **Continuous transfer:** With the continuous method of transfer, the workparts are moved continuously at constant speed. This requires the workheads to move during processing in order to maintain continuous registration with the workpart. For some types of operations, this movement of the workheads during processing is not feasible. It would be difficult, for example, to use this type of system on a machining transfer line because of inertia problems due to the size and weight of the workheads. In other cases, continuous transfer would be very practical. Examples of its use are in beverage bottling operations, packaging, manual assembly operations where the human operator can move with the moving flow line, and relatively simple automatic assembly tasks. In some bottling operations, for instance, the bottles are transported around a continuously rotating drum. Beverage is discharged into the moving bottles by spouts located at the drum's periphery. The advantage of this application is that the liquid beverage is kept moving at a steady speed and hence there are no inertia problems. Continuous transfer systems are relatively easy to design and fabricate and can achieve a high rate of production.
2) **Intermittent transfer:** As the name suggests, in this method the workpieces are transported with an intermittent or discontinuous motion. The workstations are fixed in

position and the parts are moved between stations and then registered at the proper locations for processing. All workparts are transported at the same time and, for this reason, the term" synchronous transfer system" is also used to describe this method work part transport.

3) **Asynchronous transfer:** This system of transfer, also referred to as a "power-and-free system," allows each workpart to move to the next station when processing at the current station has been completed. Each part moves independently of other parts. Hence, some parts are being processed on the line at the same time that others are being transported between stations.

   Asynchronous transfer systems offer the opportunity for greater flexibility than do the other two systems, and this flexibility can be a great advantage in certain circumstances. In-process storage of workparts can be incorporated into the asynchronous systems with relative ease. Power-and-free systems can also compensate for line balancing problems where there are significant differences in process times between stations. Parallel stations or several series stations can be used for the longer operations, and single stations can be used for the shorter operations. Therefore, the average production rates can be approximately equalized. Asynchronous lines are often used where there are one or more manually operated stations and cycle-time variations would be a problem on either the continuous or synchronous transport systems. Larger workparts can be handled on the asynchronous systems. A disadvantage of the power and free systems is that the cycle rates are generally slower than for the other types.

TRANSFER MECHANISMS

There are various types of transfer mechanisms used to move parts between stations. These mechanisms can be grouped into two types:

1) Linear transfer mechanisms
2) Rotary transfer mechanisms

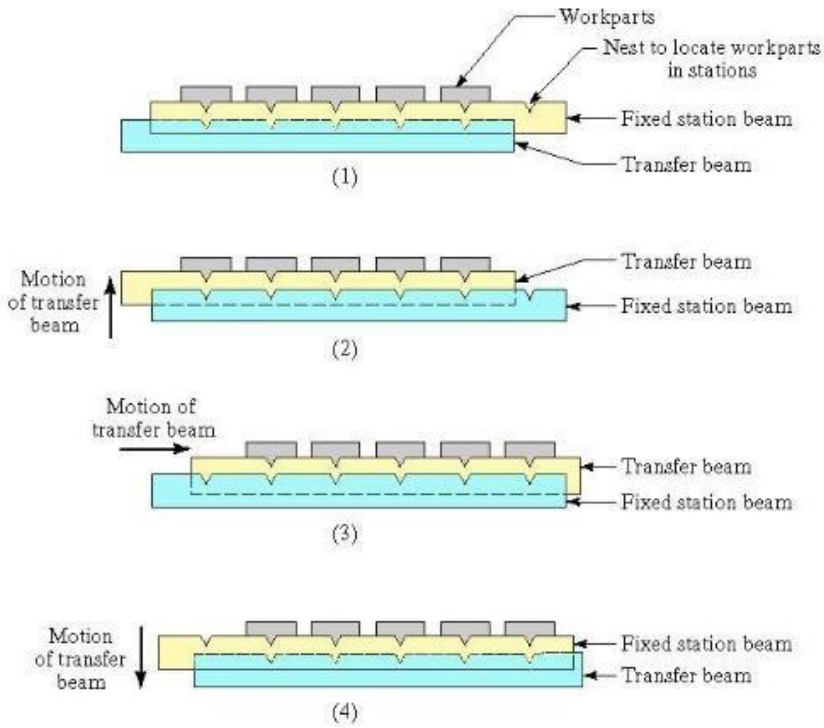
1. Linear transfer mechanisms

The commonly used linear transfer mechanisms are

a) Walking beam transfer bar system,
b) Powered roller conveyor system, and
c) Chain-drive conveyor system.

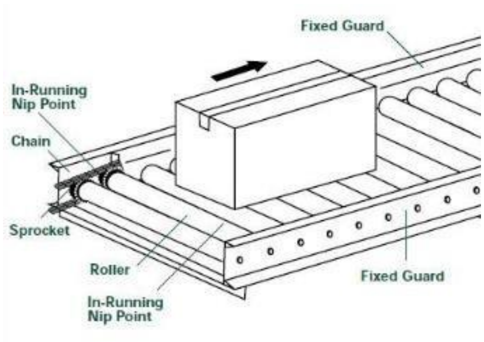
A. Walking Beam Systems

With the walking beam transfer mechanism, the work-parts are lifted up from their workstation locations by a transfer bar and moved one position ahead, to the next station. The transfer bar then lowers the pans into nests which position them more accurately for processing. For speed and accuracy, the motion of the beam is most often generated by a rotating camshaft powered by an electric motor or a roller movement in a profile powered by hydraulic cylinder. Figure shows the working of the beam mechanism.



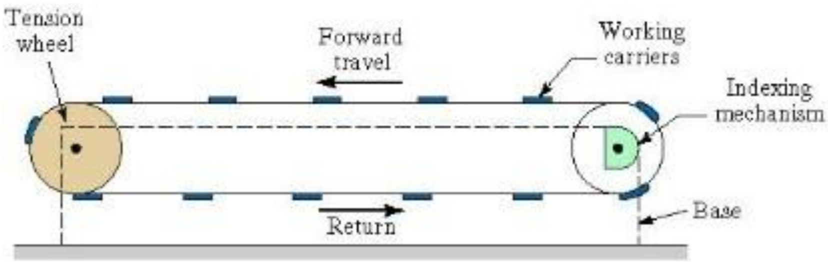
B. Powered roller conveyor system

This type of system is used in general stock handling systems as well as in automated flow lines. The conveyor can be used to move pans or pallets possessing flat riding surfaces. The rollers can be powered by either of two mechanisms. The first is a belt drive, in which a flat moving belt beneath the rollers provides the rotation of the rollers by friction. A chain drive is the second common mechanism used to power the rollers. Powered roller conveyors are versatile transfer systems because they can be used to divert work pallets into workstations or alternate tracks.



C. Chain-drive conveyor system

In chain-drive conveyor system either a chain or a flexible steel belt is used to transport the work carriers. The chain is driven by pulleys in either an "over-and under" configuration, in which the pulleys turn about a horizontal axis, or an "around-the-corner" configuration, in which the pulleys rotate about a vertical axis.



This general type of transfer system can be used for continuous, intermittent, or nonsynchronous movement of workparts. In the non-synchronous motion, the workparts are pulled by friction or ride on an oil film along a track with the chain or belt providing the movement. It is necessary to provide some sort of final location for the workparts when they arrive at their respective stations.

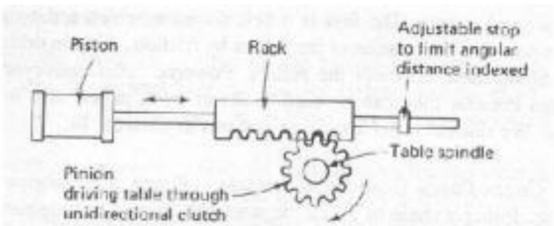
2. Rotary transfer mechanisms

There are several methods used to index a circular table or dial at various equal angular positions corresponding to workstation locations.

a) Rack and pinion
b) Ratchet and pawl
c) Geneva mechanism
d) CAM Mechanisms

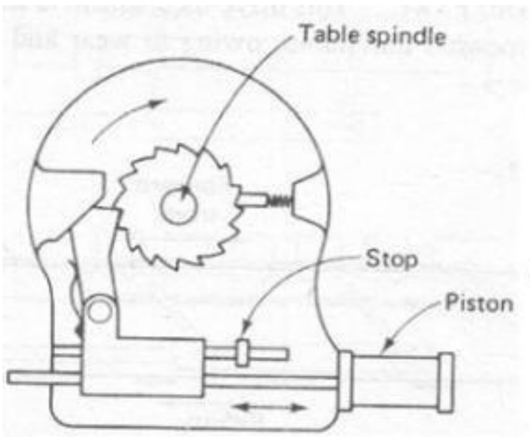
A. Rack and pinion

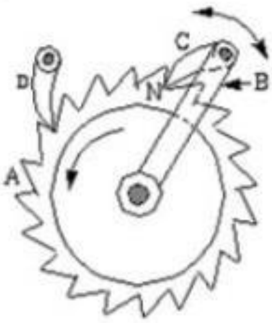
This mechanism is simple but is not considered especially suited to the high-speed operation often associated with indexing machines. The device is pictured in the below Figure and uses a piston to drive the rack, which causes the pinion gear and attached indexing table to rotate, A clutch or other device is used to provide rotation in the desired direction.



B. Ratchet and pawl

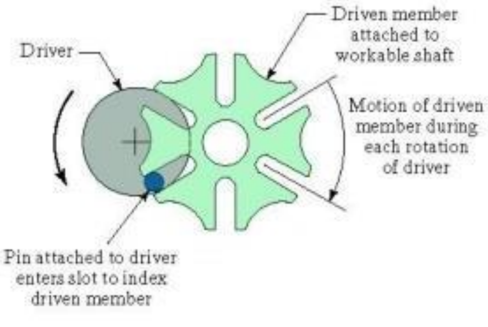
A ratchet is a device that allows linear or rotary motion in only one direction, while preventing motion in the opposite direction. Ratchets consist of a gearwheel and a pivoting spring-loaded finger called a pawl that engages the teeth. Either the teeth, or the pawl, are slanted at an angle, so that when the teeth are moving in one direction, the pawl slides up and over each tooth in turn, with the spring forcing it back with a 'click' into the depression before the next tooth. When the teeth are moving in the other direction, the angle of the pawl causes it to catch against a tooth and stop further motion in that direction. This drive mechanism is shown in the below.

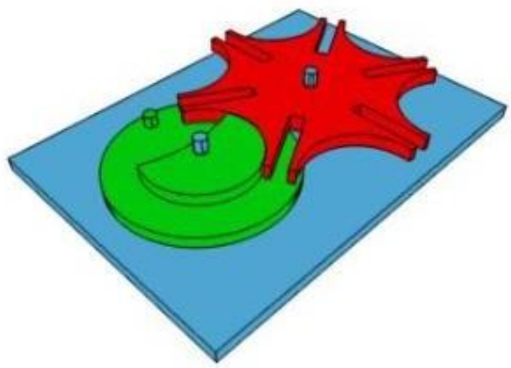




C. Geneva mechanism

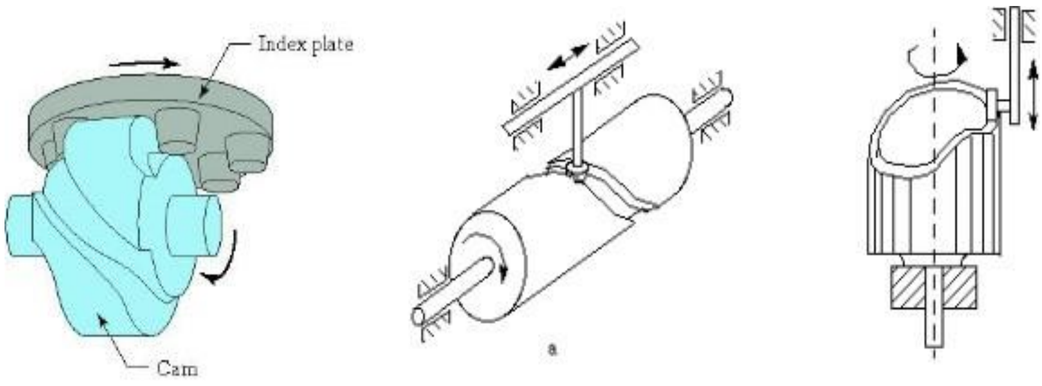
The two previous mechanisms convert a linear motion into a rotational motion. The Geneva mechanism uses a continuously rotating driver to index the table, as pictured below. If the driven member has six slots for a six-station dial indexing machine, each turn of the driver will cause the table to advance one-sixth of a turn. The driver only causes movement of the table through a portion of its rotation. For a six-slotted driven member, 120° of a complete rotation of the driver is used to index the table. The other 240° is dwell. For a four slotted driven member, the ratio would be 90° for index and 270° for dwell. The usual number of indexing per revolution of the table is four, five, six, and eight.





D. CAM Mechanisms

Various forms of cam mechanism, an example of which is illustrated in the below Figure, provide probably the most accurate and reliable method of indexing the dial. They are in widespread use 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.



CONTROL FUNCTIONS

Controlling an automated flow line is a complex problem, owing to the sheer number of sequential steps that must be carried out. There are three main functions that are utilized to control the operation of an automatic transfer system. The first of these is an operational requirement, the second is a safety requirement, and the third is dedicated to improving quality.

1. **Sequence control:** The purpose of this function is to coordinate the sequence of actions of the transfer system and its workstations. The various activities of the automated flowline must be carried out with split-second timing and accuracy. Sequence control is basic to the operation of the flow line.
2. **Safety monitoring:** This function ensures that the transfer system does not operate in an unsafe or hazardous condition. Sensing devices may be added to make certain that the cutting tool status is satisfactory to continue to process the workpart in the case of a machining-type transfer line. Other checks might include monitoring certain critical steps in the sequence control function to make sure that these steps have all been performed and in the correct order. Hydraulic or air pressures might also be checked if these are crucial to the operation of automated flow lines.
3. **Quality monitoring:** The third control function is to monitor certain quality attributes of the workpart. Its purpose is to identify and possibly reject defective workparts and assemblies. The inspection devices required to perform quality monitoring are sometimes Incorporated into existing processing stations. In other

cases, separate stations are included in the line for the sole purpose of inspecting the workpart.

4. **Alternative control strategies:** Conventional thinking on the control of the line has been to stop operation when amalfunction occurred. While there are certain malfunctions representing unsafe conditions that demand shutdown of the line, there are other situations where stoppage of the line is not required and perhaps not even desirable. There are alternative control strategies
   a) Instantaneous control and
   b) Memory control.

   Instantaneous control: This mode of control stops the operation of the flow line immediately when a malfunction is detected. It is relatively simple, inexpensive, and trouble free. Diagnostic features are often added to the system to aid in identifying the location and cause of the trouble to the operator so that repairs can be quickly made. However, stopping the machine results in loss of production from the entire line, and this is the system's biggest drawback.

   Memory control: In contrast to instantaneous control, the memory system is designed to keep the machine operating. It works to control quality and/or protect the machine by preventing subsequent stations from processing the particular workpart and by segregating the part as defective at the end of the line. The premise upon which memory-type control is based is that the failures which occur at the stations will be random and infrequent. If, however, the station failures result from cause and tend to repeat, the memory system will not improve production but, rather, degrade it. The flow line will continue to operate, with the consequence that bad parts will continue to be produced. For this reason, a counter is sometimes used so that if a failure occurs at the same station for two or three consecutive cycles, the memory logic will cause the machine to stop for repairs.

MECHATRONICS

INTRODUCTION

In 1969, a senior engineer of a Japanese company Yasakawa first coined the word mechatronics as a combination of 'Mecha' from mechanisms and 'Tronics' from electronics. Up to 1970s, in most of industries and the manufacturing processes, mechanical systems and machine tools were largely mechanical systems with limited electrical and electronic elements. Nowadays, electrical and electronic fields are developing very rapidly like electrical machines, integrated circuits (ICs), microprocessors, microcontrollers, digital control systems, data communication networks, advent combination of computers and related Softwares, process controllers, embedded systems and so forth. Electrical and electronic systems can be integrated with mechanical systems and processes because of their fantastic features and applications.

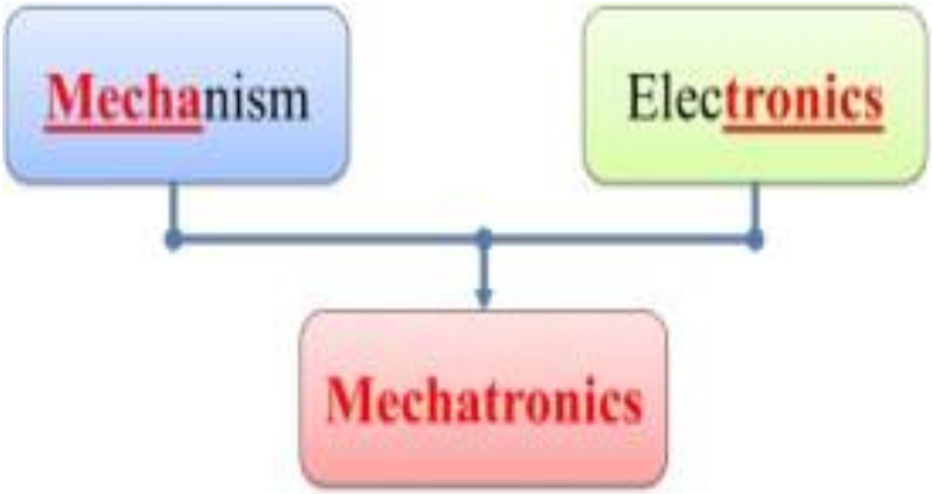


Fig 1 Derivation of Mechatronics

Basically, mechatronics is a multidisciplinary approach to product and manufacturing system design. Mechatronics is the synergistic integration of mechanical engineering with electronics and intelligent computer control in designing, manufacturing processes and production. It helps develop atomized, reliable and efficient manufacturing/production systems to produce high quality products.

Some mechatronic applications are in every field of production, consumer products, monitoring and control of welding process, intelligent robot control using ultrasonic measurements, temperature controllers and so forth.

Definition:

A. It is an application of electronics and computer technology to control the motions of mechanical systems.

B. Mechatronics is the synergistic integration of sensors, actuators, signal conditioning, power electronics, decision and control algorithms, and computer hardware and software to manage complexity, uncertainty, and communication in engineered systems. - **T. Mori, 'Mechatronics' YASAKAWA INTERNAL TREADMARK**

C. Synergistic use of precision engineering, control theory, computer science, and sensor and actuator technology to design improved products and processes. - **F. Haeshma, M. Tomizuka 'Mechatronics' What it is, why & How...?**

D. Field of study involving the analysis, design, synthesis, and selection of systems that combine electronics and mechanical components with modern controls and microprocessors. Application of complex decision making to the operation of physical systems. - **W. Boltan 'Mechatronics Electronics Control systems in mechanical engineering**

Evaluation of Mechatronics:

The technology has evolved through several stages that are termed as levels.

The evolution levels of Mechatronics are:

A. Primary level Mechatronics (first)
B. Secondary level Mechatronics (second)
C. Tertiary level Mechatronics (third)
D. Quaternary level Mechatronics (fourth)

A. Primary level Mechatronics:

In the early days Mechatronics products were at primary level containing I/O devices such as sensors, and actuators that integrated electrical signals with mechanical action at the basic control level.

Examples: electrically controlled fluid valves and relays

B. Secondary level Mechatronics:

This level integrates microelectronics into electrically controlled devices.

Examples: cassette player.

C. Tertiary level Mechatronics:

- ✓ This incorporates advances feedback functions into control strategy, thereby enhancing the quality in terms of sophistication.
- ✓ Mechatronics system at this level is called ‘smart system’.
- ✓ The control strategy includes microelectronics, microprocessor and other „application specific integrated circuits‟ (ASIC).

Examples: DVD player, CD drives, automatic washing machine, CD drives, etc.

D. Quaternary level Mechatronics:

- ✓ This level includes intelligent control in Mechatronics system.
- ✓ The level attempts to improve smartness a step ahead by introducing intelligence and fault detection and isolation (FDI) capability system.

Examples: artificial neural network and fuzzy logic technologies.

Role of Various Engineering Disciplines in Mechatronics

The primary engineering disciplines, which are important in the designing of mechatronic system, include mechanical, electrical, electronics, instrumentation and control and computer and information technology. Figure2 shows the constituents of mechatronics. These constituents are discussed further.

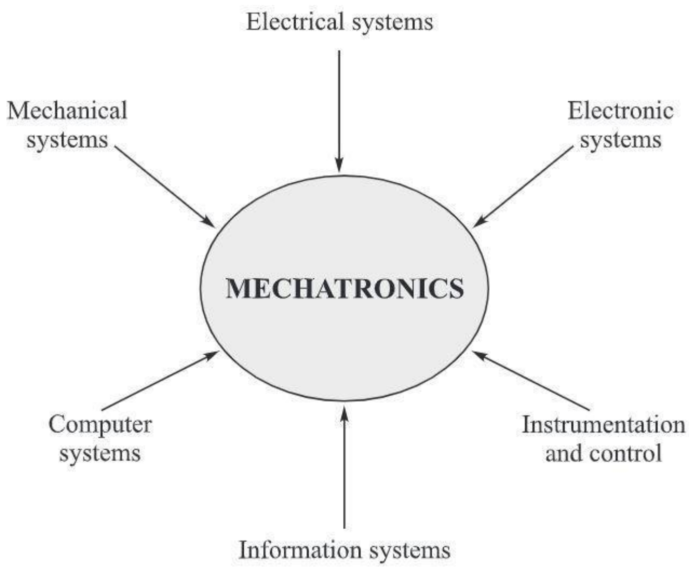


Fig 2 Constituents of mechatronics.

Mechanical systems. These systems deal with behavior of matter under the action of forces. They are classified as rigid, deformable or fluid in nature. Mechanical systems like hydraulic, pneumatic, rotational or translational, thermal, fluid, etc. are used in mechatronic applications.

These systems are interfaced with computers through sensors, actuators and electronic systems. Control valves, gears, cylinders, chains, etc. are the mechanical components used.

Electrical systems. These systems are concerned with the behavior of three fundamental quantities—charge, current, and voltage. Electrical systems are integral parts of mechatronic systems or applications. Electrical components mostly used in mechatronic systems are electrical motors (ac and dc), generators, transformers, relays, circuit breakers, switches and so forth.

Electronic systems. These systems are used to transduce information between the computer world and mechanical disciplines. In mechatronic systems, electronic devices are used to design the following electronic circuits:

Analog circuits: These circuits are designed using active and passive components. Passive components are resistors, capacitors and inductors. Active components are diodes, transistors and integrated circuits for designing.

Digital circuits: Basically, digital circuits are classified as combinational and sequential. These circuits are designed using logic gates, flip-flops, counters, digital memories, microprocessors, microcontrollers and so forth. Microprocessor- and microcontroller-based systems are most widely used in mechatronic systems.

Instrumentation and control systems. Instrumentation system covers various transducers, signal conditioning elements and output devices such as analog meters, display devices, recorders and printers. In mechatronic applications, these systems are used to measure, monitor and display various process variables, which are to be controlled at set points.

Data acquisition systems or data loggers are used for collecting, processing, storing, transmitting and monitoring the data accurately, safely and quickly.

Control system is that means by which any quantity of interest in a machine, mechanism or equipment is maintained or altered in accordance with a desired manner. It involves representation of systems, their behaviour and modifications in the system behaviour. It deals with time and frequency domain analysis and stability of systems. It involves control system components such as stepper motors, synchro's, ac and de position controls, servomotors, servomechanisms, actuators and so forth. Various process controllers like hydraulic, pneumatic, electronic and programmable logic controllers and fuzzy logic controllers, etc. are used for process control.

Information systems. It relates with all the aspects regarding information transmission from signal processing to control system and analysis techniques. It is a combination of communication systems, signal processing, control systems and numerical methods.

Computer systems. It is a combination of hardware and software. In mechatronic applications, hardware is computer-specific circuits like flip-flops, counters, registers, memories and microprocessors (as discussed in digital circuits in electronic systems). Software is nothing but system and application. Software is suitable for a typical mechatronic application or system. Computer systems are useful in product design, process planning and control, flexible manufacturing, online quality monitoring and so forth.

MECHATRONIC DESIGN ELEMENTS

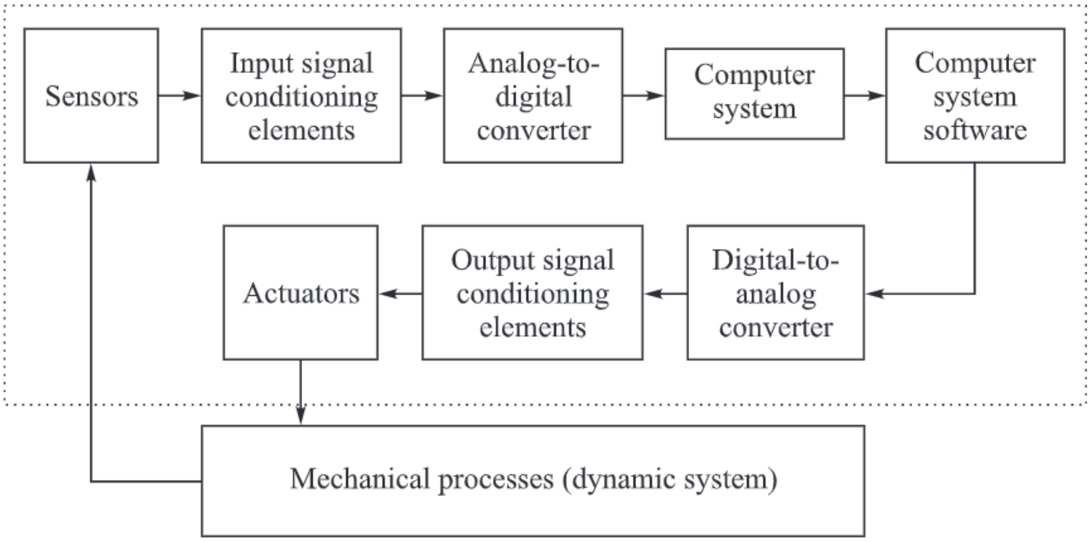


Fig 3 shows general mechatronic design elements.

The sensory system consists of sensors or transducers. In mechatronic systems, a sensor is an element, which accepts the physical. quantities (process variables) from mechanical processes (dynamic system) and convert them into a signal that can be processed by the system. At this stage, transducer is used. A transducer is defined as a device that converts physical quantities into an output, usually a voltage. The term sensor is often used to refer to a transducer or a combination of transducer and signal processor. Different physical quantities from mechanical processes are temperature, pressure, flow, force, strain, acceleration, vibration and so forth. The output of sensory system is applied to signal conditioning elements which are also called as signal processors. Function of signal conditioning clement is discussed as follows.

Usually the output of a transducer is an analog signal (voltage or current) that is continuous and time varying. The outputs of transducers are not in the desired form as we would like to process them. These signals may

- ✓ be too small (in the range of millivolts).
- ✓ be too noisy (due to electromagnetic interference, stray electric and magnetic fields).
- ✓ contain dc offset.
- ✓ not be compatible with next stages (like indicating instruments, display devices, controlling elements, etc.).
- ✓ contain wrong information (due to poor designing and wrong installation of transducers).

The above-stated problems can be recovered by using proper signal conditioning elements. Most common operational amplifiers (op-amps) with passive elements can be used as signal conditioning elements. Most commonly used signal conditioning process is amplification using amplifier in which the signal magnitude is increased. Other signal conditioning elements are adder, subtractor, integrator, differentiator, converters (voltage to current or current to voltage), comparator, sample and hold amplifier, instrumentation amplifier and so forth. If the system is microprocessor or microcontroller or computer based then analog-to-digital converters are used as signal conditioning elements.

Mechatronic systems employ actuators, which are parts of the physical process being monitored and controlled. Actuation is the result of a direct physical action on process directly. In any physical process, there is motion or some sort of action. This motion or action can be applied to mechanical processes or structure through actuators. Actuators take low-power signals from computers through signal conditioning elements and produce high output signals (physical quantities) that are applied to the process as input. Examples of actuators are steeper motor, solenoids, synchro’s and so forth.

Programmable logic controllers (PLCs) are industrial devices used for interfacing and controlling analog and digital devices. A PLC is a sequential logic device that generates output signals according to logic operations performed on the input signals. The major difference between a computer controller and a programmable controller is that the programmable controller is designed to interface with industrial processes directly, whereas a computer system requires data acquisition, signal processing, memory and logic and peripherals before process implementation. The PLCs are programmed with ladder logic, which is a graphical method of laying out the connectivity and logic between system inputs and outputs. A typical PLC consists of integrated power supply, central processing unit, memory elements, programmer/monitor, input and output modules. Microcontroller provides a small flexible control platform and it can be easily embedded in mechatronic systems. A microcontroller is basically a microcomputer on a single integrated circuit (IC) containing microprocessor, memory, input/output capabilities and other on-chip resources. Microcontrollers are low cost, versatile, small size and easy programming devices. Hence, they can be easily embedded in mechatronic system designing.

In large mechatronic systems, computers (desktop/personal computers/laptop) are used as appropriate control platforms. Computer can be easily interfaced with sensors and actuators through proper converters.

SCOPE OF MECHATRONICS

Mechatronics plays a vital role in industrial sector. The scope of mechatronic in industrial sector is discussed as follows:

Better design of products. In mechatronics, computer is the key constituent. Computer-aided designing (CAD) involves the use of computers to assist in designing of an individual part, machine tool, product or system in three stages—conceptual, preliminary and final.

Better process planning. It deals with the use of computers in process planning, i.e. computer-aided process planning (CAPP). It helps develop more logical and consistent process plans which results in lower manufacturing costs and higher product quality. It is a direct correlation between design and manufacturing.

Reliable and quality-oriented manufacturing. Because of computer-integrated manufacturing (CIM), the reliable and high quality-oriented products can be manufactured.

Intelligent process control. Due to developments in digital computer systems, their use in process control has extensively increased. In power plants, process and manufacturing industries, computer-aided process control is used for passive and active applications.

Passive applications include acquisition and manipulation (i.e. monitoring and alarming) of data from various processes.

Active applications involve acquisition and manipulation with additional features like process control, process and plant optimization and tuning of various controllers for best operating performance. Nowadays, in mechatronic systems, artificial neural networks are used in manufacturing systems for process control and inspection to improve production performance and production quality.

In general, mechatronics helps industries achieve greater productivity, reliability and higher quality by incorporating intelligent self-correcting sensory and feedback system.

General parameters for designing an intelligent mechatronic system are as follows:

- ✓ Analyze product design and development specifications
- ✓ Select process variables, set points, processes, etc.
- ✓ Design proper analog and digital circuits
- ✓ Select mechanical components and devices
- ✓ Design proper mechanical system like hydraulic, pneumatic, etc.
- ✓ Select sensors, actuators and control components
- ✓ Design accurate and precise control system for various process variables
- ✓ Develop computer-based system (real time interfacing)
- ✓ Develop necessary computer software and database
- ✓ Integrate the above-stated parameters effectively
- ✓ Monitor the performance of designed system

Advantages:

1. The products produced are cost effective and very good quality.
2. High degree of flexibility
3. Greater extent of machine utilization
4. Greater productivity
5. High life expected by proper maintenance.
6. The integration of sensor and control system in a complex system reduces capital expenses.

Disadvantages:

1. Higher initial cost of the system.
2. Imperative to have Knowledge of different engineering fields for design and implementation.
3. It is expenses to incorporate Mechatronics approaches to existing/old systems.
4. Specific problem of various systems will have to be addressed separately and properly.

Characteristics of Mechatronic system:

1. High quality product.
2. Safe.

3. Low cost.
4. Portable produced quickly
5. Serviceability, maintainability and upgradeability.

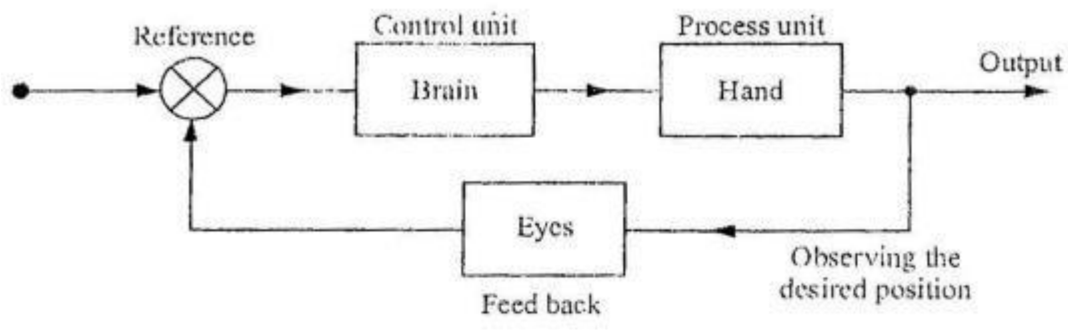
APPLICATIONS OF MECHATRONICS

General applications of mechatronics are as follows:

- ✓ In automatic washing machines, dishwashers
- ✓ In CD players, VCRs, camcorders
- ✓ In document scanners, MI equipment's
- ✓ In integrated circuits (ICs) manufacturing systems
- ✓ In robotics used in welding, nuclear inspection and robot manipulators
- ✓ In fax and photocopier machines
- ✓ in laser printers, in computer peripherals like hard disk drive head positioning systems
- ✓ In flexible manufacturing systems
- ✓ In air conditioners, elevator controls
- ✓ In automotive mechatronics (in automobiles for outdoors locking, collision avoidance and in ignition and antiroll systems, etc.).

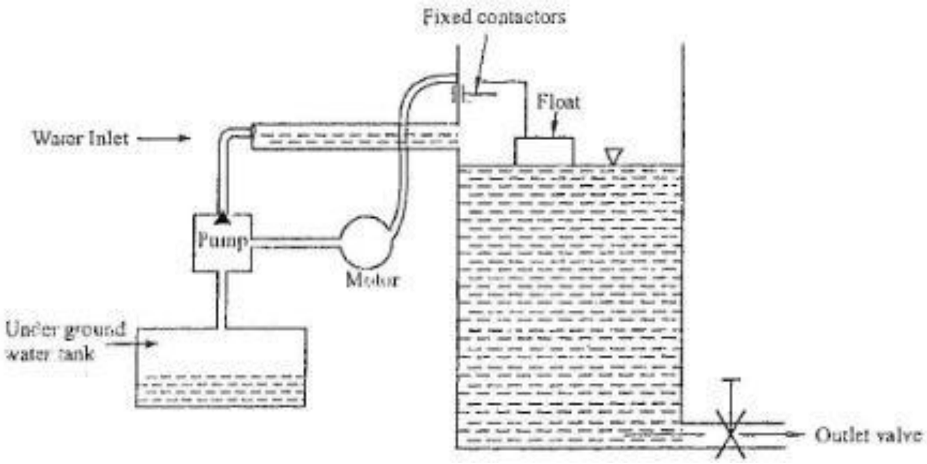
REAL TIME APPLICATIONS

Hand reaching an object.



- ✓ A person wants to reach for an object.
- ✓ Position of the object is given as reference; feedback signals and the eyes compare the actual position of the hands with reference to the position of the object.
- ✓ Error signal is given to the brain.
- ✓ Brain manipulates this error and gives signals to the hands.
- ✓ This process continues till the hand reaches the object.

Water level control of overhead tanks

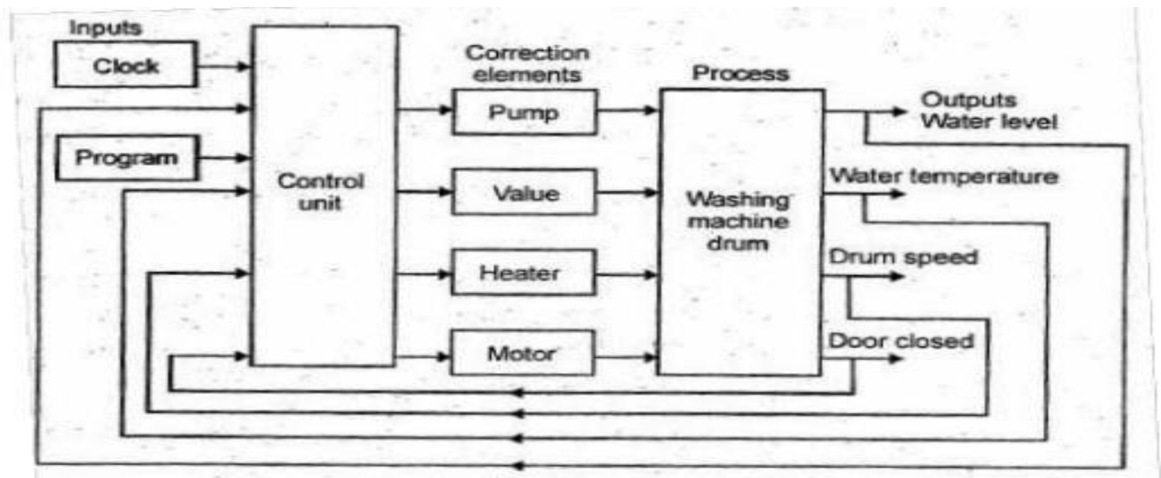


- ✓ The overhead tank has a fixed float (sensor) fixed at the desired height inside the tanks.
- ✓ The level of the water is sensed by the float. The float has an electrical contractor, which is positioned between fixed connectors.
- ✓ The inflow regulation valve is electrically operated. The electrical circuit of the system is closed when the float touches the fixed connectors and open when it is not making contact with it.

Washing Machine

The sequence of operations of a washing machine consists of following Cycles.

- ✓ Pre-wash cycle
- ✓ Main wash cycle
- ✓ Rinse cycle
- ✓ Spinning cycle



Feedbacks from outputs of water level, water temperature, drum speed and door closed.

Pre-Wash Cycle:

Pre-wash cycle may involve the following sequence of operations.

- ✓ Opening of valve to fill the drum when a current is supplied
- ✓ Microprocessor is used to operate the switch for opening closing the valve.
- ✓ Closing of valve after receiving the signal from a sensor when the required level of water is filled in the washing drum.
- ✓ Stopping the flow of water after the current is switched off by the microprocessor.
- ✓ Switch on the motor to rotate the drum for stipulated time.
- ✓ Initiates the operation of pump to empty the water from the drum.
- ✓ Pre-wash cycle involves washing the clothes in the drum by cold water

Main Wash Cycle

Main wash cycle involves washing the clothes in the drum by hot water

- ✓ Cold water is supplied after the Pre-wash cycle is completed.
- ✓ Current is supplied in large amount to switch on the heater for heating the cold water.
- ✓ Temperature sensor switches off the current after the water is heated to required temperature.
- ✓ Microprocessor or cam switches ON the motor to rotate the drum.
- ✓ Microprocessor or cam switches on the current to a discharge pump to empty the drum.

Rinse Cycle

Rinse cycle involves washing out the clothes with cold water a number of times

- ✓ Opening of valve to allow cold water into the drum when the microprocessor are given signals to supply current after the main wash cycle is completed.
- ✓ Switches off the supply current by the signals from microprocessor
- ✓ Operation of motor to rotate the drum
- ✓ Operation of pump to empty the drum and respect this sequence a number of times.

Spinning Cycle

Spinning cycle involves removing of water from the clothes

- ✓ Switching on the drum motor when the or a cam switches the supply current to rotate it at a higher speed than a rinsing cycle.

ASSISGNMENT QUESTIONS:

1. What is meant by automation? explain the types of automation with neat sketch?
2. What is meant by mechatronics and explain the levels of mechatronics
3. Explain about Mechatronic Design Elements
4. Explain about transfer mechanisms with neat sketch
5. Explain the components of hydraulic and pneumatic components?

Tutorial questions

1. Explain Automation Strategies and reasons for automation?
2. Explain the Role of Various Engineering Disciplines in Mechatronics
3. Explain the Scope, advantages and disadvantages of mechatronics
4. Explain the working of washing machine using control systems
5. Explain the working of Water level control of overhead tanks

UNIT 2

SENSORS AND TRANSDUCERS

UNIT-2

COURSE OBJECTIVE

- **Learn the constructions and working principle of different types of sensors and transducers**

COURSE OUTCOME

- **Identify different types of sensors and transducers required for specific applications**

SENSORS AND TRANSDUCERS

A transducer is a device, usually electrical, electronic, or electro-mechanical, that converts one type of energy into another for various purposes including measurement or information transfer. In a broader sense, a transducer is sometimes defined as any device that converts a signal from one form into another. The term ‘sensor’ is often used in place of the transducer. A sensor is defined as an element which when subjected to some physical change experiences a relative change. Transducers/sensors may act as passive or active devices. A sensor in which the output energy is supplied entirely or almost entirely by its input signals is called a passive element. An active element has an auxiliary source of power that supplies a major part of the output power. There may or may not be a conversion of energy from one form to another.

The treatment of the instrument performance characteristics is generally broken down into two subareas: static characteristics and dynamic characteristics. The static characteristics are the values given when steady state conditions occur. The dynamic characteristics refer to the behaviour between the time that the input value changes and the time required given by a transducer to settle down to steady state values. Accuracy, precision, threshold, resolution, hysteresis, dead band, sensitivity, non-linearity, range or span, and errors are examples of the static performance characteristic parameters. The response time, time constant, settling time, peak time, rise time are examples of the dynamic performance characteristics. For better functioning of mechatronics, sensors or transducers, both static and dynamic parameters are very important. Sensors or transducers are used in mechatronics for the following purposes:

- ✓ To provide position, velocity, and acceleration information of the measuring element in a system which provides feedback information
- ✓ To act as protective mechanism for a system
- ✓ To help eliminate mechanically complex and expensive feeding and sorting devices
- ✓ To provide identification and indication of the presence of different components
- ✓ To provide real time information concerning the nature of the task being performed

PERFORMANCE TERMINOLOGY

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 behaviour of the sensors. Following are the various specifications of a sensor/transducer system.

Static Characteristics

The static characteristics are the values given after the steady state condition has reached. These are the values given when the transducer has settled down after receiving some input.

1. **Range and Span:**
   - ✓ The range of a transducer defines the limits between which the input can vary.
   - ✓ The difference between the limits (maximum value - minimum value) is known as span.
   - ✓ **Example**: A load cell is used to measure force. An input force can vary from 20 to 100 N. Then the range of load cell is 20 to 100 N. And the span of load cell is 80 N (i.e., 100-20)
2. **Error:**
   - ✓ The algebraic difference between the indicated value and the true value of the measured parameter is termed as the error of the device.
   - ✓ **Error** = Indicated value — true value
   - ✓ **Example:** if the transducer gives a temperature reading of 30°C when the actual temperature is 29° C, then the error is + 1°C. If the actual temperature is ϖ 3 1° C, then the error is — 1°C.
3. **Accuracy:**
   - ✓ Accuracy is defined as the ability of the instrument to respond to the true value of the measure variable under the reference conditions.

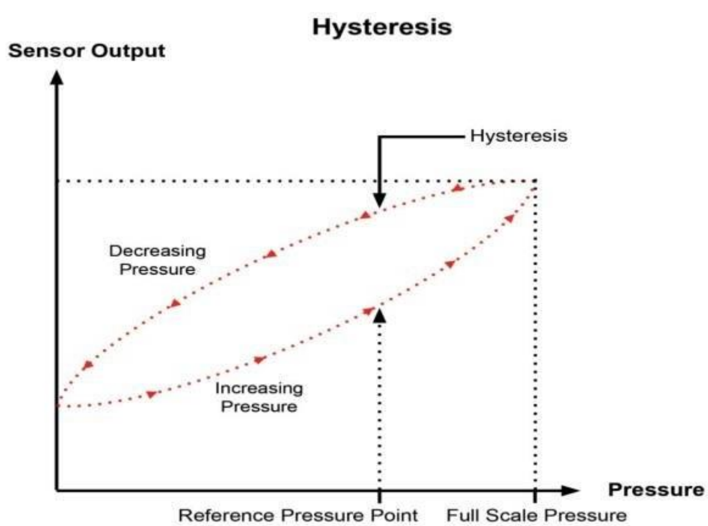
- ✓ **For example,** a thermocouple has an accuracy of ± 1° C. This means that reading given by the thermocouple can be expected to lie within + 1°C (or) — 1°C of the true value.
- ✓ Accuracy is also expressed as a percentage of the full range output (or) full scale deflection
- ✓ **For example,** a thermocouple can be specified as having an accuracy of ±4 % of full range output. Hence if the range of the thermocouple is 0 to 200°C, then the reading given can be expected to be within + 8°C (or) — 8°C of the true reading.

4. Sensitivity:

- ✓ The sensitivity is the relationship showing how much output we can get per unit input.
- ✓ **Sensitivity** = Output / Input Precision:
- ✓ It is defined as the degree of exactness for which the instrument is intended to perform.

5. Hysteresis error:

- ✓ When a device is used to measure any parameter plot the graph of output VS value of measured quantity.
- ✓ First for increasing values of the measured quantity and then for decreasing values of the measured quantity.
- ✓ The two output readings obtained usually differ from each other.



6. **Repeatability:**
   - ✓ The repeatability and reproducibility of a transducer are its ability to give the same output for repeated applications of the same input value.
7. **Reliability:**
   - ✓ The reliability of a system is defined as the possibility that it will perform its assigned functions for a specific period of time under given conditions.
8. **Stability:**
   - ✓ The stability of a transducer is its ability to give the same output when used to measure a constant input over a period of time.
9. **Drift:**
   - ✓ The term drift is the change in output that occurs over time.
10. **Dead band:**
    - ✓ There will be no output for certain range of input values. This is known as dead band.
    - ✓ There will be no output until the input has reached a particular value.
11. **Dead time:**
    - ✓ It is the time required by a transducer to begin to respond to a change in input value.
12. **Resolution:**
    - ✓ Resolution is defined as the smallest increment in the measured value that can be detected.
    - ✓ The resolution is the smallest change in the input value which will produce an observable change in the input.
13. **Backlash:**
    - ✓ Backlash is defined as the maximum distance (or) angle through which any part of a mechanical system can be moved in one direction without causing any motion of the attached part.
    - ✓ Backlash is an undesirable phenomenon and is important in the precision design of gear trains.

Dynamic Characteristics

1. **Response Time**
   - ✓ The time taken by a system to produce an output after a constant input, a step input, is applied to it is known as response time.
2. **Time Constant**
   - ✓ The time constant is the measure of the inertia of the sensor, and so how fast it will react to changes in its input. The bigger the time constant, the slower will be its reaction to a varying input signal. This is 63.2% of response time.
3. **Rise Time**
   - ✓ Rise time is the time required for the output to rise from 10% to 95% of the steady state value.
4. **Settling Time**
   - ✓ Settling time is the time required for the output to settle down within some percentage normally 3% of the steady state value. .

Classification of Sensor /Transducer

Sensors are classified in the following ways.

A. **According to the power supply**
   1. Active type
   2. Passive type
B. **According to the mode of operation**
   1. Null type
   2. Deflection type
C. **According to the signal characteristics (or) output**
   1. Analog
   2. Coded type
   3. Digital type
   4. Frequency type
D. **According to the measurement (or) Function**
   1. Displacement
   2. Velocity
   3. Acceleration
   4. Dimensional
   5. Mass
   6. Force

7. Proximity
8. Pressure
9. Fluid Flow
10. Liquid level
11. Temperature

E. According to the performance characteristics

1. Accuracy
2. Repeatability
3. Linearity
4. Sensitivity
5. Range

Displacement, Position and Proximity sensors

Displacement sensors are concerned with the measurement of the amount by which some object has been moved. **Position Sensors** are concerned with the determination of the position of the object. With reference to some reference point. **Proximity Sensors** are a form of position sensors which are used to determine when object has moved to within some particular critical distance of the sensor. Magnetic, electrical capacitance, inductance and eddy current methods are particularly suited to design a proximity sensor. They are on-off devices.

Displacement and position sensors can be grouped into two basic types: contact sensors in which the measured object comes into mechanical contact with the sensor, or non-contacting where there is no physical contact between the measured object and the sensor. For those linear displacement methods involving contact, there is usually a sensing shaft which is in direct contact with the object being monitored. The displacement of this shaft is then monitored by a sensor. The movement of the shaft may be used to cause changes in electrical voltage, resistance, capacitance or mutual inductance. For angular displacement methods involving mechanical connection, the rotation of a shaft might directly drive, through gears, the rotation of the transducer element. Non-contacting sensors might involve the presence in the vicinity of the measured object causing a change in the air pressure in the sensor, or perhaps a change in inductance or capacitance.

The following are examples of commonly used displacement sensors.

1. Potentiometer
2. Strain gauge
3. Capacitive sensors
4. Linear variable differential transformer

1. Potentiometer sensors

Potentiometers are mainly used to measure displacement pressure, position. A displacement or position transducer that uses the variable resistance transduction principle can be manufactured with a rotary or linear potentiometer.

Principle

Linear or Rotary potentiometer is a variable resistance displacement transducer which uses the **variable resistance transduction principl**e in which the displacement or rotation is converted into a potential difference due to the movement of sliding contact over a resistive element.

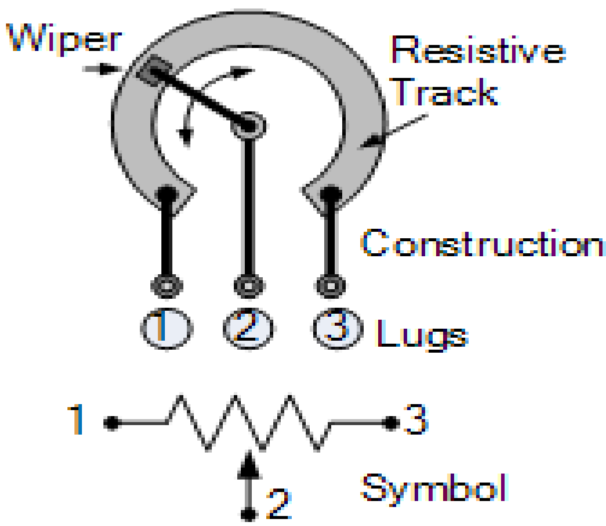
Construction of a Potentiometer

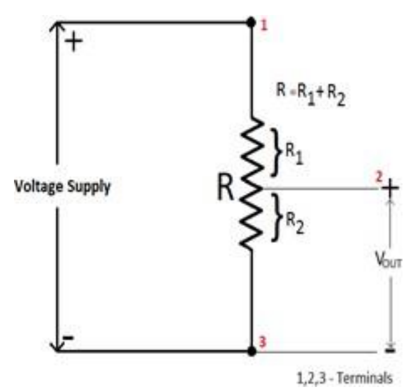
- ✓ The potentiometer essentially has a resistive element over which a moving terminal, the wiper slides. Any potentiometer is constructed of the following parts:
- ✓ The terminals: Potentiometer has three terminals, two fixed and one variable.
- ✓ The resistive element: This part is the main part of the device and it is connected to the two fixed terminals. It is one of the decisive aspects when it comes to the cost of the potentiometer, and also can govern aspects of the performance of the component including the power dissipation capability and noise generated. The resistive element used can be of the following types:
- ✓ Carbon Composition: This is made from carbon granules and is one of the most common types of resistive material used, because of its low cost. It also has a reasonably low noise and lesser wear than other naterials. However, it is not that accurate in its operation.

- ✓ Wire wound – These are basically Nichrome wires and are wound over an insulating substrate. They are mostly used in high power applications and last really long. They are precise but have limited resolution.
- ✓ Conductive plastic: Often used in high end audio applications, they have very good resolution but are really costly, and can be used in low power applications only.
- ✓ Cermet: A very stable type of material, it has a low temperature coefficient and is highly resistant to temperature. However, it has a short life and can burn a hole in your pocket.
- ✓ The wiper: This is the one terminal that slides over a resistive strip to make an electrical contact. It may be a rotary wiper that is like a half an arc, that covers over ¾ of a circle or a linear wiper
- ✓ Angular position of the rotary wiper in degrees is given by the formula:

$$\theta = (Vout/Vsupply)$$

Working of a Potentiometer





A potentiometer has three terminals. When connected to a circuit, the two fixed terminals are connected to the ends of the resistive elements while the third terminal is connected to the wiper. In the circuit diagram shown, the terminals of the potentiometer are marked 1, 2 and 3. The voltage supply is connected across terminals 1 and 3, positive lead to terminal one while negative lead to terminal three. The terminal 2 is connected to the wiper. Now a closer look into the figure, we can see that at the current position of wiper, there are two resistive paths just like the resistor is split into two resistors. Out of these two resistors, the one having longer resistive path will have a higher resistance. This is due to the fact that resistance of a resistor depends on its length (since R=ρ). Higher the length, higher is the resistance, provided the material of the resistor and its cross-sectional area remains same.

For simplicity, lets name the two resistors, R1 and R2 (Refer figure). The wiper voltage is actually the voltage across R2. The circuit now looks like a voltage divider, where the output voltage is given the equation:

$$V_{out} = \{R2/ (R1+R2)\} \times V; \text{ where } V= \text{supply voltage.}$$

So clearly, if we want to change the output voltage, we can just change the value of R2, by sliding the wiper towards the terminal 3. When the wiper is at terminal 1, R1 becomes zero and the voltage across the wiper is same as the supply voltage. Also, when the wiper is at terminal 3, the effective resistive path for R2 is zero, hence the resistance R2 is zero.

Advantages

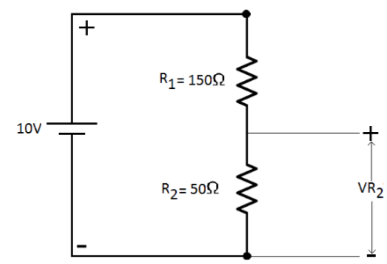
- ✓ Less expensive
- ✓ Different sizes and shapes of potentiometers in different ranges are easily available
- ✓ High output
- ✓ A.C Excitation
- ✓ Rugged Construction
- ✓ Less sensitive towards vibration and temperature
- ✓ High electrical efficiency
- ✓ Operation is simple

Disadvantages

- ✓ Slow Dynamic Response
- ✓ Low Resolution
- ✓ Early wear of the wiper is possible
- ✓ Noisy output under high speed operation or high vibrating conditions
- ✓ Noise becomes too high when the slide velocity exceeds 3 m/sec

EXAMPLE 1:

A resistor, R1 of 150Ω is connected in series with a 50 Ω resistor, R2 across a 10 Volt supply ohm resistor as shown. Calculate the total series resistance, the current flowing through the series circuit and the voltage drop across the 50 ohm resistor.



Solution:

Since the two resistance are in series, total resistance

$$R = R1 + R2 = 200\Omega.$$

The current flowing through the circuit will be

$$I = V/R = 10/200 = 0.05A.$$

Voltage drop across R2 = 50Ω can be found by voltage division rule, that is

$$V_{R2} = 10 \times (50/200) = 2.5\ V$$

2. Strain Gauges

Strain is defined as an elongation or compression per unit area. Stain gauges work on the principle of *piezo resistivity*. If a metal wire or conductor is stretched or compressed, its resistance changes because of the change in length, resistivity and cross-sectional area. This effect is called *piezoresistive effect*.

Suppose the dimensions of a wire are as follows:

- A is the uniform cross-sectional area of the wire in m^2
- L is the length of the wire in m
- ρ is the resistivity in Ω-m
- R is the resistance in Ω

If the conductor is stretched or compressed (strained), the above-mentioned parameters get changed as follows:

- ΔA is the change in cross-sectional area
- ΔL is the change in length of the wire
- Δρ is the change in the resistivity
- ΔR is the change in the resistance

The change in resistance is due to the following factors:

1. Per unit change in the length, $\Delta L/L$
2. Per unit change in the area, $\Delta A/A$.
3. Per unit change in the resistivity, $\Delta\rho/\rho$.

If change in resistivity of the material due to the strain is neglected, the gauge factor is

$$GE= 1 + 2\gamma$$

The following table shows the gauge factors of some materials:

Material	Gauge factor (GF)
Nickel	-121
Nichrome	+2.0
Soft iron	+4.2
Carbon	+20
Platinum	+4.8

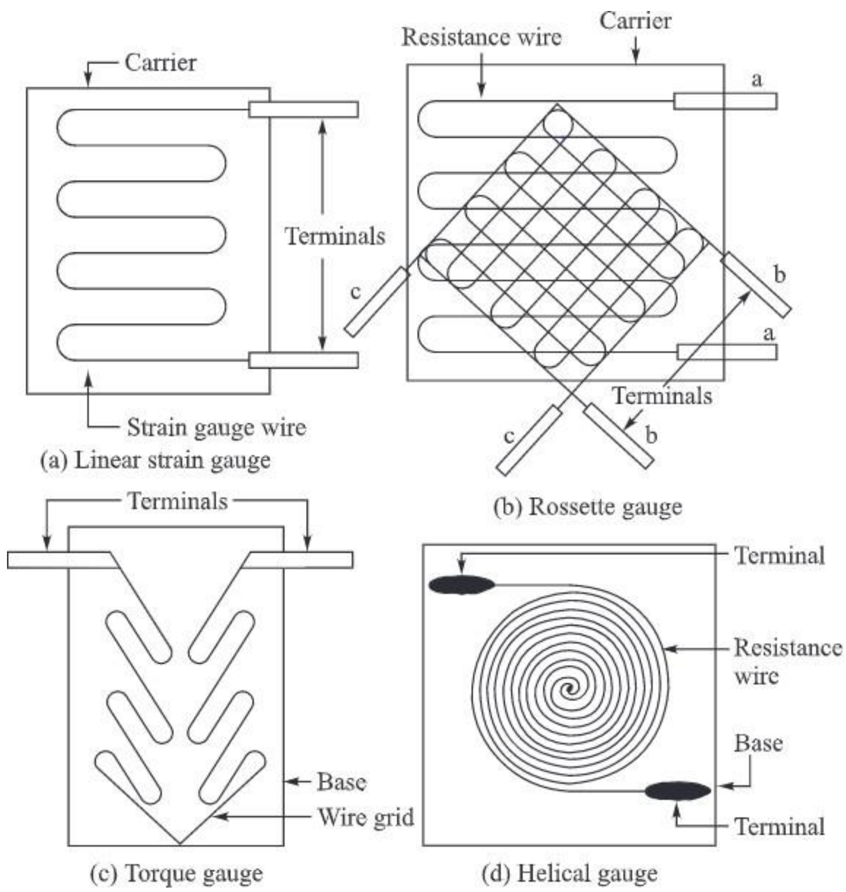
Classification of Strain Gauges

Bonded strain gauges

These are useful for stress analysis and transducer construction. Their construction is discussed further.

Bonded wire strain gauges. A grid or fine wire of resistance is cemented to a base (sheet) of paper or sheet of Teflon or bakelite. A particular resistance wire is covered on to protect it from mechanical damages and faithfully handle the compression and elongation (stress). The specifications of strain gauges vary with application. Strain gauges should have high gauge factor (G_F), low resistance temperature coefficient, no hysteresis, and resistance should be a linear function of strain.

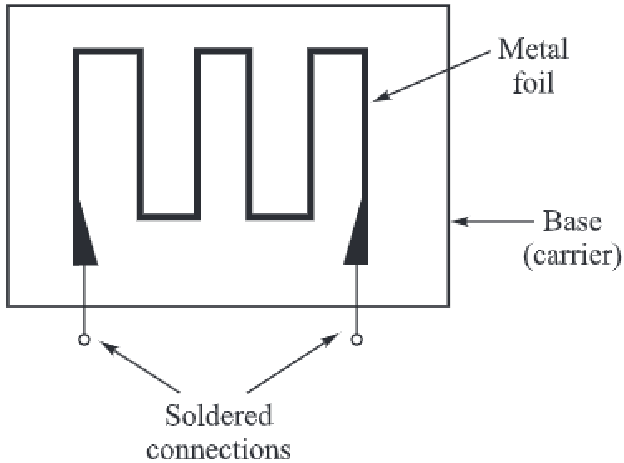
Different types of strain gauges are: linear, rossette, torque, helical, etc. as shown in Figures (a), (b), (c) and (d), respectively.



(a) Linear strain gauge (b) Rossette gauge (c) Torque gauge (d) Helical gauge

Bonded metal foil strain gauges

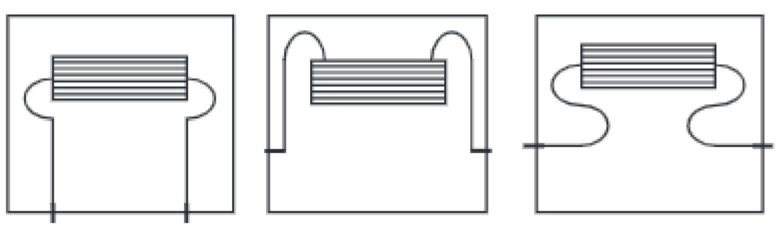
These are made up of the similar material used for bonded wire strain gauges. The gauge elements are formed by photoetching process having dimensions less than 0.0002 inch thick. Figure shows a foil-type strain gauge.



In foil-type strain gauges, the surface area is increased for the same volume, which facilitates much greater heat dissipation capacity and better bonding. Foil-type gauges are mounted on a flexible insulating carrier film about 0.025 mm thick made up of polyamide, glass, phenolic and so on.

Bonded semiconductor strain gauges

These strain gauges use silicon semiconductor material. A silicon crystal is processed and sliced in p-type and n-type. In p-type gauges, the resistance increases with tensile stain, whereas in n-type gauges, the resistance decreases with the applied strain. Figure shows some bonded semiconductor strain gauges.



Semiconductor strain gauges have high gauge factor of ±130 which is affected by high temperature, sensitivity, non-linearity and mounting difficulties. These gauges can measure very small strain of the order of 0.001 microstrain. Also, they have excellent hysteresis characteristics.

In this type of strain gauges the semiconductor material is sandwiched between the protective matrix of Teflon, and the leads are taken out.

The disadvantages of semiconductor strain gauges are that they are very sensitive to change in temperature, have poor linearity and are more expensive.

Rossette. A combination of gauges is called rossette. It is applicable for specific stress analysis or transducer applications.

Characteristics of strain gauges

- ✓ The gauge factor of a strain gauge should be high so as to achieve higher sensitivity.
- ✓ Resistance of a strain gauge should be as high as possible, due to which the unwanted variations in the resistance measurement get minimized.
- ✓ For avoiding the errors and achieving more accuracy, a strain gauge should have low resistance temperature coefficient.
- ✓ A strain gauge should have linear relationship between the strain and the change in resistance due to the applied strain.
- ✓ A strain gauge should not have hysteresis effects.
- ✓ It should have a linear frequency response. Nowadays strain gauge sensors are available in integrated circuits (ICs) formed with operational amplifier (OPAMP).

EXAMPLE 1:

A resistance wire strain gauge is constructed using nichrome material with gauge factor $G_F = 2.0$. Calculate its Poisson's ratio. (Neglect piezoresistive effects.)

Solution

The gauge factor is specified as $G_F = 1 + 2\gamma + (\Delta\rho/\rho)/\varepsilon$.

As mentioned in the problem, piezoresistive effect is neglected.

$$GF = 1 + 2\gamma$$

$$\text{or } \gamma = (G_F - 1)/2$$

$$\text{Poisson's ratio, } \gamma = 0.5$$

Metals used for strain gauges are copper-nickel, nickel-iron, nichrome-constantan alloys about mm in diameter with gauge factor of 2 to 4 and the gauge current rating is 5 to 40 mA.Strain gauges are mainly used in:

- Measurement and analysis of force, pressure, torque, acceleration and displacement and
- Stress measurement of machine and structures.

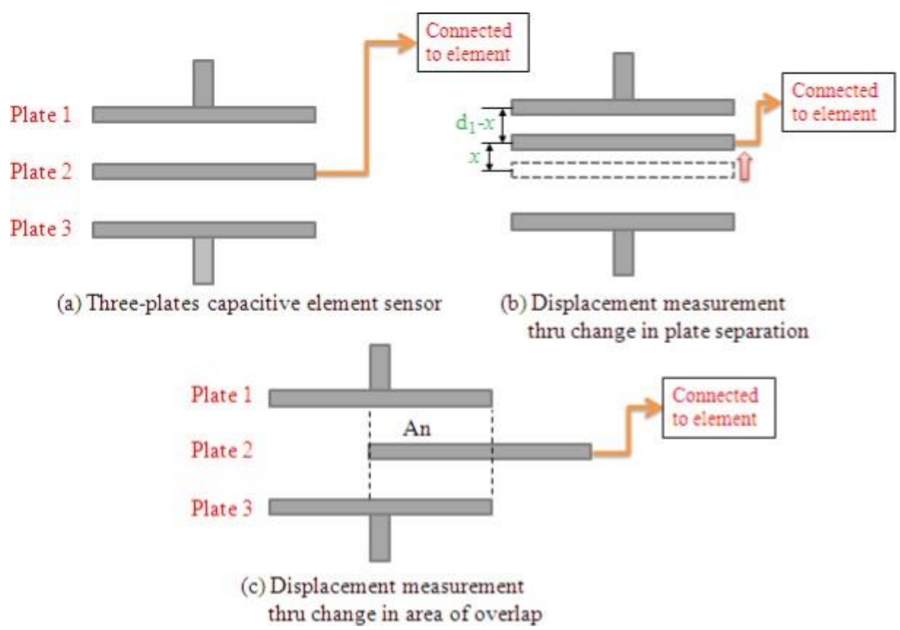
3. Capacitive sensors

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:

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

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



(a) Three-plates capacitive element sensor (b) Displacement measurement thru change in plate separation

(c) Displacement measurement thru change in area of overlap

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

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

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,

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

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

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 o 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.

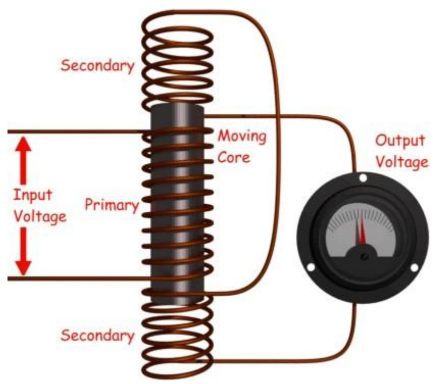
4. Linear variable differential transformer

Definition of LVDT

The term LVDT stands for the Linear Variable Differential Transformer. It is the most widely used inductive transducer that converts the linear motion into the electrical signal.

The output across secondary of this transformer is the differential thus it is called so. It is very accurate inductive transducer as compared to other inductive transducers.

Construction of LVDT



Main Features of Construction

- ✓ The transformer consists of a primary winding P and two secondary windings S_1 and S_2 wound on a cylindrical former (which is hollow in nature and contains the core).
- ✓ Both the secondary windings have an equal number of turns, and we place them on either side of primary winding
- ✓ The primary winding is connected to an AC source which produces a flux in the air gap and voltages are induced in secondary windings.
- ✓ A movable soft iron core is placed inside the former and displacement to be measured is connected to the iron core.
- ✓ The iron core is generally of high permeability which helps in reducing harmonics and high sensitivity of LVDT.

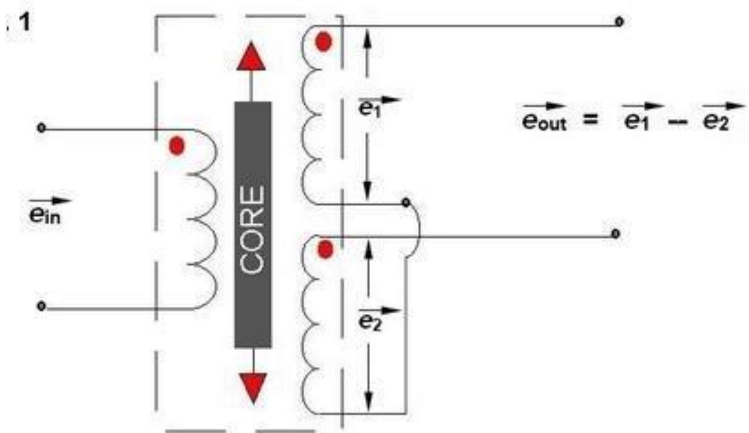
- ✓ The LVDT is placed inside a stainless-steel housing because it will provide electrostatic and electromagnetic shielding.
- ✓ The both the secondary windings are connected in such a way that resulted output is the difference between the voltages of two windings.

Principle of Operation and Working

As the primary is connected to an AC source so alternating current and voltages are produced in the secondary of the LVDT. The output in secondary S_1 is e_1 and in the secondary S_2 is e_2. So, the differential output is,

$$e_{out} = e_1 - e_2$$

This equation explains the **principle of Operation of LVDT**.



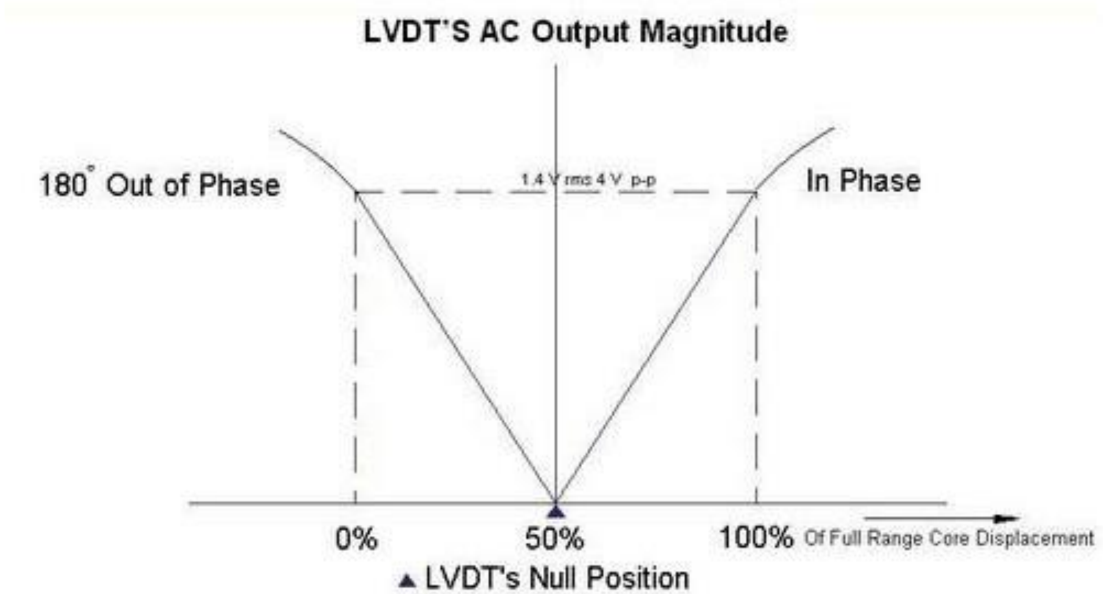
Now three cases arise according to the locations of core which explains the working of LVDT are discussed below as,

- ✓ **CASE-I**: When the core is at null position (for no displacement) When the core is at null position then the flux linking with both the secondary windings is equal so the induced emf is equal in both the windings. So, for no displacement the value of output e_{out} is zero as e_1 and e_2 both are equal. So, it shows that no displacement took place.
- ✓ **CASE-II**: When the core is moved to upward of null position (For displacement to the upward of reference point) In this case the flux linking with secondary

winding S_1 is more as compared to flux linking with S_2. Due to this e_1 will be more as that of e_2. Due to this output voltage e_{out} is positive.

- ✓ **CASE-III:** When the core is moved to downward of Null position (for displacement to the downward of the reference point). In this case magnitude of e_2 will be more as that of e_1. Due to this output e_{out} will be negative and shows the output to downward of the reference point.

Output V_S Core Displacement A linear curve shows that output voltage varies linearly with displacement of core.



AC Output of Conventional LVDT Versus Core Displacement

Some important points about magnitude and sign of voltage induced in LVDT

- ✓ The amount of change in voltage either negative or positive is proportional to the amount of movement of core and indicates amount of linear motion.
- ✓ By noting the output voltage increasing or decreasing the direction of motion can be determined
- ✓ The output voltage of an LVDT is linear function of core displacement.

Advantages of LVDT

- ✓ **High Range** – The LVDTs have a very high range for measurement of displacement. They can used for measurement of displacements ranging from 1.25 mm to 250 mm
- ✓ **No Frictional Losses –** As the core moves inside a hollow former so there is no loss of displacement input as frictional loss so it makes LVDT as very accurate device.
- ✓ **High Input and High Sensitivity –** The output of LVDT is so high that it doesn't need any amplification. The transducer possesses a high sensitivity which is typically about 40 V/mm.
- ✓ **Low Hysteresis** – LVDTs show a low hysteresis and hence repeatability is excellent under all conditions
- ✓ **Low Power Consumption** – The power is about 1W which is very as compared to other transducers.
- ✓ **Direct Conversion to Electrical Signals –** They convert the linear displacement to electrical voltage which are easy to process

Disadvantages of LVDT

- ✓ LVDT is sensitive to stray magnetic fields so it always requires a setup to protect them from stray magnetic fields.
- ✓ LVDT gets affected by vibrations and temperature.

Applications of LVDT

- ✓ We use LVDT in the applications where displacements to be measured are ranging from a fraction of mm to few cms. The LVDT acting as a primary transducer converts the displacement to electrical signal directly.
- ✓ The LVDT can also act as a secondary transducer. E.g. the Bourbon tube which acts as a primary transducer and it converts pressure into linear displacement and then LVDT coverts this displacement into an electrical signal which after calibration gives the readings of the pressure of fluid.

POSITION SENSORS

Position sensors are basically sensors for measuring the distance travelled by the body starting from its reference position. How far the body has moved from its reference or initial position is sensed by the position sensors and often the output is given as a fed back to the control system which takes the appropriate action. Motion of the body can be rectilinear or curvilinear; accordingly, position sensors are called linear position sensors or angular position sensors.

Types of Position Sensor

Position sensors use different sensing principles to sense the displacement of a body. Depending upon the different sensing principles used for position sensors, they can be classified as follows:

1. Photoelectric Sensors
2. Hall effect Sensors
3. Digital Optical Encoder

1. Photoelectric Sensors

Photoelectric sensor is a generic name for sensors which detect an object by using light. The optical signal transmitted from the emitting part of the sensor is modified by being reflected, transmitted, absorbed, etc., by the sensing object and is then detected by the receiving part of the sensor to generate a corresponding output signal. Further, it can also be a sensor which detects light radiated from the sensing object to generate an output signal.

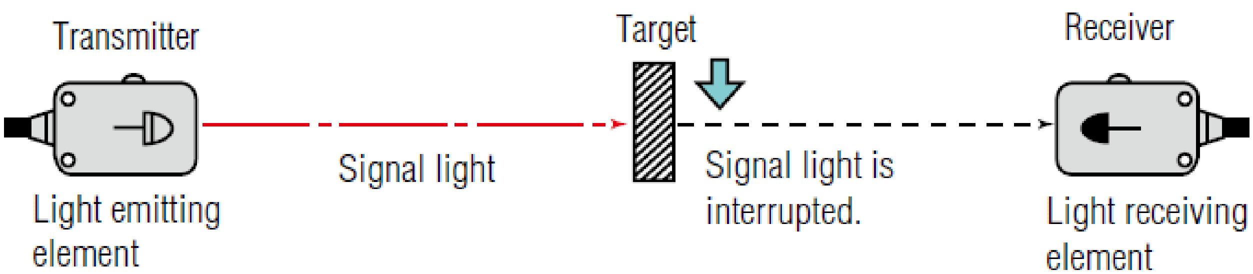
Sensing Methods or Working Principle of Photoelectric Proximity Sensor

There are three main sensing methods of the photoelectric proximity sensor and they are,

1. Through beam method
2. Retro-reflective method
3. Diffuse or Reflective method

Through beam method

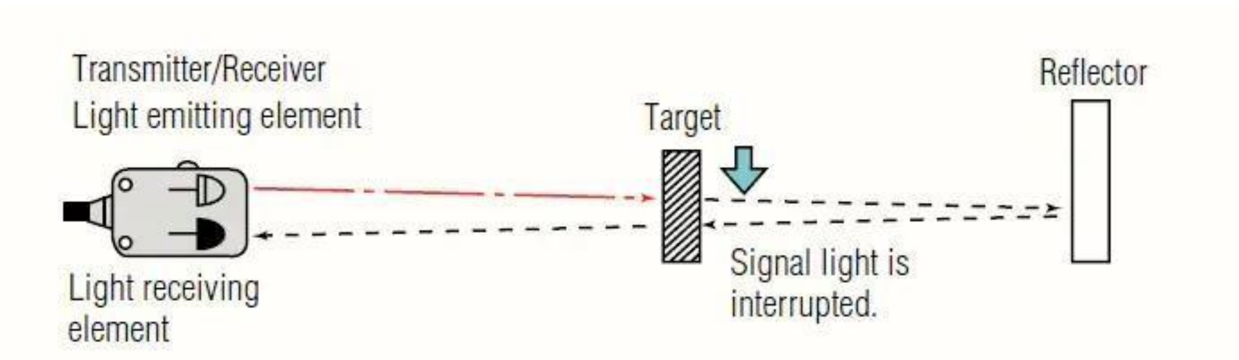
In this type of method, an emitter sends out a beam of light directly in the line-of-sight of the emitter to a receiver. When an object breaks this beam of light, it detects as a presence. This type of setup requires two components they are an emitter and a separate detector, which makes it a bit more complex to install and wire. However, the advantage is that it's the most accurate of the sensing methods with the longest sensing range.



New laser diode emitter models can transmit a well-collimated beam 60 m for increased accuracy and detection. At these distances, some through-beam laser sensors are capable of detecting an object the size of a fly, at close range, that becomes 0.01 mm. One ability unique to through beam photoelectric sensors is effective sensing in the presence of thick airborne contaminants.

Retro-reflective method

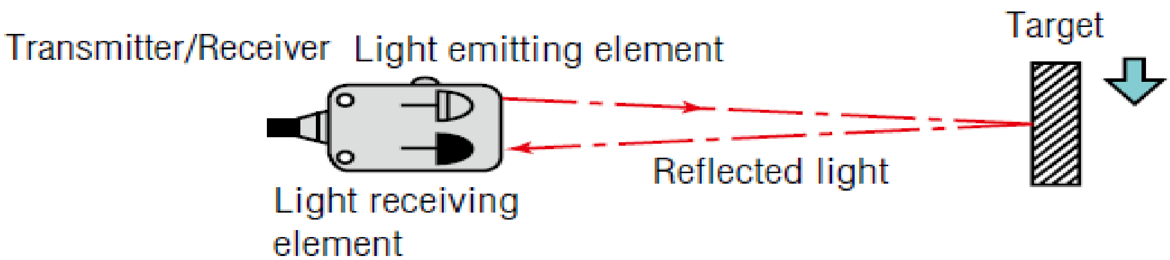
In this method, detection occurs when the light path breaks or disturbs. Both the light emitting and light receiving elements are in same housing. The light from the emitting element hits the reflector and returns to the light receiving element. When a target is present, the light gets interrupt.



One reason for using a retro-reflective sensor over a through-beam sensor is for the convenience of one wiring location, the opposing side only requires reflector mounting.

Diffuse or Reflective method

As in retro-reflective sensors, emitters and receivers located in the same housing. In this Diffuse method, Both the light emitting and light receiving elements contain in a single housing. The sensor receives the light reflected from the target.



Diffuse photoelectric sensors are similar in some respects to reflective sensors. This is because like reflective sensors they emit a light beam in the direction of the object to be detected. However, instead of a reflector used to bounce the light back to a detector, the object to be sensed functions as the reflector, bouncing some of the light back to be detected and register an object's presence.

Mostly, the diffuse sensors use in public washroom sinks, where they control automatic faucets. Hands placed under the spray head act as reflector, triggering (in this case) the opening of a water valve. diffuse sensors are somewhat color dependent, certain versions are suitable for distinguishing dark and light targets in applications that require sorting or quality control by contrast.

Advantages of Photoelectric Sensor

- ✓ The sensor senses all kinds of materials.
- ✓ It has longer life, long sensing range and very reliability.
- ✓ Very fast response time and less costly.
- ✓ Diffuse photoelectric sensor detects small objects including color mark and label detection.
- ✓ mostly retro-reflective type sensor can detect transparent objects.
- ✓ Through beam type can detect long range and it is tolerant of dirty environment.

Disadvantages of Photoelectric Sensor

- ✓ Over coarse of time lens get contaminated.
- ✓ Generally, the sensing range is affected due to color and reflectivity of the target.
- ✓ Through beam type requires transmitter (Tx) and receiver (Rx) at two separate locations
- ✓ Retro reflective type requires reflector in addition to Tx/Rx. This makes system installation complex

Applications of Photoelectric Sensor

The photoelectric sensors use in different section. Few of them are as follow,

- ✓ **Checking objects on production lines or conveyors:**
  photoelectric sensors can detect product size to spot any errors, or simply spot their absence. As well as picking up problems like misaligned caps on bottles. They are widely used in the food and pharmaceutical industries, and in packaging plants.
- ✓ **Counting of small objects:**
  In some production environments, small items will fall from a vibrating conveyor belt into a packaging system or bag – and a photoelectric sensor can count them.
- ✓ **Detection of colours:**
  Through scanning independently in red, green and blue light, with applications in multiple processes in the printing and packaging sectors.
- ✓ **Monitoring bigger areas for objects with light grids:**
  Instead of using multiple sensors, a light grid uses parallel beams of light to cover a two-dimensional area.
- ✓ **Measuring distance:**
  With multiple sensors, a triangulation process compares reflected laser beams and can use to accurately determine position and distance. for example, to check the location of manufacturing systems, or in automated transport applications.
- ✓ **Logistics and materials handling:**

In an automated warehouse with robotic pickers or trucks rely on position and object sensing to operate efficiently and safely.

- ✓ **Automatic doors:**

  In buildings or public transport, photoelectric sensors detect when someone is standing by a door.

2. Hall effect Sensors

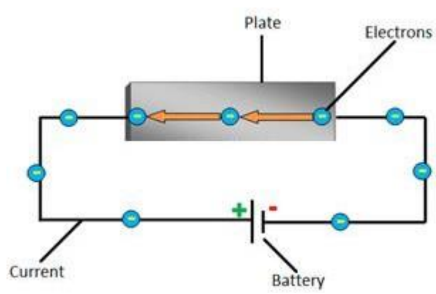
Magnetic sensors are solid state devices which generate electrical signals proportional to the magnetic field applied on it. These electrical signals are then further processed by a user specific electronic circuit to give the desired output.

Now days, these Magnetic sensors are capable in responding for a wide range of magnetic fields. One of such magnetic sensors is Hall Effect Sensor whose output (Voltage) is a function of magnetic field density.

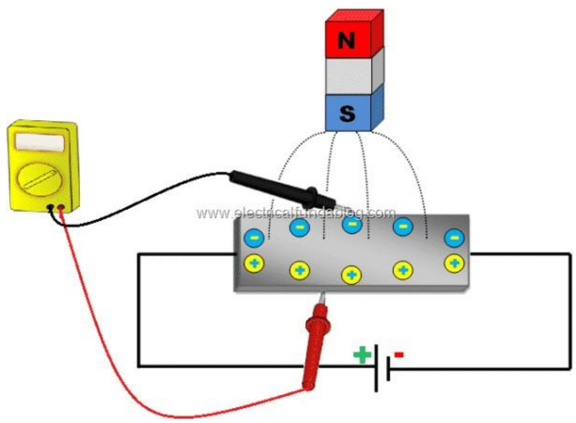
An external magnetic field is used to activate these Hall Effect Sensors. When the magnetic flux density in the vicinity of Sensor goes beyond a specific defined threshold, it is detected by the Sensor. On detection, the Sensor generates an output voltage which is also known as Hall Voltage.

Working Principle

Hall Effect Sensor is based on Hall Effect Principle. This principle says that when a conductor or semiconductor with current flowing in one direction is introduced perpendicular to a magnetic field a voltage could be measured at right angles to the current path.



- ✓ When an electric current flow through the Sensor, the electrons move through it in a straight line.
- ✓ When an external magnetic field acts on the Sensor, the Lorentz force deviates the charge carriers to follow a curved path.
- ✓ Due to this, the Negative Charge Electrons will deflect towards one side of the Sensor and the Positive Charge Holes to another.



- ✓ Due to this accumulation of electrons and holes at different side of the plate, a voltage (potential difference) can be observed between the sides of the plate. The voltage obtained is directly proportional to the electric current and magnetic field strength.

Applications of Hall Effect Sensor

The applications of Hall Effect Sensors have been represented in two categories for ease of understanding.

- ✓ Applications of Analog Hall Effect Sensors
- ✓ Applications of Digital Hall Effect Sensors

Applications of Analog Hall Effect Sensors

Analog Hall Effect Sensors are utilized for:

- ✓ Direct Current sensing in Clamp meters (also known as Tong Testers).
- ✓ Wheel speed detection for the anti-lock braking system, (ABS).

- ✓ Motor control devices for protection and indications.
- ✓ Sensing the availability of Power supply.
- ✓ Motion Sensing.
- ✓ Sensing the rate of flow.
- ✓ Sensing Diaphragm pressure in Diaphragm pressure gauge.
- ✓ Sensing Vibration.
- ✓ Sensing Ferrous Metal in Ferrous Metal Detectors.
- ✓ Voltage Regulation.

Applications of Digital Hall Effect Sensors

Digital Hall Effect Sensors are utilized for :

- ✓ Sensing the angular position of the crank shaft for the firing angle of the spark plugs.
- ✓ Sensing the position of the car seats and seat belts for air-bag control .
- ✓ Wireless Communications.
- ✓ Sensing Pressure.
- ✓ Sensing Proximity.
- ✓ Sensing rate of flow.
- ✓ Sensing position of Valves.
- ✓ Sensing position of Lens.

Advantages of Hall Effect Sensors

- ✓ They can be used for multiple sensor functions like position sensing, speed sensing as well as for sensing the direction of movement too.
- ✓ As they are solid state devices, there is absolutely no wear and tear due to absence of moving parts.
- ✓ They are almost maintenance free.
- ✓ They are robust.
- ✓ They are immune to vibration, dust and water.

Disadvantages of Hall Effect Sensors

- ✓ They are not capable to measure current flow at a distance more than 10 cm. The only solution to overcome this issue is to use a very strong magnet that can generate a wide magnetic field.
- ✓ Accuracy of the measured value is always a concern as external magnetic fields may affect the values.
- ✓ High Temperature affects the conductor resistance. This will in turn affect the charge carrier's mobility and sensitivity of Hall Effect Sensors.

3. Digital Optical Encoder:

A position encoder is a device that provides a digital output as a result of a linear or angular displacement. It converts motion into a sequence of digital pulses. By counting a single bit or by decoding a set of bits, the pulses can be converted to relative or absolute position measurements. Encoders have both linear and rotary configurations, but the most common type is rotary. The following diagram shows fundamental principle of optical encoder construction. A beam of light passes through slots in a disc and is detected by a suitable light sensor. When the disc is rotated, a pulsed output is produced by the sensor with number of pulses being proportional to the angle through which the disc rotates.

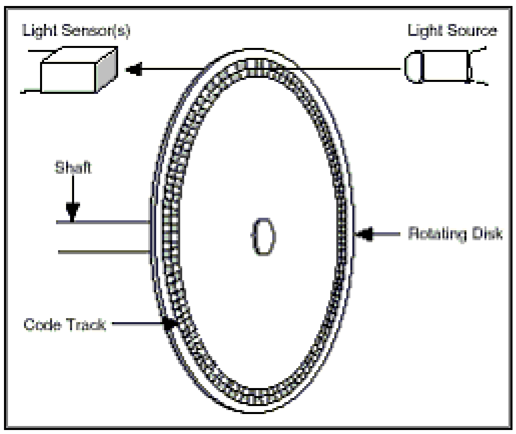
Rotary encoders are manufactured in two basic forms:

- ✓ **Incremental:** An incremental encoder produces incremental digital signals that provide data about the general position of an object.
- ✓ **Absolute:** An absolute encoder measures the absolute position of the angle of a rotating shaft, and produces either a digital or an analog signal.

Incremental Encoder:

- ✓ Incremental encoders, that gives changes in rotation from a reference or datum position. An incremental encoder has three concentric tracks with three sensors.
- ✓ The inner most track has one hole that is used to locate the home position of the disc.

- ✓ The other two tracks have a series of equally spaced holes that go completely round the disc but holes in the middle track offset from the holes in the outer track by one-half the width of a hole.
- ✓ This offset enables the direction of rotation to be determined.
- ✓ In case of clockwise rotation of the shaft the pulses generated by the outer tracks holes leads those in the inner track; whereas in case of anti-clockwise direction pulses generated by the outer track lags that of the inner track.
- ✓ The resolution is determined by the number of slots (opening) in the disc.
- ✓ There can be an optional third output: reference, which happens once every turn. This is used when there is the need of an absolute reference, such as positioning systems.



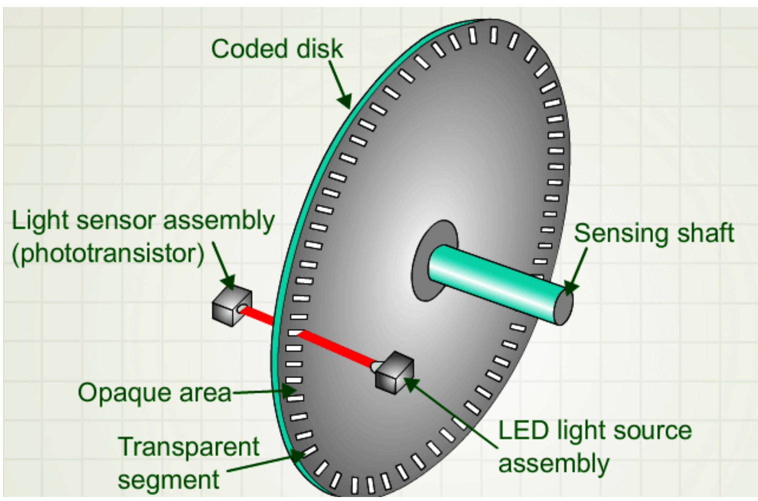
The incremental can be either mechanical or optical. In the optical type there are two gray coded tracks. The incremental rotary encoder is the most widely used of all rotary encoders due to its low cost: only two sensors are required. The fact that incremental encoders use only two sensors does not compromise their accuracy. One can find in the market incremental encoders with up to 10,000 counts per revolution, or more. The optical type is used when higher RPMs are encountered or a higher degree of precision is required

Example: With 60 slots disc, resolution will be 360/60 = 6º. This means position of the shaft could be determined as small as 6º movement.

Incremental Rotary Encoder Advantages

- ✓ Good for simple pulse counting or frequency monitoring applications such as speed, direction, and position monitoring
- ✓ More cost-effective and less complex than an absolute encoder
- ✓ A, B, Z, and inverted signals as HTL (Push-Pull) or TTL (RS422).
- ✓ Any pulse count up to 16384 PPR available
- ✓ Flexible scaling functionality
- ✓ Magnetic measuring principle
- ✓ Incremental encoders have a resolution of up to 50,000 PPR.

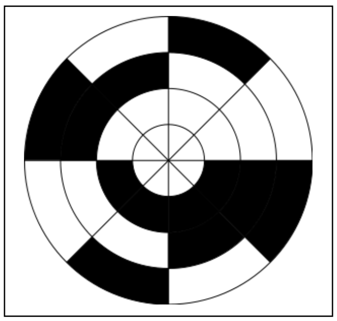
Absolute Encoder:



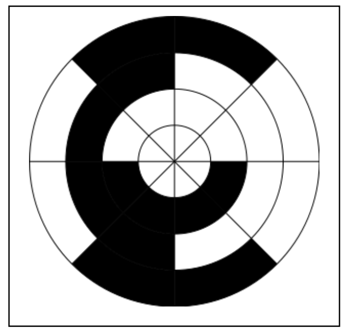
Absolute encoders, that produce a unique digital word corresponds to each rotational position of the shaft. Absolute encoders have three or more concentric circles having slot-patterns that generate unique binary code based on the position of the shaft. Number of concentric tracks determines the number of binary bits. The optical disc of the absolute encoder is designed to produce a digital word that distinguishes N distinct positions of the shaft. Typically, encoders have 10 or 12 tracks. Thus a 10-track encoder has 10-bit binary word and that will produce 1024 (210=1024) unique position code. This means resolution of detection of position will be 360/1024 = 0.35º. This also means that the shaft movement can be determined as accurate as 0.35º.

The normal form of binary code is not used as the position distinguishing position code because changing from one binary number to the next can result in more than one bit changing. For example: change from 001 (001 = binary 1) to 010 (010 = binary 2) are two adjacent number but two binary bits (bit 0 changes from 1 to 0 and bit 1 changes from 0 to 1) need to change during the transition. Thus to overcome the problem another type of code called ***Gray code*** is used

Standard Binary Code Disc



Gray Code Disc



Output from a three concentric circle Binary Coded Disc and Gray Code Disc

	Normal binary	Gray code
0	0000	0000
1	0001	0001
2	0010	0011
3	0011	0010
4	0100	0110
5	0101	0111
6	0110	0101
7	0111	0100
8	1000	1100
9	1001	1101
10	1010	1111

Absolute Rotary Encoder Advantages

- ✓ Remembers its position after a power outage and offers continuous position monitoring
- ✓ Typically have speed, scaling, preset, and fieldbus functions

- ✓ Allow you to determine the exact position of a machine and control over the storage of electronic data
- ✓ Multiple interface options: Analog, Ethernet, Fieldbus, Parallel, Serial
- ✓ Single-turn and Multi-turn revolution options available
- ✓ Optical a magnetic measuring principle
- ✓ Absolute encoders have a resolution of up to 16 bits, or 65,536 pulses per revolution (PPR).

PROXIMITY SENSOR

A proximity sensor consists of an *element that changes either its state or analog signal when it is close to, but often not actually touching, an object.*

Magnetic, electrical capacitance, inductance, and eddy current methods are particularly suited to the design of a proximity sensor.

- A photoemitter-detector pairs represents another approach, where interruption of reflection of a beam of light in used to detect an object in a non-contact manner. The emitter and detector are usually a phototransistor and a photodiode.

Common applications for proximity sensors and limit switches include:

1. Counting moving objects;
2. Limiting the traverse of a mechanism.

1. Eddy Current Proximity Sensors

Working principle:

When a coil is supplied with an alternating current an alternating magnetic field is produced. If there is a metal object in close proximity to this attending magnetic field, then eddy currents are induced in it. The eddy currents themselves produce a magnetic field which distorts the magnetic field responsible for their production. Consequently, the impedance of the coil changes and so the amplitude of the alternating current. This change, at some preset level, can be used to trigger a switch.

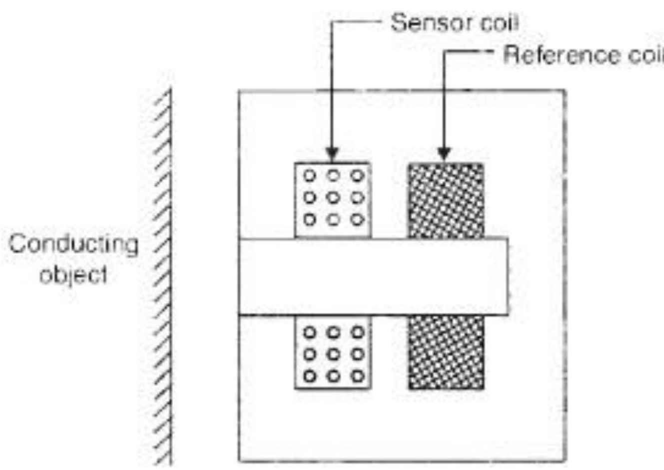


Fig. shows the basic form of an Eddy current proximity sensor. It is used for the detection of non-magnetic but inductive materials.

Advantages:

(i) Small in size.

(ii) Relatively inexpensive.

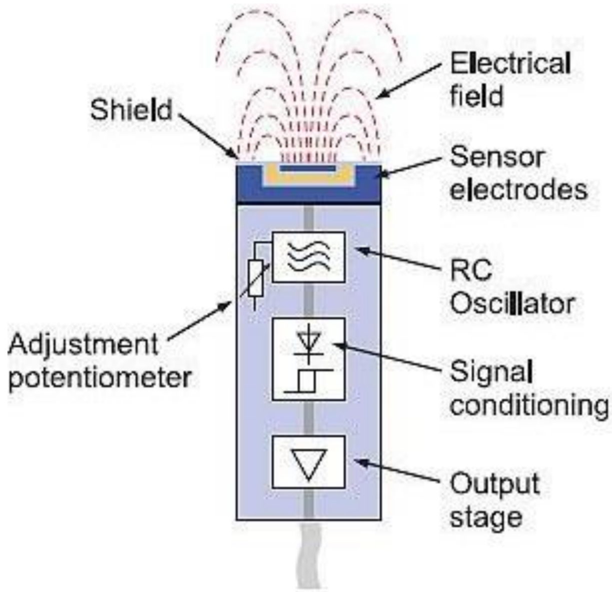
(iii) High flexibility.

(iv) High sensitivity to small displacements.

2. Capacitive proximity sensors

capacitive proximity sensors operate by noting a change in the capacitance read by the sensor. A typical capacitor consists of two conductive elements (sometimes called plates) separated by some kind of insulating material that can be one of many different types including ceramic, plastic, paper, or other materials.

he way a capacitive proximity sensor works is that one of the conductive elements, or plates, is inside the sensor itself while the other one is the object to be sensed. The internal plate is connected to an oscillator circuit that generates an electric field. The air gap between the internal plate and the external object serves as the insulator or dielectric material. When an object is present, that changes the capacitance value and registers as the presences of the object.



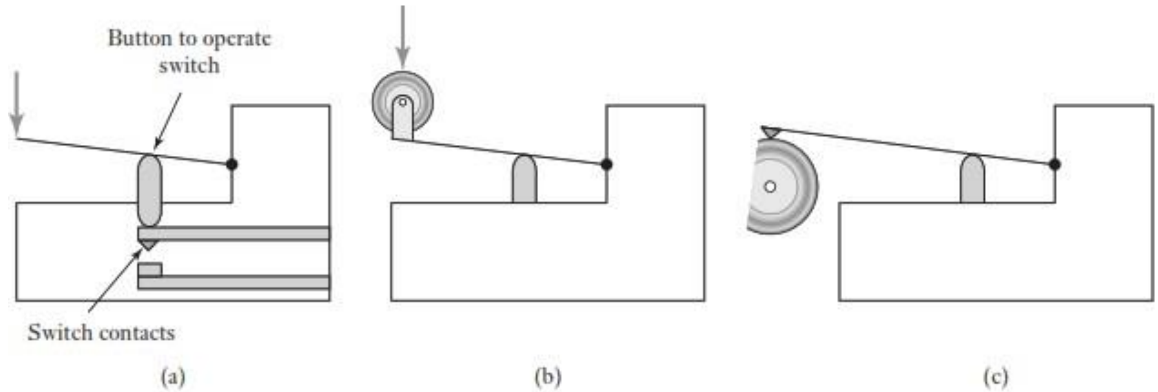
Capacitive proximity sensors are useful in detecting a wide range of objects. The easiest types of objects to detect are ones with a high density (such as metals) or a high dielectric constant (i.e. water). And detecting these objects doesn't require that the sensors be fairly close to the objects to be detected, another plus if used in settings with little space to work in. Overall, good sensing targets for capacitive sensors include solids and liquids such as various metals, water, wood and plastic.

A typical sensing range for capacitive proximity sensors is from a few millimeters up to about 1 in. (or 25 mm), and some sensors have an extended range up to 2 in. Where capacitive sensors really excel, however, is in applications where they must detect objects through some kind of material such as a bag, bin, or box. They can tune out non-metallic containers and can be tuned or set to detect different levels of liquids or solid materials.

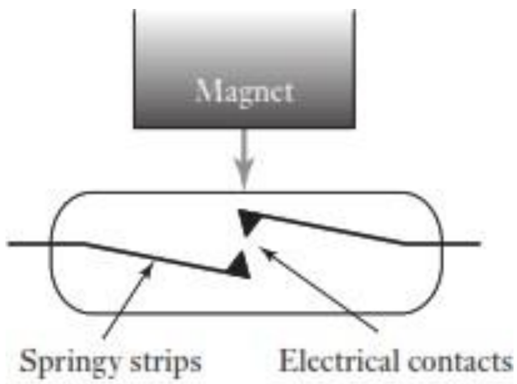
3. Proximity Switch's

There are a number of forms of switch which can be activated by the presence of an object in order to give a proximity sensor with an output which is either on or off. The microswitch is a small electrical switch which requires physical contact and a small operating force to close the contacts. For example, in the case of determining the presence of an item on a conveyor belt, this might be actuated by the weight of the item on the belt depressing the belt and hence a spring-loaded platform under it, with the movement of this platform then closing the switch. Figure shows examples of ways such switches can be actuated.

c



(a) Lever-operated, (b) roller-operated, (c) cam-operated switches.

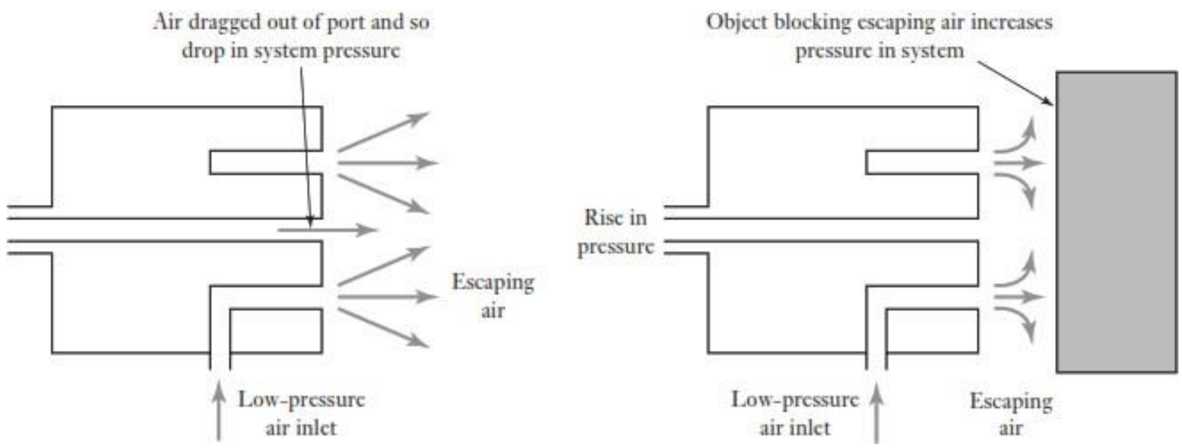


Reed switch.

The above figure shows the basic form of a reed switch. It consists of two magnetic switch contacts sealed in a glass tube. When a magnet is brought close to the switch, the magnetic reeds are attracted to each other and close the switch contacts. It is a non-contact proximity switch. Such a switch is very widely used for checking the closure of doors. It is also used with such devices as tachometers, which involve the rotation of a toothed wheel past the reed switch. If one of the teeth has a magnet attached to it, then every time it passes the switch it will momentarily close the contacts and hence produce a current/voltage pulse in the associated electrical circuit.

4. Pneumatic proximity sensor

Pneumatic sensors involve the use of compressed air, displacement or the proximity of an object being transformed into a change in air pressure. The figure shows the basic form of such a sensor. Low-pressure air is allowed to escape through a port in the front of the sensor. This escaping air, in the absence of any close-by object, escapes and in doing so also reduces the pressure in the nearby sensor output port. However, if there is a close-by object, the air cannot so readily escape and the result is that the pressure increases in the sensor output port. The output pressure from the sensor thus depends on the proximity of objects. Such sensors are used for the measurement of displacements of fractions of millimeter's in ranges which typically are about 3 to 12 mm.

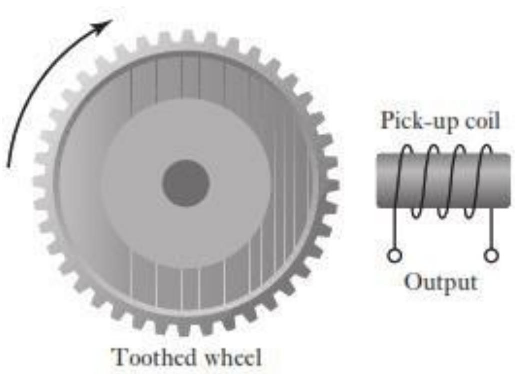


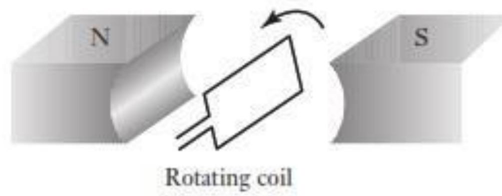
Velocity, Motion, Force

1. Tachogenerator

The tachogenerator is used to measure angular velocity. One form, the variable reluctance tachogenerator, consists of a toothed Wheel of ferromagnetic material which is attached to the rotating shaft (Figure). A pick-up coil is wound on a permanent magnet. As the wheel rotates, so the teeth move past the coil and the air gap between the coil and the ferromagnetic material changes.

We have a magnetic circuit with an air gap which periodically changes. Thus, the flux linked by a pick-up coil change. The resulting cyclic change in the flux produces an alternating e.m.f. in the coil.





If the wheel contains n teeth and rotates with an angular velocity ω, then the flux change with time for the coil can be considered to be of the form

$$\Phi = \Phi_0 + \Phi_a \cos n\omega t$$

where Φ_0 is the mean value of the flux and Φ_a the amplitude of the flux variation. The induced e.m.f. *e* in the N turns of the pick-up coil is -N dΦ / dt and thus

and so we can write

$$e = N\Phi_a n\omega \sin \omega t$$

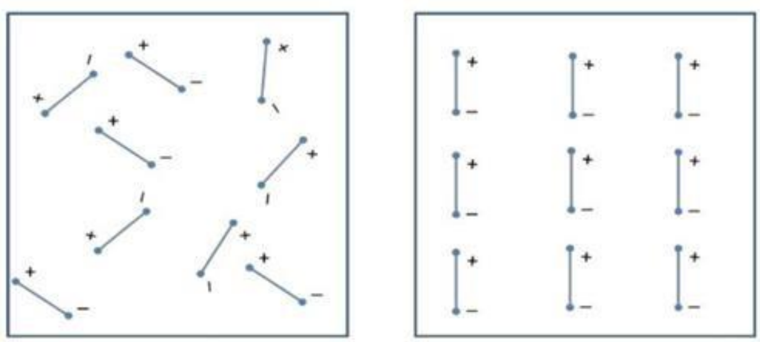
where the maximum value of the induced e.m.f. E_{max} is NΦ $n\varpi$ and so is a measure of the angular velocity.

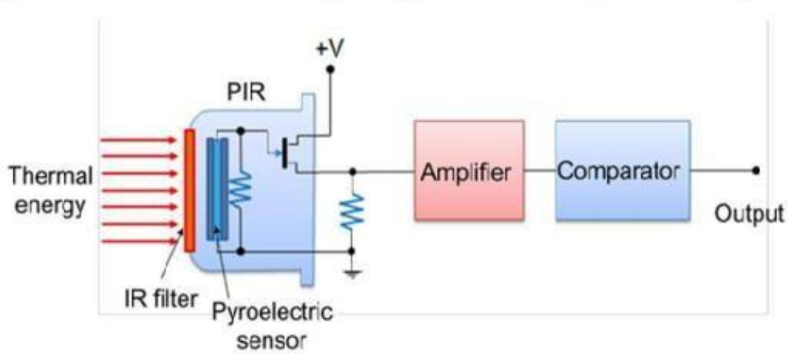
Instead of using the maximum value of the e.m.f. as a measure of the angular velocity, a pulse-shaping signal conditioner can be used to transform the output into a sequence of pulses which can be counted by a counter, the number counted in a particular time interval being a measure of the angular velocity.

Another form of tachogenerator is essentially an a.c. generator. It consists of a coil, termed the rotor, which rotates with the rotating shaft. This coil rotates in the magnetic field produced by a stationary permanent magnet or electromagnet the above figure and so an alternating e.m.f. is induced in it. The amplitude or frequency of this alternating e.m.f. can be used as a measure of the angular velocity of the rotor. The output may be rectified to give a d.c. voltage with a size which is proportional to the angular velocity. Non-linearity for such sensors is typically of the order of 60.15% of the full range and the sensors are typically used for rotations up to about 10 000 rev/min.

2. Pyroelectric sensors

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. This is called as polarization. On cooling, the material retains its polarization. In absence of electric field, when this polarized material is subjected to infrared irradiation, its polarization reduces. This phenomenon is the measure of detection of movement of an object.



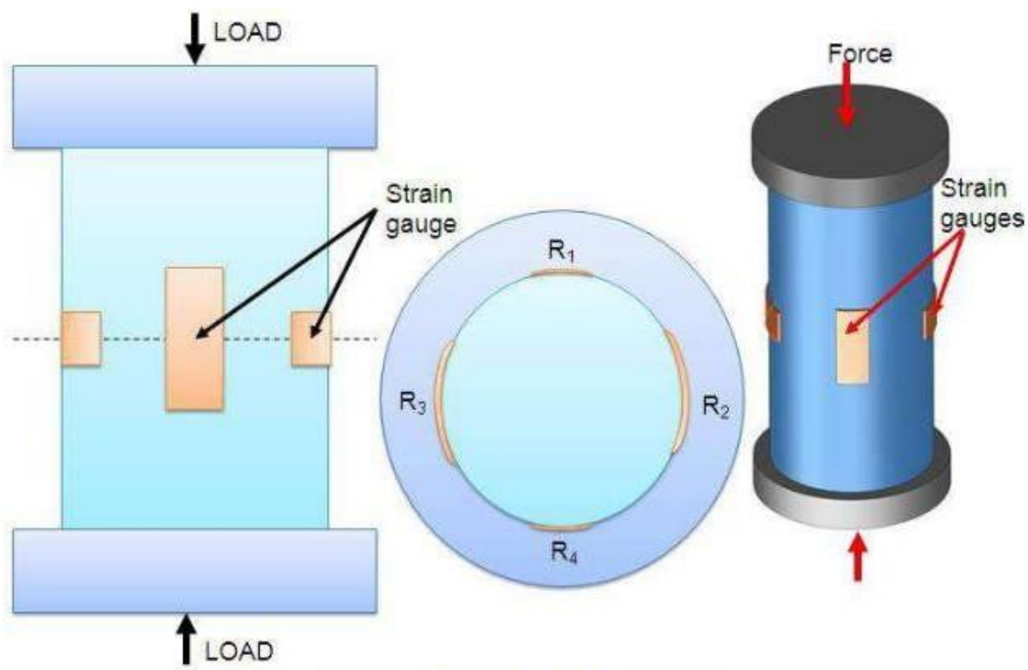


Pyroelectric sensor comprises of a thick element of polarized material coated with thin film electrodes on opposite faces as shown in above figure. Initially the electrodes are in electrical equilibrium with the polarized material. On incident of infra-red, the material heats up and reduces its polarization. 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

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

3. Strain Gauge as force Sensor



Strain gauge based Load cell

A very commonly used form of force-measuring transducer is based on the use of electrical resistance strain gauges to monitor the strain produced in some member when stretched, compressed or bent by the application of the force. The arrangement is generally referred to as a load cell. Figure shows an example of such a cell. This is a cylindrical tube to which strain gauges have been attached. When forces are applied to the cylinder to compress it, then the strain gauges give a resistance change which is a measure of the strain and hence the applied forces. Since temperature also produces a resistance change, the signal conditioning circuit used has to be able to eliminate the effects due to temperature. Typically, such load cells are used for forces up to about 10 MN, the non-linearity error being about (+ or -) 0.03% of full range, hysteresis error (+ or -) 0.02% of full range and repeatability error (+ or -) 0.02% of full range. Strain gauge load cells based on the bending of a strain-gauged metal element tend to be used for smaller forces, e.g. with ranges varying from 0 to 5 N up to 0 to 50 kN. Errors are typically a non-linearity error of about (+ or -) 0.03% of full range, hysteresis error (+ or -) 0.02% of full range and repeatability error (+ or -) 0.02% of full range.

Pressure Sensors

1. Diaphragm

Diaphragms are widely used for the measurement of pressure ranges from 0 to 6.7 kPa and 0 to 350 kPa.

Principle and construction

The diaphragm is a thin membrane made from sheet metal of precise dimensions. It is used for the measurement of pressure. When the pressure, which is to be measured, is applied to the diaphragm, it gets deflected. The deflection of diaphragm is proportional to the applied pressure.

A diaphragm is a suitable transducer for sensing the pressure. The unknown pressure is applied to one side of the diaphragm. This unknown pressure is determined by measuring the deflection or displacement.

Thin membrane-type diaphragms are applicable for measurement of low-pressure ranges. For higher pressure ranges, circular flexible disc diaphragms are used.

Materials used

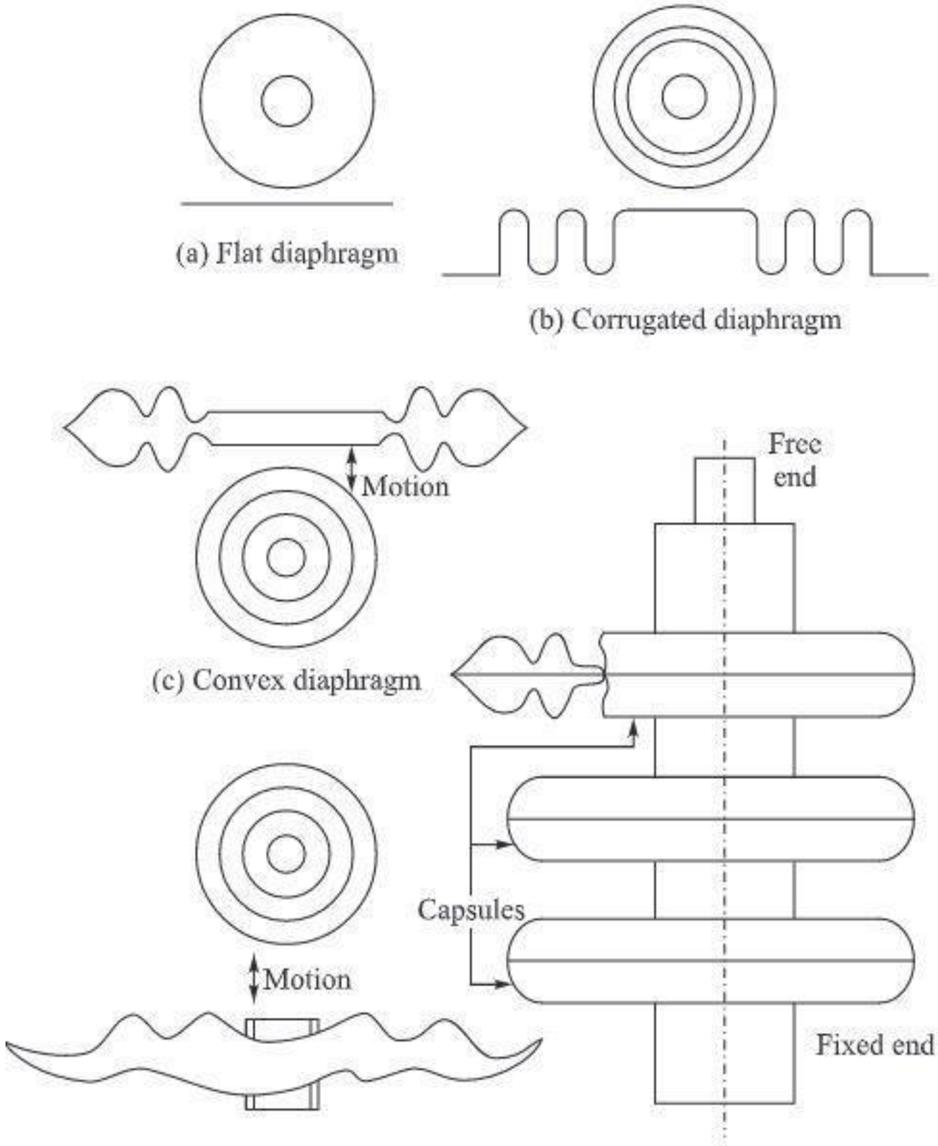
Important aspect to be considered for a diaphragm is elasticity. The material should have good elasticity and low temperature coefficient of elasticity. Phosphor bronze, beryllium copper, Monel, brass, tantalum, Teflon, duranickel the Ni span C are used for the manufacturing (construction) of diaphragms. In quartz diaphragm, minimum hysteresis and drift can be achieved.

Types of diaphragms

Flat-type diaphragm. It consists of a thin flexible circular metallic plate. These diaphragms provide low deflection because they operate on low-pressure ranges. Figure (a) shows a flat diaphragm.

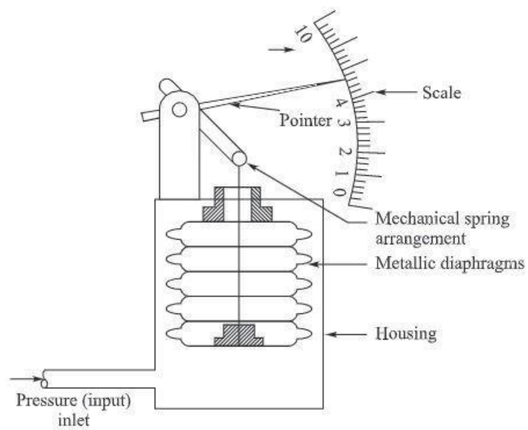
Corrugated diaphragm. In this type of diaphragm, the surface area is increased due to which the pressure handling capacity is increased and ultimately the deflection also becomes higher. Figure (b) shows a single corrugated diaphragm.

Bonding or welding two single corrugated diaphragms can increase the pressure handling capacity of single corrugated diaphragm. They are useful for highly sensitive measurement. When the two diaphragms are welded together at the peripheries, the resulting diaphragm is called capsule. The capsule diaphragms are again classified into three categories—convex capsule, nested capsule and multiple capsules. Figures (c) and (d) show the convex capsule and nested capsule diaphragms, respectively. When a number of convex or nested capsules are joined, the resulting device is a multiple capsule element. The capsule elements are connected axially with each other. The total deflection is sum of the deflections of individual capsules. This element provides increased output displacement in accordance with the change in applied pressure. Figure (e) shows a multiple capsule diaphragm.



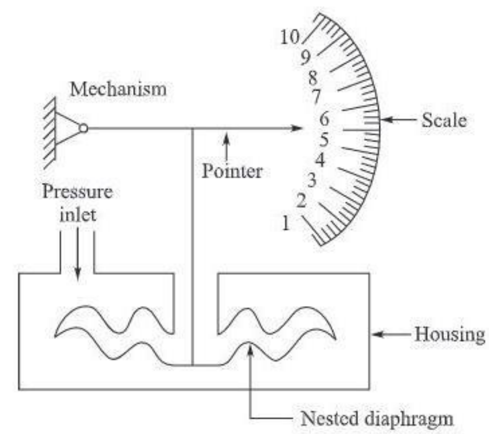
Pressure measurement using diaphragm

The system consists of number of metallic diaphragms connected to each other on a metallic element. The metallic element is connected to a pointer through mechanism or spring arrangement. The pointer slides over a calibrated scale as shown in Figure. When the pressure, which is to be measured, is applied through the pressure inlet, the deflection of metallic diaphragm takes place. This deflection is applied to a pointer through spring or proper mechanism arrangement, due to which the pointer slides over the calibrated scale. The reading is indicated by indicating or recording instrument, which is proportional to the applied pressure.



Pressure measurement using diaphragm.

Pressure measurement using a nested diaphragm



Pressure measurement using a nested diaphragm.

The arrangement consists of a metallic housing in which a nested diaphragm is placed. Displacement of the diaphragm is applied to a pointer through mechanism. This pointer slides over a calibrated scale and measures the displacement.

When pressure is applied through the pressure inlet, deflection of nested diaphragm takes place. The pointer indicates this deflection over a calibrated scale, which is proportional to the applied input pressure.

Advantages

- A diaphragm has low cost.
- It is useful for measurement of absolute and differential pressures.
- It has good linearity.
- It has small size and good compactness.
- It is fabricated by using non-corrosion resistive elements.

Disadvantages

- The performance of a diaphragm may be affected due to vibrations and shocks.
- Repairing of diaphragm is very complex and tedious job.
- It is applicable only for low-pressure measurements.

2. Bourdon Tube

These are the primary pressure sensing elements used for measurement of medium and high pressures. Bourdon tubes are elastic members and convert the pressure into mechanical displacements. An important aspect is that Bourdon tube is a primary sensing element, which senses pressure and converts it into mechanical displacement. This displacement can be converted into electrical signals using secondary transducers. Materials used for construction of Bourdon tube are phosphor bronze, beryllium copper, monel, Ni-Span C and alloy steel. Pressure range is 100 kPa to 690 MPa.

Working principle

When the pressure, which is to be measured, is applied to the pressure sensitive element, it deflects and resulting into mechanical displacement. Mechanical displacement is proportional to the applied pressure. This mechanical displacement is converted into electrical signals by using electrical transducers. From this discussion, it is noted that the electrical signal is proportional to the mechanical displacement and hence proportional to the applied pressure.

There are various types of bourdon tubes according to shape or form, namely C-type, helical, spiral and twisted.

C-Bourdon tube. It is made by winding an elliptical flattened tube to form a segment of a circle having an arc of 250°. This tube has two ends, out of which one end is sealed. The other end is opened for applying the process pressure and fixed at the socket as shown in Figure (a).

When the pressure is applied at the open end, the tube tends to straighten out because the internal and outer radii of the bourdon tube are different. So the tube takes different areas for the pressure. The non-linear motion is converted into linear motion or displacement by means of a pointer and calibrated scale (deflection) arrangement. Necessary link, lever gear and pinion attachment is provided to the deflection system. Thus the applied pressure is measured by means of deflection over linear scale.

Spiral Bourdon tube. Spiral Bourdon tube is made by winding the elliptical flattened tube into spiral form of 2 or 3 windings around the same axis as shown in Figure (b). One end of the tubes is sealed and the other is open.

When the pressure is applied to a spiral Bourdon tube, it tends to uncoil and produces the deflection and displacement at the free end. This displacement is used for indication or transmission. The produced displacement is applied to the pointer and scale arrangements for measurement. The displacement is more, so there is no need of magnification elements, i.e. mechanical amplification. Due to this, the gear and pinion arrangement is eliminated which increases the accuracy.

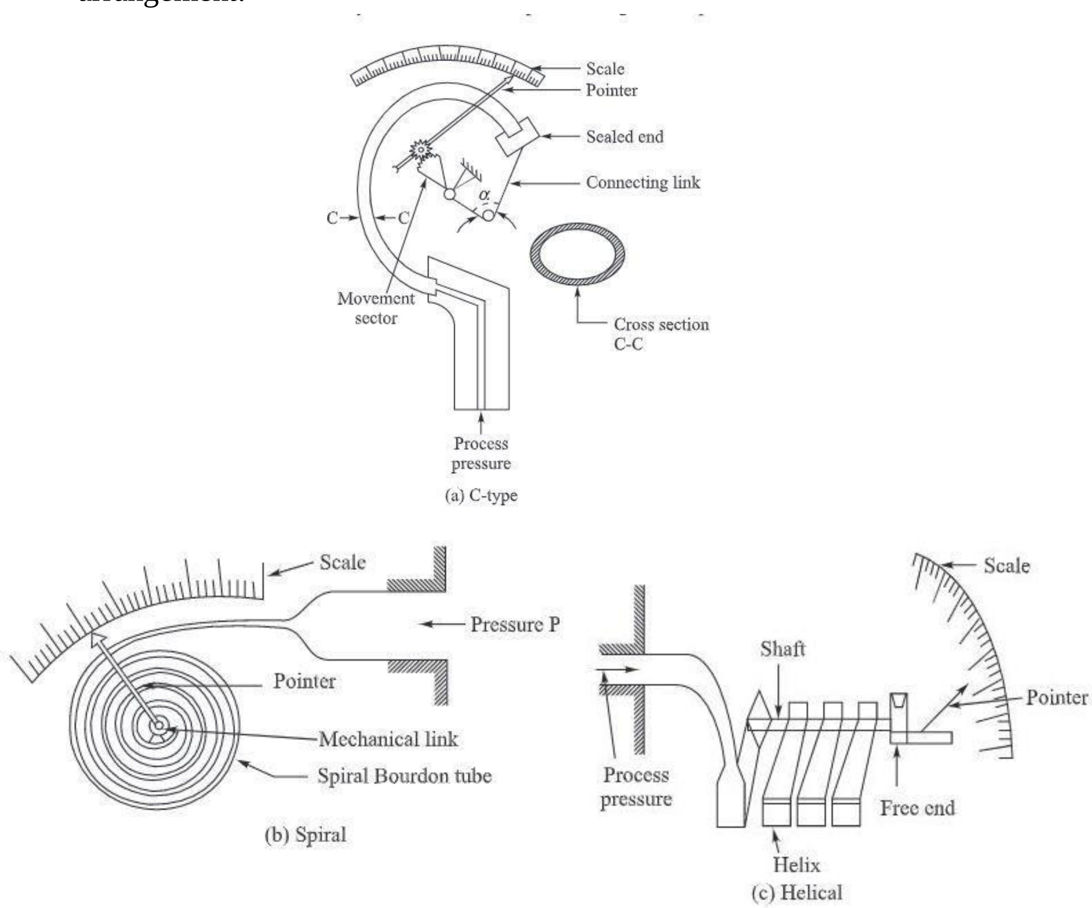
Spiral Bourdon tube has the following advantages:

1. It has more accuracy.
2. There is no friction because there is no gear and pinion arrangement
3. It has higher sensitivity because there is no friction and loss of motion.

Helical Bourdon tube. By winding the elliptically flattened tube into helical (helix) form, this tube is manufactured. This tube provides higher movement of the free end. Mechanical movement or displacement of helical Bourdon tube is more than that of spiral Bourdon tube. A shaft is connected at the centre of the helical winding and a pointer is attached at the shaft using proper connecting link. As the applied pressure changes, the helical winding provides circular displacement, which is indicated by the pointer connected to the shaft.

Helical Bourdon tube has the following advantages:

1. It provides satisfactory operation over continuous fluctuating pressure signals.
2. It has higher capacity to handle the overrange pressures.
3. There is no necessity of mechanical amplification gear and pinion arrangement.



Different types of Bourdon tubes.

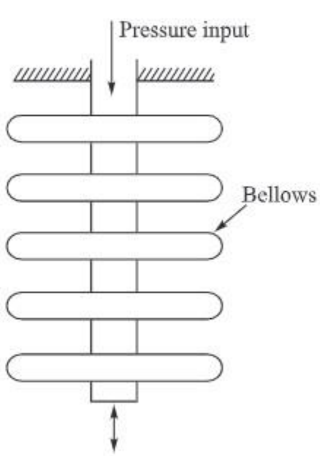
Pressure range of a Bourdon tube depends upon diameter of the coil, thickness of the tube, constructional material used and number of helical coils/tubes. For low-pressure measurements, two or three coils are used whereas for high-pressure measurements, 16 to 20 coils can be used. Accuracy of a Bourdon tube depends upon the diameter of tube, design quality, materials used to construction and calibration arrangement. It is ± 0.5 to ± 2%

3. Bellows

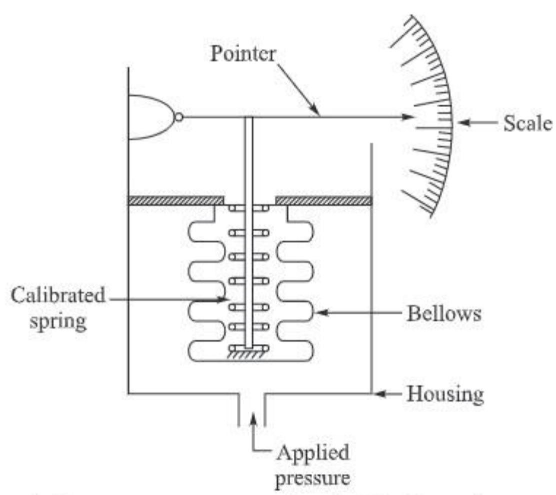
This is a pressure-sensing element used to measure low pressure and vacuum or absolute pressure. Welding a number of preformed plates makes bellows. The circular plates are welded together so that they can be expanded or contradicted by the application of pressure. The materials used for construction of bellows are brass, stainless steel, beryllium copper, monel, bronze, Inconel Ni-span. The material should be ductile and flexible and should have high strength and low hysteresis. Figure (a) shows a basic bellows element.

Seamless tubes prepare bellows by hydraulic or mechanical roll formation. Seamless bellows can also be formed. They can be directly attached to or compatible with indicators or recorders.

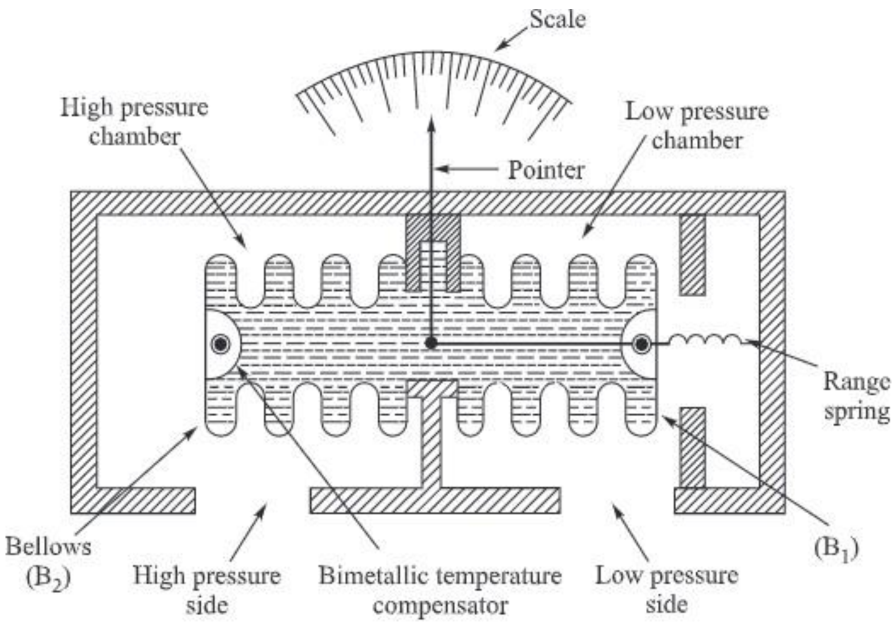
Pressure measurement using single bellows the bellows element is exposed to atmospheric pressure which functions as the reference pressure. At the bottom, the process pressure is applied. A calibrated spring is provided so as to counterbalance the deflection of bellows and pointer.



(a) A basic bellows element



(b) Pressure measurement using single bellows element



(c) Pressure measurement using differential bellows

As the pressure is applied to the spring-loaded metal bellows, it gets compressed and hence forces the lower end of the bellow in upward direction. This results in opposing the spring force. The pointer is connected to the spring through suitable linkage and calibration. When pressure is applied in vertical movement, the pointer moves over the calibrated scale. In this way, the unknown pressure can be measured by this arrangement.

Limitations of bellows

1. Sensitivity of bellows may be affected by ambient temperature, friction and drift.
2. It is not suitable for high pressures.
3. If the elasticity of bellow is not sufficient, a spring arrangement has to be attached for accurate measurement.
4. Work-hardening of the metals are used of construction of bellows.

Applications

1. It is suitable for low and moderate pressure ranges of 9-13 kPa to 0-240 kPa.
2. It is used for absolute and differential pressure handling.

4. Piezoelectric sensors

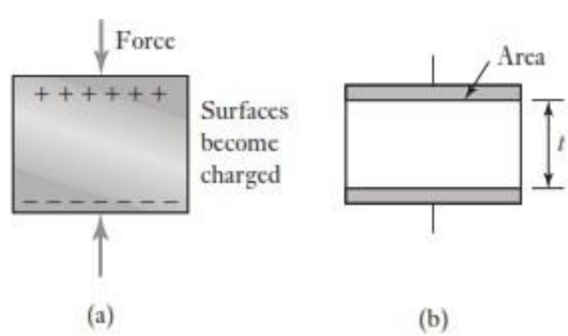
Piezoelectric materials when stretched or compressed generate electric charges with one face of the material becoming positively charged and the opposite face negatively charged (Figure(a)). As a result, a voltage is produced. Piezoelectric materials are ionic crystals, which when stretched or compressed result in the charge distribution in the crystal changing so that there is a net displacement of charge with one face of the material becoming positively charged and the other negatively charged. The net charge q on a surface is proportional to the amount x by which the charges have been displaced, and since the displacement is proportional to the applied force F:

$$q = kx = SF$$

Where k is a constant and S a constant termed the *charge sensitivity*. The charge sensitivity depends on the material concerned and the orientation of its crystals. Quartz has a charge sensitivity of 2.2 pC/N when the crystal is cut in one particular direction and the forces applied in a specific direction; barium titanite has a much higher charge sensitivity of the order of 130 pC/N and lead zirconate–titanate about 265 pC/N.

Metal electrodes are deposited on opposite faces of the piezoelectric crystal (Figure (b)). The capacitance C of the piezoelectric material between the plates is

$$C = \frac{e_0 e_r A}{t}$$



where er is the relative permittivity of the material, A is area and t its thickness. Since the charge q = Cv, where v is the potential difference produced across a capacitor, then

$$v = \frac{St}{e_0 e_r A} F$$

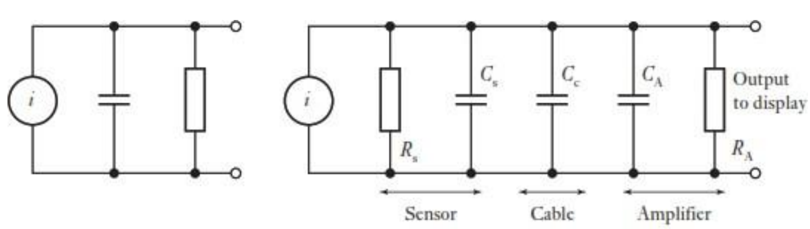
The force F is applied over an area A and so the applied pressure p is F/A and if we write $S_v = \frac{S}{e_0 e_r}$, this being termed the voltage sensitivity factor, then

$$v = S_v t p$$

The voltage is proportional to the applied pressure. The voltage sensitivity for quartz is about 0.055 V/m Pa. For barium titanate it is about 0.011 V/m Pa.

Piezoelectric sensors are used for the measurement of pressure, force and acceleration. The applications have, however, to be such that the charge produced by the pressure does not have much time to leak off and thus tends to be used mainly for transient rather than steady pressures.

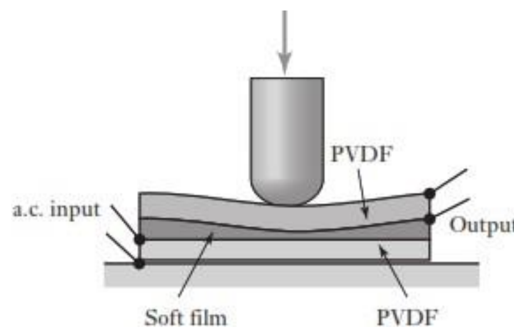
The equivalent electric circuit for a piezoelectric sensor is a charge generator in parallel with capacitance C_s and in parallel with the resistance R_s arising from leakage through the dielectric (Figure (a)). When the sensor is connected via a cable, of capacitance C_c, to an amplifier of input capacitance C_A and resistance R_A, we have effectively the circuit shown in Figure (b) and a total circuit capacitance of $C_s + C_c + C_A$ in parallel with a resistance of $R_A R_s/(R_A + R_s)$. When the sensor is subject to pressure it becomes charged, but because of the resistance the capacitor will discharge with time. The time taken for the discharge will depend on the time constant of the circuit.



(a) (b)

5. **Tactile sensor**

A tactile sensor is a particular form of pressure sensor. Such a sensor is used on the ‘fingertips’ of robotic ‘hands’ to determine when a ‘hand’ has come into contact with an object. They are also used for ‘touch display’ screens where a physical contact has to be sensed. One form of tactile sensor uses piezoelectric polyvinylidene fluoride (PVDF) film. Two layers of the film are used and are separated by a soft film which transmits vibrations (Figure). The lower PVDF film has an alternating voltage applied to it and this results in mechanical oscillations of the film (the piezoelectric effect described above in reverse). The intermediate film transmits these vibrations to the upper PVDF film. As a consequence of the piezoelectric effect, these vibrations cause an alternating voltage to be produced across the upper film. When pressure is applied to the upper PVDF film its vibrations are affected and the output alternating voltage is changed.

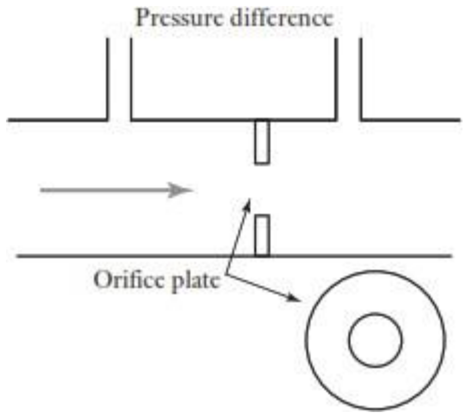


LIQUID FLOW SENSORS

- There are many devices used to measure the liquid flow.
- The basic principle in measuring flow is the fluid flowing through the pipe per second is proportional to square root of pressure difference.
- The following flow measuring devices are used to measure the liquid flow.

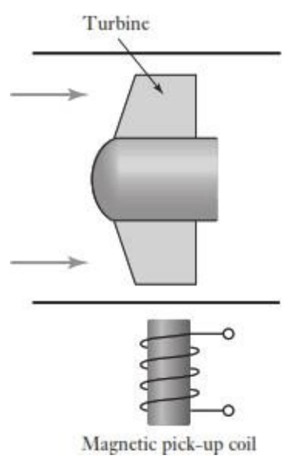
1. **Orifice plate**

The orifice plate is simply a disc, with a central hole, which is placed in the tube through which the fluid is flowing. The pressure differences is measured between a point equal to the diameter of the tube upstream and a point equal to half the diameter downstream. The orifice plate is simple, cheap, with no moving parts, and is widely used. It does not, however, work well with slurries. The accuracy is typically about ±1.5% of full range, it is non-linear, and it does produce quite an appreciable pressure loss in the system to which it is connected.



2. **Turbine meter**

The turbine flowmeter consists of a multi-bladed rotor that is supported centrally in the pipe along which the flow occurs. The fluid flow results in rotation of the rotor, the angular velocity being approximately proportional to the flow rate. The rate of revolution of the rotor can be determined using a magnetic pick-up. The pulses are counted and so the number of revolutions of the rotor can be determined. The meter is expensive with an accuracy of typically about ±0.3%.



LEVEL MEASUREMENT

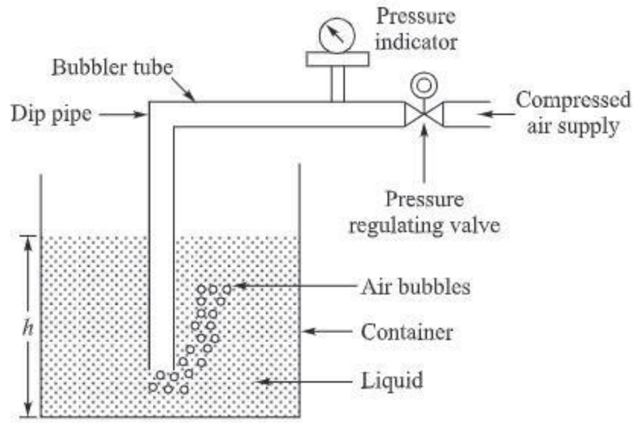
Liquid level measurement is an important and the oldest function in measurements. It is widely useful in power plants, petrochemical, paper and sugar industries. It is also useful for level measurement of exotic and hazardous process matters, fuel handling and so on. The liquid level affects pressure and rate of flow in and out of a container or vessel, due to which it is necessary to measure and control liquid levels. The service of level measurements is applicable for both solid and liquid materials or any process material. But the most important factor is to consider the nature and type of material. In the following sub-sections, various level measurements are discussed. Both solid and liquid level measurements are covered here.

1. Bubbler Method

It consists of a hollow bubbler tube or dip pipe inserted in a liquid which is stored in a tank. Figure (b) shows different shapes of the tip of dip pipe or bubbler tube available which can be selected according to the requirement. This tube is fed with air supply from a compressor through a pressure regulating valve. Another connection of the tube is provided to a pressure indicating instrument like pressure gauge or manometer which is calibrated in terms of liquid level. Generally, diameter of the tube or bubbler tube is 2 inches to 50 mm and tip of the pipe should be placed 3 inches above bottom of the tank so as to avoid clogging or blocking due to deposition of particles in the liquid.

Pressure of the regulator is adjusted so as the air pressure in the bubbler tube should be greater than the hydrostatic (pressure) head of the fluid or liquid under test. Due to this adjustment, air bubbles come out from the bottom.

When there is no liquid in the tank or liquid level is below the tip of the bubbler tube or pipe, compressor air flows out from the bottom and pressure indicator will indicate zero reading. As the liquid level starts to increase, air pressure in the dip pipe or tube changes. This pressure is indicated by the pressure indicating instrument. Because of increase in the liquid level, air flow gets restricted because of depth of the liquid. Hence air pressure acts against the liquid head which is back pressure indicated by the instrument. Pressure indicated by a pressure measuring instrument is directly proportional to the liquid level.



(a) Liquid level measurement using the bubbler method


(b) Different shapes of the dip pipe (or bubbler tube)

Precautions

- ✓ Material used for dip pipe or tube should be free from corrosion. The material can be selected according to the fluid involved in process.
- ✓ Air pressure fed to a dip pipe or tube should be slightly higher than the maximum pressure of the head in tank.
- ✓ Accuracy depends upon the pressure sensing element, so it should be properly calibrated.
- ✓ Dip pipe or tube should be cleaned properly in regular manner.

Advantages

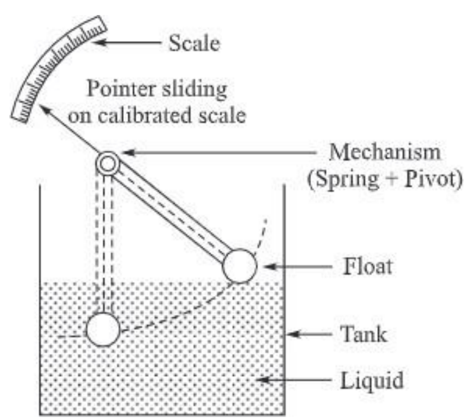
- ✓ It is a simple method.
- ✓ Pressure monitoring element or device can be installed at top or bottom of the tank. It can also be placed up to 12.7 meters from the tank by using proper piping arrangements.

Bubbler method is suitable for measurement of corrosive or abrasive liquid levels.

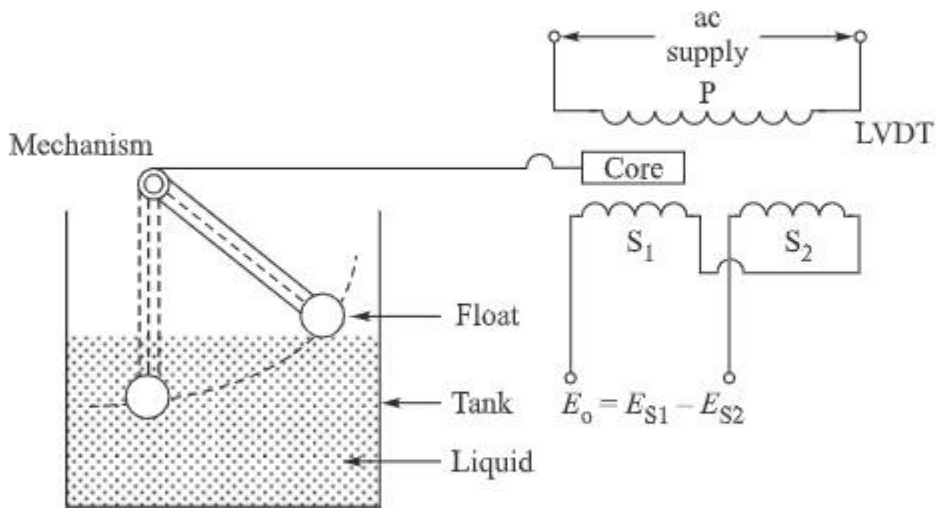
2. Liquid Level Measurement Using Float

Float is a body which has characteristic of always to float and follow the changing liquid level. Normally the floating device has hollow spheres, cylindrical and disk shaped. Floats can be designed according to requirements, i.e. whether low or high-level measurement is carried out, density of liquid and so on. Floats are available in the range of 3 to 7 inches in diameter. The materials used for floats are brass, copper, Mane!, polysulfone and plastics. The material used for a float should be free from corrosion, oxidation and should be properly sealed. A float rests on the surface of liquids and follows changing levels of liquids. Because of change in the liquid level, movement of the float takes place that is transmitted to the pointer and the calibrated scale through a mechanism like spring. The following methods are discussed for liquid level measurement using float.

Using float and shaft arrangement Figure shows liquid level measurement using a float and shaft arrangement. It consists of a float resting on a liquid surface, which is connected to a pointer using a mechanism arrangement. As liquid level changes, the position of the float varies on the surface, i.e. the float moves according to position of the liquid level. This movement of float is transmitted to the pointer that slides over the calibrated scale through the mechanism. The displacement of the pointer over the calibrated scale is directly proportional to the liquid level. The displacement can be calibrated or converted into electrical voltage by using linear variable differential transformer (LVDT). This method is discussed further.

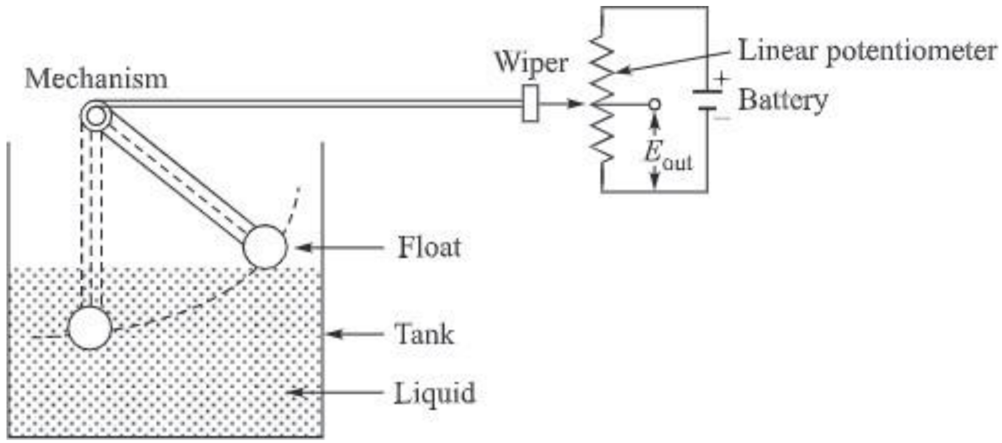


Using float and LVDT Figure shows a liquid level measurement using float and LVDT. The float resting on the surface of the liquid is connected to core of the LVDT through mechanical linkage.

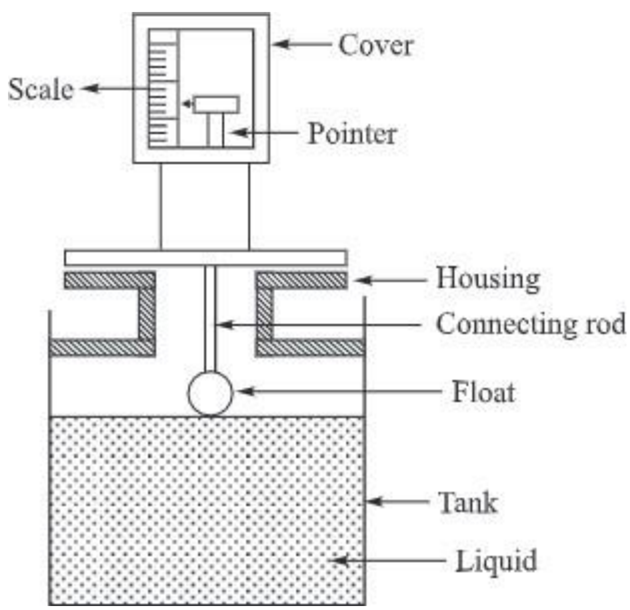


As liquid level varies (increases or decreases), displacement of the float takes place. This displacement is applied to the core of the LVDT. The LVDT produces differential output voltage that is proportional to displacement of the core. This voltage can be transmitted to control devices or relays. In this method, the float acts as a primary transducer and the LVDT functions as a secondary transducer.

Using float and potentiometer This is a simple and direct method to measure the liquid level in terms of electrical voltage. It can be achieved by using either linear or rotary potentiometer. Figure shows implementation of liquid level measurement scheme using a linear potentiometer. The float is connected to the wiper of potentiometer through mechanical linkage. As the float displaces according to variations in liquid level, the wiper slides over resistive element of potentiometer resulting in change in its resistance. Change in resistance is directly proportional to displacement of wiper due to float movement. E_{out} is the output voltage drop across the potentiometer that is proportional to the liquid level. This voltage can be used to operate relay or alarm units or control elements.

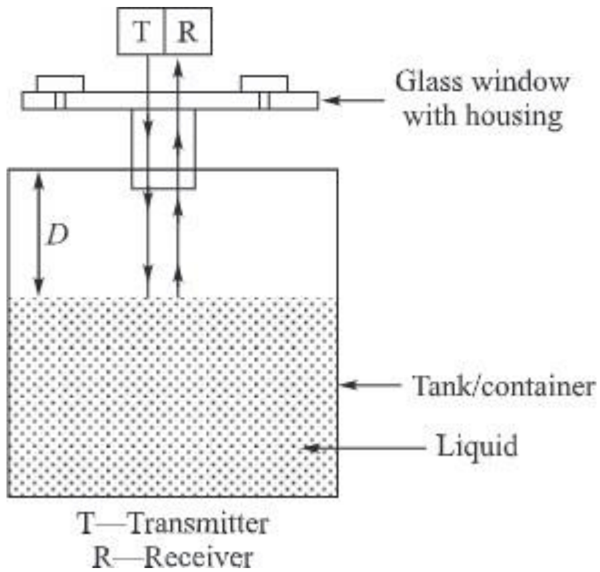


Using float and rotameter Figure shows a simple arrangement of liquid level measurement using float and rotameter. It consists of a float, which is connected to a solid shaft. An indicator is placed over this shaft. The indicator slides over a calibrated scale. When the liquid level varies, the position of the float displaces resulting in sliding the pointer over the scale. The indication by pointer is proportional to the liquid level. Materials used to construct float and rod arrangement are stainless steel, Monel and so on. Generally, a glass indicator is used. This method is applicable for non-hazardous applications and low-level measurements.



3. Laser level sensor or level measurement using laser

The term LASER stands for Light Amplification by with housing Stimulated Emission of Radiation. It is a source of coherent electromagnetic waves at infrared and light frequencies. These are high frequency signals ranging from 430 to 750 terahertz (THz). This method is applicable for solids, liquids with transparent vapours.



Liquid This method consists of a laser transmitter and receiver set installed above a container or tank. A glass window is placed on top of the tank using proper housing of rubber or plastic. From the transmitter end, a sharp beam of laser is focused towards the liquid level by modulation. When this signal reaches at the surface of the liquid, it gets reflected. This reflected signal is received by the receiver. The time period (t) from reflection of the signal to reaching at the receiver is calculated so as to measure the liquid level. The time period (t) is function of distance D from the liquid level, i.e. the level from which the signal is reflected to the receiver), that is represented by the following equation:

$$t=f(d)$$

where C = velocity of light = 3×10^8 m/sec

The liquid level can be measured by calibrating time period in pulses using counter circuit.

Advantages

- ✓ No direct physical contact with the process material.
- ✓ Suitable if vapour can be present with the process material.
- ✓ No moving part is involved in the system, so operation is free from friction and spark.
- ✓ More reliable.

Limitations

- ✓ Accuracy depends upon light reflection characteristics of the process material.
- ✓ The process material should be dust-free.
- ✓ The glass window and housing should be clean and dust-free.

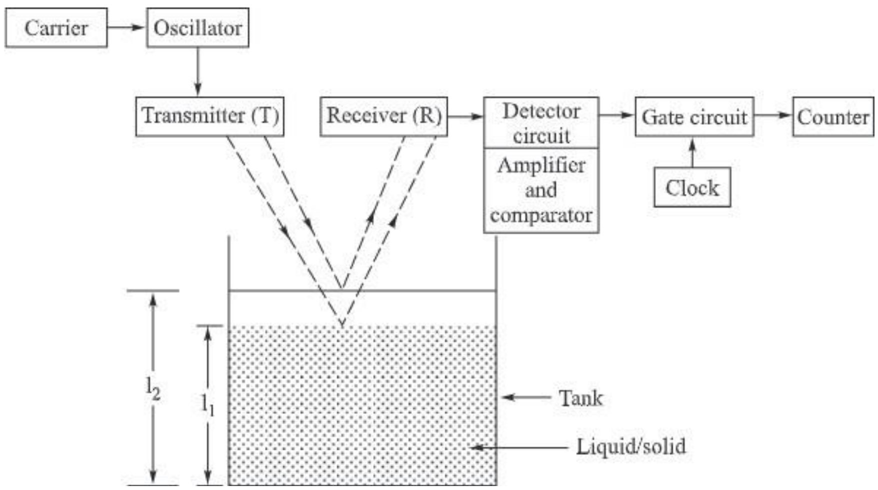
Applications

- ✓ To measure the levels of liquid aluminium, liquid polyethylene, brown tobacco and so on.
- ✓ To measure levels of wood pulp in paper industries.
- ✓ To measure levels of hazardous and toxic liquids and acids.

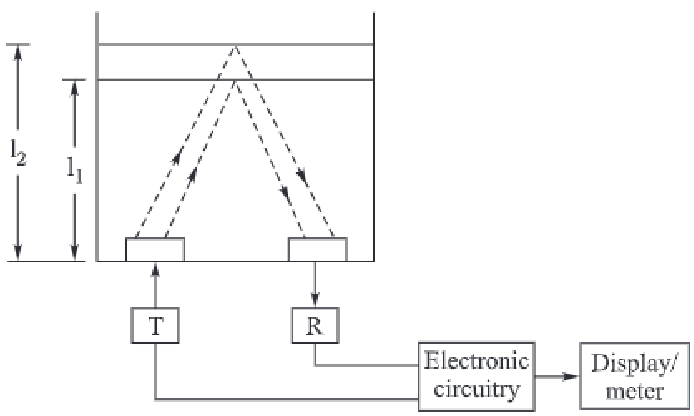
4. Ultrasonic liquid level detector

It is a conventional method used for measurement of liquid levels. This method uses the principle of reflection of acoustic signals from liquid surface. It consists of an ultrasonic transmitter, which generates frequency signals of range 35 kHz to 40 kHz. Figure 7.70 shows an ultrasonic liquid level indicator.

This method consists of a set of ultrasonic transmitter T and receiver R placed on top of a tank. The transmitter transmits the ultrasonic wave towards the surface of liquid or solid. This beam is reflected back from the surface and received by the receiver R. The measurement is carried out on the basis of time taken by the received echo beam to reach at the receiver end. As liquid level changes, the transit time required to reach the beam at the receiver also changes, e.g. for level l_i, the transit time will be different from time required for the level 1_2.



The received echo beam is detected by means of detector circuit. Sometimes amplifier can be used with comparator to detect the echo. By passing the detected signal through the gate and the flip-flop circuit, the time period can be measured in the form of pulses. Piezoelectric crystals such as Rochelle salt, barium titanate and quartz can be used as transmitter. In some situations of level measurement, the ultrasonic transmitter and receiver may be installed at the bottom of the tank as shown in Figure.



Advantages

- ✓ No moving part is involved in the system, hence no problem of development of friction or spark.
- ✓ No physical contact with process material so useful for measurements of conductive, corrosive, hazardous process materials.
- ✓ More reliability.

- ✓ Applicable for both solids and liquids.
- ✓ Performance does not affected by moisture, humidity, and dielectric constants of process materials.

Limitations

- ✓ Performance may get affected if the received pulse is weak.
- ✓ Weak refractive properties of the surfaces of process fluids.
- ✓ Careful installation of transmitter and receiver set is necessary.

Applications

- ✓ To measure levels of oil storage tanks
- ✓ To measure levels of chemicals
- ✓ In mines and oil wells
- ✓ To measure levels of slurries

TEMPERATURE SENSORS

Temperature measurement is a widely useful technique in various processes, plants and industries. This is an old technique, but nowadays various techniques and methods are in existence and under research. Temperature is a fundamental quantity and totally different in nature from the quantities like mass, time, length and area.

The term temperature is defined as the degree of hotness or coldness of a substance or medium. Temperature may be defined as degree of heat.

Due to heating or cooling, the following effects are used for measurement:

(i) Change in physical or chemical state of the substance or medium

(ii) Change in physical dimensions

(iii) Change in electrical properties such as resistance

(iv) If two dissimilar metals get joined or welded, an emf gets developed at the junction.

(v) Change in the intensity of total radiation emitted.

The calibration of given temperature measuring devices is carried out using the following two methods:

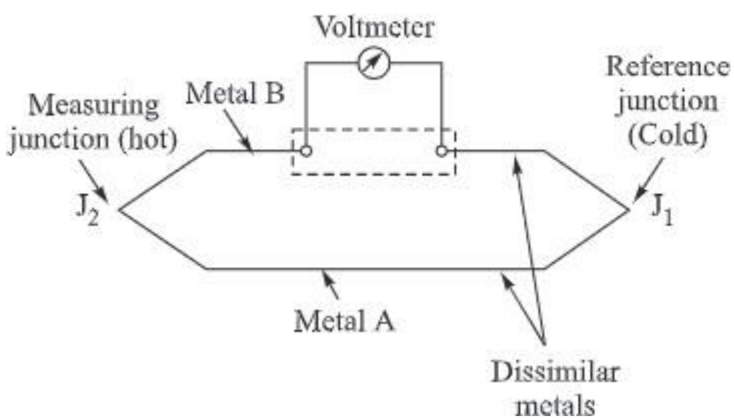
(i) By subjecting it to some established fixed-point environment such as melting or boiling points of standard substances.

(ii) By comparing its reading with more accurate, stable and calibrated temperature sensor or by secondary standard.

1. Thermocouple

This transducer is widely used in industrial applications for temperature measurement. Thermocouple is an active transducer because there is no need of voltage source and transducer bridge circuitry.

A thermocouple works on the following principle: When two dissimilar metals A and B are welded or joined together to form a closed circuit and the junctions (J_1 and J_2) are kept at two different temperatures (T_1 and T_2), then an emf is generated resulting flow of current in the circuit or loop." One of the two junctions in the loop is reference or cold junction which is generally kept at 0°C and the other is the measuring or hot junction at which the temperature is to be measured as shown in Figure.



The generated emf (E) is proportional to the difference of the temperatures T_1 and T_2 the materials used for the thermocouple. This phenomenon is called *seebeck effect.* Thus, the amount of emf generated is a function of temperature at hot and cold junctions.

Construction

In thermocouples, welding or soldering two different metals forms the thermojunctions. Gas or electric welding welds the metals. Thermocouples are available in different sizes, shapes, temperature ranges for different applications. According to media and the temperature range, various combinations of materials in fixed proportions are used for manufacturing of thermocouples.

The following important parameters are to be considered for thermocouple materials:

- ✓ Linear relationship between temperature and output voltage
- ✓ To withstand highest temperature and temperature variations
- ✓ Corrosion resistance
- ✓ Sensitivity figure (S)

The sensitivity figure (S) is given by

$$SE = \frac{dX}{dT} = \sum a_n t_{n-1}$$

where a_n is the Seebeck coefficient which depends upon the material and temperature

t is the hot junction temperature when cold junction temperature is at 0°C

E is the fermi energy

This sensitivity figure depends upon the material to be used for the thermocouple. The thermocouple should generate high thermoelectric power.

Advantages of thermocouple

- ✓ Construction is mechanically strong and rigid.
- ✓ It is suitable for reading (measurement) of rapidly varying temperatures.
- ✓ It has low cost.
- ✓ There is no need of bridge circuit.
- ✓ Installation and calibration is easy.
- ✓ It is suitable for temperature range of —270 to 2800°C.

Disadvantages of thermocouple

- ✓ It requires a protective wall or sheath.
- ✓ Thermocouple needs compensating arrangement.
- ✓ Amplifier circuit is necessary to increase the output voltage level.
- ✓ For long distance temperature measurement, compensating wires are necessary.

2. Resistance Temperature Detector (RTD)

This type of transducer is used for temperature measurement. Here the basic concept used is that electrical resistance of different material changes in accordance with the temperature, i.e. for temperature measurement. The principle used is that the resistance of a conductor changes in proportion with the change in temperature. The unknown temperature is determined in terms of electrical resistance of the conductor, which senses the temperature. The change in resistance of this device is precisely determined either by bridge circuit or ohmmeter. Otherwise a separate circuit can be used to calibrate the value of resistance in terms of voltage or current.

For different metals, the variations of resistance value (R) with temperature (T) is expressed as follows:

$$R = R_0\ (1 + a_1T + a_2T^2 + \cdots \ldots \ldots \ldots \ldots \ldots + a_nT^n$$

where Ro is the resistance of the conductor at temperature T = 0

$a_1, a_2, \ldots \ldots \ldots a_n$ are constants

In metals, the resistance increases with increase in temperature.

Metals used for RTD

- ✓ "Balco" handles the temperature range of —23°C to +204°C having resistance of 2000 Ω.
- ✓ Platinum has resistance temperature coefficient 0.39 and temperature range of —260°C to 110°C.
- ✓ Nickel has resistance temperature coefficient 0.62 and temperature range of —220°C to 300°C.
- ✓ For tungsten, resistance temperature coefficient is 0.45 and temperature range is —200°C to 1000°C.

Figure shows the resistance versus temperature curve for different metals. Generally, the metals used for RTD are platinum, copper and nickel. The most widely used metal for resistance wire is platinum because of the following features:

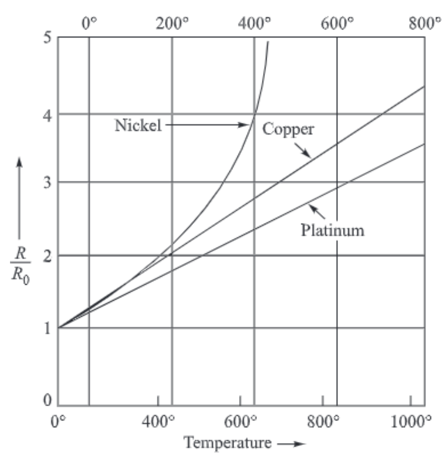
- ✓ It can operate on wide range of temperature.
- ✓ Platinum provides good stability and accuracy.
- ✓ It has good linearity over wide temperature range.
- ✓ There is less error during the operation.

An RTD fabricated using platinum is called platinum RTD (PRTD).

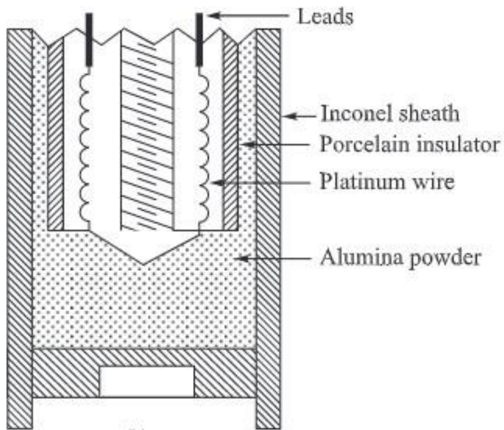
Figures (b) and (c) show the construction of an RID. The important aspects to be considered for the designing of an RID are the following:

- ✓ Operating point
- ✓ Fast response
- ✓ Environmental conditions
- ✓ Ability to withstand corrosion, friction and so on.

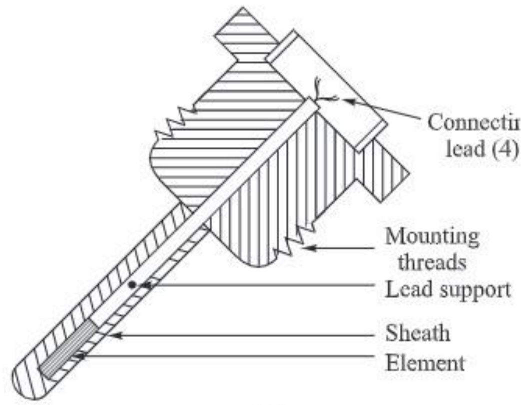
The RTD is used for temperature measurement of fluids and gases. It is of probe type and immersed into medium whose temperature is to be measured. It consists of a platinum wire in spiral shape enclosed in an insulating material such as mica or ceramic. It is enclosed in a protective glass or porcelain tube. This assembly is placed at the tip of the probe. The RTD is placed inside a well or tube to provide the protection to the resistive element from corrosion, environmental conditions, mechanical damages and so on. Mostly a well arrangement is used in liquid and gaseous media at higher temperature, e.g. in power plants, pipelines and so on.



(a)



(b)



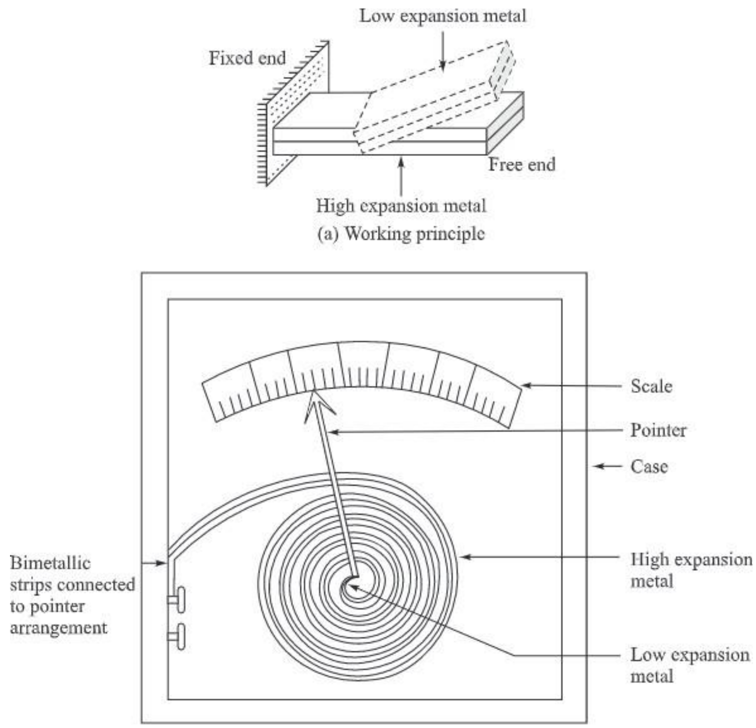
(c)

3. Bimetallic Thermometers

It uses the concept of differential expansion of bonded strips of two metals. In certain metals, the volume changes with temperature and the coefficient of change is not the same for all the metals.

Working principle : If the two different metal strips are joined or welded together and heated, the resultant strip having lower expansion rate gets bend. The deflection of the strip is directly proportional to the square of the length and temperature and inversely proportional to the thickness of the metal.

As the name indicates, a bimetallic thermometer consists of two different metal strips. According to the change (rise) in temperature, the length of the metal gets changed with respect to the rate of thermal expansion. This expansion results the bending of bimetallic strip towards the side having low coefficient of thermal expansion as shown in Figure (a). The deflection of a metal strip is applied to the pointer sliding over scale, which is proportional to the temperature variations. The deflection or movement produced by the bimetallic strips is small. Also, if the size of the strip is small, deflection is small. For large deflections, size of the strip should be large. To avoid this, the metal strip element is wound in spiral or helical shape. At the outer part of the spiral strips, a pointer is attached which moves over the calibrated scale. As temperature increases, the spiral strips wind up and the pointer deflects over the calibrated scale in clockwise direction as shown in Figure (b). The complete assembly is placed in a case.



(a) Working principle
(b) Construction

The metals mostly used for bimetallic strips are low-expansion invar (64% Fe, 36% Ni) and higher-expansion nickel-alloy with chromium or manganese. This complete set (bimetallic strip) is sealed in stainless steel with plastic or glass crystals which is a protective tube or well.

Advantages

- ✓ It is easy to install.
- ✓ Its maintenance is not complex.
- ✓ It is mechanically rigid and tough.
- ✓ It has low cost.
- ✓ It has wide operating temperature range.

Disadvantages

- ✓ Calibration changes because of tough handling.
- ✓ Accuracy is not as good because of glass stern design.

Applications Helical bimetallic thermometers are used in industrial and residential temperature measurements.

4. Thermistors (Semiconductor Temperature Sensors)

Thermistors are also called thermal resistors. For thermistors, the absolute temperature-resistance relationship is given by

$$R_T = R_{T1}\, exp\, [\beta(\frac{1}{T_1} - \frac{1}{T_2})]$$

where R_T is the resistance of the thermistor at absolute temperature T (°K.)

R_{T1} is the resistance of the thermistor at absolute temperature Ti (°K)

β is a constant and

T_1 and T_2 are the absolute temperatures (°K)

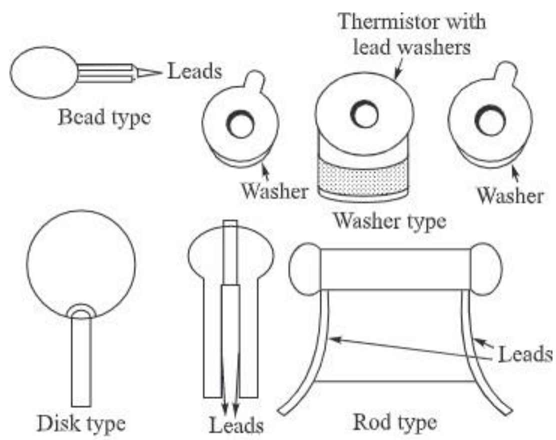
Thermistors are made up of semiconductor materials. As temperature changes, resistance of a material also changes. The temperature coefficient of resistance for thermistors is mentioned below:

- If the value of the resistance increases with increase in temperature, it is positive temperature coefficient (PTC) thermistor.
- If the value of the resistance decreases with increase in temperature, it is negative temperature coefficient (NTC) thermistor.

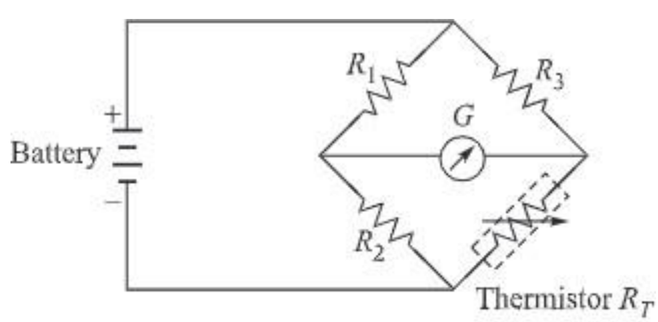
(a) Symbol

Construction: Thermistors are semiconductors and made up of sintered mixtures of manganese, cobalt, zinc, aluminum, iron, copper, and uranium oxide powder above 982°C in combination with binders. The mixture of these materials is pressed into different shapes and sizes like beads, washer, rods, disks and flakes. All these types are represented in Figure (b). The electrical connections or leads are embedded before the sintering process. These thermistors are placed in glass or plastic encapsulation so as to protect from damage, vibrations, flow rates and so on. Thermistors are used to determine temperature, liquid level, rate of flow and so on.

The temperature range for a thermistor is - 60°C to +15°C. Its resistance varies from 0.5 Ω to 0.75 MΩ. A thermistor is placed in contact with the media whose temperature is to be measured. As the temperature of the media changes, the resistance of the thermistor gets changed. The resistance-temperature characteristics of a thermistor are shown in Figure (c). The change of resistance with the temperature can be measured by connecting the thermistor to any one arm of a Wheatstone bridge. According to change in the temperature (i.e. increase or decrease in the temperature), the resistance varies which causes to unbalance the bridge. It results to flow of the current through the galvanometer as shown in Figure (d). The galvanometer indicates the readings calibrated as a temperature scale.



(b) Various configurations of a thermistor



(d) A Wheatstone bridge with thermistor R_T

Advantages of thermistor

- ✓ It has small size and is compact.
- ✓ It gives good response time from fraction of seconds to minutes.
- ✓ It can be installed in small areas like pipeline, inlet or outlet of tanks.
- ✓ There is no need of cold junction compensation.
- ✓ It has good stability.

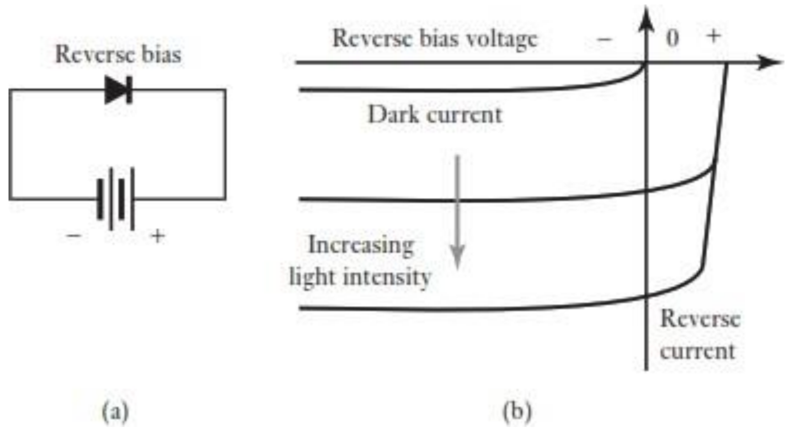
Disadvantages of thermistor

- ✓ It has non-linear performance, i.e. temperature versus change in resistance graph.
- ✓ It is not suitable for higher temperatures.
- ✓ It requires bridge circuit arrangement for converting the change in resistance to voltage.

Light sensors

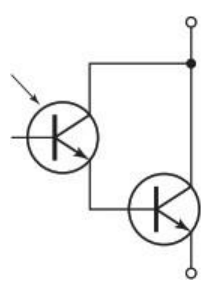
1. Photodiodes

Photodiodes are semiconductor junction diodes which are connected into a circuit in reverse bias, so giving a very high resistance (Figure (a)). With no incident light, the reverse current is almost negligible and is termed the dark current. When light falls on the junction, extra hole–electron pairs are produced and there is an increase in the reverse current and the diode resistance drops (Figure (b)). The reverse current is very nearly proportional to the intensity of the light. For example, the current in the absence of light with a reverse bias of 3 V might be 25 μA and when illuminated by 25 000 lumens/m^2 the current rises to 375 μA. The resistance of the device with no light is $3 / (25 * 10^{-6}) = 120\ k\Omega$ and with light is $3 / (375 * 10^{-6}) = 8\ k\Omega$. A photodiode can thus be used as a variable resistance device controlled by the light incident on it. Photodiode have a very fast response to light.



2. Phototransistors

The phototransistors have a light-sensitive collector–base p–n junction. When there is no incident light there is a very small collector-to-emitter current. When light is incident, a Base current is produced that is directly proportional to the light intensity. This leads to the production of a collector current which is then a measure of the light intensity. Phototransistors are often available as integrated packages with the phototransistor connected in a Darlington arrangement with a convectional transistor (Figure). Because this arrangement gives a higher current gain, the device gives a much greater collector current for a given light intensity.



3. Photoresistor

A photoresistor has a resistance which depends on the intensity of the light falling on it, decreasing linearly as the intensity increases. The cadmium sulphide photoresistor is most responsive to light having wavelengths shorter than about 515 nm and the cadmium selinide photoresistor for wavelengths less than about 700 nm.

An array of light sensors is often required in a small space in order to determine the variations of light intensity across that space. An example of this is in the digital camera to capture the image being photographed and convert it into a digital form. For this purpose, a charge-coupled device (CCD) is often used. A CCD is a light-sensitive arrangement of many small light-sensitive cells termed pixels. These cells are basically a p-layer of silicon, separated by a depletion layer from an n-type silicon layer. When exposed to light, a cell becomes electrically charged and this charge is then converted by electronic circuitry into an 8-bit digital number. In taking a photograph the digital camera electronic circuitry discharges the light sensitive cells, activates an electromechanical shutter sensitive cell, activates an electromechanical shutter to expose the cells to the image, then reads the 8-bit charge value for each cell and so captures the image. Since the PN cells are colour blind and we need colour photographs, the light passes through a colour filter matrix before striking the cells. This allows just green light to fall on somecells, blue on others and red light on others. Then, by later taking account of the outputfrom neighbouring cells, a colour image can be created.

SELECTION OF SENSORS

The factors to be considered while selecting sensors are

- ✓ The nature of output required from the sensor.
- ✓ The nature of measurement required.
- ✓ The accuracy of the sensor.
- ✓ The cost of the sensor.
- ✓ The power requirement of the sensor.
- ✓ The speed response of the sensor.
- ✓ The linearity of the sensor.
- ✓ The Reliability and Maintainability of the sensor.
- ✓ Environmental conditions under which the measurement is to be made.
- ✓ Signal conditioning requirements.
- ✓ The nominal and range of values of the sensor.
- ✓ Suitable output signals from the measurement.

ASSISGNMENT QUESTIONS:

1. Define sensors, transducers and explain the performance characteristics of sensors / transducers
2. Explain the working of any two of displacement sensors
3. Explain the working of any two of position sensors
4. Explain the working of any two of velocity sensors
5. Explain the working of any two of fluid pressure sensors

Tutorial questions

1. Explain the process of selection of sensors and transducers
2. Explain the working of any two of Temperature sensors
3. Explain the working of any two of light sensors
4. Explain the working of any two of motion sensors
5. Explain the working of any two of fluid proximity sensors

UNIT 3

ACTUATORS AND DRIVE SYSTEMS

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

(Autonomous Institution – UGC, Govt. of India)

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT-3

COURSE OBJECTIVE

- **Understand the fundamental concepts of electro mechanics and fluid mechanics (hydraulics and pneumatics) of Actuators and drive systems.**

COURSE OUTCOME

- **Handle different types of Actuators and Drive systems and Characteristics and limitations.**

Actuators

The power source can be electric, pneumatic (compressed air), or hydraulic (the flow of oil). There are two main types of actuators. They are rotary and linear.

In a mechanical device, an actuator is a component that turns the control signal into movement. Examples of actuators include: Electric motors, Solenoids, Hard drive stepper motors.

Actuators have either a linear or rotary output and can be classified into three basic types:
(1) Cylinders or jacks. (2) Motors. (3) Rotary actuators.

Types of Actuators

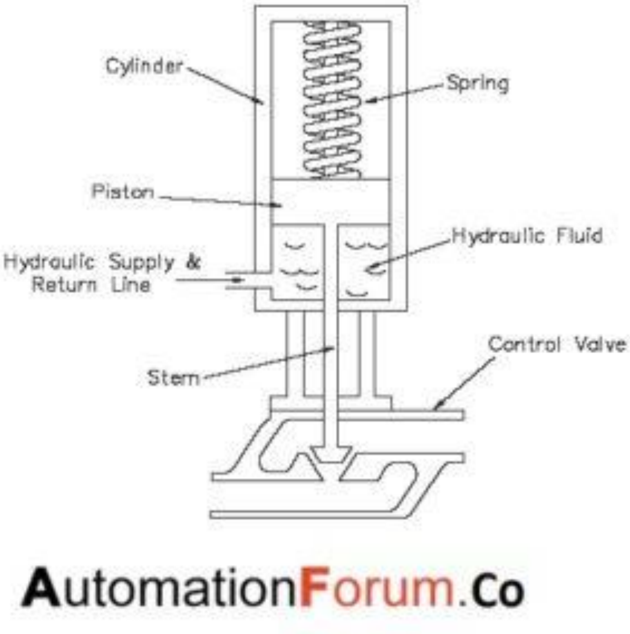
1. Hydraulic actuators

2. Pneumatic actuators

3. Electric Motors, like: Servomotors, Stepper motors or Direct-drive electric motors

1. Hydraulic Actuators

Hydraulic Actuators, as used in industrial process control, employ hydraulic pressure to drive an output member. These are used where high speed and large forces are required. The fluid used in hydraulic actuator is highly incompressible so that pressure applied can be transmitted instantaneously to the member attached to it.



Pascal's Law

Pressure applied to a confined fluid at any point is transmitted undiminished and equally throughout the fluid in all directions and acts upon every part of the confining vessel at right angles to its interior surfaces.

Since pressure P applied on an area A gives rise to a force F, given as,F = P×A Thus, if a force is applied over a small area to cause a pressure P in a confined fluid, the force generated on a larger area can be made many times larger than the applied force that crated the pressure. This principle is used in various hydraulic devices to such hydraulic press to generate very high forces

Advantages of Hydraulic Actuators

Variable hydraulic actuators are widely used as drives of machine tools, rolling mills, pressing and the foundry equipment, road and building machines, transport and agricultural machines,etc. A number of advantages in comparison with mechanical and electric transfers explains such their wide application

- infinitely variable control of gear-ratio in a wide range and an opportunity to create the big reduction ratio;
- small specific weight, i.e. the weight of a hydro actuator is in ratio to transmitted capacity(0,2…0,3 kg / kWt);
- opportunity of simple and reliable protection of the engine from overloads;
- small sluggishness of the rotating parts, providing fast change of operating modes (start-up, dispersal, a reverser, a stop);
- simplicity of transformation of rotary movement into reciprocating one;
- opportunity of positioning a hydraulic engine on removal(distance) from an energy source and freedom in making configuration.

Disadvantages of hydraulic actuators:

- efficiency of a volumetric hydraulic actuator is a little bit lower, than efficiency of mechanical and electric transfers, and during regulation it is reduced;
- conditions of operation of a hydraulic actuator (temperature) influence its characteristics;
- efficiency of a hydraulic actuator is a little reduced in the process of exhaustion of itsresource owing to the increase in backlashes and the increase of outflow of liquid (falling of volumetric efficiency);
- sensitivity to pollution of working liquid and necessity of high culture service.

2. Pneumatic Actuators

A set of devices into with one or more pneumo engines, which are determined to start mechanisms or some other objects by means of pressed working gas is called pneumatic actuator,or pneumo actuator.The devices intended for transformation of potential and kinetic energy of the stream of compressed gas in mechanical energy of the output link that can be, for example, a rod of the piston, a shaft of the turbine or the case of the jet device is called pneumatic engines of the automated actuator.All pneumatic actuators can be subdivided into the following types:

•diaphragm pneumatic actuators;

•pneumatic power cylinders;

•gas-engine pneumatic actuators;

The principle of transformation of potential or kinetic energy of the gas stream into mechanical energy of the engine output link of the engine provide the base for division into types

Advantages of Pneumatic Actuators:

•simplicity of realization relatively to small back and forth motions;

•sophisticated transfer mechanisms are not required;

•low cost;

•high speed of moving;

•ease at reversion movements;

•tolerance to overloads, up to a full stop;

•high reliability of work;

•explosion and fire safety;

•ecological purity;

•ability to accumulation and transportation.

Disadvantages of Pneumatic Actuators:

•compressibility of the air ;

•impossibility to receive uniform and constant speed of the working bodies movement ;

•difficulties in performance at slow speed;

•limited conditions – use of compressed air is beneficial up to the definite values of pressure;

•compressed air requires good preparation

3. Electric motor Actuators

An electric actuator is powered by a motor that converts electrical energy into mechanical torque. The electrical energy is used to actuate equipment such as multi-turn valves.

Advantages:-

Compact

Very high stiffness

High output capability

Supply pressure piping not required

Disadvantages:-

High cost

Lack of fail-safe action

Limited duty cycle

Slow stroking speed

Electro-Hydraulic Actuators

Hydraulic systems work because of Pascal's law, which states that an increase of pressure in any part of a confined fluid causes an equal increase of pressure throughout the container. If force is applied to one part of a hydraulic system, it travels through the hydraulic fluid to the rest of the system.

Advantages:-

High output capability

High actuator stiffness

Excellent throttling ability

Fast stroking speed

Disadvantages:-

High cost

Complexity and maintenance difficulty

Fail-safe action only with accessories

a. 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. It has four rotor teeth, 90º apart and six stator poles, 60º 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 30º 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.

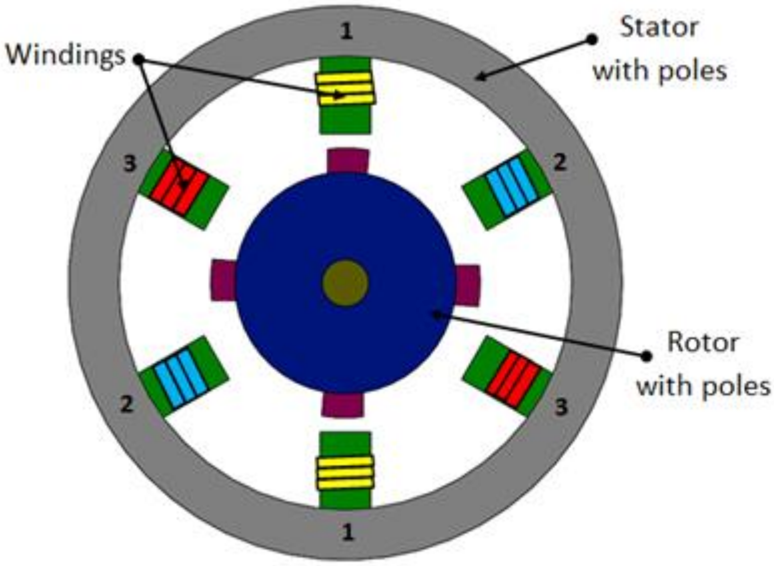


Fig. Variable reluctance stepper motor

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, 90º 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 7.5º to 15º .

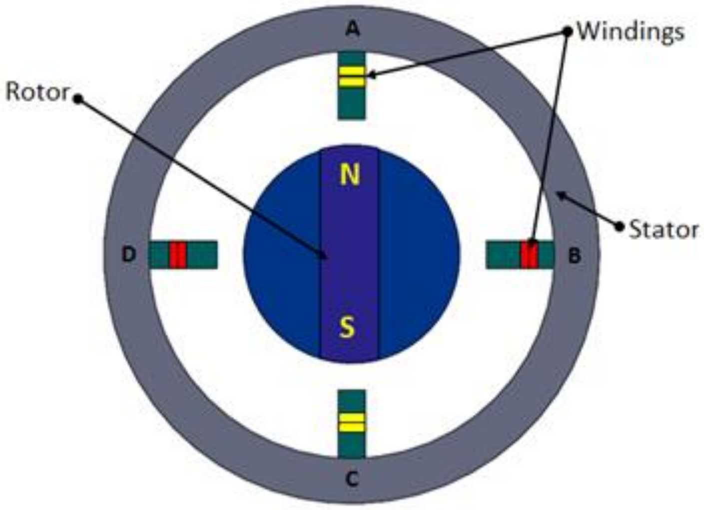


Fig. Permanent magnet stepper

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.)

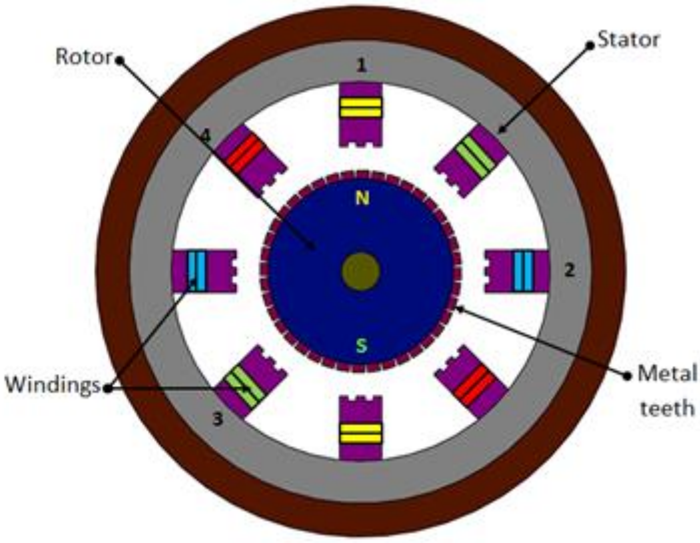


Fig. Hybrid stepper

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,

$$\text{Step angle} = \frac{360^\circ}{\text{Number of poles}}$$

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.

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.

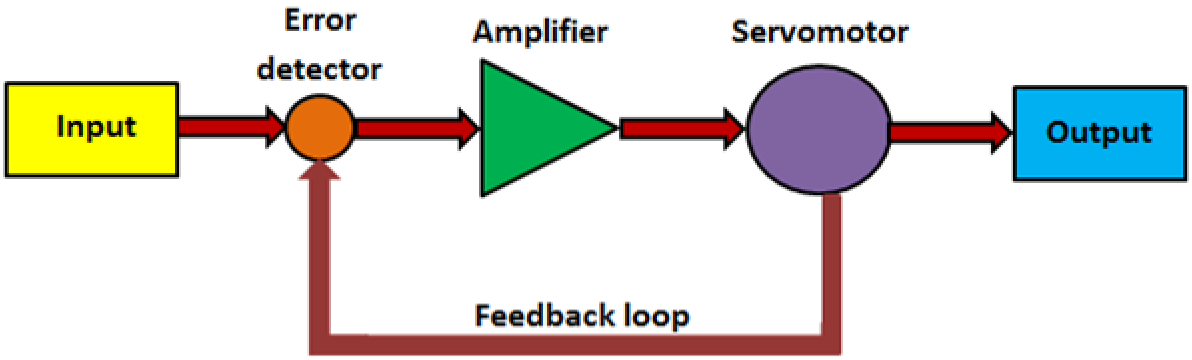


Fig. Servo system block diagram

b. 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

C. AC servo motor

In this type of motor, t he 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 ha zardous environments or in vacuum
- Excessive current can result in partial demagnetization of DC type servo motor

Mechanical Drive Systems

The drive system determines the speed of the arm movement, the strength of the robot, dynamic performance, and, to some extent, the kinds of application

A robot will require a *drive system* for moving their arm, wrist, and body. A drive system is usually used to determine the capacity of a robot. For actuating the robot joints, there are *three different types* of drive systems available such as:

Electric drive system,

Hydraulic drive system, and

Pneumatic drive system.

The most importantly used two types of drive systems are electric and hydraulic

Electric Drive System:

The electric drive systems are capable of moving robots with *high power* or speed. The actuation of this type of robot can be done by either DC servo motors or DC stepping motors. It can be well – suited for rotational joints and as well as linear joints. The electric drive system will be perfect for *small robots* and precise applications. Most importantly, it has got greater accuracy and repeatability. The one disadvantage of this system is that it is slightly costlier.

Hydraulic Drive System:

The hydraulic drive systems are completely meant for the *large – sized robots*. It can deliver high power or speed than the electric drive systems. This drive system can be used for both linear and rotational joints. The rotary motions are provided by the rotary vane actuators, while the linear motions are produced by hydraulic pistons. The *leakage* of hydraulic oils is considered as the major disadvantage of this drive. An example for the hydraulic drive system is *Unimate 2000 series robot.*

Pneumatic Drive System:

The pneumatic drive systems are especially used for the *small type robots*, which have less than five degrees of freedom. It has the ability to offer fine accuracy and speed. This drive system can produce rotary movements by actuating the rotary actuators. The translational movements of sliding joints can also be provided by operating the piston. The price of this system is *less* when compared to the hydraulic drive. The drawback of this system is that it will not be a perfect selection for the *faster operations.*

ASSISGNMENT QUESTIONS:

1. Define Actuator? Explain types of Actuators?

2. Explain about Hydraulic and Pneumatic Actuators?

3. Explain about different Drive systems?

4. Explain the characteristics of different drive systems?

5. What are the Limitations of different drive systems?

Tutorial questions

1. Explain about Electrical Actuators?

2. Differentiate about Hydraulic and Pneumatic Actuators?

3. Write about the three Drive systems?

UNIT 4

CONTROL SYSTEM COMPONENTS

UNIT-4

COURSE OBJECTIVE

- **To impart knowledge on the control elements**

COURSE OUTCOME

- **Describe and analyze working principles of various types of motors, differences, characteristics and selection criteria, control methods.**

Control System Components

INTRODUCTION

Automatic control system is playing a vital role in the fields of engineering and science. Due to advancement in the control system, it is most widely used in manufacturing and industrial processes, power systems, space vehicles, missile guidance, machine tool control and so on. It is also used to control different parameters in the industrial processes like temperature, flow, liquid level, pressure and so on. Nowadays, control system is also used in non-engineering applications such as resource and company management, economic, environmental and biomedical systems.

Human being is the most sophisticated control system in nature. An average human being performs wide range of activities in daily life like walking from one place to another, picking up objects, decision making and so on. Under certain conditions and by adopting the best possible method, these activities have to be completed.

Consider the example of simple action of a human being in picking up a book from a table that satisfies the definition of feedback control system. In this example, two feedback paths are involved, which are as follows:

I. Visual feedback data enable the current positions of fingers to be signalled to optical system and hence to the brain.
II. On locating the book, feedback data is transmitted to the brain via the nervous system to decide the amount of pressure to be applied to the hand (finger) to pick the book.

Here, the objective of the brain is to establish the desired positions for hand and desired degrees of hand (fingers) pressure and to compare these desired values with the actual values being transmitted back to the brain. To use the result of comparison for computing appropriate course of action to be implemented by using appropriate body muscles on receiving signals from the brain. Here the feedback data is used.

Feedback control system. It is defined as the system which maintains a prescribed relationship between the output and the reference input by comparing them and using the difference as a means of control system.

In studying the control system, we need to define additional terms to define the control system. These definitions are discussed below.

Plant. Any physical object which is to be controlled is called plant. It can also be defined as a set parts of a machine to perform a particular operation. The examples are spacecraft, heating furnace, water tank level controller and so on.

Process. Any operation made to achieve an aim or a particular result is called a process, e.g. chemical process and mechanical process.

System. It is defined as a combination or collection of components (physical objects), which work together to achieve an objective or goal.

Disturbance. It is a signal which adversely affects the system output. The disturbance may be internal, which is generated in the system itself, or external, which is generated outside the system but is input to the system.

CLASSIFICATION OF CONTROL SYSTEMS

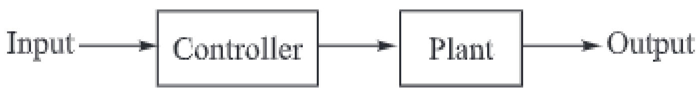
1. Open and Closed Loop Control Systems

In general control systems are classified into two categories—open loop and closed loop.

Open loop control system

It is a control system in which the control action is independent of the desired output. In such type of systems, there is no provision to correct the variations at the output automatically. In these systems, the output remains constant for constant input signal provided that external conditions remain unchanged. But due to external unwanted parameters, the system output varies from desired value in an uncontrolled fashion.

Figure shows general block diagram of an open loop control system, in which no feedback is present, hence there is no effect on the control action. In this system, the output is neither measured nor connected back for comparison with the input.



Two examples of open loop control system are discussed below:

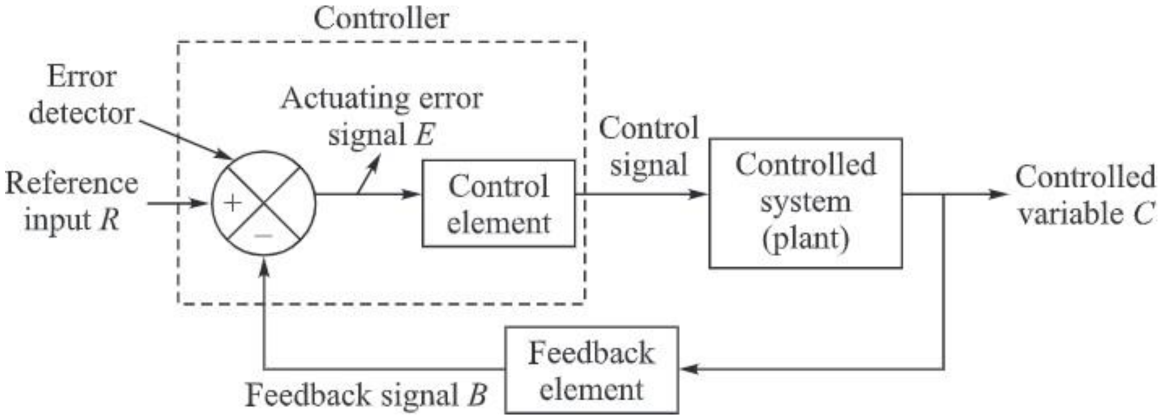
Automatic toaster. In this control system, timer is used to make the toast. But the user has to set the time required to make "good toast" by using timer. On the other hand, user is not the component of this system. As soon as the set time gets elapsed, the toaster gets switched off irrespective of the desired quality of the toast, i.e. output. Hence it is an open loop control system.

Traffic control system using lights. Consider a traffic control system to regulate the flow of traffic at crossing of two roads. In this system, red and green lights are used to control the traffic on timer basis set for predetermined fixed intervals of time. This arrangement does not account traffic flow on the crossing of two roads. It only changes the positions of red and green lights on timer basis irrespective of traffic flow. Hence it is an open loop control system.

Closed loop control system

In this system, the control action is dependent on the desired output. Commonly the closed loop control systems are called feedback control systems. Feedback allows the comparison of the output with input to the system so that an appropriate control action may be generated as some function of input and output.

Figure shows general block diagram of a closed loop control system. It is divided into three basic components—feedback element, controller and controlled system. These components are discussed further.



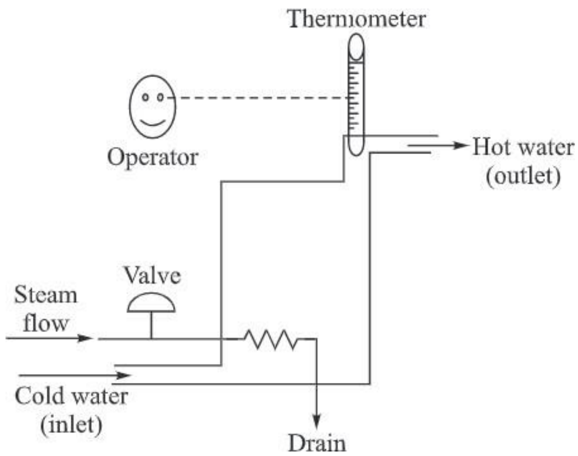
Controller. It consists of two parts error detector and control elements. The function of error detector is to compare the feedback signal B and reference input R and generate a difference signal which is called an actuating error signal E This error signal E is applied to control element, which generates the necessary control signal. The control element may contain power stage like amplifier so that the control signal can drive controlled system or plant to produce the desired output variable.

Feedback element It is a device which converts the controlled output signal into another suitable variable, i.e. the feedback signal B. This signal is used to compare with the reference input R.

Controlled system (plant). It is a physical object or set of machine parts functioning together to perform a particular operation. This physical object is to be controlled according to the control signal generated by the control elements.

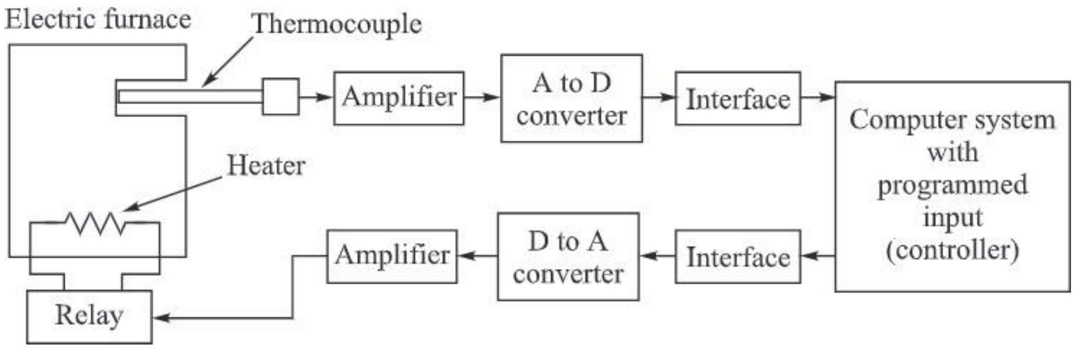
The closed loop control system is divided into two types—manually controlled closed loop system, in which a human operator behaves as a controller, and automatic closed loop control system, in which the controller may be electrical, electronic, hydraulic, pneumatic or combination of them.

Manually-controlled closed loop control system. Figure shows a manually controlled thermal system. Here human operator acts as a controller. If we want to maintain the temperature of hot water at a desired value, then a thermometer is placed at the outlet to measure the temperature. The operator reads temperature by thermometer and sets the valve position accordingly, i.e. by controlling steam flow in order to maintain the desired temperature.



Drawbacks of manually controlled closed loop system are that it is not suitable for complex, fast acting and self-destructing systems.

Automatic closed loop control system. Figure shows automatic temperature control of an electric furnace. Initially, the temperature of the furnace is converted into proportional electric voltage by the sensor, i.e. the thermocouple. This analog voltage is converted into digital format by analog-to-digital converter and fed to the computer system (controller) through proper interface. This digital temperature is compared with the programmed input temperature. If there is any error at the controller stage, it sends a control signal to the heater element through the interface, digital-to-analog converter and relay. This sets the temperature at the desired value.



Difference Between Open Loop & Closed Loop System

Comparison	**Open Loop System**	**Closed Loop System**
Definition	The system whose control action is free from the output	In closed loop, the output depends on the control action of the system.
Other Name	Non-feedback System	Feedback System
Components	Controller and Controlled Process.	Amplifier, Controller, Controlled Process, Feedback.
Construction	Simple	Complex
Reliability	Non-reliable	Reliable
Accuracy	Depends on calibration	Accurate because of feedback.
Stability	Stable	Less Stable
Optimization	Not-Possible	Possible
Response	Fast	Slow
Calibration	Difficult	Easy
System Disturbance	Affected	Not-affected
Linearity	Non-linear	Linear
Examples	Traffic light, automatic washing machine, immersion rod, TV remote etc.	Air conditioner, temperature control system, speed and pressure control system, refrigerator, toaster.

2. Linear and Non-linear Control Systems

A linear control system consists of the components having a linear relationship between the input and output signals under steady state conditions. Any system is called linear when the principle of superposition is applied. Principle of superposition states that the response produced by the simultaneous application of two different forcing functions is the sum of two individual responses. For a linear system, treating one input at a time and adding the results can calculate the response to several inputs. A non-linear control system consists of one or more elements, which exhibits a non-linear relationship between the input and output signals. In such system, principle of superposition is not applicable.

3. Linear-time Varying and Time-invariant Systems

In a control system, most physical systems are characterized by differential equations. A differential equation is linear if the coefficients are constants or functions only of an independent variable. If the coefficients of describing differential equations are functions of time, then the mathematical model is time varying. The systems which consist of linear time-variant components or elements described by linear time-variant differential equations, whose coefficients are functions of time, are called linear time-varying systems. On the other hand, dynamic systems that are composed of linear time-invariant components by linear time-invariant differential equations are called linear time-invariant systems (parameters do not vary with time).

4. Continuous-time and Discrete-time Control Systems

A control system in which all the system parameters are continuous functions of time t is called continuous-time control system. A control system in which all the system parameters are discrete functions of time t is called discrete-time control system.

5. Lumped Parameter and Distributed Parameter Control System

The control system which can be described by ordinary differential equations is called lumped parameter control system. On the other hand, the control system which can be represented by partial differential equations, is called distributed parameter control system.

6. Deterministic and Stochastic Control System

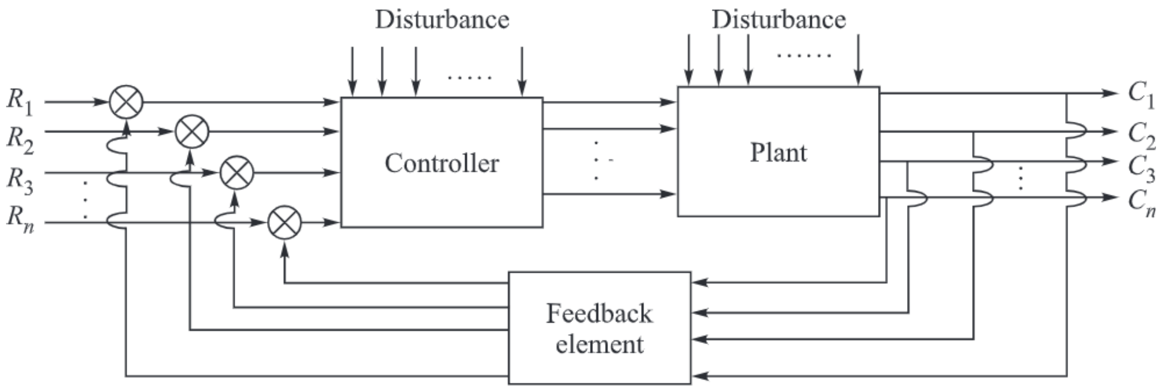
In any control system if the response to input is predictable and repeatable, then the system is called deterministic control system. If the response to input is unpredictable and non-repeatable, then the system is called stochastic control system.

7. Classification of Control Systems on the Basis of Control Signal Used

Depending upon the nature of signals involved like electrical, mechanical, hydraulic, pneumatic or combination of these signals, the control systems may be classified as single input-single output (SISO) and multiple input-multiple output (MIMO) systems.

SISO system. As the name indicates, it is a system having a single input and a single controlled variable. The output is produced by the single input solely. Only one input signal flows or passes through the system. The examples of SISO systems are voltage regulators, temperature controllers and so on.

MIMO system. There are certain systems having multiple inputs and multiple outputs. The systems in which any change in one of the outputs causes a subsequent change in the other output during transient and steady state conditions are called MIMO systems. The examples are boiler in which the controlled variables are steam pressure, temperature, water level and so on. Figure shows block diagram of an MIMO system.



8. Adaptive Control System

Adaptive means the ability to self-adjust or self-modify with respect to unpredictable changes in environmental or structural conditions (parameters). The dynamic response (e.g. time response, frequency response) parameters of most of the control systems do not remain constant due to environmental conditions or deterioration of the system components as time elapses. Effect of these small changes in parameters in the feedback control system gets attenuated. But if these effects are significant, the system should be satisfactory enough to adapt these effects of small changes. The control systems in which the system parameters are automatically adjusted to keep the system at an optimum level are called adaptive control systems. Such type of control systems itself detects changes in the plant parameters and make essential adjustments in the controller parameters to maintain optimum level or performance.

9. Process Control System

It is an automatic regulating system (feedback control system) in which the output is a variable (physical parameters) such as temperature, pressure, pH value, flow, liquid level and so on. It is widely used in different industries like paper, sugar, petrochemical, rubber and so on.

TRANSFER FUNCTION

In a control system, transfer functions are commonly used functions to characterize the input-output relationships of the control system or components, which can be represented by linear and time-invariant differential equations.

The *transfer function* of a linear time-invariant system is defined as the ratio of Laplace transform of the output variable to Laplace transform of the input variable under the assumption that all the initial conditions are zero. The concept of the transfer function is limited to linear, time-invariant, differential equations systems. It is widely used in designing and analysis of such systems.

I. Let G(s) is the transfer function of single-input single-output system with input r(t) and controlled output c(t).
II. Consider an nth order differential equation for input-output relation of linear time-invariant system.

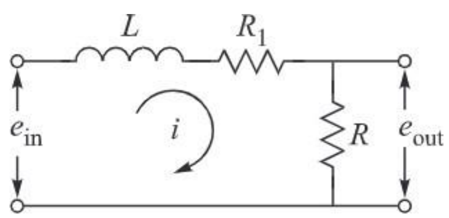
To obtain transfer function of any equation, take Laplace transforms on both sides and assume all initial conditions as zero.

Properties of transfer function

- Transfer function is applicable only for linear time-invariant system.
- While defining the transfer function, all initial conditions of the system are set to zero.
- Transfer function is independent of magnitude and nature of input of the system.
- It includes the unit essential to relate the input to output but does not provide any information regarding physical structure of the system.
- It is a mathematical model which relates the output variable to the input variable.
- If transfer function is known, the output response can be studied for various forms of inputs.
- If the transfer function is unknown, it can be determined experimentally by applying known inputs and studying output of the system.

1. **Transfer function for Electrical systems**

   Case -1: Determine the Transfer function for below circuit



Suppose a current i is flowing through the circuit (loop).

Step 1. Write Kirchhoff's voltage equation for the system (apply KVL to the system).

$$L\frac{di}{dt} + R_1 i + Ri = e_{in}$$

$$Ri = e_{out}$$

Step 2. Take Laplace transform of the above equations.

$$LsI(s) + R_1 I(s) + RI(s) = E_{in}(s)$$

$$RI(s) = E_{out}(s)$$

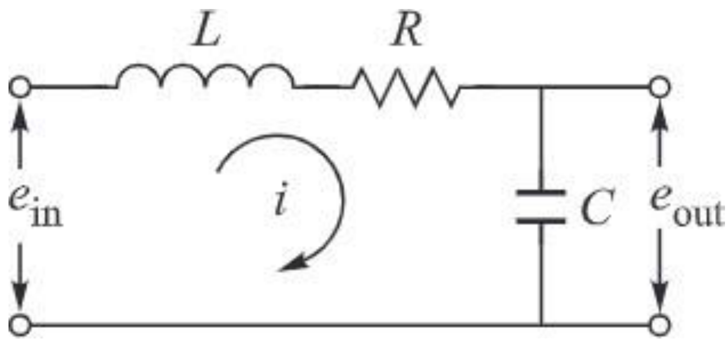
$$(Ls + R_1 + R)\, I(s) = E_{in}(s)$$

$$RI(s) = E_{out}(s)$$

Step 3. Determine the transfer functions from above equations.

$$TF = \frac{E_{out}(s)}{E_{in}(s)} = \frac{R}{Ls + R_1 + R}$$

Case -2: Determine the Transfer function for below circuit



Suppose a current i is flowing through the circuit (loop).

Step 1. Write Kirchhoff's voltage equation for the system (apply KVL to the system).

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int i dt = e_{in}$$

$$\frac{1}{C}\int i dt = e_{out}$$

Step 2. Take Laplace transform of the above equations.

$$LsI(s) + RI(s) + \frac{1}{C}\frac{1}{s} I(s) = E_{in}(s)$$

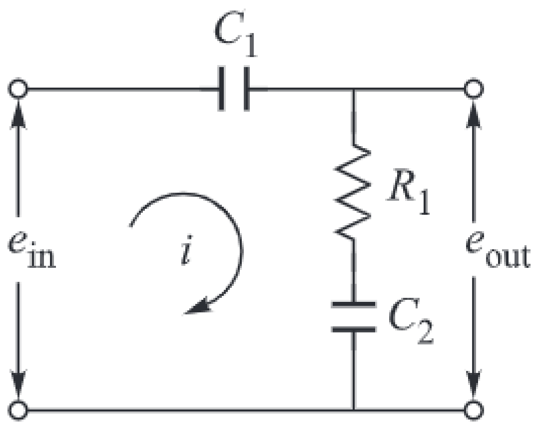
$$\frac{1}{C}\frac{1}{s} I(s) = E_{out}(s)$$

Step 3. Determine the transfer functions from above equations.

$$TF = \frac{E_{out}(s)}{E_{in}(s)} = \frac{\frac{1}{Cs}\ I(s)}{I(s)\ [\ Ls + \frac{1}{Cs} + R\ ]}$$

$$= \frac{1}{I(s)\ [\ LCs^2 + RCs + 1\ ]}$$

Case -3: Determine the Transfer function for below circuit



Suppose a current i is flowing through the circuit (loop).

Step 1. Write Kirchhoff's voltage equation for the system (apply KVL to the system).

$$\frac{1}{C_1} \int idt + \frac{1}{C_2} \int idt + R_1 i = e_{in}$$

$$\frac{1}{C_2} \int idt + R_1 i = e_{out}$$

Step 2. Take Laplace transform of the above equations.

$$\frac{1}{C_1}\frac{1}{s} I(s) + \frac{1}{C_2}\frac{1}{s} I(s) + R_1 I(s) = E_{in}(s)$$

$$\frac{1}{C_2}\frac{1}{s} I(s) + R_1 I(s) = E_{out}(s)$$

Step 3. Determine the transfer functions from above equations.

$$I(s)\ [\frac{1}{C_1 s} + \frac{1}{C_2 s} + R_1\ ] = E_{in}(s)$$

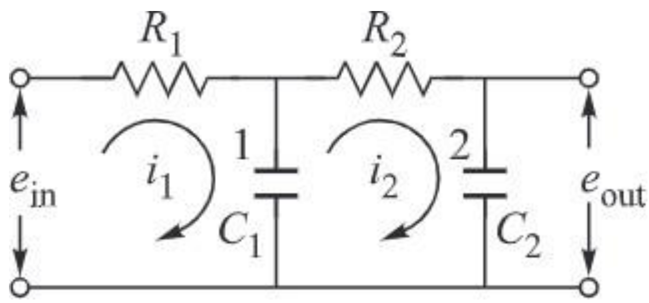
$$I(s)\ [\frac{1}{C_2 s} + R_1\ ] = E_{out}(s)$$

$$TF = \frac{E_{out}(s)}{E_{in}(s)} = \frac{(R_1C_2s + 1)\,C_1s}{R_1C_1C_2s^2 + C_1s + C_2s}$$

$$= \frac{1}{I(s)\,[\,LCs^2 + RCs + 1\,]}$$

2. **Transfer function for Cascade systems**

Case -1: Determine the Transfer function for below circuit



In this system, E_{in} is the input and E_{out} is the output. There are two identical RC networks connected in cascade so that output of the first RC circuit is fed as input to the second RC circuit. The currents i_1 and i_2 are flowing in the loops 1 and 2, respectively.

Step 1. Write Kirchhoff's voltage equation for the system (apply KVL to the system).

$$\frac{1}{C_1}\int (i_1 - i_2)\,dt \; + R_1i_1 = e_{in}$$

$$\frac{1}{C_1}\int (i_1 - i_2)\,dt \; + R_2i_2 \; = \frac{-1}{C_2}\int i_2\,dt \; = e_{out}$$

Step 2. Take Laplace transform of the above equations.

$$\frac{1}{C_1s}\,[\,I_1(s) - I_2(s)] + R_1I_1(s) \; = E_{in}(s)$$

$$\frac{1}{C_1s}\,[\,I_1(s) - I_2(s)] + R_2I_2(s) \; = \frac{1}{C_2s}\,I_2(s) = E_{out}(s)$$

Step 3. Determine the transfer functions from above equations.

$$TF = \frac{E_{out}(s)}{E_{in}(s)} = \frac{1}{R_1C_1R_2C_2s^2 + (R_1C_1 + R_2C_2 + R_1C_2)s + 1}$$

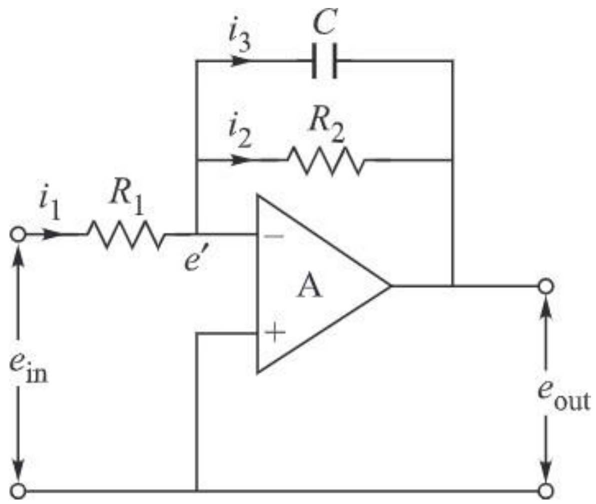
As stated above, the circuit (system) contains two RC circuits cascaded. But their overall transfer function is not a product of $\frac{1}{R_1C_1s+1}$ and $\frac{1}{R_2C_2s+1}$. If we derive transfer function for single circuit, the output is unloaded. Also, when input of the second circuit is taken from the first circuit, the original transfer function is no longer valid. The degree of loading effect of the circuit decides modified transfer function.

3. Transfer Function of Passive and Active Elements

Passive elements. These elements do not take part in any energy transformation, e.g. resistors, capacitors and inductors. Such elements in the system store the energy but can also be used later in the system. This energy cannot exceed when delivered to the system. System elements which contain passive elements are called passive systems.

Active elements. These elements take part in energy transformation. They can deliver external energy into the system. The examples of such elements are transistor, diode, op-amp.

Case -1: Determine the Transfer function for below circuit



The circuit contains both active and passive elements. here A is the operational amplifier

Step 1. Determine e_{out}

Step 2. Calculate i_1, i_2, and i_3

$$i_1 = \frac{e_{in} - e'}{R_1} \;;\quad i_2 = \frac{e' - e_{out}}{R_2} \;; i_1 = \frac{Cdv_c}{dt} = C\frac{d(e' - e_{out})}{dt}$$

$$i_1 = i_2 + i_3$$

$$\frac{e_{in} - e'}{R_1} = \frac{e' - e_{out}}{R_2} + C\frac{d(e' - e_{out})}{dt}$$

Step 3. According to virtual ground concept of op-amp, $e' = 0$

$$\frac{e_{in}}{R_1} = \frac{-e_{out}}{R_2} - C\frac{de_{out}}{dt}$$

Step 4. Take Laplace transform of the above equations.

$$\frac{E_{in}(s)}{R_1} = \frac{-E_{out}(s)}{R_2} - CsE_{out}(s)$$

$$\frac{E_{in}(s)}{R_1} = -E_{out}(s)\left(\frac{1}{R_2} + Cs\right)$$

$$\frac{E_{in}(s)}{R_1} = -E_{out}(s)\left(\frac{1 + R_2 Cs}{R_2}\right)$$

Step 5. Determine the transfer functions from above equations.

$$TF = \frac{E_{out}(s)}{E_{in}(s)} = -\frac{R_2}{R_1}\left[\frac{1}{R_1 C_2 s + 1}\right]$$

BLOCK DIAGRAM ALGEBRA OF CONTROL SYSTEMS

In a control system, block diagram is used to simplify the interconnections and compositions of the system. Any complex system comprising several non-loading elements can be represented by interconnecting the blocks for individual elements. Lines connect these blocks with arrows indicating the unidirectional flow of information from output of one block to input of the other. A single block can replace any number of connected or cascaded blocks.

Block diagram representations of some control systems become complex or very complicated. Hence these block diagrams should be reduced or simplified. The technique used to reduce or simplify complex block diagrams is called block diagram reduction technique in which complicated block diagram containing many feedbacks loops can be simplified by step-by-step rearrangements. It is also called block diagram algebra involving different rules, which will be discussed in this section. This simplification or reduction of block diagram reduces the labour required for mathematical analysis.

1. Symbols Used in Block Diagram Algebra Block diagram.

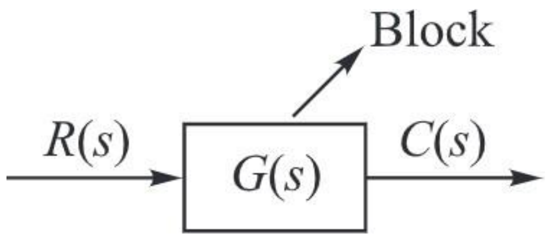


Figure shows block diagram of a transfer function G(s). R(s) is the reference input and C(s) is the output signal or controlled variable

Block diagram elements. Block diagram elements include symbols for addition (summing) and subtraction (differencing). In feedback control system, sensing device is an important component, which acts as a function point for signal comparisons. It includes differential amplifier, synchro's, potentiometers, signal processing transducers and so on. Figures (a) and (b) represents symbols for summing and differencing, respectively.

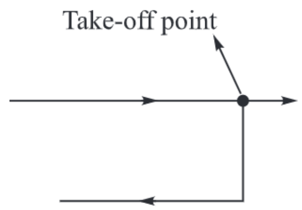
(a) Symbol for differencing (b) Symbol for summing

In Figures (a) and (b): R(s) is the reference input E(s) is the error signal and B(s) is the feedback signal

Therefore, for Figure (a), E(s) = R(s) - B(s) and

Figure (b), E(s) = R(s) + B(s)

Take-off point. Figure shows a take-off point.



Block diagram of closed loop control system. Figure (a) shows complex block diagram of a closed loop control system.

In Figure (a),

- R(s) is the reference input
- E(s) is the error signal
- B(s) is the feedback signal
- C(s) is the output signal or controlled variable
- H(s) is the transfer function of the feedback element
- G(s) is the forward path transfer function
- T(s) is the closed loop transfer function

We have

$$G(s) = \frac{C(s)}{E(s)} \quad ; T(s) = \frac{C(s)}{R(s)} \quad ; \; H(s) = \frac{B(s)}{C(s)}$$

$$G(s) * E(s) = C(s) - - - - - (1)$$

$$C(s) * H(s) = B(s) - - - - - (2)$$

$$E(s) = R(s) - B(s)$$

$$E(s) = R(s) - C(s) * H(s) - - - - - (3)$$

Substitute E(s) value in eq (1)

$$C(s) = G(s) * E(s) = G(s) * \{ R(s) - C(s) * H(s)\}$$

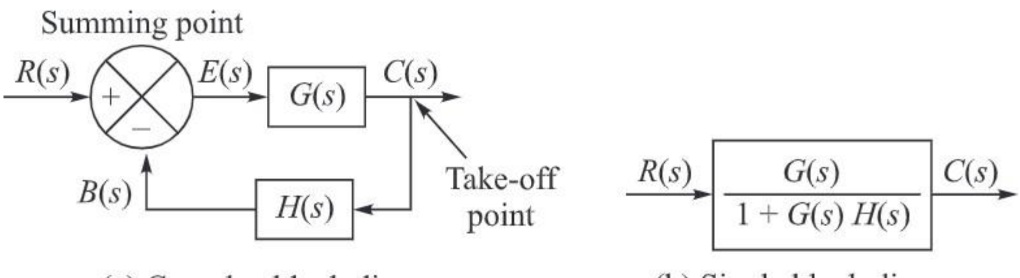
$$C(s) = G(s)R(s) - G(s)C(s) * H(s)$$

$$C(s) + G(s)C(s)H(s) = G(s)R(s)$$

$$C(s) (1 + G(s)H(s)) = G(s)R(s)$$

$$TF = \frac{C(s)}{R(s)} = \frac{G(s)}{(1 + G(s)H(s))}$$

Thus, the system block diagram can be reduced to a single block as shown in Figure(b).

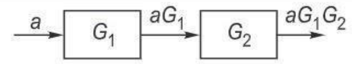
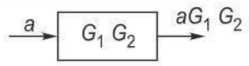
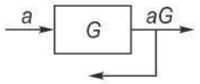
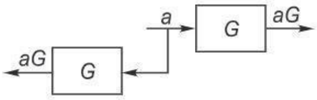
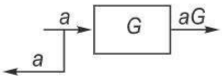
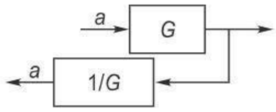
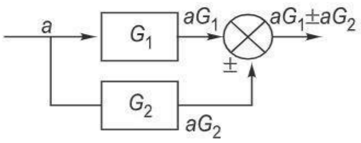
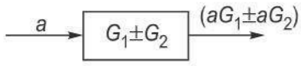
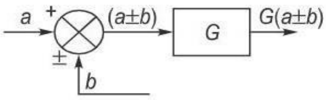
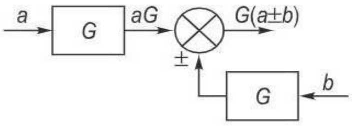
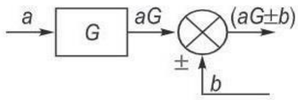
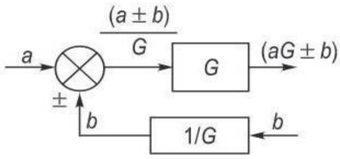
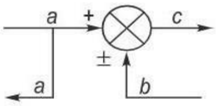
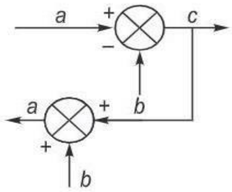
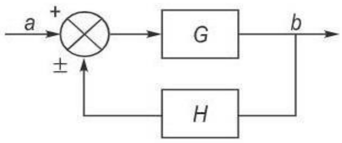
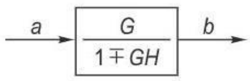
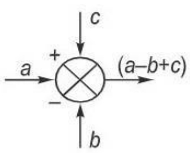
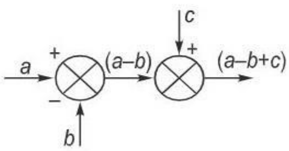
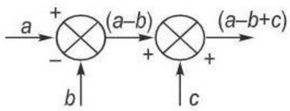
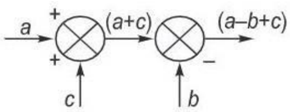
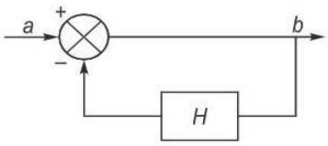
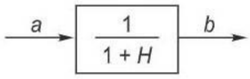
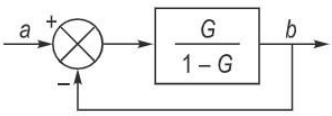
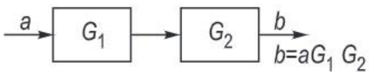
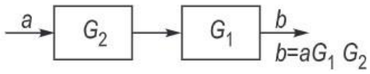


(a) Complex block diagram (b) Single block diagram

Rules for block diagram reduction

As discussed above, a complex block diagram can be simplified by rearranging the blocks using rules of block diagram reduction algebra. Some important rules are listed in Table

Rules for block diagram reduction

Sr. No.	Rule	Original diagram	Equivalent diagram
1.	Combining cascaded blocks		
2.	Moving a take-off point ahead a block		
3.	Moving a take-off point after a block		
4.	Eliminating a forward loop		
5.	Moving a summing point after a block		
6.	Moving a summing point before a block		
7.	Moving a take-off point beyond a summing point		
8.	Eliminating a feedback loop		
9.	Expansion of summing point		
10.	Interchange of summing point		
11.	Eliminating a feedback loop		
12.	Inserting a feedback path		
13.	Interchange of blocks		

2. Block Diagram Algebra of Multiple Input-Multiple Output System

In some process control systems, there may be multiple inputs and outputs, and it is desired that changes in one reference input affect only one output. When multiple inputs are applied to any linear system, each input can be treated independent of the others. The outputs corresponding to each input get added together.

Consider a three-input linear system as shown in Figure (a). Here three inputs R_1, R_2 and R_3 are applied.

Step 1. First, we will consider only one input, i.e. $R_1(s)$. The block diagram becomes as shown in Figure (b).

$$\frac{C_1(s)}{R_1(s)} = \frac{G_1G_2G_3}{(1 + G_1G_2G_3H)}$$

$$C_1(s) = \frac{G_1G_2G_3}{(1 + G_1G_2G_3H)} R_1(s)$$

Step 2. Assume, that only one input, i.e. $R_2(s)$. The block diagram becomes as shown in Figure (c).

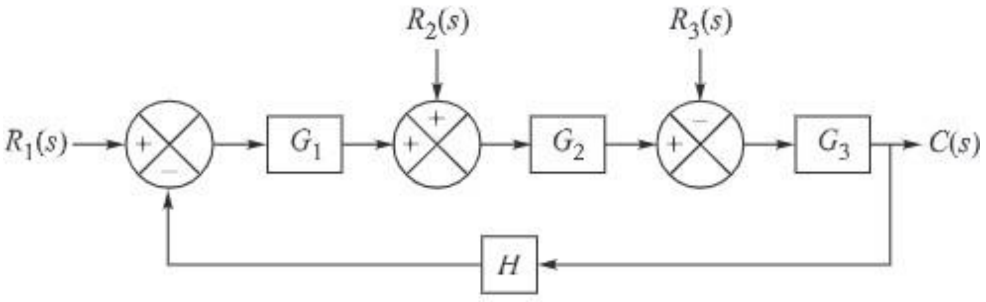
$$\frac{C_2(s)}{R_2(s)} = \frac{G_2G_3}{(1 + G_1G_2G_3H)}$$

$$C_2(s) = \frac{G_2G_3}{(1 + G_1G_2G_3H)} R_2(s)$$

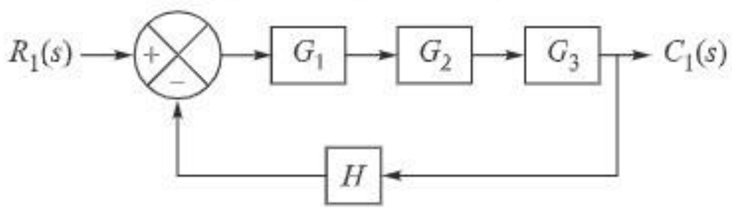
Step 3. Suppose only one input, i.e. $R_3(s)$. The block diagram becomes as shown in Figure (c).

$$\frac{C_3(s)}{R_3(s)} = \frac{G_3}{(1 + G_1G_2G_3H)}$$

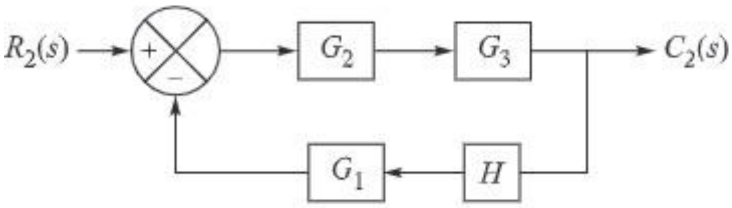
$$C_3(s) = \frac{G_3}{(1 + G_1G_2G_3H)} R_3(s)$$



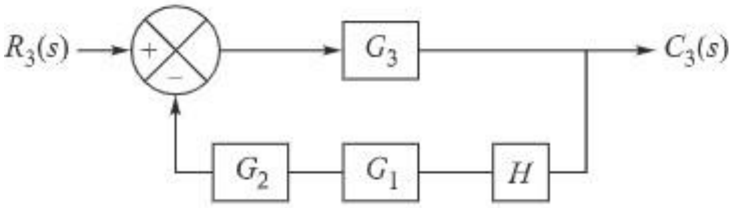
(a) Three-input linear system



(b) The system with the input $R_1(s)$



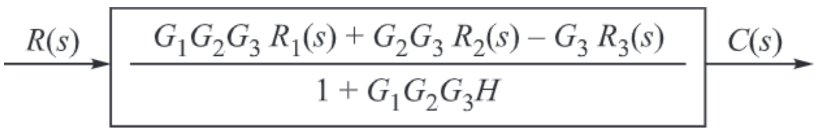
(c) The system with the input $R_2(s)$



(d) The system with the input $R_3(s)$

Step 4. By applying the superposition theorem, the total output of the system is as follows.

$$C(s) = C_1(s) + C_2(s) + C_3(s)$$



COMMONLY USED CONTROL SYSTEM COMPONENTS

1. DC Servomotors

DC motors which are used in servosystems are called tic servomotors. This motor provides high starting torque due to low inertia. This low inertia can be achieved by reducing armature diameter with increasing armature length so that the desired output power can be achieved. Low power rating dc servomotors are used in computer disk drives, printer, tape drives and so on. Medium and large power dc servomotors are used in machine tool industries, robots and numerically-controlled machines.

In dc servomotors, field winding may be connected either in series with the armature or separate from the armature.

DC servomotors may be used in two different control modes as follows:

- Armature control mode, in which the speed of the dc servomotor is controlled by armature current with field current constant.
- Field control mode, in which the armature current is maintained constant and speed of the dc servomotor is controlled by field voltage.

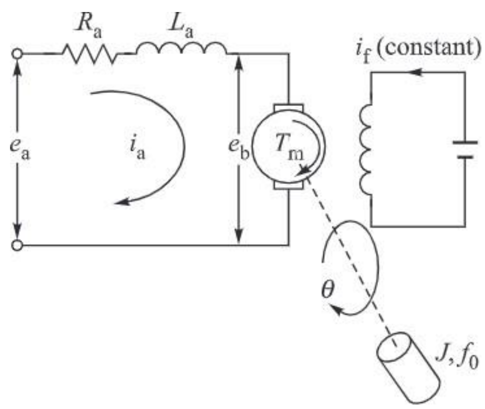
Both control modes of dc servomotor with their transfer functions are discussed further.

Armature control of dc servomotor

Consider an armature-controlled dc servomotor as shown in Figure.

In this control mode, the field current is constant.

Let



R_a is the armature resistance in SI

L_a is the armature winding inductance in henry

i_a is the armature current in ampere

i_f is the field current in ampere

e_a is applied voltage across the armature in volt

E_b is the back emf in volt

θ is angular displacement of the motor shaft-shaft in radian

T_m is torque developed by the motor in N-m

f_o is equivalent viscous friction coefficient of the motor and the load referred to the motor shaft in N-m rad^{-1}/sec.

J is equivalent moment of inertia of the motor and the load referred to the motor shaft in kg - m^2.

The air gap flux $\emptyset$ is proportional to the field current i_f, i.e.

$$\emptyset \text{ a } i_f$$

$$\emptyset = k_f\, i_f$$

where k_f is a constant.

The torque T_m developed by the motor is proportional to the product of the armature current and the air gap flux, i.e.

$$T_m \text{ a } i_a\emptyset$$

$$T_m = k_1\, i_a\emptyset$$

$$T_m = k_1\, i_a k_f\, i_f$$

where k_1 is a constant.

In this condition, the field current is constant. Hence the flux is constant and the above equation can be written as

$$T_m = k_T\, i_a$$

where k_T is motor-torque constant

When the armature is rotating, a voltage proportional to product of the flux and the angular velocity is induced in the armature.

At constant flux, the induced voltage E_b is directly proportional to the angular velocity $\frac{d\theta}{dt}$.

$$E_b = -k_b * \frac{d\theta}{dt}$$

where kb is the back emf constant.

This is an armature-controlled servomotor. Its speed is controlled by an armature voltage. The differential equation for an armature circuit is as follows:

$$L_a \frac{di_a}{dt} + R_a\, i_a + E_b = -E_a$$

As the armature current flows, it produces a torque, which is represented by the equation

$$J\frac{d^2\theta}{dt} + f_0\frac{d\theta}{dt} = T_m = k_T i_a$$

By assuming all initial conditions zero and taking Laplace transforms of the above equations,

$$E_b(s) = k_b s\theta(s)$$

$$E_a(s) = (L_a s + R_a)I_a(s) + E_b(s)$$

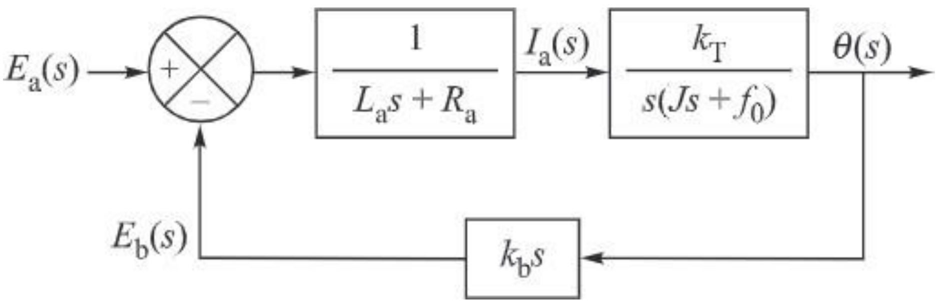
$$(Js^2 + f_0 s)\theta(s) = T_m(s) = k_T I_a(s)$$

The transfer function of dc servomotor from the above equations is obtained as follows.

$$\frac{\theta(s)}{E_a(s)} = \frac{k_T}{s\,[L_a J s^2 + (L_a f_0 + R_a J)s + R_a f_0 + k_T k_b}$$

Armature-controlled dc servomotor is a feedback system. As voltage e_a is applied, it is opposed by back emf E_b. Hence the net applied voltage across the circuit containing resistance (R_a) and inductance (La) is (E_a — E_b). Hence the armature currents I_a(s) flows through this circuit. As the field current is constant, a torque k_T I_a(s) is produced which rotates the load at a speed θ(s) against the moment of inertia J and the coefficient of viscous friction f_o.

Figure shows the block diagram representation of an armature-controlled dc motor. In this diagram, the back emf signal E_b(s) = $k_b\theta$(s) is taken off from the shaft speed θ(s) and the feedback negatively to the summing point.

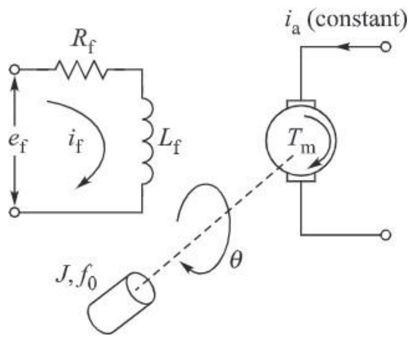


Field control of dc servomotor

Consider a field-controlled dc motor as shown in Figure.

In this mode, the armature current (i_a) is constant.

Let



R_f is resistance of field winding in Ω

L_f is the field winding inductance in henry

i_a is the armature current in ampere

i_f is the field current in ampere

E_f is the field control voltage in volt

θ is angular displacement of the motor shaft in radian

T_m is torque developed by the motor in N-m

f_o is equivalent viscous friction coefficient of the motor and the load referred to the motor shaft in N-m rad^{-1}/sec.

J is equivalent moment of inertia of the motor and the load referred to the motor shaft in kg-m^2.

The torque equation of the motor is

$$T_m = k_1\, i_a k_f\, i_f = k_T\, i_f$$

where k_1, k_f and k_T are constants.

Equation for the field circuit is as follows:

$$L_f \frac{di_f}{dt} + R_f i_f = E_f$$

When the field current flows, it produces the torque, which is applied to the inertia and the friction. It is given by

$$J\frac{d^2\theta}{dt^2} + f_0\frac{d\theta}{dt} = T_m = k_T i_f$$

By assuming all initial conditions zero and taking Laplace transforms of the above equations,

$$(L_f s + R_f)I_f(s) = E_f(s)$$
$$(Js^2 + f_0 s)\theta(s) = T_m(s) = k_T I_f(s)$$

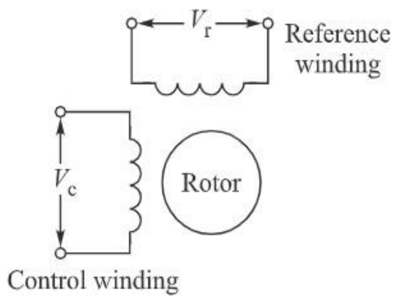
The transfer function of de servomotor in field control mode from the above equations is obtained as

$$\frac{\theta(s)}{E_f(s)} = \frac{k_T}{s(L_f s + R_f)(Js + f_0)}$$

Field-controlled dc motor requires low power servo amplifier and constant armature current can be supplied from inexpensive constant current amplifier.

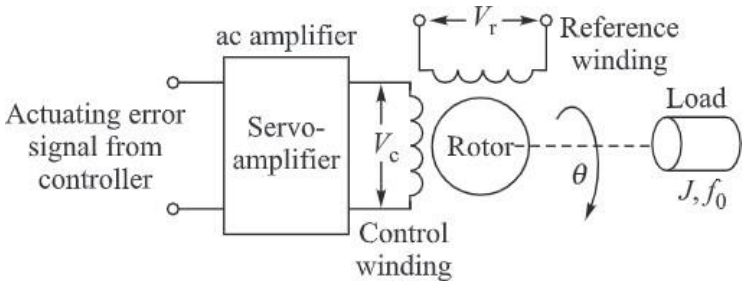
2. AC Servomotors

Basically, an ac servomotor is a two-phase induction motor having special design features. It is useful in low-power control applications and low drift ac amplifier can drive it. Figure shows an ac servomotor. It consists of two stator windings—reference winding and control winding. These two windings are placed 90° electrical apart in space and excited by ac voltages which differ in time-phase by 90°. The reference winding is excited by a fixed voltage V_r, and the control winding voltage V_c is 90° phase shifted by phase shifting network with respect to the reference voltage V_r. The rotor is squirrel cage or drag cup-type having small diameter in order to reduce the inertia.



The two windings are excited by voltage of equal rms. magnitude and 90° phase shift. It results in developing a magnetic field of constant magnitude rotating at synchronous speed. The direction of rotation depends upon the phase relationship between V_r and V_c. The rotating magnetic field interacts with the currents and produces torque on the rotor in the direction of rotation.

Figure shows control scheme for an ac servomotor. The reference winding is excited by a reference voltage source. The control winding is supplied by a servo-amplifier having variable magnitude (phase difference ± 90° with respect to the reference phase) and polarity.



Advantages of ac servomotors are as follows:

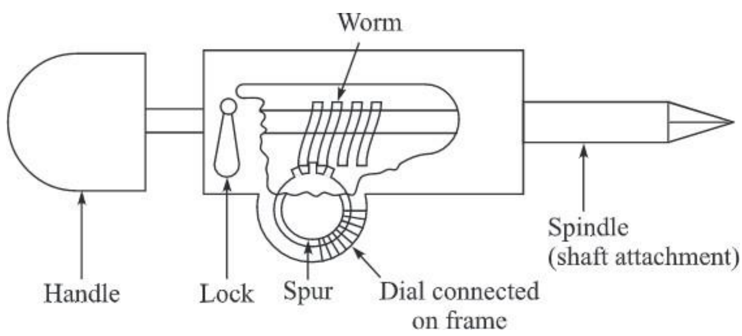
(i) Drift-free ac amplifier
(ii) Low rotor inertia
(iii) Rugged construction
(iv) Rotor withstands at higher temperature

3. Tachometers

Tachometer is used for angular speed measurement. Basically, tachometers are classified as mechanical and electrical tachometers. Electrical tachometers are further divided into ac and dc tachometers. In control system, tachometer is used as a feedback element.

Mechanical tachometers

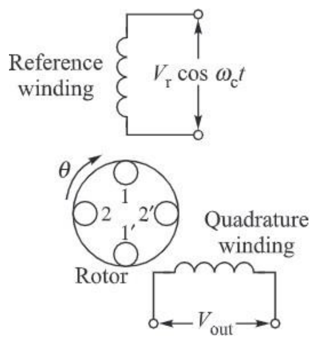
This type of tachometer consists of mechanical assembly and movements for the measurement of speed. Revolution counter is a type of mechanical tachometer. Figure shows the construction of a revolution counter (mechanical counter).



It is a very simple method for the measurement of rotational speed. It consists of a worm gear connected to a spindle. The worm gear meshes with spur gear moves a calibrated dial to indicate the revolutions. The spindle or shaft is driven by the source speed which is to be measured. The counter has two dials, inner and outer, to indicate the speed (revolutions) of the spindle or shaft. A stopwatch is attached to the assembly for indicating time and the revolution counter measures both revolutions and time. For measurement of the speed, the spindle is connected to the rotating shaft whose speed is to be measured. This instrument is held and operated manually to start the counter and the stopwatch. It is a direct speed measurement device and its operation cannot be affected by any environmental variations.

Electrical tachometers

This type of tachometer converts the angular or rotational speed into electrical signal and indicates on the indicator provided.



AC tachometer. Figure shows the arrangement of an ac tachometer. It consists of two stator field coils or windings placed 90° electrical apart or mounted at right angles to each other. These windings are reference winding and quadrature winding. A rotating element, i.e. a rotor, is placed in the air gap between the magnetic structure. Generally, the rotor is a thin aluminum cup to minimize the losses and low inertia. When the reference ac voltage, i.e. Vr cosωt it is applied to the reference winding, a magnetic flux gets developed in the air gap.

The rotor is connected to the rotating shaft whose angular speed is to be measured, due to which the rotor rotates and an output voltage gets induced. This output voltage is proportional to the angular speed. The emf induced in quadrature winding is proportional to the rotor speed and in phase with voltage applied to the reference winding.

Let

θ is the angular speed and

V_{out} is the output voltage

According to speed theory, the output voltage (V_{out}) is proportional to the angular speed (θ), i.e.

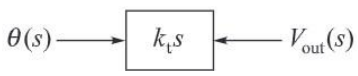
$$V_{out} \text{ a } \theta$$

$$V_{out} = k_t\theta$$

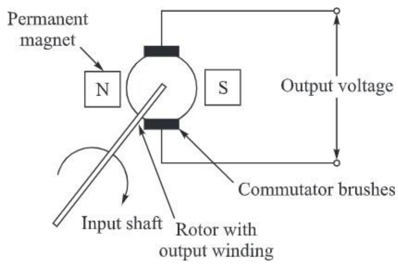
where k_t is the proportionality constant.

Taking Laplace transform of the equation $V_{out}(s) = k_t s\theta(s)$, we have Transfer function,

$$\text{Transfer function, } \frac{V_{out}(s)}{\theta(s)} = k_t s$$



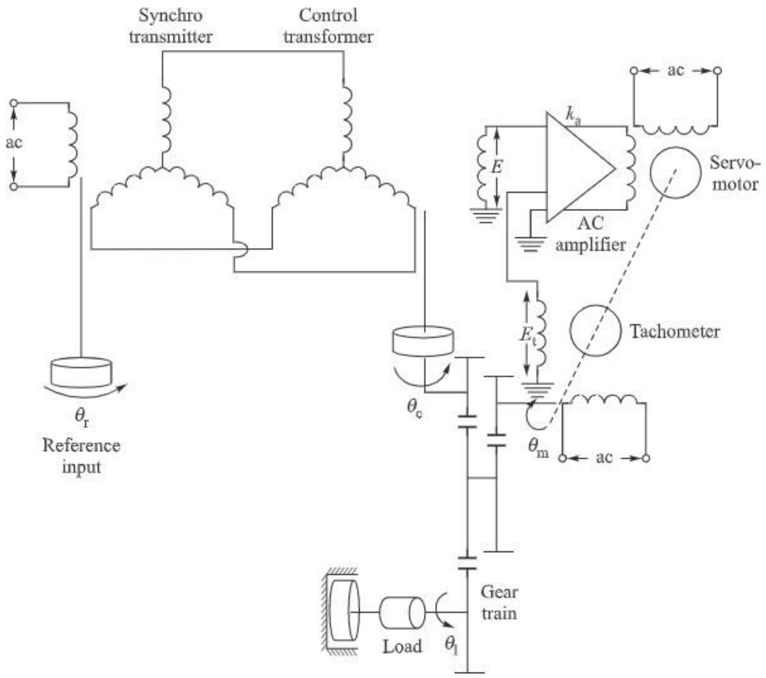
DC tachometer. Figure shows construction of a dc tachometer. It consists of a permanent magnet which provides the magnetic flux. An output winding is placed on a rotor called armature winding. When the rotor speed is zero, there is no relative motion in the magnetic field and winding. Hence the output voltage is zero. As the rotor speed increases, the relative motion between the magnetic field and the winding increases resulting in increasing the output voltage. As the rotor speed increases, the output voltage also increases. This output voltage is sinusoidal, which is converted into dc voltage using commutator and brushes.



4. **AC Position Control System**

Figure shows an ac position control system. It uses synchro transmitter-control transformer pair as an error detector and an ac amplifier to amplify the signal. An ac servomotor is used to drive the load shaft through a gear train arrangement. The ac tachometer is used for providing the rate feedback.

In this system, the position of mechanical load is controlled with respect to the position of reference shaft. θ_r is the angular displacement of reference input shaft of ac synchro transmitter. The ac servomotor is supplied by carrier voltages on the two phases 90° out of phase with respect to each other. This is achieved by exciting reference motor phase and synchro transmitter rotor coil directly from the carrier supply, while the carrier voltage driving the control phase of the motor is obtained by amplifying the error signal. The carrier phase is shifted 90° by using two RC networks.



$\theta_1$is angular displacement of the load shaft in rad and θ_m is angular displacement of the motor shaft in radian

The overall transfer function of the system is

$$\frac{\theta_c(s)}{\theta_r(s)} = \frac{k_m k_a k_s n}{T_m s^2 + (1 + k_m k_a k_s) s + k_m k_a k_s n}$$

where k_a is the amplifier gain in volts/volt

k_m is the motor gain constant in rad/volt

k_s, is the synchro sensitivity in volts/rad

AC position control systems are used in aircraft and missile systems and instrumentation field.

Advantages of ac position control systems are as follows:

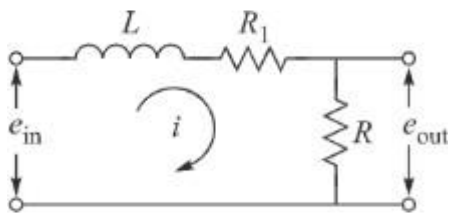
(i) AC amplifiers are more stable so there is no drift in operation.

(ii) Because of small size of ac components, the system is compact.

(iii) It has low cost.

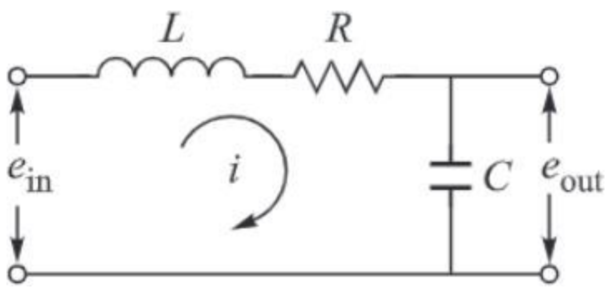
ASSISGNMENT QUESTIONS:

1. What is meant by control system? explain about open and closed loop control system
2. Enumerate the difference the between open and closed loop control system
3. Explain about adaptive control system with neat sketch
4. What is meant by transfer function?
5. Determine the Transfer function for below circuit



Tutorial questions

1. Explain the working principle of tachometers and explain the types of tachometers
2. Determine the Transfer function for below circuit



3. Explain the Commonly Used Control System Components

UNIT 5

PROCESS CONTROL

UNIT-5

COURSE OBJECTIVE

- **To understand the different control schemes generally used to get best output.**

COURSE OUTCOME

- **Identify different types of process control required for specific application**

PROCESS CONTROL

INTRODUCTION

Process controls is a mixture between the statistics and engineering discipline that deals with the mechanism, architectures, and algorithms for controlling a process. A process is the science of automatic control, denotes an operation or series of operation on fluid or solid material during which the materials are placed in more and useful state. The physical and chemical state at the materials is not necessarily altered .many external and internal conditions affect the performance of a process those conditions may be expressed in terms of process variable such as temperature, pressure, flow, liquid level, dimensions, weight, volume etc.

The role of process control has changed throughout the years and is continuously shaped by technology. The traditional role of process control in industrial operations was to contribute to safety, minimized environmental impact, and optimize processes by maintaining process variable near the desired values. Generally, anything that requires continuous monitoring of an operation involve the role of a process engineer. In years past the monitoring of these processes was done at the unit and were maintained locally by operator and engineers. Today many chemical plant have gone to full automation which means that engineers and operators are helped

Benefits of Process Control:

The benefits of controlling or automating process are in a number of distinct area in the operation of a unit or chemical plant. Safety of workers and the community around a plant is probably concern number one or should be for most engineers as they begin to design their processes. Chemical plants have a great potential to do severe damage if something goes wrong and it is inherent the setup of process control to set boundaries on specific unit so that they don"t injure or kill workers or individuals in the community.

Definitions:

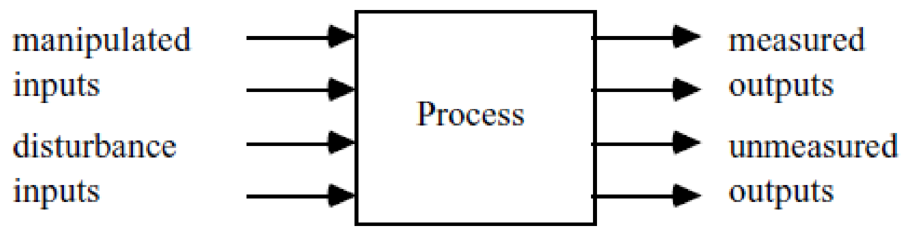
In controlling a process there exist two type of classes of variables.

Classes of process variables

- **Input Variable**

- ✓ **Manipulated inputs**
- ✓ **Disturbances**

- ➢ **Output Variable or Control Variable**
  - ✓ **Measured output variable**
  - ✓ **Unmeasured output variable**
- ➢ **Controlled variable**
- ➢ **Manipulated Variable**
- ➢ **Load variable**



a. Input/Output representation

- ➢ **Input Variable** – This variable shows the effect of the surroundings on the process. It normally refers to those factors that influence the process
  - ✓ *Manipulated inputs:* variable in the surroundings can be control by an operator or the control system in place.
  - ✓ . *Disturbances:* inputs that cannot be controlled by an operator or control system. There exist both measurable and immeasurable disturbances.
- ➢ **Output variable** - Also known as the *control variable* These are the variables that are process outputs that effect the surroundings. These variables may or may not be measured.
  - ✓ Measured output variable: Measurements can be made continuously or discrete interval of time.
  - ✓ Unmeasured output variable:The variables cannot be determined.
- ➢ **Controlled variable-** The controlled variable of the process should be that variable which most directly indicates the desired for or state of the product.
- ➢ **Manipulated Variable-** the Manipulated variable of the process should be that variable which most directly indicates the desired form or state of the product.
- ➢ **Load Variable-** The load variables of the process are all other independent variables except the controlled variable and manipulated variable.

As we consider a controls problem. We are able to look at two major control structures.

- Single input-Single Output (SISO): for one control(output) variable there exist one manipulate (input) variable that is used to affect the process
- Multiple input-multiple output(MIMO): There are several control (output) variable that are affected by several manipulated (input) variables used in a given process.

Design Procedure for process control

- **Understand the process:** Before attempting to control a process it is necessary to understand how the process works and what it does.
- **Identify the operating parameters:** Once the process is well understood, operating parameters such as temperatures, pressures, flow rates, and other variables specific to the process must be identified for its control.
- **Identify the hazardous conditions:** In order to maintain a safe and hazard-free facility, variables that may cause safety concerns must be identified and may require additional control.
- **Identify the measurables:** It is important to identify the measurables that correspond with the operating parameters in order to control the process.
- **Identify the points of measurement:** Once the measurables are identified, it is important locate where they will be measured so that the system can be accurately controlled.
- **Select measurement methods:** Selecting the proper type of measurement device specific to the process will ensure that the most accurate, stable, and cost-effective method is chosen. There are several different signal types that can detect different things.
- **Select control method:** In order to control the operating parameters, the proper control method is vital to control the process effectively. On/off is one control method and the other is continuous control. Continuous control involves Proportional (P), Integral (I), and Derivative (D) methods or some combination of those three.
- **Select control system:** Choosing between a local or distributed control system that fits well with the process effects both the cost and efficacy of the overall control.
- **Set control limits:** Understanding the operating parameters allows the ability to define the limits of the measurable parameters in the control system.
- **Define control logic:** Choosing between feed-forward, feed-backward, cascade, ratio, or other control logic is a necessary decision based on the specific design and safety parameters of the system.

A controller is a device, using mechanical, hydraulic, pneumatic or electronic techniques often in combination, which monitors and physically alters the operating conditions of a given dynamical system. Broad classifications of different controller modes used in process control are as follows:

Controller Modes

Controller modes refer to the methods to generate different types of control signals to final control element to control the process variable.
Broad classifications of different controller modes used in process control are as follows:

(1) Discontinuous Controller Modes
   (a) Two-position (ON/OFF) Mode
   (b) Multiposition Mode
   (c) Floating Control Mode: Single Speed and Multiple Speed

(2) Continuous Controller Modes
   (a) Proportional Control Mode
   (b) Integral Control Mode
   (c) Derivative Control Mode

(3) Composite Controller Modes
   (a) Proportional-Integral Control (PI Mode)
   (b) Proportional-Derivative Control (PD Mode)
   (c) Proportional-Integral-Derivative Control (PID or Three Mode Control)

Based on the controller action on the control element, there are two modes:

(1) *Direct Action*: If the controller output increases with increase in controlled variable then it is called direct action.
(2) *Reverse Action*: If the controller output decreases with increase in controlled variable then it is called reverse action

The choice operating mode for any given process control system is complicated decision. It involves not only process characteristics but cost analysis, product rate, and other industrial factors. The process control technologist should have good understanding of the operational mechanism of each mode and its advantages and disadvantages.

In general, the controller operation for the error e_p is expressed as a relation:

$$p = F(e_p) \qquad (2.1)$$

where $F(e_p)$ represents the relation by which the appropriate controller output is determined.

Discontinuous Controller Modes

In these controller modes the controller output will be discontinuous with respect to controlled variable error.

Two-Position (ON/OFF) Mode

The most elementary controller mode is the two-position or ON/OFF controller mode. It is the simplest, cheapest, and suffices when its disadvantages are tolerable. The most general form can be given by

$$P = \begin{cases} 0\ \% & e_p < 0 \\ 100\ \% & e_p > 0 \end{cases} \qquad (2.2)$$

The relation shows that when the measured value is less than the setpoint (i.e. $e_p > 0$), the controller output will be full (i.e. 100%), and when the measured value is more than the setpoint (i.e. $e_p < 0$), the controller output will be zero (i.e. 0%).

Neutral Zone: In practical implementation of the two-position controller, there is an overlap as e_p increases through zero or decreases through zero. In this span, no change in the controller output occurs which is illustrated in Fig. 2.1

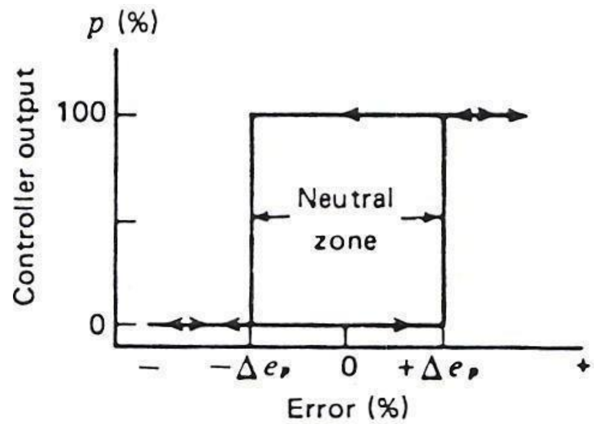


Fig. 2.1 Two-position controller action with neutral zone.

It can be observed that, until an increasing error changes by Δe_p above zero, the controller output will not change state. In decreasing, it must fall Δe_p below zero before the controller changes to 0%. The range $2\Delta e_p$ is referred to as *neutral zone or differential gap*. Two-position controllers are purposely designed with neutral zone to prevent excessive cycling. The existence of such a neutral zone is an example of desirable hysteresis in a system.

Applications: Generally the two-position control mode is best adapted to:

- Large-scale systems with relatively slow process rates

Example: Room heating systems, air-conditioning systems.

Systems in which large-scale changes are not common
Examples: Liquid bath temperature control, level control in large-volume tanks.

Problem 2.2

A liquid- level control system linearly converts a displacement of 2 to 3 m into a 4 to 20 mA control signal. A relay serves as the two-position controller to open and close the inlet valve. The relay closes at 12 mA and opens at 10 mA. Find (a) the relation between displacement level and current, and (b) the neutral zone or displacement gap in meters.

Solution

Given data: Liquid- level range = 2 to 3 m i.e. H_{min} = 2m & H_{max} = 3m

Control signal range = 4 to 20 mA i.e. I_{min} = 4mA & I_{max} = 20mA

(a) Relation between displacement level (H) and current (I)

(b) Neutral zone (NZ) in meters.

(a) The linear relationship between level and current is given by

$$H = K\,I + Ho$$

The simultaneous equations for the above range are:

For low range signal $2 = K \times 4 + Ho$

For higher range signal $3 = K \times 20 + Ho$ Solving

the above simultaneous equations we get:

$$K = 0.0625 \text{ m/mA}, \quad \& \quad Ho = 1.75 \text{ m}$$

Therefore, the relation between displacement level (H) and current (I) is given by

$$\mathbf{H = 0.0625\, I + 1.75}$$

(b) The relay closes at 12 mA, which is high level, H_H

$$H_H = 0.0625 \times 12 + 1.75 = 2.5$$

m The relay opens at 10 mA, which is low level, H_L

$$H_L = 0.0625 \times 12 + 1.75 = 2.375 \text{ m}$$

Therefore, the neutral zone, NZ = (H_H - H_L) = (2.5 - 2.375) = 0.125 m

Proble m 2.3

As a water tank loses heat, the temperature drops by 2 K/min when a heater is on, the system gains temperature at 4 K/min. A two- position controller has a 0.5 min control lag and a neutral zone of ± 4% of the setpoint about a setpoint of 323 K. Plot the heater temperature versus time. Find the oscillation period.

Solution

Given data:

Temperature drops = 2 K/min

Temperature rises = 4 K/min

Control Lag = 0.5 min

Neutral zone = ± 4%

Setpoint = 323 K

± 4% of 323 = 13 K. Therefore, the temperature will vary from 310 to 336 K (without considering the lag)

Initially we start at setpoint value. The temperature will drop linearly, which can be expressed by

$$T_1(t) = T(ts) - 2\,(t - ts)$$

where ts = time at which we start the observation

T(ts) = temperature when we start observation i.e. 323.

The temperature will drop till - 4% of setpoint (323K), which is 310 K.

Time taken by the system to drop temperature value 310 K is

$$310 = 323 - 2\,(t - 0)$$

$$t = 6.5 \text{ min}$$

Undershoot due to control lag = (control lag) x (drop rate) = 0.5 min x 2 K/min = 1 K Due control lag temperature will reach 309 instead of 310 K.

From this point the temperature will rise at 4 K/min linearly till +4% of set point i.e.336K which can be expressed by

$$T_2(t) = T(t_h) + 2\ (t - t_h)$$

where t_h = time at which heater goes on

$T(t_h)$ = temperature at which heater goes on

$$336 = (310\text{-}1) + 4\ [t - (6.5 + 0.5)]$$

$$t = 13.75 \text{ min}$$

Overshoot due to control lag = (control lag) x (rise rate) = 0.5 min x 4 K/min = 2 K Due control lag temperature will reach 338 instead of 336 K.

The oscillation period is = 13.75 + 0.5 +0.5 + 6.5 = 21.25 ≈ 21.5 min
The system response is plotted as shown in Fig. 2.2 with undershoot and overshoot values

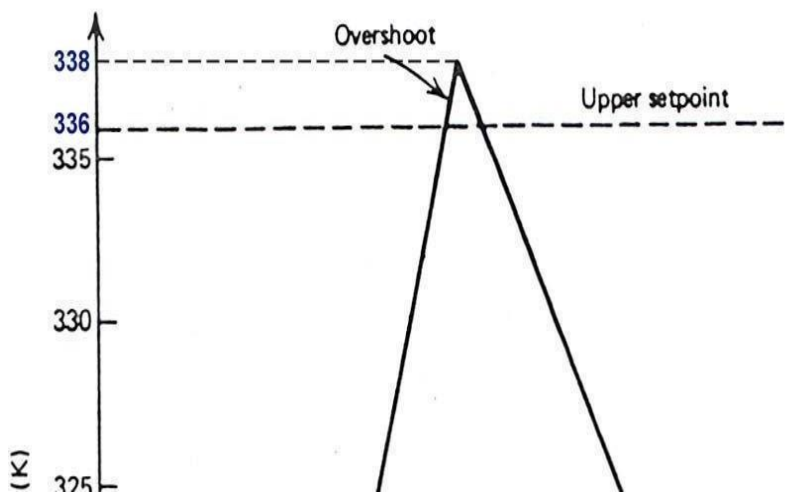


Fig. 2.2 Plot of heater temperature versus time for Problem 2.3

Proble m 2.4

A 5m diameter cylindrical tank is emptied by a constant outflow of 1.0 m^3/min. A two position controller is used to open and close a fill valve with an open flow of 2.0 m^3/min. For level control, the neutral zone is 1 m and the setpoint is 12 m. (a) Calculate the cycling period (b) Plot the level vs time.

Solution

Given data: Diameter cylindrical tank = 5 m, therefore radius, r = 2.5 m

Output flow rate (Q_{out}) = 1.0 m^3/min

Input flow rate (Q_{in}) = 2.0 m^3/min

Neutral Zone (h) = 1 m

Setpoint = 12 m

(a) The volume of the tank about the neutral zone is

$$V = \Pi r^2 h$$

$$V = 3.142 \times (2.5)^2 \times 1 = 19.635 \text{ m}^3$$

$Q_{in} = 2.0 \text{ m}^3/\text{min}$, and $Q_{out} = 1.0 \text{ m}^3/\text{min}$

Therefore, net inflow into the tank = $Q = Q_{in} - Q_{out} = 2\text{-}1 = 1 \text{ m}^3/\text{min}$

To fill 1 m^3 of tank it requires 1 min, therefore to fill 19.635 m^3 of tank requires 19.63min

Similarly it takes same time for the tank to get emptied by 19.635 m^3 i.e. 19.635 min.

Therefore, Cycling period = 19.635 + 19.635 = 39.27 ≈ 39.3 min

(b) Plot the level vs time

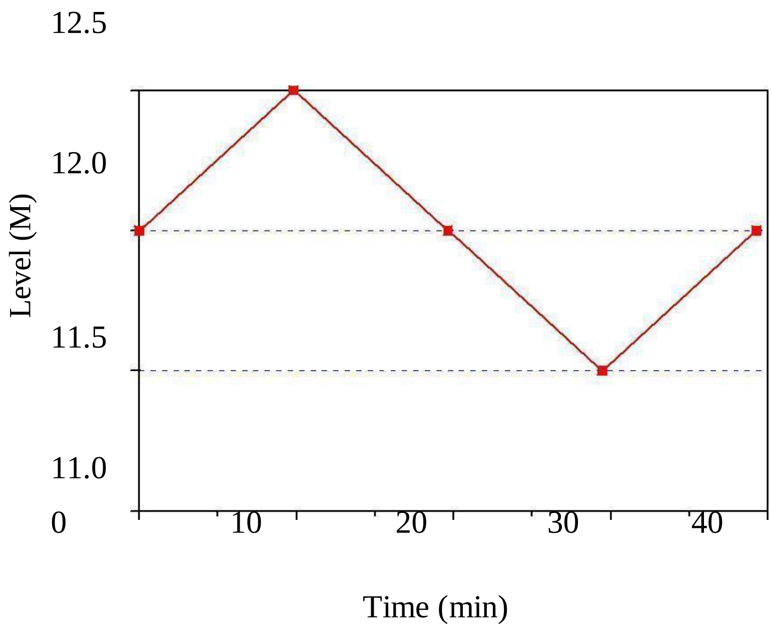


Fig. 2.3 Plot of level versus time for Problem 2.4

Multiposition Control Mode

It is the logical extension of two-position control mode to provide several intermediate settings of the controller output. This discontinuous control mode is used in an attempt to reduce the cycling behaviour and overshoot and undershoot inherent in the two-position mode. This control mode can be preferred whenever the performance of two-position control mode is not satisfactory.

The general form of multiposition mode is represented by

$$p = p_i \qquad e_p > |e_i| \quad i = 1, 2, ..., n \qquad (2.3)$$

As the error exceeds certain set limits $\pm e_i$, the controller output is adjusted to present values p_i.

Three-position Control Mode: One of the best example for multiposition control mode is three-position control mode, which can be expressed in the following analytical form:

$$p = \begin{cases} 100\% & e_p > -e_1 \\ 50\% & -e_1 < e_p < +e_1 \\ 0\% & e_p < -e_1 \end{cases}$$

As long as the error is between $+e_1$ *and* $-e_1$ of the set point, the controller stays at some nominal setting indicated by a controller output of 50%. If the error exceeds the set point by $+e_1$ or more, then the output is increased to 100%. If it is less than the set point by $-e_1$ or more, the controller output is reduced to zero. Figure 2.4 illustrates three-position mode graphically.

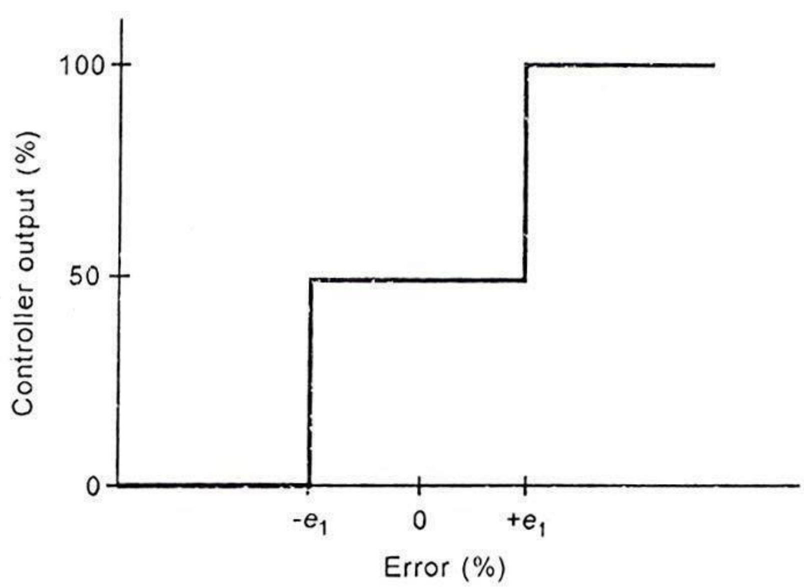


Fig. 2.4 Three-position controller action

The three-position control mode usually requires a more complicated final control element, because it must have more than two settings. Fig. 2.5 shows the relationship between the error and controller output for a three-position control. The finite time required for final control element to change from one position to another is also shown. The graph shows the overshoot and undershoots of error around the upper and lower setpoints. This is due to both the process lag time and controller lag time, indicated by the finite time required for control element to reach new setting.

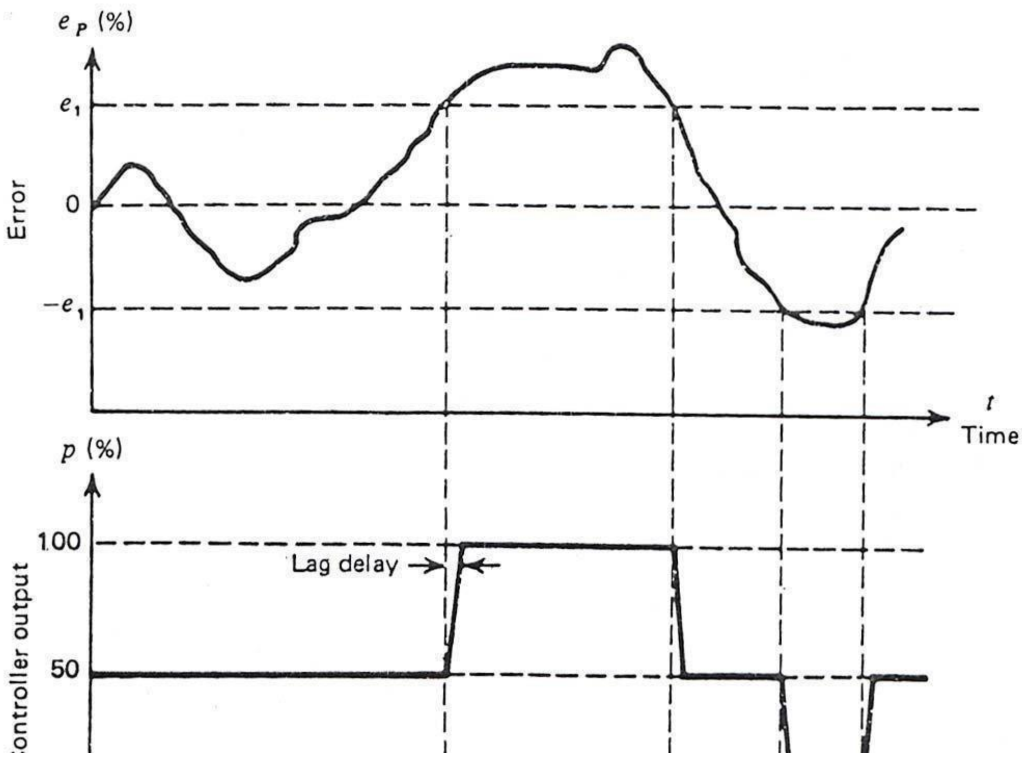


Fig. 2.5 Relationship between error and three-position controller action, including the effectsoflag.

Floating Control Mode

In floating control, the specific output of the controller is not uniquely determined by error. If the error is zero, the output does no t change but remains (floats) at whatever setting it was when error went to zero. When error moves of zero, the controller output again begins to change. Similar to two-position mode, there will be a neutral zone around zero error where no change in controller output occurs. Popularly there are two types:

(a) Single Speed

(b) Multiple Speed

(a) Single Speed: In this mode, the output of the control element changes at a fixed rate when the error exceeds the neutral zone. The equation for single speed floating mode is:

$$\frac{dp}{dt} = \pm K_F \qquad |e_p| > \Delta e_p \tag{2.5}$$

where dp/dt = rate of change of controller output with time
K_F = rate constant ($\%/s$)
Δe_p = half the neutral zone

If the equation (5) is integrated for actual controller output, we get

$$p = \pm K_F t + p(0) \qquad |e_p| > \Delta e_p \tag{2.6}$$

where $p(0)$ = controller output at $t = 0$

The equation shows that the present output depends on the time history of errors that have previously occurred. Because such a history is usually not known, the actual value of p floats at an undetermined value. If the deviation persists, then equation (6) shows that the controller saturates at 100% or 0% and remains there until an error drives it toward the opposite extreme. A graph of single speed floating control is shown in Fig.2.6

The single- speed controller action as output rate of change to input error is shown in Fig.2.6 (a). The graph in Fig.2.6 (b) shows a reverse acting controller, which means the controller output decreases when error exceeds neutral zone, which corresponds to negative K_F in equation (5). The graph shows that the controller starts at some output p(0). At time t_1, the error exceeds the neutral zone, and the controller output decreases at a constant rate until t_2 , when the error again falls below the neutral zone limit. At t_3 , the error falls below the lower limit of neutral zone, causing controller output to change until the error again moves within the allowable band.

(b) Multiple Speed: In this mode several possible speeds (rate) are changed by controller output. Usually, the rate increases as the deviation exceeds certain limits. For speed change point e_{pi} error there will be corresponding output rate change Ki. The expression can be given by

$$\frac{dp}{dt} = \pm K_{Fi} \qquad |e_p| > e_{pi} \tag{2.7}$$

If the error exceeds e_{pi} , then the speed is K_{Fi} . If the error rises to exceed e_{p2}, the speed is increased to K_{F2} , and so on. The graph of multiple-speed mode is shown in Fig. 2.7

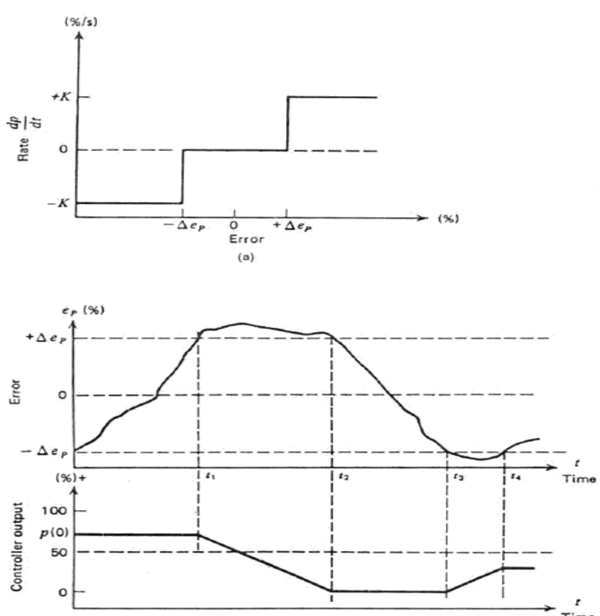


Fig. 2.6 Single speed floating controller (a) Controller action as output rate of change to input error, and (b) Error versus controller response.

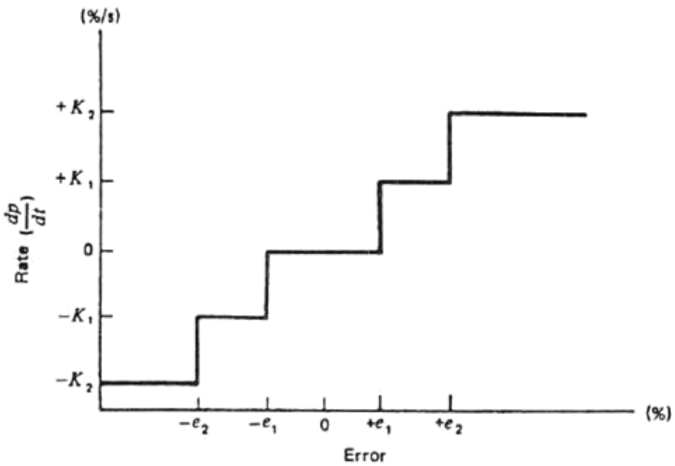


Fig. 2.7 Multiple-speed floating control mode action.

Applications:

- Primary applications are in single-speed controllers with neutral zone
- This mode is well suited to self-regulation processes with very small lag or dead time, which implies small capacity processes. When used for large capacity systems, cycling must be considered.

The rate of controller output has a strong effect on the error recovery in floating control mode.In continuous controller modes the controller output changes smoothly in response to the error or rate of change of error. These modes are an extension of discontinuous controller modes. In most of the industrial processes one or combination of continuous controllers are preferred.

Proportional Control Mode

In this mode a linear relationship exits between the controller output and the error. For some range of errors about the setpoint, each value of error has unique value of controller output in one-to-one correspondence. The range of error to cover the 0% to 100% controller output is called proportional band, because the one-to-one correspondence exits only for errors in this range. The analytical expression for this mode is given by:

$$p = K_p e_p + p_0 \qquad (2.8)$$

where K_p = proportional gain (% per %)

p_0 = controller output with no error or zero error (%)

The equation (8) represents reverse action, because the term $K_p e_p$ will be subtracted from p_0 whenever the measured value increases the above setpoint which leads negative error. The equation for the direct action can be given by putting the negative sign in front of correction term i.e. - $K_p e_p$. A plot of the proportional mode output vs. error for equation (8) is shown in Fig.2.9

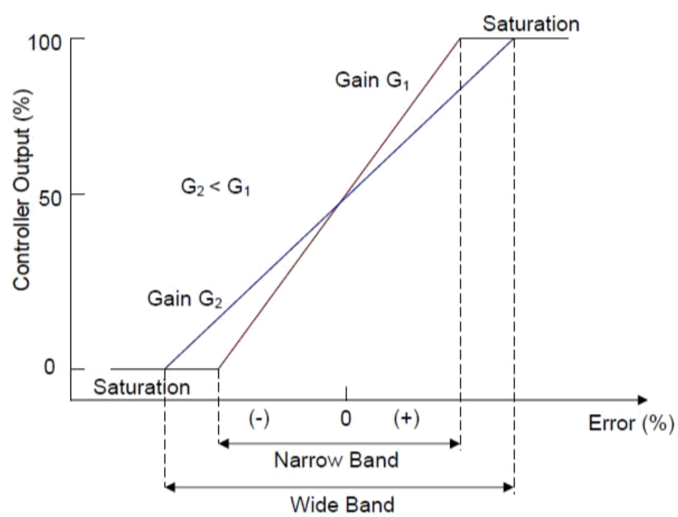


Fig. 2.9 Proportional controller mode output vs. error.

In Fig.2.9, p_0 has been set to 50% and two different gains have been used. It can be observed that proportional band is dependent on the gain. A high gain (G_1) leads to large or fast response, but narrow band of errors within which output is not saturated. On the other side a low gain (G_2) leads to small or slow response, but wide band of errors within which output is not saturated. In general, the proportiona l band is defined by the equation:

$$PB = \frac{100}{K_p} \tag{2.9}$$

The summary of characteristics of proportional control mode are as follows:

1. If error is zero, output is constant and equal to p_0.

2. If there is error, for every 1% error, a correction of K_p percent is added or subtracted from p_0, depending on sign of error.

3. There is a band of errors about zero magnitude PB within which the output is not saturated at 0% or 100%.

Offset: An important characteristic of the proportional control mode is that it produces a permanent residual error in the operating point of the controlled variable when a load change occurs and is referred to as offset. It can be minimized by larger constant K_p which also reduces the proportional band. Figure 2.10 shows the occurrence of offset in proportional control mode.

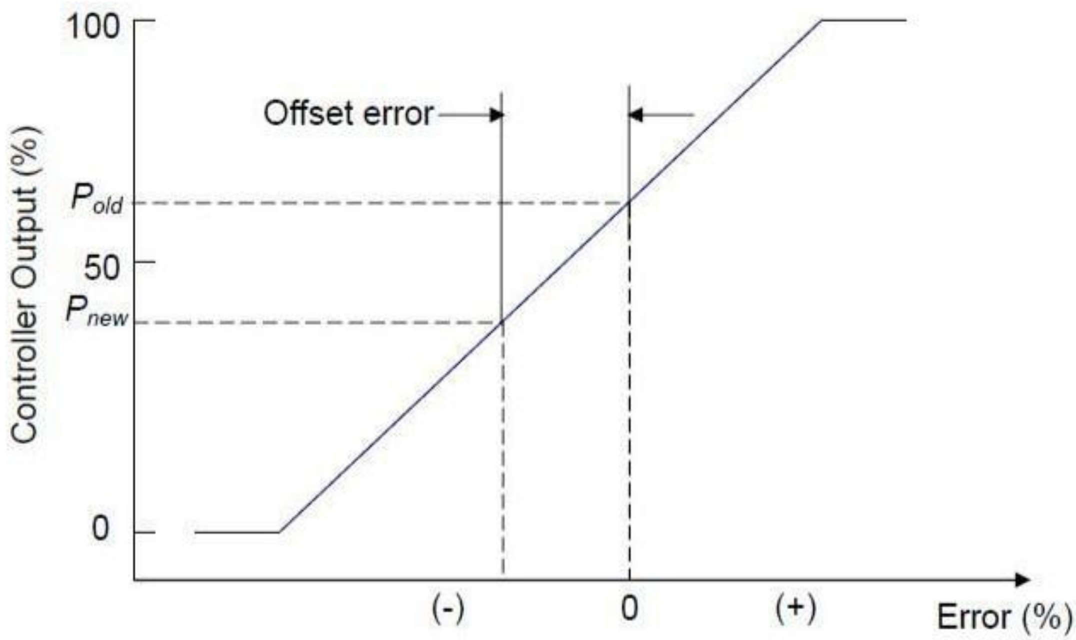


Fig. 2.10 Occurrence of offset error in proportional controller for a load change.

Consider a system under nominal load with the controller output at 50% and error zero as shown in Fig.2.10 If a transient error occurs, the system responds by changing controller output in correspondence with the transient to effect a return-to-zero error. Suppose, however, a load change occurs that requires a permanent change in controller output to produce the zero error state. Because a one-to-one correspondence exists between controller output and error, it is clear that a new zero-error controller output can never be achieved. Instead, the system produces a small permanent offset in reaching compromise position of controller output under new loads.

Applications:

- Whenever there is one-to-one correspondence of controller output is required with respect to error change proportional mode will be ideal choice.

- The offset error limits the use of proportional mode, but it can be used effectively wherever it is possible to eliminate the offset by resetting the operating point.
- Proportional control is generally used in processes where large load changes are unlikely or with moderate to small process lag times.

- If the process lag time is small, the PB can be made very small with large K_p, which reduces offset error.

- If K_p is made very large, the PB becomes very small, and proportional controller is going to work as an ON/OFF mode, i.e. high gain in proportional mode causes oscillations of the error.

Proble m 2.5

For a proportional controller, the controlled variable is a process temperature with a range of 50 to 130 ^oC and a setpoint of 73.5 ^oC. Under nominal conditions, the setpoint is maintained with an output of 50%. Find the proportional offset resulting from a load change that requires a 55% output if the proportional gain is (a) 0.1 (b) 0.7 (c) 2.0 and (d) 5.0.

Solution:

Given data: Temperature Range = 50 to 130 ^oC

Setpoint (Sp)	= 73.5 ^{o}C
Po	= 50%
P	= 55%
e_p	= ?
Offset error	= ? for Kp=0.1, 0.7, 2.0 & 5.0

For proportional controller: P = Kp e_p + Po

e_p = [p-Po] / Kp = [55 – 50] / Kp = 5 / Kp %

(a) when	Kp = 0.1	Offset error, e_p = 5/0.1 = 50%
(b) when	Kp = 0.7	Offset error, e_p = 5/0.7 = 7.1%
(c) when	Kp = 2.0	Offset error, e_p = 5/2.0 = 2.5%
(d) when	Kp = 5.0	Offset error, e_p = 5/5.0 = 1%

[It can be observed from the results that as proportional gain Kp increases the offset error decreases.]

Proble m 2.6

A proportional controller has a gain of Kp = 2.0 and Po = 50%. Plot the controller output for the error given by Fig.2.11.

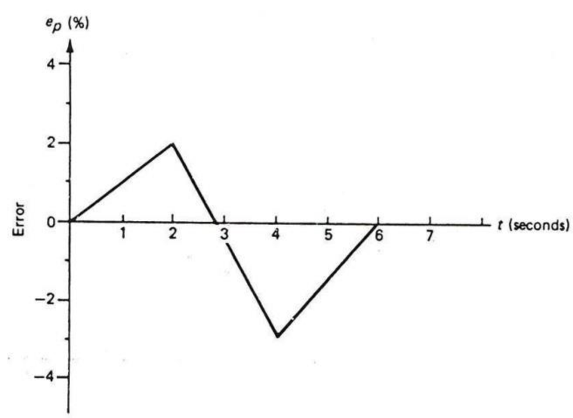


Fig. 2.11 Error graph

Solution:

Given data: Kp = 2.0 Po

= 50%

Error graph as in Fig.2.11

To find the controller output and plot the response, first of all we need to find the error which is changing with time and express the error as function of time. The error need to be found in three time regions: (a) 0-2 sec (b) 2-4 sec (c) 4-6 sec.

Since, the error is linear, using the equation for straight line we find the error equation

i.e. Ep = mt + c (i.e. Y = mX + c)

(a) For error segment 0-2 sec:

Slope of the line, $m = [Y_2-Y_1] / [X_2-X_1] = [2-0]/[2-0] = 1$

Y = mX + c

2 = 1 x t + c, 2 = 1x 2 + c, c = 0

Therefore, error equation, Ep = t

Controller output P = Kp Ep + Po = 2 t + 50

Therefore, at **t = 0 sec, P = 50%** and **at t = 2 sec, P = 54%**

(b) For error segment 2-4 sec:

Slope of the line, $m = [Y_2-Y_1] / [X_2-X_1] = [-3-2]/[4-2] = -2.5$

Y = mX + c

2 = (-2.5) x 2 + c, c = 7

Therefore, error equation, Ep = -2.5t + 7

Controller output P = Kp Ep + Po = 2 (-2.5t +7) + 50

Therefore, at t = 2 sec, P = 54% and, at **t = 4 sec, P = 44%**

(b) For error segment 4-6 sec:

Slope of the line, $m = [Y_2-Y_1] / [X_2-X_1] = [0+3]/[6-4] = 1.5$

$$Y = mX + c$$

$$-3 = 1.5 \times 4 + c, \qquad c = -9$$

Therefore, error equation, $E_p = 1.5t - 9$

Controller output $\qquad P = K_p E_p + P_o = 2\,(1.5t - 9) + 50$

Therefore, $\qquad$ at $t = 4$ sec, $P = 44\%$ and, at $\mathbf{t = 6}$ **sec,** $\mathbf{P = 50\%}$

Therefore, the controller output for the error shown in Fig. 2.11 is given by Fig.2.12.

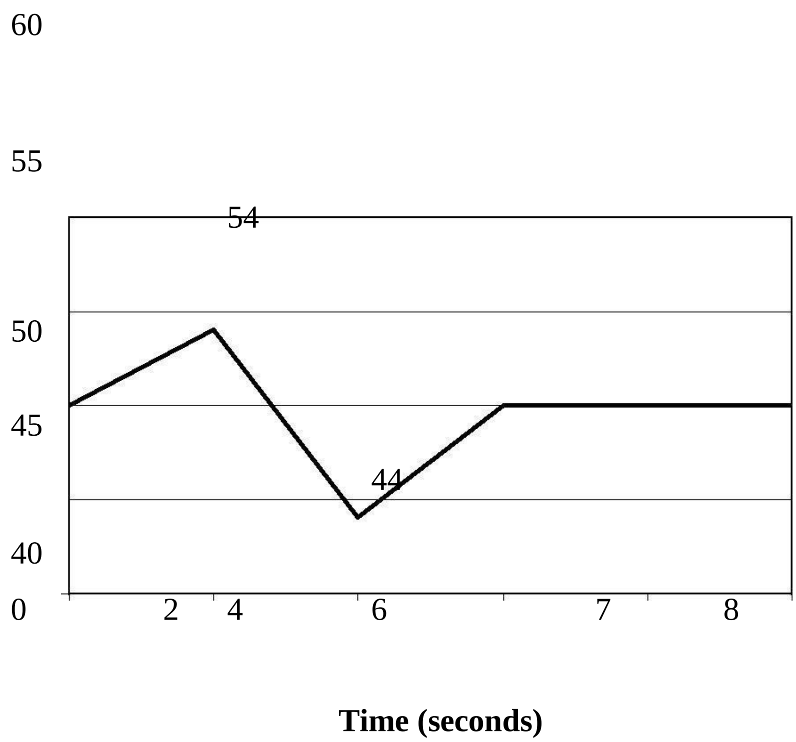


Fig. 2.12 Controller output for the error shown in Fig. 2.11

Integral Control Mode

The integral control eliminates the offset error problem by allowing the controller to adapt to changing external conditions by changing the zero-error output.

Integral action is provided by summing the error over time, multiplying that sum by a gain, and adding the result to the present controller output. If the error makes random excursions above and below zero, the net sum will be zero, so the integral action will not contribute. But if the error becomes positive or negative for an extended period of time, the integral action will begin to accumulate and make changes to the controller output. The analytical expression for integral mode is given by the equation

$$p(t) = K_I \int_0^t e_p \, dt + p(0) \qquad (2.10)$$

where *p(0)* = controller output when the integral action starts (%)

K_I = Integral gain (s^{-1})

Another way of expressing the integral action is by taking derivative of equation (10), which gives the relation for the rate of change of controller output with error.

$$\frac{dp}{dt} = K_I \, e_p \qquad (2.12)$$

The equation (12) shows that when an error occurs, the controller begins to increase (or decrease) its output at a rate that depends upon the size of the error and the gain. If the error is zero, controller output is not changed. If there is positive error, the controller output begins to ramp up at a rate determined by Equation (12). This is shown in Fig.2.13 for two different values of gain. It can be observed that the rate of change of controller output depends upon the value of error and the size of the gain. Figure 2.14 shows how controller output will vary for a constant error & gain.

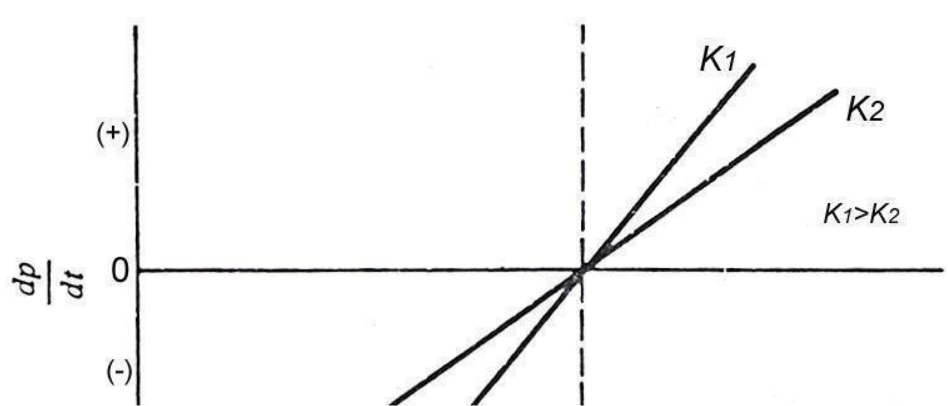


Fig. 2.13 Integral control action showing the rate of output change with error & gain

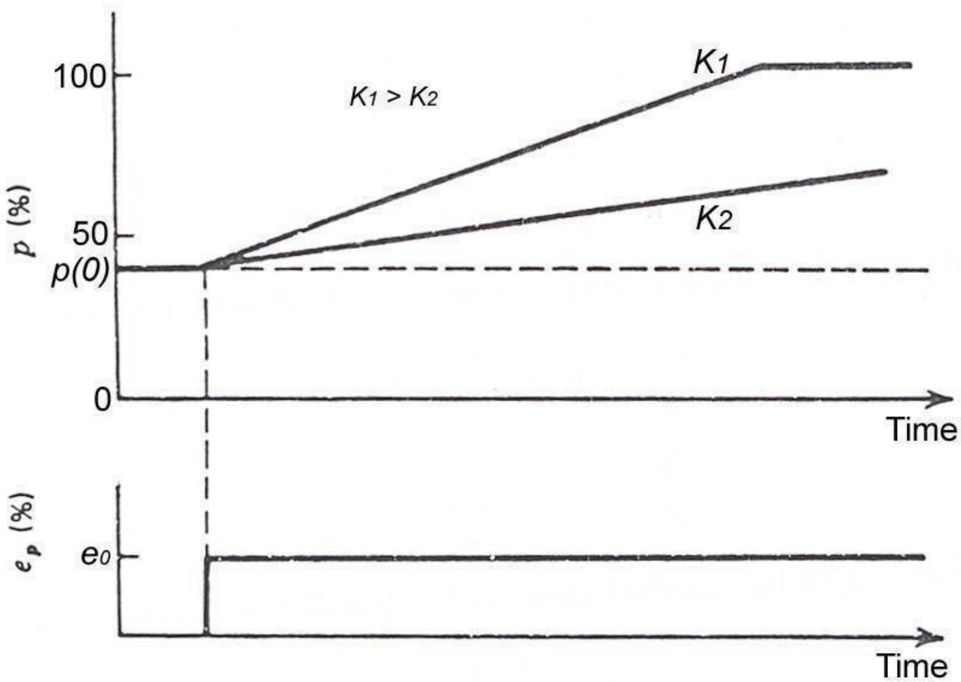


Fig. 2.14 Integral controller output for a constant error

It can be observed that the controller output begins to ramp up at a rate determined by the gain. In case of gain K_1, the output finally saturates at 100%, and no further action can occur.

The summary of characteristics of integral control mode are as follows:

1. If the error is zero, the output stays fixed at a value equal to what it was when the error went to zero (i.e. *p(0)*)
2. If the error is not zero, the output will begin to increase or decrease at a rate of K_I %/sec for every 1% of error.

Area Accumulation: It is well known fact that integral determines the area of the function being integrated. The equation (1.12) provides controller output equal to the net area under error- time curve multiplied by K_I. It can be said that the integral term accumulates error as function of time. Thus, for every 1%-sec of accumulated error-time area, the output will be K_1 percent.The integral gain is often represented by the inverse, which is called the integral time or reset action, i.e. $\boldsymbol{T_I = 1 / K_I}$, which is expressed in minutes instead of seconds because this unit is more typical of many industrial process speeds. The integral operation can be better understood by the Fig. 2.15

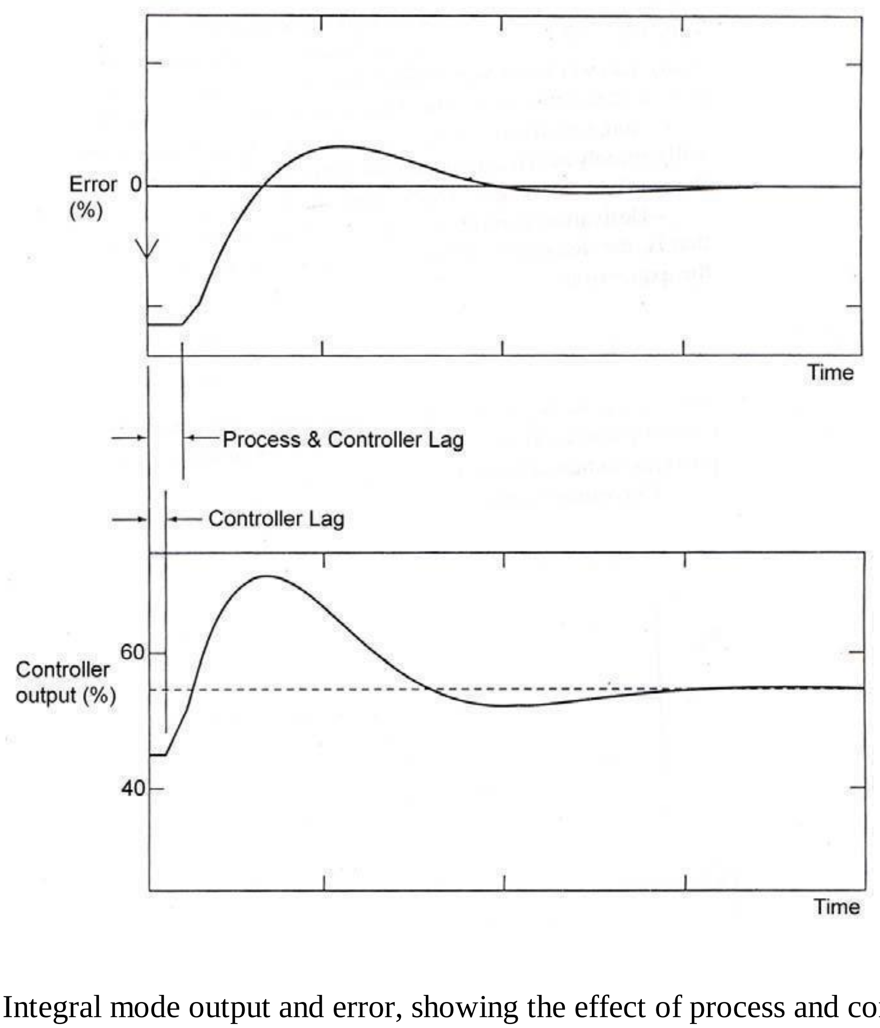


Fig. 2.15 Integral mode output and error, showing the effect of process and control lag.

A load change induced error occurs at t = 0. Dashed line is the controller output required to maintain constant output for new load. In the integral control mode, the controller output value initially begins to change rapidly as per Equation (12). As the control element responds and error decreases, the co ntroller output rate also decreases. Ultimately the system drives the error to zero at a slowing controller rate. The effect of process and control system lag is shown as simple delays in the controller output change and in the error reduction when the controller action occurs. If the process lag is too large, the error can oscillate about zero or even be cyclic.

Applications: In general, integral control mode is not used alone, but can be used for systems with small process lags and correspondingly small capacities.

Proble m 2.7

An integral controller has a reset action of 2.2 minutes. Express the integral controller constant in s^{-1}.Find the output of this controller to a constant error of 2.2%.

Solution:

Given Data: Reset action time = T_I = 2.2 min = 132 Seconds

Error = e_p = 2.2%

Asked: Integral controller constant = K_I = ?

Controller output = p = ?

$K_I = 1 / T_I = 1 / 132 = 0.0076\ s^{-1}$

$$p(t) = K_I \int_0^t e_p\, dt + p(0)$$

$$p = 0.0076 \int_0^t (2.2)\, dt + 0$$

$$p = 0.0167\, t$$

Derivative Control Mode

The need for derivative control mode can be explained with the error graph shown in Fig.2.16

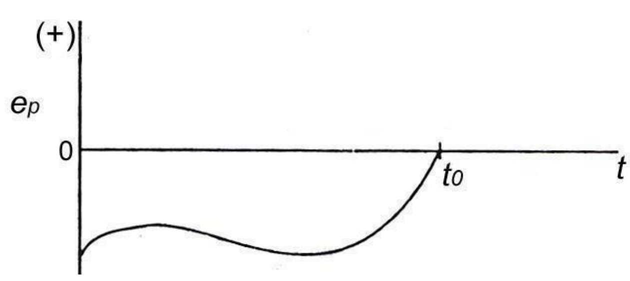


Fig. 2.16 Error graph with zero error and large rate of change.

It can be observed that even though the error at t_0 is zero, it is changing in time and will certainly not be zero in the following time. Under such situations some action should be taken even though the error is zero. Such scenario describes the nature and need for derivative action.

Derivative controller action responds to the rate at which the error is changing- that is, derivative of the error. The analytical expression for derivative control mode is given by;

$$p(t) = K_D \frac{de_p}{dt} \tag{2.13}$$

where K_D = Derivative gain (s)

Derivative action is not used alone because it provides no output when the error is constant. Derivative controller action is also called *rate action* and *anticipatory control*. Figure 2.17 illustrates how derivative action changes the controller output for various rates of change of error. For this example, it is assumed that the controller output with no error or rate of change of error is 50%. When the error changes very rapidly with a positive slope, the output jumps to a large value, and when the error is not changing, the output returns to 50%. Finally, when error is decreasing - that is negative slope - the output discontinuously changes to a lower value.

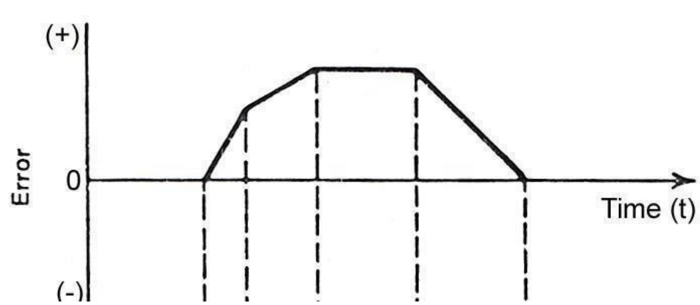


Fig.2.17 Derivative controller output for different rate of error.

The derivative mode must be used with great care and usually with a small gain, because a rapid rate of change of error can cause very large, sudden changes of controller output and lead to instability.

The summary of characteristics of derivative control mode are as follows:

1. If the error is zero, the mode provides no output.
2. If the error is constant in time, the mode provides no output
3. If the error is changing with time, the mode contributes an output of KD percent for every 1% per second rate of change of error.
4. For direct action, positive rate of change of error produces a positive derivative mode output.

Proble m 2.8

How would a derivative controller with K_D = 4 s respond to an error that varies as e_p=2.2 Sin(0.04t)?

Solution

Given: K_D = 4 s e_p = 2.2 Sin(0.04t) Asked: Derivative controller o/p=? For derivative mode, $\mathbf{p(t) = K_D (de_p/dt)}$

p(t) = 4 x d/dt(2.2 Sin(0.04t))

$= 4 \times 2.2 \times Cos(0.04t) \times 0.04$

$= 0.352\ Cos(0.04t)$

Composite Control Modes

It is found from the discontinuous and continuous controller modes, that each mode has its own advantages and disadvantages. In complex industrial processes most of these control modes do not fit the control requirements. It is both possible and expedient to combine several basic modes, thereby gaining the advantages of each mode. In some cases, an added advantage is that the modes tend to eliminate some limitations they individually posses. The most commonly used composite controller modes are: Proportional-Integral (PI), Proportional- Derivative (PD) and Proportional- Integral-Derivative (PID) control modes.

Proportional-Integral Control Mode (PI Mode):

This control mode results from combination of proportional and integral mode. The analytical expression for the PI mode is given by:

$$p = K_p e_p + K_p K_I \int_0^t e_p\, dt + p_I(0) \qquad (2.14)$$

where $p_I(0)$ = integral term value at t = 0 (initial value)

The main advantage of this composite control mode is that one-to-one correspondence of the proportional control mode is available and integral mode eliminates the inherent offset. It can be observed from the equation (2.14) that the proportional gain also changes the net integration mode gain, but the integration gain, through K_I, can be independently adjusted. The proportional mode when used alone produces offset error whenever load change occurs and nominal controller output will not provide zero error. But in PI mode, integral function provides the required new controller output, thereby allowing the error to be zero after a load change. The integral feature effectively provides a reset of the zero error output after a load change occurs. Figure 2.18 shows the PI mode response for changing error. At time t_1 , a load change occurs that produces the error shown. Accommodation of the new load condition requires a new controller output. It can be observed that the controller output is provided through a sum of proportional plus integral action that finally brings the error back to zero value.

The summary of characte ristics of PI mode are as follows:

1. When the error is zero, the controller output is fixed at the value that the integral term had when the error went to zero, i.e. output will be $p_I(0)$ when e_p=0 at t = 0.

2. If the error is not zero, the proportional term contributes a correction, and the integral term begins to increase or decrease the accumulated value [i.e. initial value $p_I(0)$], depending on the sign or the error and direct or reverse action.

The integral term cannot become negative. Thus, it will saturate at zero if the error and action try to drive the area to a net negative value.

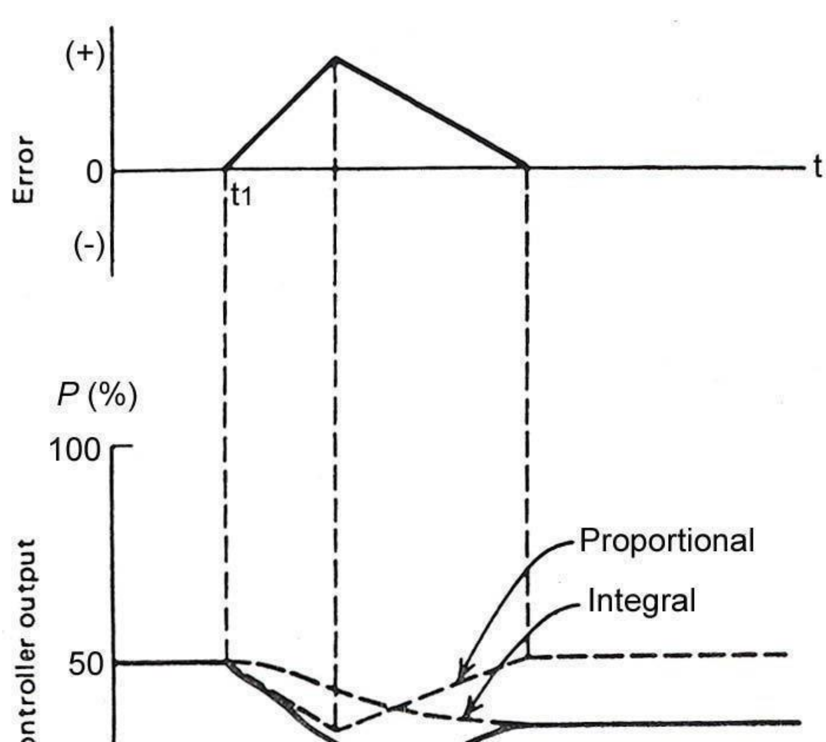


Fig. 2.18 PI mode action for changing error (for reverse acting system)

Application, Advantages and Disadvantages:

- This composite PI mode eliminates the offset problem of proportional controller.
- The mode can be used in systems with frequent or large load changes
- Because of integration time the process must have relatively slow changes in load to prevent oscillations induced by the integral overshoot.
- During start-up of a batch process, the integral action causes a considerable overshoot of the error and output before settling to the operation point. This is shown in Fig.1.20, the dashed band is proportional band (PB). The PB is defined as hat positive and negative error for which the output will be driven to 0% and 100%. Therefore, the presence of an integral accumulation changes the amount of error that will bring about such saturation by the proportional term. In Fig. 2.19, the output saturates whenever the error exceeds the PB limits. The PB is constant, but its location is shifted as the integral term changes.

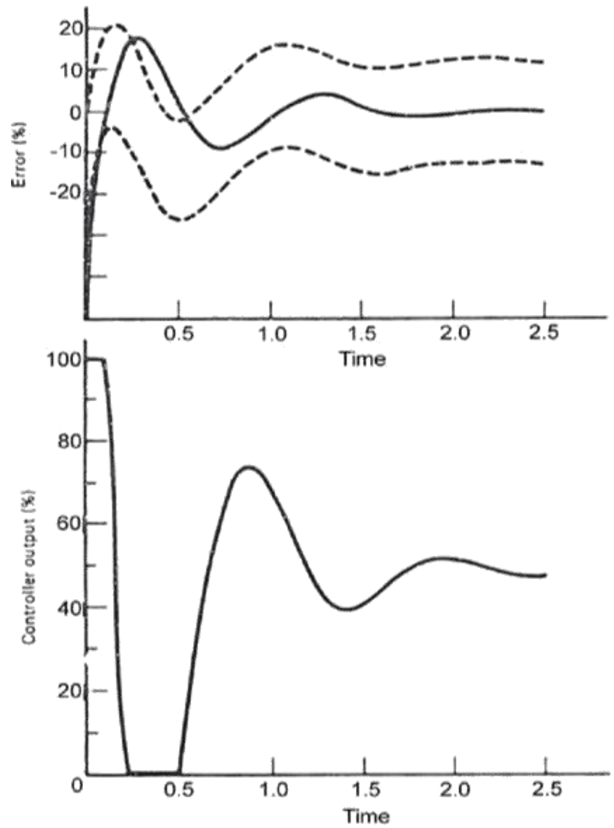


Fig. 2.19 Overshoot and cycling when PI mode control is used in start-up of batch processes. The dashed lines show PB.

Proportional-Derivative Control Mode (PD Mode):

The PD mode involves the serial (cascaded) use of proportional and derivative modes and this mode has many industrial applications. The analytical expression for PD mode is given by

$$p = K_p e_p + K_p K_D \frac{de_p}{dt} + p_0 \qquad 2.15$$

This system will not eliminate the offset of proportional controller, however, handle fast process load changes as long as the load change offset error is acceptable. Figure 2.20 shows a typical PD response for load changes. It can be observed that the derivative action moves the controller output in relation to the error rate change.

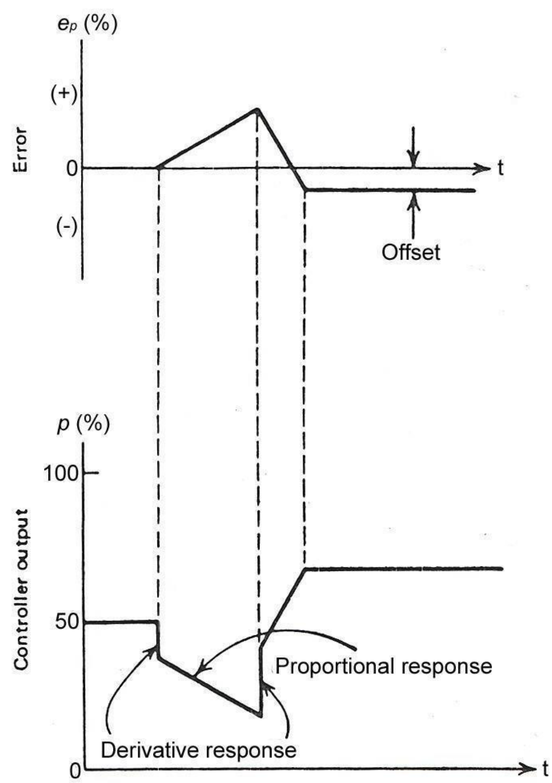


Fig. 2.20 PD control mode response, showing offset error from proportional mode and derivative action for changing load, for reverse acting system.

Proportional-Integral-Derivative Control Mode (PID or Three Mode):

One of the most powerful but complex controller mode operations combines the proportional, integral, and derivative modes. This PID mode can be used for virtually any process condition. The analytical expression is given by

$$p = K_p e_p + K_p K_I \int_0^t e_p \, dt + K_p K_D \frac{de_p}{dt} + p_I(0) \qquad (2.16)$$

This mode eliminates the offset of the proportional mode and still provides fast response for changing loads. A typical PID response is shown in Fig. 2.21

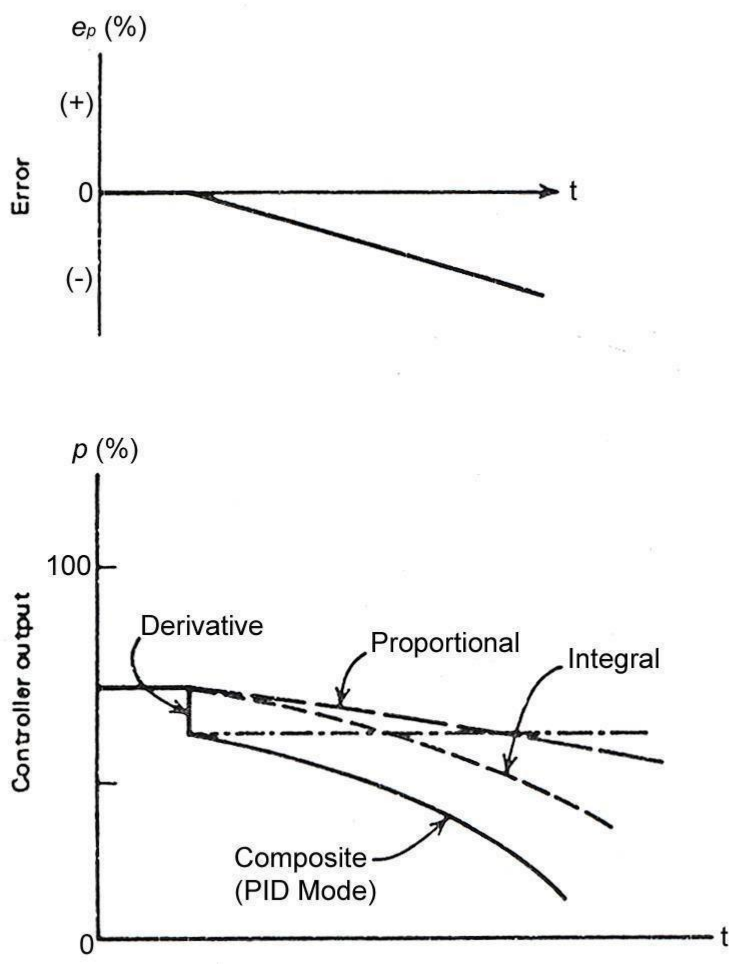


Fig. 2.21 Three mode (PID) controller action, exhibiting proportional, integral and derivative action.

Proble m 2.9

A PI controller is reverse acting, PB=20, 12 repeats per minute. Find (a) Proportional gain (b) Integral gain, and (c) Time that the controller output will reach 0% after a constant error of 1.5% starts. The controller output when the error occurred was 72%.

Solution:

Given : PB = 20

Integral time = T_I = 1/12 min = 60/12 s = 5 s

$P_I(0)$ = 72%, e_p = 1.5%

Asked : (a) Kp = ? (b) K_I = ? t =? when P = 0%

(a) Kp = 100 / PB = 100 / 20 = 5

(b) $K_I = 1 / T_I = 1/5 = 0.2\ s^{-1}$

(c) For PI mode, $p = -\{K_p e_p + K_p K_I \int_0^t e_p\, dt\} + p_I(0)$

-ve sign is for reverse acting

$$p = -\{5 \times (1.5) + 5 \times 0.2 \int_0^t 1.5\, dt\} + 72$$

$$p = -\{7.5 + 1.5t\} + 72$$

When P = 0% $1.5t = 64.5$ **t = 43 s = 0.72 min**

Proble m 2.10

A PD controller has Kp = 2.0, K_D = 2 s, and P_0 = 40%. Plot the controller output for the error input shown in Fig.2.22

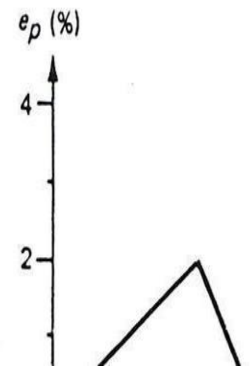


Fig. 2.22 Error graph

Solution: Given data: Kp = 2.0 K_D = 2 s Po = 40%

To find the controller output and plot the response, first of all we need to find the error which is changing with time and express the error as function of time. The error need to be found in three time regions: (a) 0-2 sec (b) 2-4 sec (c) 4-6 sec.

Since, the error is linear, using the equation for straight line we find the error equation

i.e. Ep = mt + c (i.e. Y = mX + c)

(a) For error segment 0-2 sec:

Y = mX + c, 2 = 1 x t + c, 2 = 1x 2 + c, c = 0

Therefore, error equation, Ep = t

Controller output P = Kp Ep + KpK_D [dEp/dt] + Po

= 2 t + 2 x 2 [d/dt (t)] + 40

= 2 t + 4 + 40

Therefore, at **t = 0 sec, P = 44%** and **at t = 2 sec, P = 48%**

(b) For error segment 2-4 sec:

Y = mX + c, 2 = (-2.5) x 2 + c, c = 7

Therefore, error equation, Ep = -2.5t + 7

Controller output P = 2 [-2.5t+7] + 2 x 2 [d/dt (-2.5t+7)] + 40

$= -5t + 14 – 10 + 40$

Therefore, **at t = 2 sec, P = 34%** and, at **t = 4 sec, P = 24%**

(c) For error segment 4-6 sec:

Slope of the line, $m = [Y_2-Y_1] / [X_2-X_1] = [0+3]/[6-4] = 1.5$

$Y = mX + c$, $-3 = 1.5 \times 4 + c$, $c = -9$

Therefore, error equation, $E_p = 1.5t – 9$

Controller output $P = 2 [1.5t - 9] + 2 \times 2 [d/dt (1.5t-9)] + 40$

$= 3t -18 + 6 + 40$

Therefore, **at t = 4 sec, P = 40%** and, at **t = 6 sec, P = 46%**

Therefore, the controller output for the error shown in Fig. 2.22 is given by Fig.2.23.

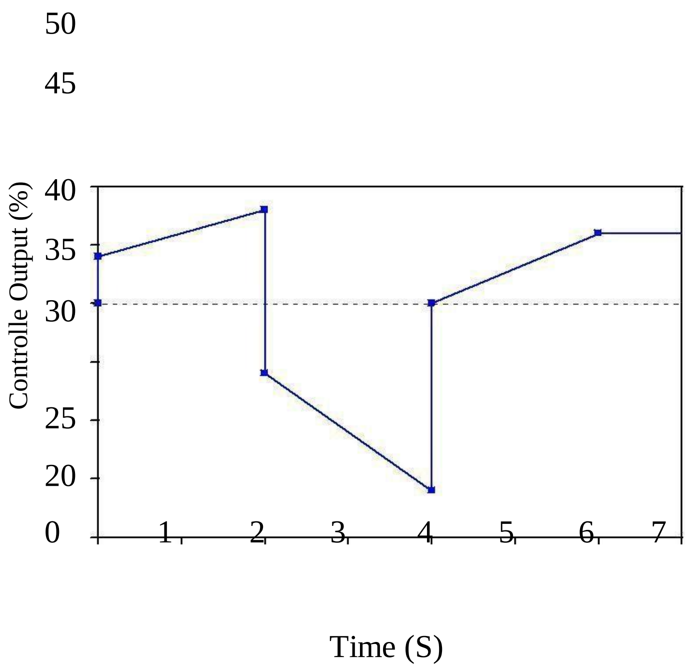


Fig. 2.23 Controller output for the error shown in Fig.2.22

Summary:

In this chapter general characteristics of controller operating modes without considering implementation of these modes are discussed. The terms that are important to understand the process control and controller operations are defined. The important points which are discussed in this chapter are as follows:

1. In considering the controller operating mode for industrial process control, it is important to know all the *process characteristics* and *control system parameters* which may influence the process and controller operations.
2. Discontinuous controller modes refer to instances where the controller output does not change smoothly for input error. The examples are two-position, multiposition, and floating control modes.
3. Continuous controller modes are modes where the controller output is a smooth function of the error input or rate of change. Examples are proportional, integral and derivative control modes.
4. The continuous controller modes, such as proportional, integral and derivative modes have their own advantages and disadvantages. In complex industrial processes most of these control modes do not fit the control requirements. It is both possible and expedient to combine several basic modes, thereby gaining the advanta ges of each mode. In some cases, an added advantage is that the modes tend to eliminate some limitations they individually posses. Examples are proportional- integral (PI), proportional-derivative (PD) and proportional- integral-derivative (PID) control modes.

INTRODUCTION TO PNEUMATIC CONTROL

The word „Pneuma‟ means breath or air . Pneumatics is application of compressed air in automation. In Pneumatic control, compressed air is used as the working medium, normally at a pressure from 6 bar to 8 bar. Using Pneumatic Control, maximum force up to 50 kN can be developed. Actuation of the controls can be manual, Pneumatic or Electrical actuation. Signal medium such as compressed air at pressure of 1-2 bar can be used [Pilot operated Pneumatics] or Electrical signals [D.C or A.C source- 24V – 230V] can be used [Electro pneumatics]

Characteristics of Compressed Air

The following characteristics of Compressed air speak for the application of Pneumatics

- Abundance of supply of air
- Transportation

- Storage
- Temperature
- Explosion Proof

Selection Criteria for Pneumatic Control System

- Stroke
- Force
- Type of motion [Linear or Angular motion]
-
- Size
- Service

- Cleanliness
- Speed
- Regulation
- Overload Proof
- Sensitivity
- Safety and Reliability
- Energy Cost
- Controllability
- Handling
- Storage

Advantages of Pneumatic Control

- Unlimited Supply
- Storage
- Easily Transportable
- Clean
- Explosion Proof
- Controllable (Speed, Force)
- Overload Safe
- peed of Working Elements

Disadvantages

- Cost
- Preparation
- Noise Pollution
- Limited Range of Force (only economical up to 25 kN)

General Applications of Pneumatic Control

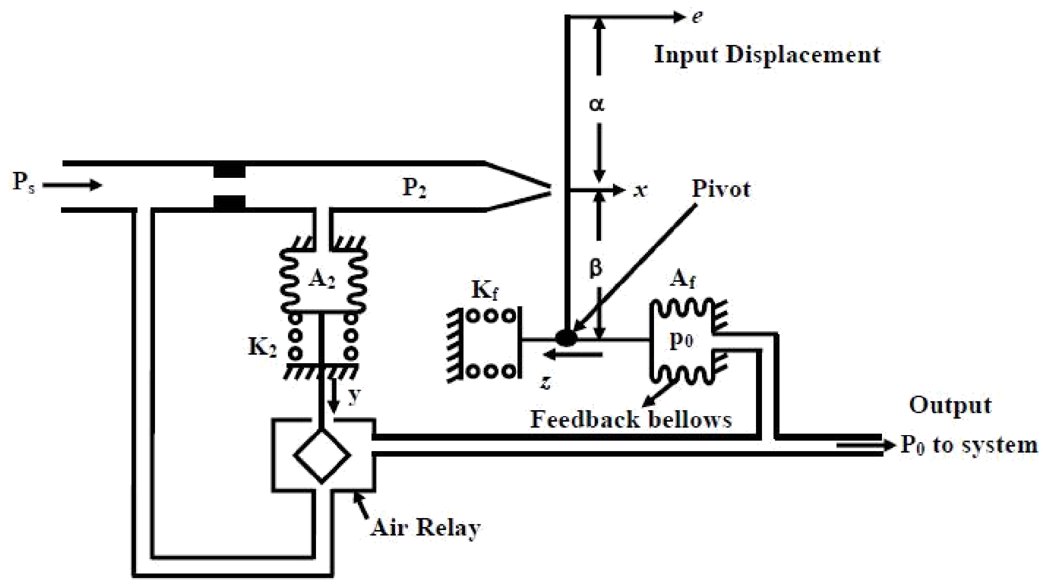
- Clamping
- Shifting
- Metering
- Orienting
- Feeding
- Ejection
- Braking
- Bonding
- Locking
- Packaging
- Feeding
- Door or Chute Control
- Transfer of Material
- Turning or Inverting of Parts
- Sorting of Parts
- Stacking of Components
- Stamping and Embossing of components

Applications in Manufacturing

- Drilling Operation
- Turning
- Milling
- Sawing
- Finishing
- Forming
- Quality Control

Pneumatic Proportional Controller

Consider the pneumatic system shown in Fig 2.24. It consists of several pneumatic components The components, which can be easily identified, are: flapper nozzle amplifier, air relay, bellows and springs, feedback arrangement etc. The overall arrangement is known as a pneumatic proportional controller. It acts as a controller in a pneumatic system generating output pressure proportional to the displacement e at one end of the link. The input to the system is a small linear displacement e and the output is pressure Po. The input displacement may be caused by a small differential pressure to a pair of bellows, or by a small current driving an electromagnetic unit. There are two springs K_2 and K_f those exert forces against the movements of the bellows A_2 and A_f. For a positive displacement of e (towards right) will cause decrease of pressure in the flapper nozzle. This will cause an upward movement of the bellows A_2 (decrease in y). Consequently the output pressure of the air relay will increase. The increase in output pressure will move the free end of the feedback bellows towards left, bringing in the gap between the flapper and nozzle to almost its original value. We will first develop the closed loop representation of the scheme and from there the input output relationship will be worked out. The air is assumed to be impressible here.



2.24 A pneumatic proportional controller

Pneumatic PID Controller

Many pneumatic PID controllers use the force-balance principle. One or more input signals (in the form of pneumatic pressures) exert a force on a beam by acting through diaphragms, bellows, and/or bourdon tubes, which is then counter-acted by the force exerted on the same beam by an output air pressure acting through a diaphragm, bellows, or bourdon tube. The self-balancing mechanical system "tries" to keep the beam motionless through an exact balancing of forces, the beam‟s position precisely detected by a nozzle/baffle mechanism.

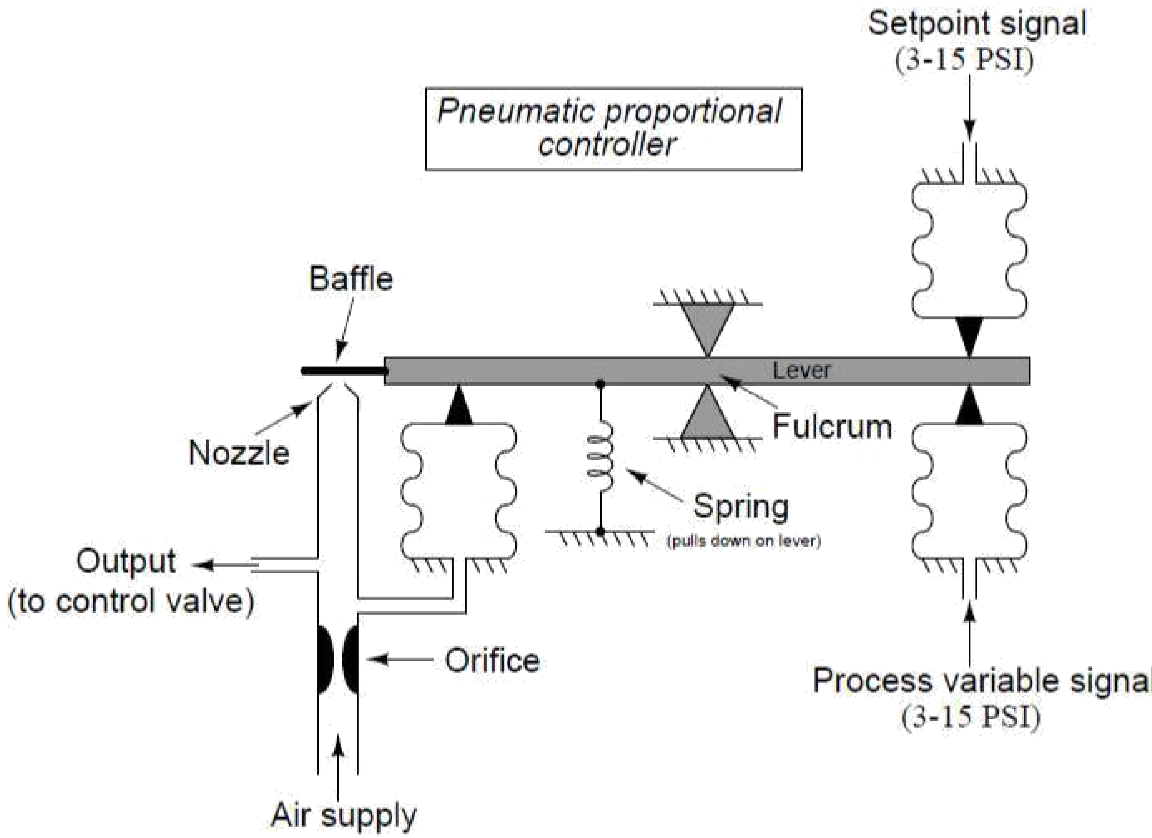


Fig 2.25 Proportional Controllers

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 caus es 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 wished to reverse the co ntroller"s action, all we would need to do is swap the pneumatic signal connections between the input bellows, so that the PV pressure was applied to the upper bellows and the SP pressure to the lower bellows. Any factor influencing the ratio of input pressure(s) to output pressure may be exploited as a gain (proportional band) adjustment in this mechanism. Changing bellows area (either both the PV and SP bellows equally, or the output bellows by itself) would influence this ratio, as would a change in output bellows position (such that it pressed against the beam at some difference distance from the fulcrum point). Moving the fulcrum left or right is also an option for gain control, and in fact is usually the most convenient to engineer.

Derivative and integral actions

Interestingly enough, derivative (rate) and integral (reset) control modes are relatively easy to add to this pneumatic controller mechanism. To add derivative control action, all we need to do is 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:

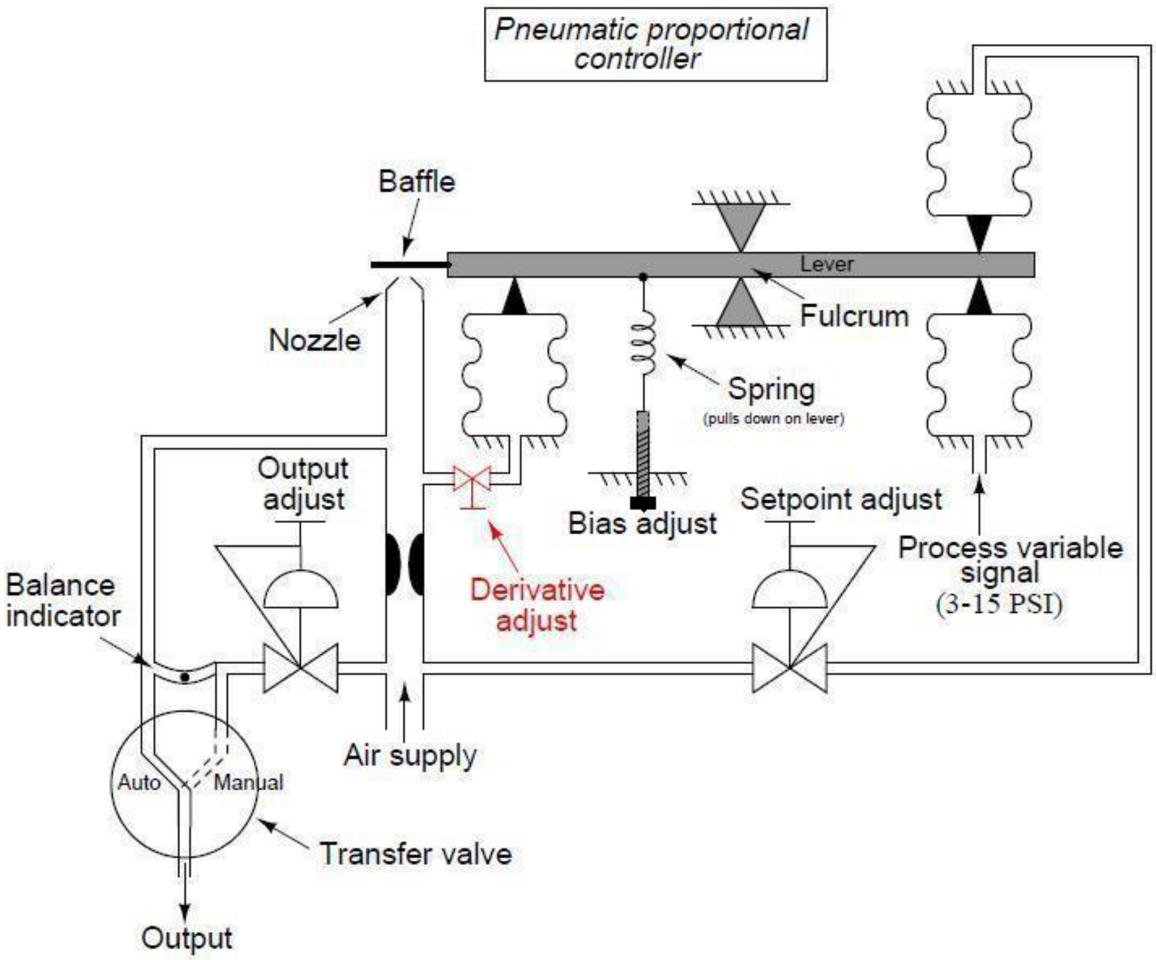


Fig 2.26 Proportional + Derivative Controllers

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 also 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 force necessary 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: exactly what we would expect from a controller with both proportional and derivative control actions.

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

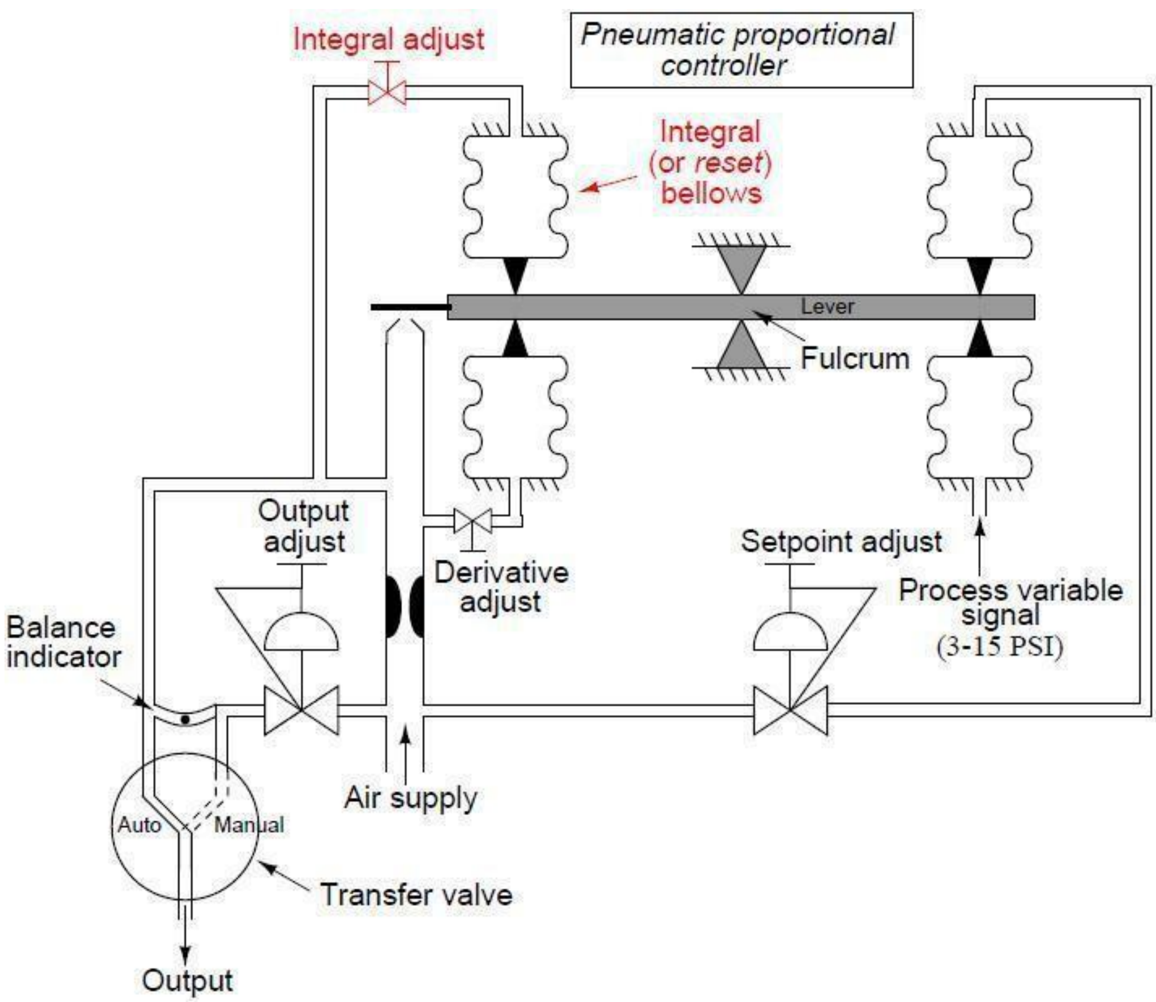


Fig 2.27 Proportional + Derivative + Integral

This second bellows takes air pressure from the output line and translates it into force that opposes the original feedback bellows. At first, this may seem counter-productive, for it nullifies the ability of this mechanism to continuously balance the force generated by the PV and SP bellows. Indeed, it would render the force-balance system completely ineffectual if this new “reset” bellows were allowed to inflate and deflate with no time lag. However, with a time lag provided by the restriction of the integral adjustment valve and the volume of the bellows (a sort of pneumatic "RC time constant"), the nullifying force of this bellows becomes delayed over time. As this bellows slowly fills (or empties) with pressurized air from the nozzle, the change in force on the beam causes the regular output bellows to have to "stay ahead" of the reset bellows action by constantly filling (or emptying) at some rate over time.

Pneumatic Integral Controller

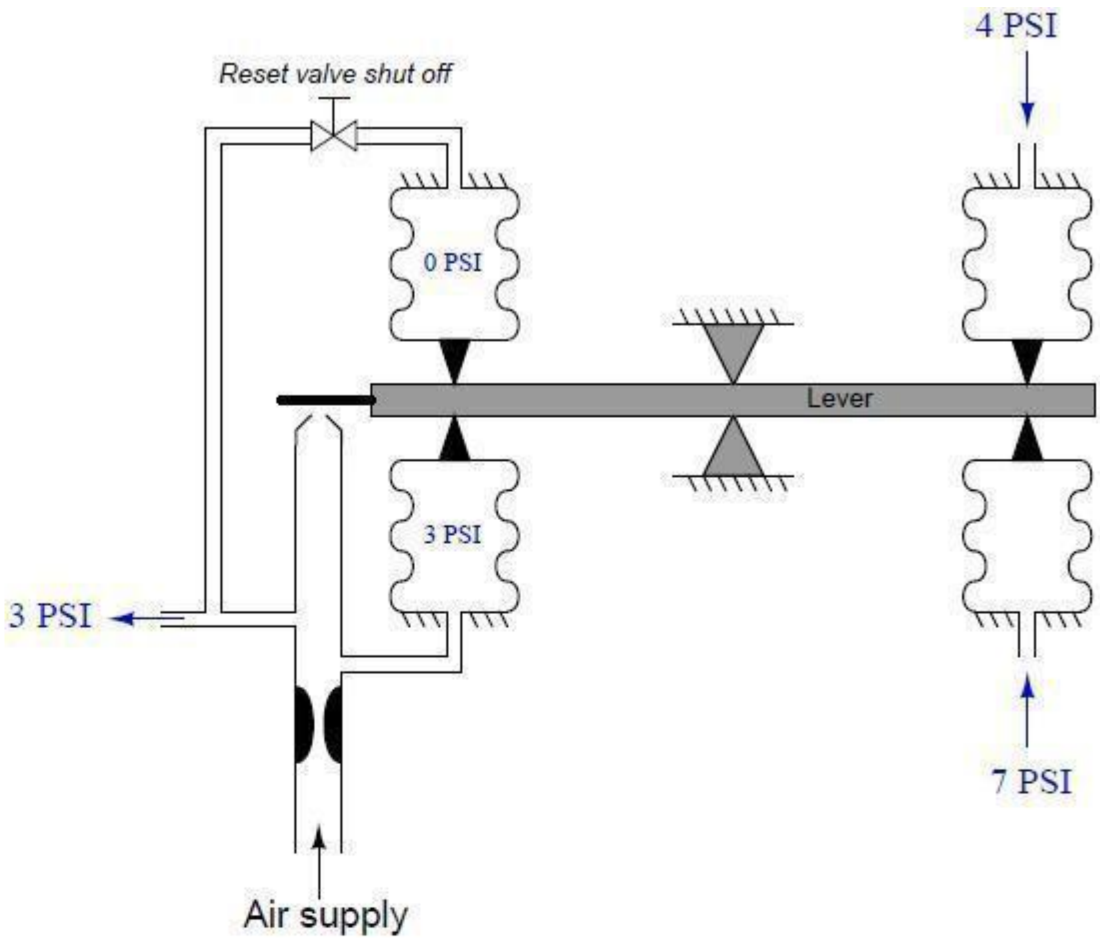


Fig 2.28 Pneuamtic Integral controllers

Here, the PV and SP air pressure signals differ by 3 PSI, causing the force-balance mechanism to instantly respond with a 3 PSI output pressure to the feedback bellows (assuming a central fulcrum location, giving a controller gain of 1). The reset (integra l) valve has been completely shut off to begin our analysis The result of these two bellows" opposing forces (one instantaneous, one time-delayed) is that the lower bellows must always stay 3 PSI ahead of the upper bellows in order to maintain a force-balanced condition with the two input bellows whose pressures differ by 3 PSI. This creates a constant 3 PSI differential pressure across the reset restriction valve, resulting in a constant flow of air into the reset bellows at a rate determined by that press ure drop and the opening of the restrictor valve. Eventually this will cause the output pressure to saturate at maximum, but until then the practical importance of this rising pressure action is that the mechanism now exhibits integral control response to the constant error between PV and SP

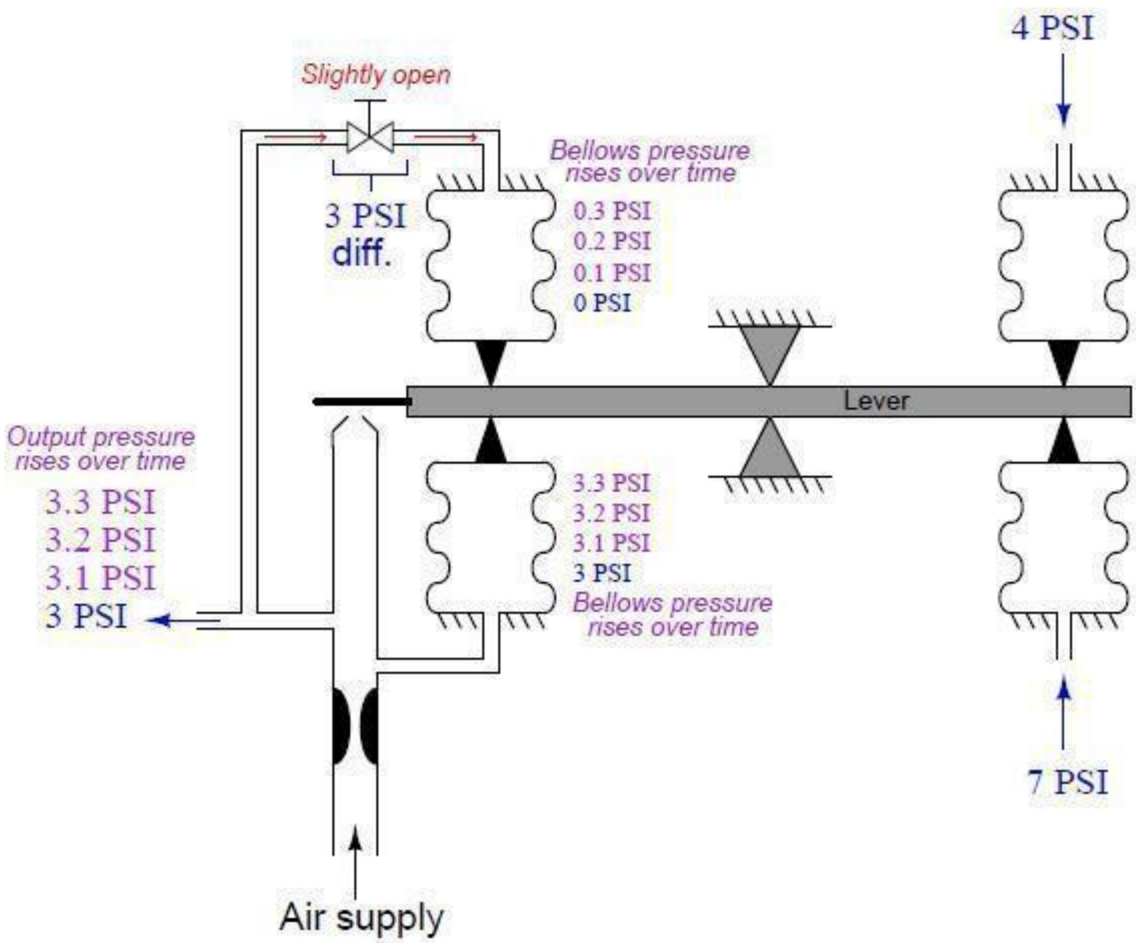


Fig 2.29 Integral Control Action

The greater the difference in pressures between PV and SP (i.e. the greater the error), the more pressure drop will develop across the reset restriction valve, causing the reset bellows to fill (or empty, depending on the sign of the error) with compressed air at a faster rate2, causing the output pressure to change at a faster rate. Thus, we see in this mechanism the defining nature of integral control action: that the magnitude of the error determines the velocity of the output signal (its rate of change over time, or dmdt). The rate of integration may be finely adjusted by changing the opening of the restrictor valve, or adjusted in large steps by connecting capacity tanks to the reset bellows to greatly increase its effective volume.

INTRODUCTION TO ELECTRONIC CONTROLLERS

A controller is a comparative device that receives an input signal from a measured process variable, compares this value with that of a predetermined control point value (set point), and determines the appropriate amount of output signal required by the final control element to provide corrective action within a control loop. An Electronic Controller uses electrical signals to perform its receptive, comparative and corrective functions.

Two Position controller using OPAMP

Fig. 2.30 represents the OPAMP implementation of ON/OFF controller with adjustable neutral zone.

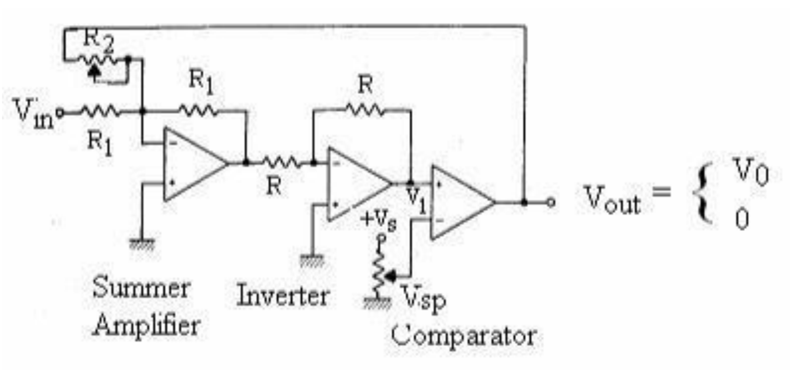


Fig 2.30 A two position controller with neutral zone made from op amps and a Comparator

Assume that, if the controller input voltage, Vin reaches a value VH then the comparator output should go to the ON state, which is defined as some voltage V0. When the input voltage falls bellow a value VL the comparator output should switch to the OFF state, which is defined as 0 V. This defines a two position controller with a neutral zone of NZ = VH - VL as shown in the Fig. 2.31

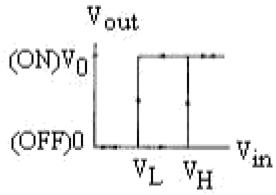


Fig. 2.31. Two position controller response in terms of voltages

Assume that, in the beginning, the comparator is in the OFF state. i.e. the voltage, V1 at the input of the comparator is less than the setpoint voltage, Vsp. Hence,

Vout = 0 (2.17)

The comparator output switches states when the voltage on its input, V1 is equal to the set point value Vsp Analyzing this circuit,

$$V_1 = V_{in} + \frac{R_1}{R_2} V_{out} \tag{2.18}$$

Substituting Eq. 2.17, in Eq. 2.18, yields

V1 = Vin

The comparator changes to ON state when V1 = Vin = VH. Thus, the high (ON) switch voltage is

VH = Vsp (2.19)

and the corresponding output voltage Vout is

Vout = V0 (2.20)

With this V1 changes to

$$V_1 = V_{in} + \frac{R_1}{R_2} V_0$$

(2.21) If Vin = VL the comparator changes to OFF state, giving the relation,

$$V_1 = V_{sp} = V_L + \frac{R_1}{R_2} V_0 \tag{2.22}$$

This gives the low (OFF) switching voltage of

$$V_L = V_{SP} - \frac{R_1}{R_2} V_o \tag{2.23}$$

As mentioned before, Fig 2.31 shows typical two position relationship between input and output voltage for the circuit. The width of the neutral zone between VL and VH can be adjusted by variation of R2. The relative location of the neutral zone is calculated from the difference between the equations (2.19) and (2.23).

The inverter resistance value in Fig. 2.30 can be chosen as any convenient value. Typically it is in the 1 to 100 K Ω range.

Three position Controllers

Fig. 2.32 shows how a simple three position controller can be realized with op amps and comparators.

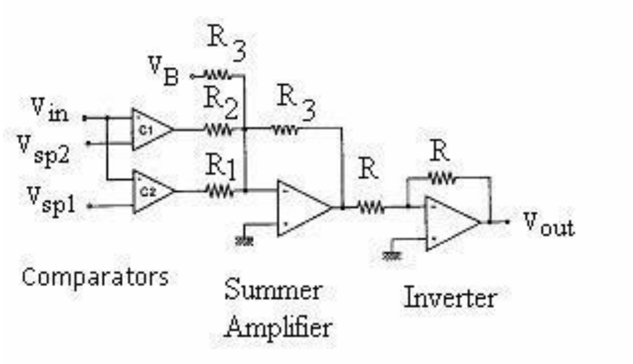


Fig 2.32 Three Position Controller

Fig. 2.32 A three position controller using two comparators and op amps Assume that, the output of the comparators is 0 V for the OFF state and V0 volts for the ON state. The summing amplifier also includes a bias voltage input, VB which allows the three position mode response to be biased up or down in voltage to suit particular needs. The inverter is needed to convert the sign of the inverting action of the summing amplifier.

When Vin < VSP1 ,

Comparator C1 is OFF, C2 is OFF (Because VSP1< VSP2) Outputs of both comparators are 0 V. Thus,

Vout = VB

When VSP1 < Vin< VSP2 , Comparator C1 is OFF, C2 is ON Outputs of comparator

C1 = 0 and Output of Comparator $C2 = \frac{R_3}{R_1} V_0$ Volts. Thus,

$$V_{out} = V_B + \frac{R_3}{R_1} V_0$$

Outputs of comparator $C1 = \frac{R_3}{R_2} V_0$ and Output of Comparator $C2 = \frac{R_3}{R_1} V_0$ Volts. Thus,

$$V_{out} = V_B + \frac{R_3}{R_1} V_0 + \frac{R_3}{R_2} V_0$$

Thus,

When $V_{in} < V_{SP1}$, $\quad V_{out} = V_B$

$V_{SP1} < V_{in} < V_{SP2}$, $\quad V_{out} = V_B + \frac{R_3}{R_1} V_0$

$V_{in} > V_{SP2}$, $\quad V_{out} = V_B + \frac{R_3}{R_1} V_0 + \frac{R_3}{R_2} V_0$

Here, the output need not be symmetric. (e.g. 0%, 50% and 100%). Fig. 2.33 shows the response of this circuit for a particular case VB = 0

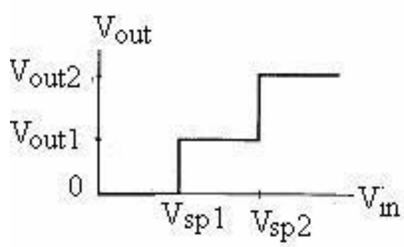


Fig. 2.33. Response of the three position controller with VB = 0

Proportional Mode

Implementation of this mode requires a circuit that has the response given by:

P = Kpep + P0 (2.24)

Where P = controller output 0 – 100 %

Kp = Proportional gain

ep = error in percent of variable range

P0 = Controller output with no error

Implementation of P – Mode controller using OPAMP

If both the controller output and error expressed in terms of voltage, then the above Eq. 2.24 is a summing amplifier. Fig.2.34 shows such an electronic proportional controller.

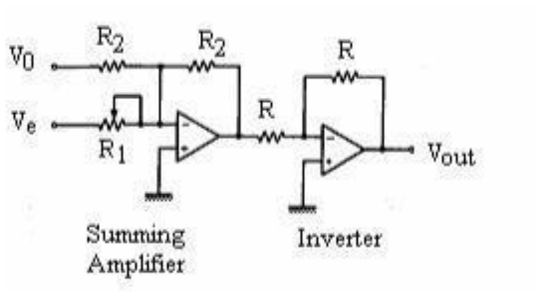


Fig.2.34. An op amp proportional mode controller

Now, the analog electronic equation for the output voltage is:

Vout = GpVe + V0 (2.25)

Where, Vout = output voltage

Gp = R2/R1 = gain

Ve = Error voltage

V0 = output with zero error

To use the circuit of Fig.2.34 for proportional mode, a relationship must be established with the characteristics of the mode, defined already, in chapter 1. In Eq. 2.35, the error is expressed as the percent of measurement range, and the output is simply 0 % to 100%. Yet Fig. 2.34 deals with voltage on both the input and output.

Thus, first identify that the output voltage range of the circuit, whatever it is, represents a swing of 0% to 100%. Thus, if a final control element needs 0 to 5 V, then a Zener is added as shown in the Fig.2.35 so that the op amp output can swing only between 0 and 5V.

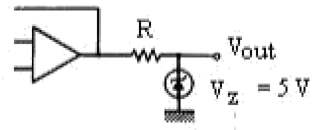


Fig.2.35. A zener diode used to clamp the output swing of an op amp controller

Integral Mode

The general representation of integral controller is

$$P(t) = K_I \int_0^t e_p(t)dt + P_I(0) \tag{2.26}$$

Where, P(t) = controller output in percent of full

scale KI = integration gain (s-1)

ep(t) = deviations in percent of full scale variable

value PI(0) = Controller output at t = 0

Implementation Using OPAMP

Integral controller implemented using OPAMPs is shown in Fig.

2.36 Analysis of the circuit gives,

$$V_{out} = G_I \int_0^t V_e dt + V_{out}(0) \tag{2.27}$$

Where, Vout = Output voltage

GI = 1/RC = Integration gain

Ve = error voltage

Vout(0) = Initial output voltage.

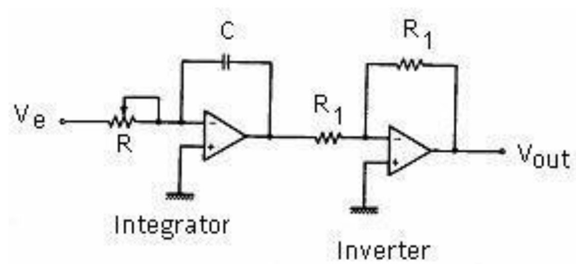


Fig. 2.36. An op amp integral mode controller

The values of R and C can be adjusted to obtain the desired integration time. The initial controller output is the integrator output at t = 0.

If K_I is made too large, the output rises so fast that overshoots of the optimum setting occur and cycling is produced.

Determination of G_I

The actual value of G_I and therefore R and C, is determined from KI and the input and output voltage ranges. Integral gain says that, an input error of 1 % must produce an output that changes as K_I % per second. Or if an error of 1 % lasts for 1 s, the output must change by KI percent.

e.g. Consider an input range of 6 V

Output range of 5V

KI = 3.0 %/(%- min)

Note: Integral gain is often given in minutes because industrial processes are slow, compared to a time of seconds. This gain is often expressed as integration time, TI, which is just the inverse of the gain.

Solution

First convert the time units to seconds. Therefore, [(3 %)/(%- min)][(1min/60s)]

= 0.05%/(%-s) Error of 1 % for 1 sec = (0.01)(6V)(1s) = 0.06 V-s

KI % of the output = (0.0005)(5V) = 0.0025 V

The integral gain GI = (KI % of the output) / (Error of 1 % for 1 sec)

= (0.0025V)/(0.06 V-s)

= 0.0417 s-1

Values of R and C can be selected from this.

Derivative mode

The derivative mode is never used alone because it can not provide a controller output when the error is zero or constant. The control mode equation is given by

$$P(t) = K_D \frac{de_p}{dt} \tag{2.28}$$

where, P = Controller output in percent of full

output KD = Derivative time constant (s)

ep = error in percent of full scale range

where, P = Controller output in percent of full output

KD = Derivative time constant (s)

ep = error in percent of full scale range

Implementation of derivative controller using OPAMP:

Consider an OPAMP differentiator circuit shown in Fig. 2.37 The theoretical transfer function for this circuit will be given by

$$V_{out} = -RC\frac{dV_e}{dt} \tag{2.29}$$

where, the input voltage has been set equal to the controller error voltage

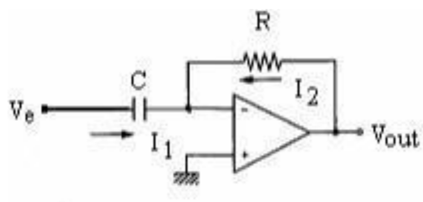


Fig 2.37 OPAMP differentiator circuit

Composite controller modes

Composite modes combine the advantages of each mode and in some cases eliminate the disadvantages. Composite modes are implemented easily using opamp techniques.

Proportional – Integral mode

PI controller is the combination of proportional and integral controller defined by:

$$P = K_p e_p + K_p K_I \int_0^t e_p dt + P_I(0) \tag{2.30}$$

Where, P = controller output in percent of full

scale ep = process error in percent of the maximum

Kp = Proportional gain

KI= Integral gain

PI(0) = initial controller integral output

Implementation of PI controller using opamps

Figure 2.38 a shows one method of implementation of the PI controller using opamps.

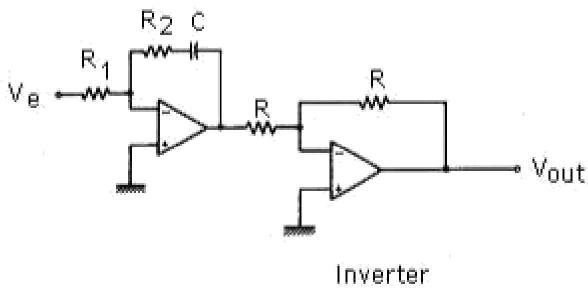


Fig. 2.38 a. An op amp proportional integral (PI) mode controller

To derive an expression for the output voltage of this circuit, first define nodes and currents as shown in the Fig. 2.38 b.

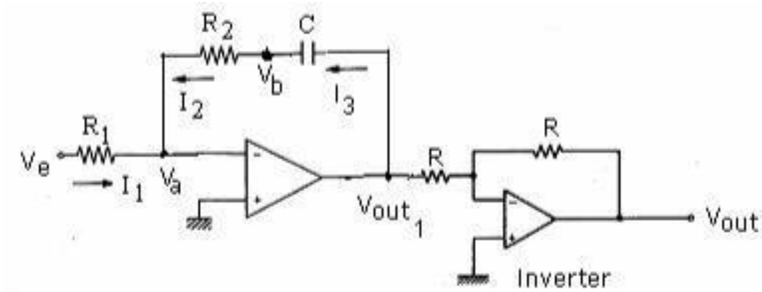


Fig.2.38 b. An op amp proportional integral (PI) mode controller

Note that, there is no current through op amp input terminals and no voltage across the input terminals. Therefore, Va = 0 and

I1 + I2 = 0 (2.31)

I3 – I2 = 0 (2.32)

The relationship between the voltage across the capacitor and current through a capacitor is given by

$$I_c = C\frac{dV_c}{dt} \qquad (2.33)$$

Where Vc is the voltage across the capacitor. Combining this with Ohm‟s law allows the preceding current equations (2.31 and 2.32) to be written in terms of voltage as

$$\frac{V_e}{R_1} + \frac{V_b}{R_2} = 0 \tag{2.34}$$

$$C\frac{d}{dt}\left[V_{out_1} - V_b\right] - \frac{V_b}{R_2} = 0 \tag{2.35}$$

The Eq. 2.34 can be solved for Vb as:

$$V_b = -\frac{R_2}{R_1}V_e \tag{2.36}$$

Substituting this in to Eq. 2.35

$$C\frac{dV_{out_1}}{dt} - C\frac{d}{dt}\left(-\frac{R_2}{R_1}V_e\right) - \frac{1}{R_2}\left(-\frac{R_2}{R_1}V_e\right) = 0 \tag{2.37}$$

$$C\frac{dV_{out_1}}{dt} + C\frac{R_2}{R_1}\frac{d}{dt}V_e + \frac{1}{R_1}V_e = 0$$

Or, $$\frac{dV_{out_1}}{dt} + \frac{R_2}{R_1}\frac{d}{dt}V_e + \frac{1}{R_1 C}V_e = 0$$

In order to solve for Vout, integrate this equation to eliminate the derivative on Vout. i.e.:

$$V_{out_1} = -\frac{R_2}{R_1}V_e - \frac{1}{R_1 C}\int_0^t V_e dt + V(0) \tag{2.38}$$

$$V_{out_1} = -\frac{R_2}{R_1}V_e - \frac{R_2}{R_1}\frac{1}{R_2 C}\int_0^t V_e dt + V(0)$$

After inverting

$$V_{out} = \frac{R_2}{R_1}V_e + \frac{R_2}{R_1}\frac{1}{R_2 C}\int_0^t V_e dt + V(0)$$

$$\text{Or, } V_{out} = G_p V_e + G_p G_I \int_0^t V_e dt + V(0) \tag{2.39}$$

Where, Proportional gain, Gp = R2/R1 and integral gain GI = 1/ (R2C)

Proportional Derivative Mode of controller

PD controller is the combination of proportional and derivative mode of controllers. The general definition of PD controller is

$$\mathrm{P(t)} = K_p \mathrm{e_p} + \mathrm{K_p K_D}\frac{\mathrm{de_p}}{\mathrm{dt}} + P(0) \tag{2.40}$$

Where, P = Controller output in percent of full output

Kp = Proportional gain

KD = Derivative time constant (s)

ep = error in percent of full scale range

P(0) = Zero error controller output

Implementation of PD controller using opamps.

Fig. 2.39 a shows how a PD controller can be implemented using op amps. Where the quantities are defined in the figure and the output inverter has been included. This circuit includes the clamp to protect against high gain at high frequency in the derivative term.

$$R = \frac{R_1 R_3}{R_1 + R_3}$$

Then the condition becomes as usual, 2π fmax RC = 0.1. Assuming this criterion has been met, while deriving the equation for the PD response given below

$$V_{out} = \left(\frac{R_2}{R_1 + R_3}\right)V_e + \left(\frac{R_2}{R_1 + R_3}\right)R_3 C\frac{dV_e}{dt} + V_0$$

$$V_{out_1} = G_p V_e + G_p G_D \frac{dV_e}{dt} + V_0$$

Where the proportional gain is

And the derivative gain is GD = R3 C

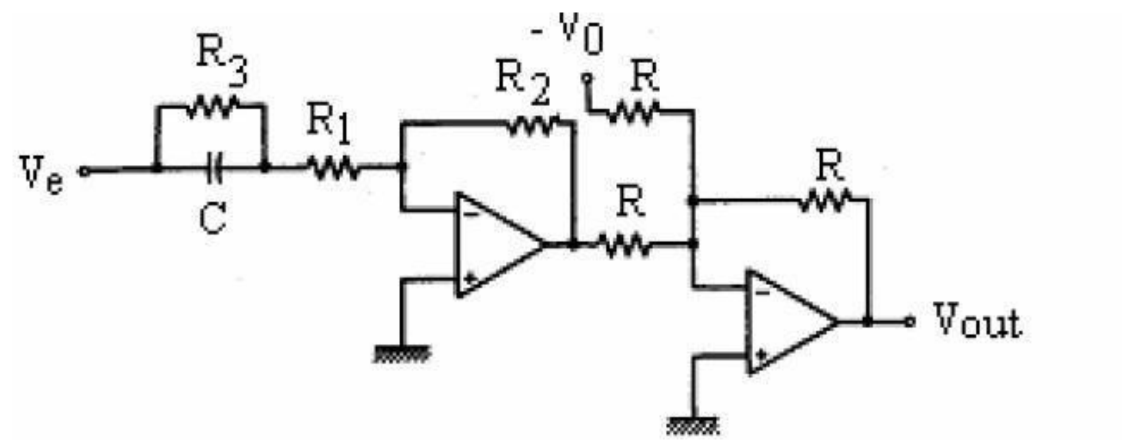


Fig.2.39 a An op amp Proportional Derivative (PD) mode controller

Derivation of PD controller response:

Analysis of PD circuit can be performed using the circuit shown in Fig. 2.39b showing currents and nodes. The voltage across the op amp input terminals, Vb = 0. Also there is no current in to the op amp inputs.

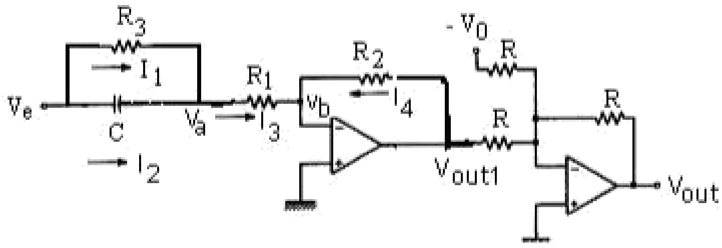


Fig.2.39 b An op amp Proportional Derivative (PD) mode controller

Application of KCL, to the two active nodes provides the equations:

$I_1 + I_2 - I_3 = 0$

$I_4 + I_3 = 0$

Ohm's law and the differential relation between current and voltage for a capacitor can be used to express these equations in terms of voltage.

$$\frac{V_e - V_a}{R_3} + C\frac{d}{dt}\left[V_e - V_a\right] - \frac{V_a}{R_1} = 0$$

$$\frac{V_{out_1}}{R_2} + \frac{V_a}{R_1} = 0$$

$$V_a = -\frac{R_1}{R_2}V_{out_1}$$

$$\frac{V_e}{R_3} + \frac{R_1}{R_2R_3}V_{out_1} + C\frac{dV_e}{dt} + \frac{R_1}{R_2}C\frac{dV_{out_1}}{dt} + \frac{1}{R_2}V_{out_1} = 0$$

Or, $V_e + \frac{R_1}{R_2}V_{out_1} + R_3C\frac{dV_e}{dt} + \frac{R_3R_1}{R_2}C\frac{dV_{out_1}}{dt} + \frac{R_3}{R_2}V_{out_1} = 0$

After rearranging and some more algebra, this reduces to:

$$V_{out_1} + \left(\frac{R_1}{R_1 + R_3}\right)R_3C\frac{dV_{out_1}}{dt} = -\left(\frac{R_2}{R_1 + R_3}\right)V_e - \left(\frac{R_2}{R_1 + R_3}\right)R_3C\frac{dV_e}{dt}$$

After inverting

$$V_{out} + \left(\frac{R_1}{R_1 + R_3}\right)R_3C\frac{dV_{out_1}}{dt} = \left(\frac{R_2}{R_1 + R_3}\right)V_e + \left(\frac{R_2}{R_1 + R_3}\right)R_3C\frac{dV_e}{dt}$$

Or, $V_{out} = \left(\frac{R_2}{R_1 + R_3}\right)V_e + \left(\frac{R_2}{R_1 + R_3}\right)R_3C\frac{dV_e}{dt} + V_0$

$$V_{out} = G_pV_e + G_pG_D\frac{dV_e}{dt} + V_0$$

Where the proportional gain is $G_p = \left(\frac{R_2}{R_1 + R_3}\right)$

And the derivative gain is $G_D = R_3C$

PD controller still has the offset error of a proportional controller because the derivative term cannot provide reset action.

Three Mode Controller

Three mode controllers is the combination of proportional, integral and derivative mode of controllers. Characterized by

$$P = K_p e_p + K_p K_I \int_0^t e_p dt + K_p K_D \frac{de_p}{dt} + P_I(0)$$

Where, P = controller output in percent of full

scale ep = process error in percent of the maximum

Kp = Proportional gain

KI= Integral gain

KD= Derivative gain

PI(0) = initial controller integral output

The zero error term of the proportional mode is not necessary because the integral automatically accommodates for offset and nominal setting.

Implementation of three mode controller using op amps

Three mode controller can be implemented by a straight application of op amps as shown in Fig. 2.40a.

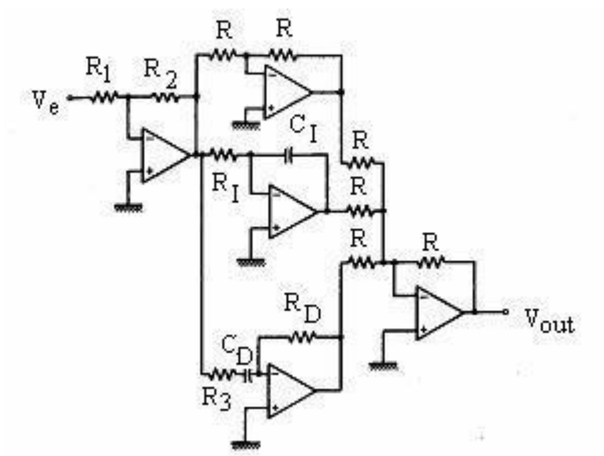


Fig. 2.40a. Implementation of a three mode (PID) controller with op amps

For the analysis, assume the voltages as indicated in Fig. 2.40b

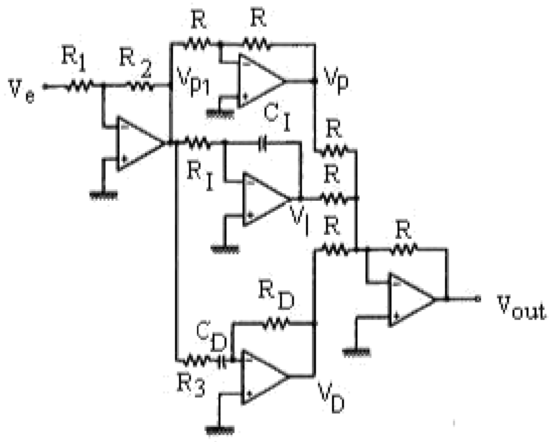


Fig. 2.40b. Implementation of a three mode (PID) controller with op amps

$$V_{p1} = -\frac{R_2}{R_1}V_e$$

$$V_p = \frac{R_2}{R_1}V_e$$

$$V_I = -\frac{1}{R_I C_I}\int_0^t V_{p1}dt \quad \text{or, } V_I = \frac{R_2}{R_1}\frac{1}{R_I C_I}\int_0^t V_e dt$$

$$V_D = -R_D C_D \frac{d}{dt}V_{p1} \quad \text{or, } V_D = \frac{R_2}{R_1}R_D C_D \frac{d}{dt}V_e$$

$- V_{out} = V_p + V_I + V_D$

$$-V_{out} = \left(\frac{R_2}{R_1}\right)V_e + \left(\frac{R_2}{R_1}\right)\frac{1}{R_I C_I}\int V_e dt + \left(\frac{R_2}{R_1}\right)R_D C_D \frac{dV_e}{dt} + V_{out}(0)$$

R_3 has been chosen from $2\pi f_{max} R_3 C_D = 0.1$ for stability. Comparing equations

$$G_p = \left(\frac{R_2}{R_1}\right),\ G_I = \left(\frac{1}{R_I C_I}\right) \quad \text{and } G_D = R_D C_D$$

$$-V_{out} = G_p V_e + G_p G_I \int V_e dt + G_p G_D \frac{dV_e}{dt} + V_{out}(0)$$

Adding an inverter at the output stage,

$$V_{out} = G_p V_e + G_p G_I \int V_e dt + G_p G_D \frac{dV_e}{dt} + V_{out}(0)$$

Suggested Readings and Websites:

1. Instrument Engineers Handbook: Volume 2-Process Control, by Bela J. Liptak, Chilton Book Company.
2. Computer based industrial control by Krishna Kant, PHI, 2002
3. Computer Control of Processes by M.Chidambaram, Narosa Pub., 2003
4. Computer Aided Process Control by S.K.Singh, PHI
5. www. controlmagazine.com
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7. www. xnet.com/~blatura/control.shtml
8. www.honeywell.com
9. www.controlguru.com/
10. www.processautomationcontrol.com

Glossary:

Control lag: It refers to the time for the process control loop to make necessary adjustments to the final control element.

Control parameter range : It is the range associated with the controller output

Control System: All the elements necessary to accomplish the control objective i.e. regulation of some parameters to have specific or desired values

Control: The methods/techniques to force parameters or variables in the environment / process to have specific values.

Controlled Variable : The process variable regulated by process control loop.

Controller: The element in a process control loop that evaluates error of the controlled variable and initiates corrective action by a signal to controlling variable.

Controlling Variable : The process variable changed by the final control element under the command of controller to effect regulation of controlled variable.

Cycling: It is defined as the oscillations of the error about zero value or nominal value.

Dead time : It is the elapsed time between the instant a deviation (error) occurs and the corrective action first occurs.

Direct Action: If the controller output increases with increase in controlled variable then it is called direct action.

Dynamic variable: The process variable that can change from moment to moment because of unknown sources.

Error: The algebraic difference between the measured value of variable and setpoint. **Process Control**: It deals with the elements and methods of control system operations used in industry to control industrial processes.

Process Equation: It is a function which describes the process and provides the information about other process parameters which influence the controlled variable **Process Lag:** It refers to the time consumed by the process itself to bring the controlled variable to setpoint value during load change

Process Load: It refers to set of all process parameters excluding the controlled variable in a process.

Process: In general, process constitutes a sequence of events in which a raw material will be converted into finished product. "Any system composed of dynamic variables, usually involved in manufacturing & production operations".

Regulation: It means to maintain a quantity or variable at some desired value regardless of external influences.

Reverse Action: If the controller output decreases with increase in controlled variable then it is called direct action

Self-regulation: Some processes adopt to stable value without being regulated via process control loop.

Setpoint: The desired value of a controlled variable in process control loop.

Variable range: The variable range can be expressed as the minimum and maximum value of the variable or the nominal value ± the deviation spread about the nominal value.

Controller

A controller is a mechanism that seeks to minimize the difference between the actual value of a system (i.e. the process variable) and the desired value of the system (i.e. the setpoint). Controllers are a fundamental part of control engineering and used in all complex control systems.

Before we introduce you to various controllers in detail, it is very essential to know the uses of controllers in the theory of control systems. The important uses of the controllers include:

1. Controllers improve the steady-state accuracy by decreasing the steady state error.
2. As the steady-state accuracy improves, the stability also improves.
3. Controllers also help in reducing the unwanted offsets produced by the system.

4. Controllers can control the maximum overshoot of the system.
5. Controllers can help in reducing the noise signals produced by the system.
6. Controllers can help to speed up the slow response of an overdamped system.

Different varieties of these controllers are codified within industrial automotive devices such as programmable logic controllers and SCADA systems. The various types of controllers are discussed in detail below.

Types of Controllers

There are two main types of controllers: continuous controllers, and discontinuous controllers.

In discontinuous controllers, the manipulated variable changes between discrete values. Depending on how many different states the manipulated variable can assume, a distinction is made between two position, three position, and multi-position controllers. Compared to continuous controllers, discontinuous controllers operate on very simple, switching final controlling elements.

The main feature of continuous controllers is that the controlled variable (also known as the manipulated variable) can have any value within the controller's output range. Now in the continuous controller theory, there are three basic modes on which the whole control action takes place, which are:

1. **Proportional controllers**.
2. **Integral controllers**.
3. **Derivative controllers**.

We use the combination of these modes to control our system such that the process variable is equal to the setpoint (or as close as we can get it). These three types of controllers can be combined into new controllers:

1. Proportional and integral controllers (PI Controller)
2. Proportional and derivative controllers (PD Controller)
3. Proportional integral derivative control (PID Controller)

Now we will discuss each of these control modes in detail below.

Proportional Controllers

All controllers have a specific use case to which they are best suited. We cannot just insert any type of controller at any system and expect a good result – there are certain conditions that must be fulfilled. For a **proportional controller,** there are two conditions and these are written below:

1. The deviation should not be large; i.e. there should not be a large deviation between the input and output.
2. The deviation should not be sudden.

Now we are in a condition to discuss proportional controllers, as the name suggests in a proportional controller the output (also called the actuating signal) is directly proportional to the error signal. Now let us analyze the proportional controller mathematically. As we know in proportional controller output is directly proportional to the error signal, writing this mathematically we have,

$$A(t) \propto e(t)$$

Removing the sign of proportionality we have,

$$A(t) = K_p \times e(t)$$

Where K_p is proportional constant also known as controller gain.

It is recommended that K_p should be kept greater than unity. If the value of K_p is greater than unity (>1), then it will amplify the error signal and thus the amplified error signal can be detected easily.

Advantages of Proportional Controller

Now let us discuss some advantages of the proportional controller.

1. The proportional controller helps in reducing the steady-state error, thus makes the system more stable.
2. The slow response of the over damped system can be made faster with the help of these controllers.

Disadvantages of Proportional Controller

Now there are some serious disadvantages of these controllers and these are written as follows:

1. Due to the presence of these controllers, we get some offsets in the system.
2. Proportional controllers also increase the maximum overshoot of the system.

Now, we will explain the Proportional Controller (P-controller) with a unique example. With this example reader's knowledge about 'Stability' and 'Steady State Error' will also enhance. Consider the feedback control system shown in Figure-1

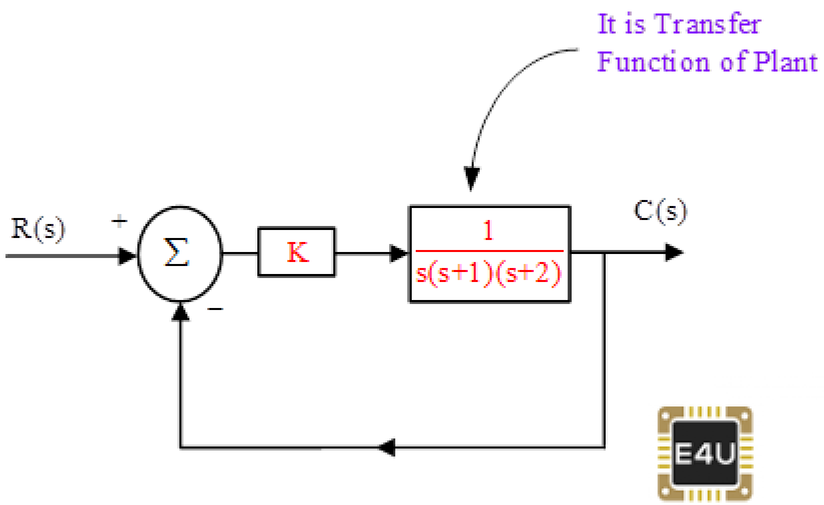


Figure-1: A Feedback Control System with Proportional Controller

'K' is called a proportional controller (also called error amplifier). Characteristics equation of this control system can be written as:

$s^3+3s^2+2s+K=0$

If the Routh-Hurwitz is applied in this characteristics equation, then the range of 'K' for the stability can be found as 0<K<6. (It implies that for the values K>6 system will be unstable; for the value of K=0, the system will be marginally stable).

Root locus of above control system is shown in Figure-2

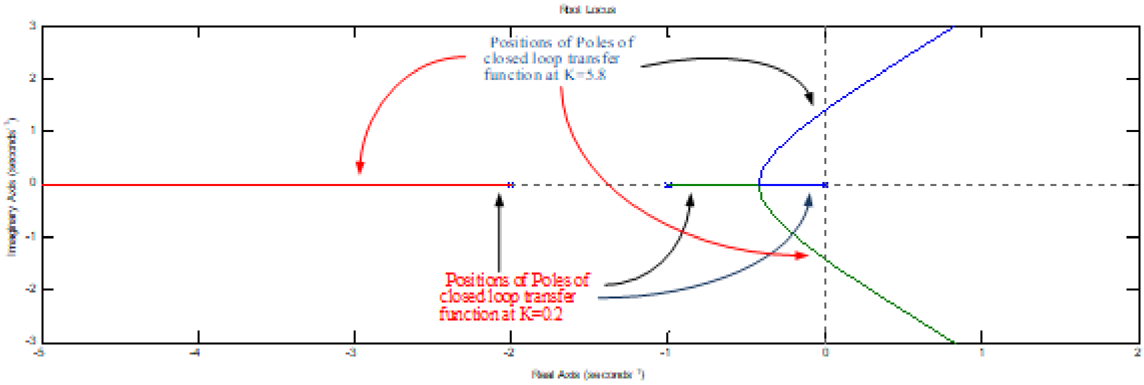


Figure-2: Root locus of the system shown in Figure-1, Root Locus provides an idea that what should be the value of 'K'

(You can understand that root locus is drawn for the open-loop transfer function (G(s)H(s), but it gives an idea about the poles of the closed-loop transfer function, i.e. roots of characteristics equation, also called zeros of the characteristics equation. The Root locus is helpful in designing the value of 'K', i.e. gain of the proportional controller). So, the system (in Figure-1) is stable for values such as K= 0.2, 1, 5.8 etc.; but what value we should select. We will analyze each value and show you the results. As a summary, you can understand that the high value of 'K' (i.e., for example, K=5.8) will reduce the stability (it is a disadvantage) but improves the steady-state performance (i.e. reduce the steady-state error, which will be an advantage).

You can understand that

$K_p = \lim_{s\to 0} KG(s)H(s)$, Steady state error ($e_{ss}$)= $\frac{1}{1+K_p}$(It is applicable in case of step input)

$K_v = \lim_{s\to 0} sKG(s)H(s)$, Steady state error ($e_{ss}$)= $\frac{1}{K_v}$(It is applicable in case of ramp input)

$K_a = \lim_{s\to 0} s^2KG(s)H(s)$, Steady state error ($e_{ss}$)= $\frac{1}{K_a}$(It is applicable in case of parabolic input)

It can be observed that for the high value of 'K', values of Kp, Kv and Ka will be high and steady-state error will below.

Now we will take each case and explain the results

1. At K=0.2

In this case characteristics equation of the system is s^3+ $3s^2$+ 2s+0.2=0; roots of this equation are -2.088, -0.7909 and -0.1211; We can ignore -2.088 (as it is far away from imaginary axis). On the basis of the remaining two roots, it can be termed as an overdamped system (as both the roots are real & negative, no imaginary parts). Against step input, its time response is shown in Fig-3. It can be seen that the response has no oscillations. (if roots are complex then time response exhibits oscillations). The overdamped system has damping more than '1'.

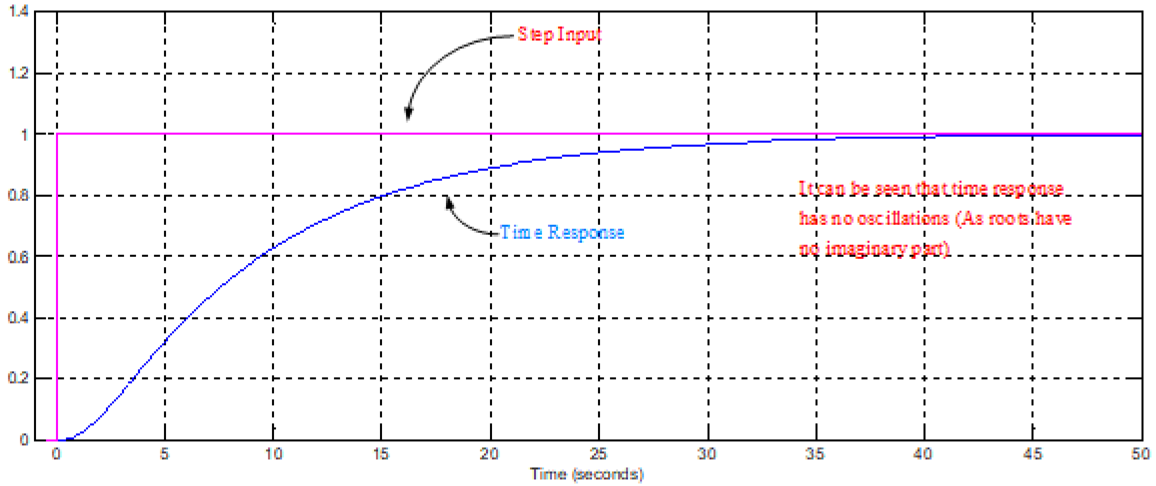


Figure-3: Response has no oscillations, it is the response of the overdamped system

In the present case open loop transfer function is $G(s)H(s) = \frac{0.2}{s(s+1)(s+2)}$

Its Gain Margin (GM)=29.5 dB, Phase Margin (PM)=81.5°,

It should be noted that in the designing of control systems, overdamped systems are not preferred. Roots (poles of closed-loop transfer function) should have slight imaginary parts. In the case of overdamped, damping is more than ‘1’, while damping around 0.8 is preferred.

2. At K=1

In this case characteristics equation of the system is $s^3 + 3s^2 + 2s + 1 = 0$; roots of this equation are -2.3247, -0.3376 ±j0.5623; We can ignore -2.3247. On the basis of the remaining two roots, it can be termed as an underdamped system (as both the roots are complex having negative real parts). Against step input, its time response is shown in Fig-4.

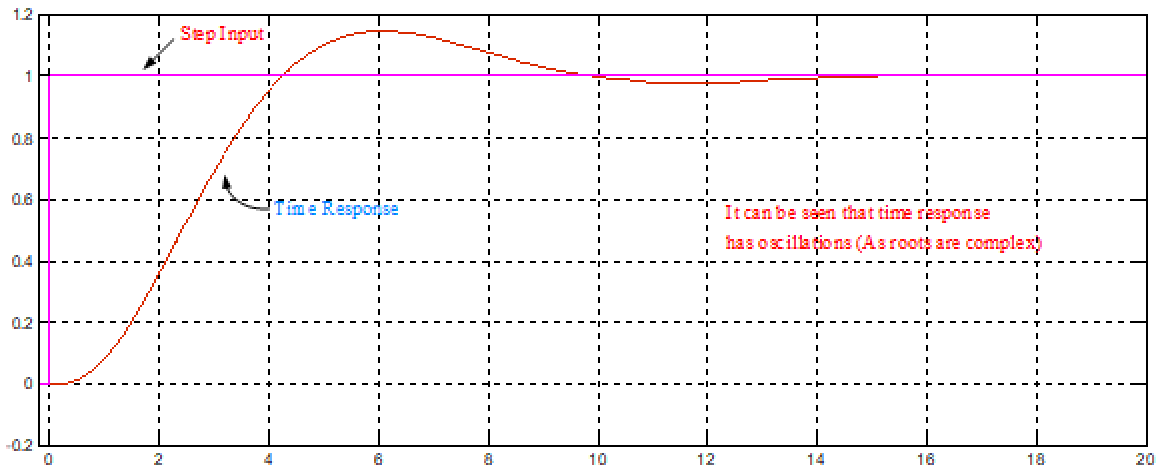


Figure-4: Response has oscillations, it is the response of an underdamped system

In the present case open loop transfer function is $G(s)H(s) = \frac{1}{s(s+1)(s+2)}$

Its Gain Margin (GM)=15.6 dB, Phase Margin (PM)=53.4°,

3. At K=5.8

As 5.8 is very close to 6, so you can understand that system is stable, but almost on the border. You can find the roots of its characteristics equation. One root can be ignored, the remaining two roots will be very close to the imaginary axis. (Roots of its characteristics equation will be -2.9816, -0.0092±j1.39). Against step input, its time response is shown in Fig-5.

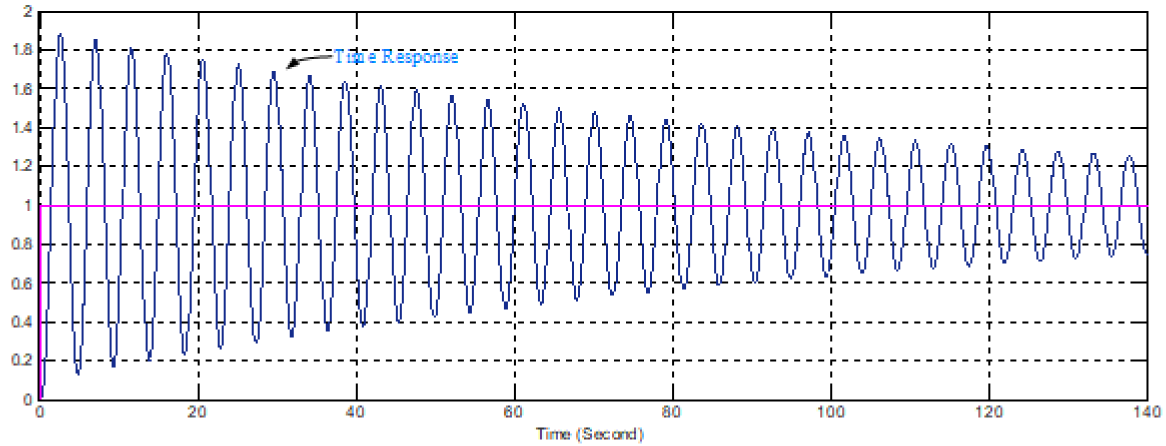


Figure-5: Response has oscillations, it is the response of the underdamped system (Response in Figure-4 is also belongs to the underdamped system)

In the present case open loop transfer function is $G(s)H(s) = \frac{5.8}{s(s+1)(s+2)}$

Its Gain Margin=0.294 db, Phase Margin =0.919°

It can be analyzed, as compared to the previous cases, GM & PM are reduced drastically. As the system is very close to instability, hence GM & PM are also very close to zero value.

Integral Controllers

As the name suggests in **integral controllers** the output (also called the actuating signal) is directly proportional to the integral of the error signal. Now let us analyze integral controller mathematically. As we know in an integral controller output is directly proportional to the integration of the error signal, writing this mathematically we have,

$$A(t) \propto \int_0^t e(t)dt$$

Removing the sign of proportionality we have,

$$A(t) = K_i \times \int_0^t e(t)dt$$

Where Ki is an integral constant also known as controller gain. The integral controller is also known as reset controller.

Advantages of Integral Controller

Due to their unique ability, Integral Controllers can return the controlled variable back to the exact set point following a disturbance that's why these are known as reset controllers.

Disadvantages of Integral Controller

It tends to make the system unstable because it responds slowly towards the produced error.

Derivative Controllers

We never use **derivative controllers** alone. It should be used in combinations with other modes of controllers because of its few disadvantages which are written below:

1. It never improves the steady-state error.
2. It produces saturation effects and also amplifies the noise signals produced in the system.

Now, as the name suggests in a derivative controller the output (also called the actuating signal) is directly proportional to the derivative of the error signal. Now let us analyze the derivative controller mathematically. As we know in a derivative controller output is directly proportional to the derivative of the error signal, writing this mathematically we have,

$$A(t) \propto \frac{de(t)}{dt}$$

Removing the sign of proportionality we have,

$$A(t) = K_d \times \frac{de(t)}{dt}$$

Where, K_d is proportional constant also known as controller gain. The derivative controller is also known as the rate controller.

Advantages of Derivative Controller

The major advantage of a derivative controller is that it improves the transient response of the system.

Proportional and Integral Controller

As the name suggests it is a combination of proportional and an integral controller the output (also called the actuating signal) is equal to the summation of proportional and integral of the error signal. Now let us analyze proportional and integral controller mathematically. As we know in a proportional and integral controller output is directly proportional to the summation of proportional of error and integration of the error signal, writing this mathematically we have,

$$A(t) \propto \int_0^t e(t)dt + A(t) \propto e(t)$$

Removing the sign of proportionality we have,

$$A(t) = K_i \int_0^t e(t)dt + K_p e(t)$$

Where, K_i and k_p proportional constant and integral constant respectively.

Advantages and disadvantages are combinations of the advantages and disadvantages of proportional and integral controllers.

Through the PI controller, we are adding one pole at origin and one zero somewhere away from the origin (in the left-hand side of complex plane). As the pole is at the origin, its effect will be more, hence PI controller may reduce the stability; but its main advantage is that it reduces steady-state error drastically, due for this reason it is one of the most widely used controllers.

The schematic diagram of the PI controller is shown in Fig-6. Against step input, For the values of K=5.8, K_i=0.2, Its time response, is shown in Fig-7. At K=5.8 (As a P- controller, it was on the verge of instability, so just by adding the small value of an Integral part, it became unstable. Please note the Integral part reduces the stability, which does not mean that system will be always unstable. In the present case, we have added an integral part and the system became unstable).

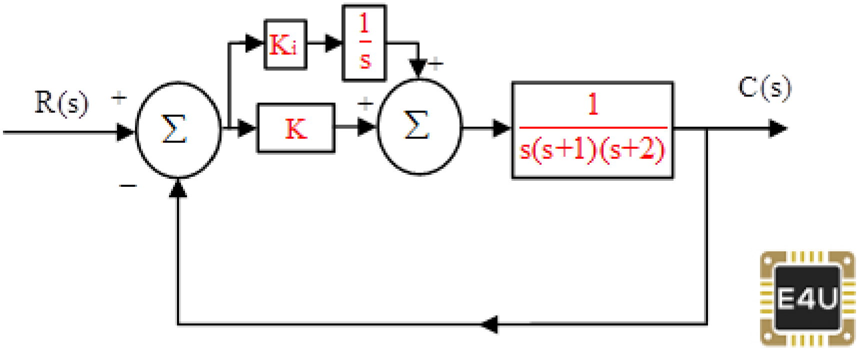


Figure-6: The closed loop control system with PI Controller

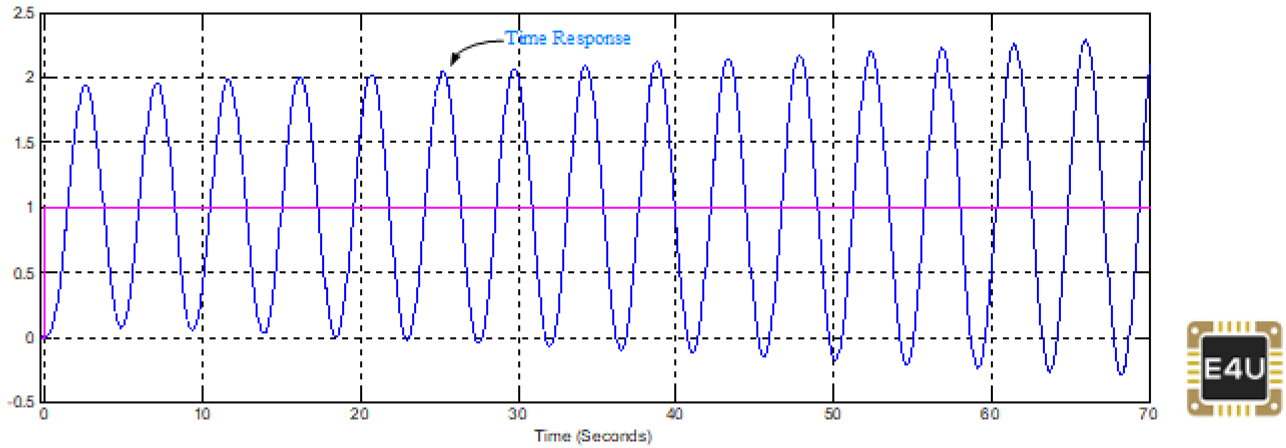


Figure-7: The response of the system shown in Figure-6, with K=5.8, Ki=0.2

Proportional and Derivative Controller

As the name suggests it is a combination of proportional and a derivative controller the output (also called the actuating signal) is equals to the summation of proportional and derivative of the error signal. Now let us analyze proportional and derivative controller mathematically. As we know in a proportional and derivative controller output is directly proportional to the summation of proportional of error and differentiation of the error signal, writing this mathematically we have,

$$A(t) \propto \frac{de(t)}{dt} + A(t) \propto e(t)$$

Removing the sign of proportionality we have,

$$A(t) = K_d \frac{de(t)}{dt} + K_p e(t)$$

Where, K_d and K_p proportional constant and derivative constant respectively. Advantages and disadvantages are combinations of advantages and disadvantages of proportional and derivative controllers.

Readers should note that adding 'zero' at the proper location in the open-loop transfer function improves stability, while the addition of pole in the open-loop transfer function may reduce the stability. The words "at proper location" in the above sentence are very important & it is called designing of the control system (i.e. both zero & pole should be added at proper points in the complex plane to get the desired result).

Inserting the PD controller is like the addition of zero in open-loop transfer function [G(s)H(s)]. Diagram of PD Controller is shown in Fig-8

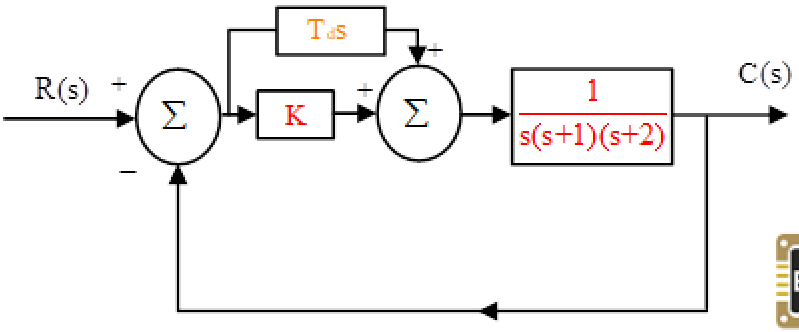


Figure-8: Closed-loop control system with PD Controller

In the present case, we have taken the values of K=5.8, Td=0.5. Its time response, against step input, is shown in Fig-9. You can compare Fig-9, with Fig-5 and can understand the effect of inserting the derivative part in the P-controller.

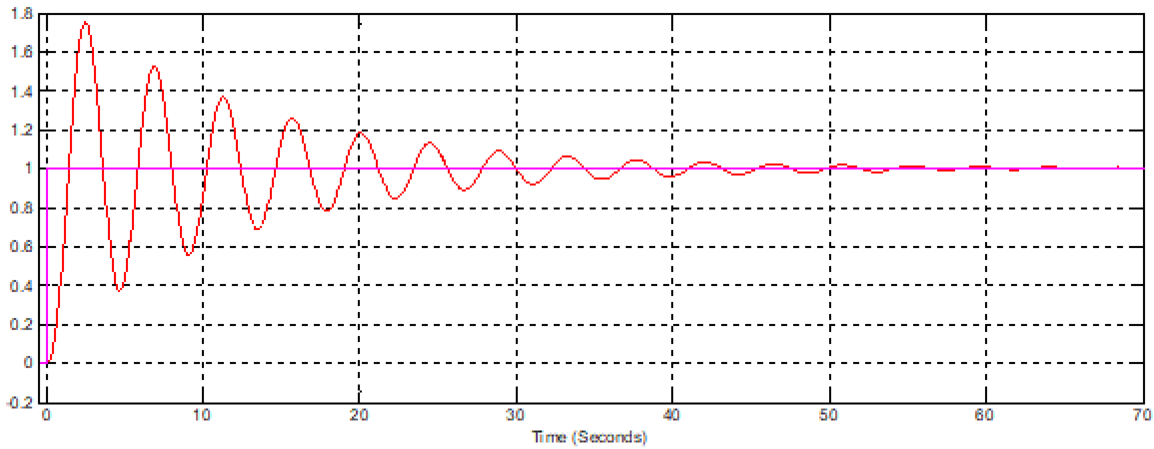


Figure-9: Response of system shown in Figure-8, with K=5.8, Td=0.5

The transfer function of the PD controller is K+Tds or Td(s+K/Td); so we have added one zero at -K/Td. By controlling the value of 'K' or 'Td', the position of the 'zero' can be decided. If 'zero' is very far away from the imaginary axis, its influence will decrease, if 'zero' is on the imaginary axis (or very close to the imaginary axis) it will also be not accepted (root locus generally starts from 'poles' & terminates at 'zero', Designer's aim is generally such that root locus should not go towards the imaginary axis, due to this reason 'zero' very near to imaginary axis is also not acceptable, hence a moderate position of 'zero' should be kept)

Generally, it is said, PD controller improves transient performance and the PI controller improves the steady-state performance of a control system.

Proportional plus Integral plus Derivative Controller (PID Controller)

A PID controller is generally used in industrial control applications to regulate temperature, flow, pressure, speed, and other process variables.

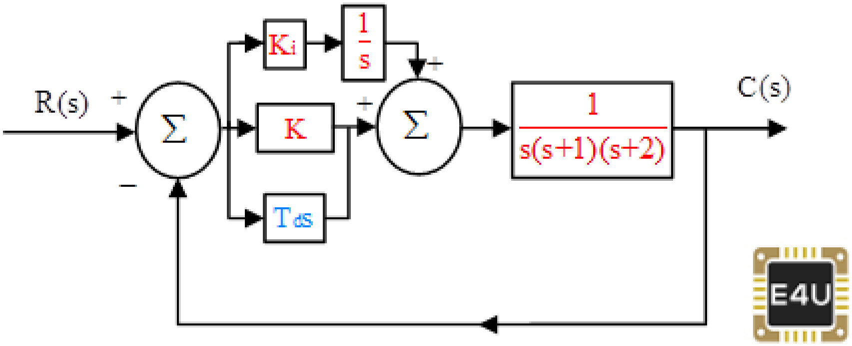


Figure-10: Closed loop control system with PID Controller

The transfer function of the PID Controller can be found as:

$Tds + K + \frac{Ki}{s}$ or $\frac{Tds^2+Ks+Ki}{s}$

It can be observed that one pole at origin is fixed, remaining parameters T_d, K, and Ki decide the position of two zeros. In this case, we can keep two complex zeros or two real zeros as per the requirement, hence PID controller can provide better tuning. In the olden days, the PI controller was one of the best choice of control engineers, because designing (tuning of parameters) of the PID controller was a little difficult, but nowadays, due to the development of software designing of PID controllers have become an easy task.

Against step input, For the values of K=5.8, K_i=0.2, and T_d=0.5, Its time response, is shown in Fig-11. Compare Fig-11 with Fig-9 (We have taken values such that all the time response can be compared).

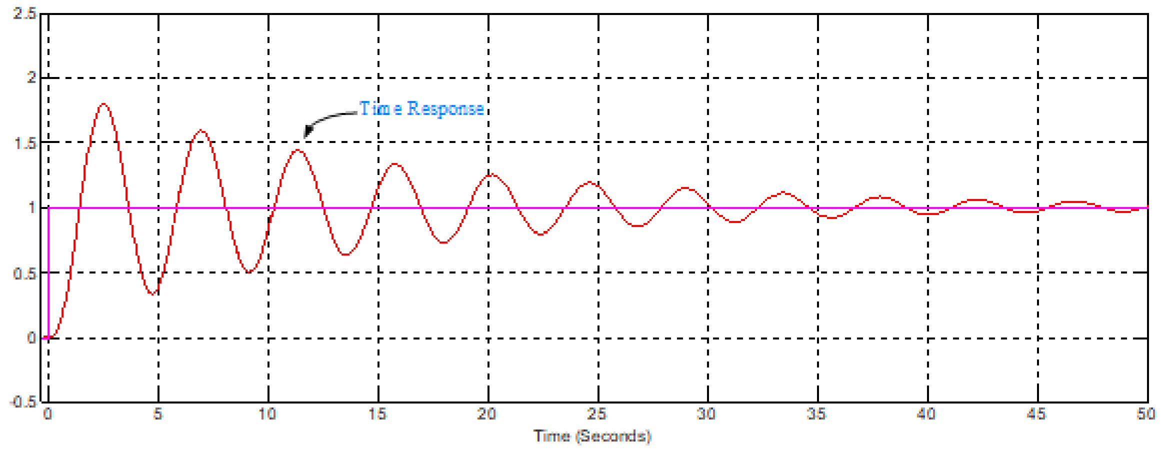
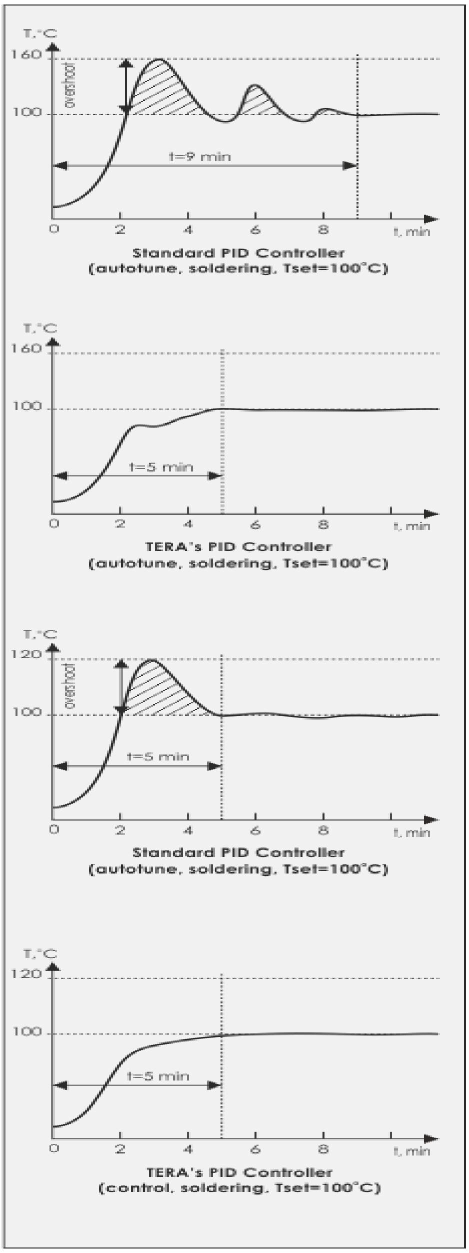


Figure-11: Response of system shown in Figure-10, with K=5.8, Td=0.5, Ki=0.2

General Guidelines for Designing a PID Controller

When you are designing a PID controller for a given system, general guidelines to obtain the desired response are as follows:

1. Obtain the transient response of closed-loop transfer function and determine what needs to be improved.
2. Insert the proportional controller, Design the value of 'K' through Routh-Hurwitz or suitable software.
3. Add an integral part to reduce steady-state error.
4. Add the derivative part to increase damping (damping should be between 0.6-0.9). The derivative part will reduce overshoots & transient time.
5. Sisotool, available in MATLAB can also be used for proper tuning and to obtain a desired overall response.
6. Please note, above steps of tuning of parameters (designing of a control system) are general guidelines. There are no fixed steps for designing controllers.



If devices contain a function of PID (proportional-integral-derivative) control, it means that it's possible to realize three types of control: P, PI and PID.

P Control. Output power is directly proportional to control error. The higher the proportion coefficient, the less the output power at the same control error. Proportional control can be recommended for fast-response systems with a large transmission coefficient. To adjust the propotional controller you should first set the maximum proportion coefficient where in the output power decreases to zero. When the measured value is stabilized, set a specified value and gradually reduce the proportion coefficient and the control error will decrease. If there are periodic oscillations in the system, the proportion coefficient should be increased so that control error is minimal periodic oscillations decrease to the limit.

PI Control. Output power equals to the sum of proportion and integration coefficients. The higher the proportion coefficient, the less the output power at the same control error. The higher the integration coefficient, the slower the accumulated integration coefficient. PI control provides zero control error and and is insensitive to interference of the measurement channel. The PI control disadvantage is slow reaction to disturbances. To adjust the PI controller you should first set the integration time equal to zero, and the maximum proportion time. Then by decreasing the coefficient of proportionality, achieve periodic oscillations in the system. Close to the optimum value of the coefficient of proportionality is twice higher than that at which any hesitation, and close to the optimum value of the integration time constant - is 20% less than the oscillation period.

PID Control. Output power equals to the sum of three coefficients: proportional, integral and differential. The higher the proportion coefficient, the less the output power at the same control error. The higher the integration coefficient, the slower the accumulated integration coefficient. The higher the differentiation coefficient, the greater the response of the system to the disturbance. The PID controller is used in inertial systems with relatively low noise level of the measuring channel. The advantage of PID is fast warm up time, accurate setpoint temperature control and fast reaction to disturbances. Manual tuning PID is extremely complex, so it is recommended is to use the autotune function.

PID control autotune in TERA's devices:

The main thing that determines the quality of PID controller is its ability to achieve a setpoint temperature accurately and fast. For this purpose all modern PID controllers have autotune function. Standard algorithms of auto-tuning PID does not exist, in practice each manufacturer uses its own algorithm. Therefore, when a user purchases the same device named PID controller from different manufacturers, more likely he may receive different results of its application.

The main advantages of auto-tuning algorithm TERA's PID controllers are:

- autotuning and control without overshoot (in standard PID controllers overshoot can reach 50-70% of the set temperature which is not desirable or even prohibited in some technologies)
- autotune duration on the average 2 times shorter than that of other manufacturers (extremely important characteristic for applications with freqently changed properties)

Auto-tuning can be done at any stable state of the controlled system. Furthermore, the greater the difference between the starting and set temperature, the more accurate the coefficients of the PID controller. All PID coefficients are stored in nonvolatile memory.

Autotune must be repeated if::

- actuator power has changed
- physical properties of the controlled system (weight, capacity, heat transfer, etc.) have changed
- control system has been replaced by another non-identical
- significant changes in a set temperature

ASSISGNMENT QUESTIONS:

1. What is meant by controller? Briefly explain about Process control?
2. Explain about Automatic controllers?
3. Explain about Electronic and Pneumatic controllers?
4. What is meant by P-I, PD and P-I-D controllers explain briefly?
5. Explain about Hydraulic controllers?

Tutorial questions

1. Why derivative mode of control is not recommended for a noisy process?

   Why is it necessary to choose controller settings that satisfy both gain margin and phase margin
2. What are the basic control actions in process control?
3. Define proportional band and Define reset time?
4. What are the advantages and disadvantages of PI control?
5. What are the advantages, disadvantages and applications of PD controller?
6. What are the advantages and disadvantages of PID control actions?