PNEUMATIC SYSTEM:

Pneumatic is a technology which deals with power of air.

In pneumatic system air is empowered by compressing it and then its power is used to obtain mechanical advantage i.e. to do useful work

Pneumatic are used to a wide varieties of industries, including construction, healthcare, mining, the automotive industry and many other.

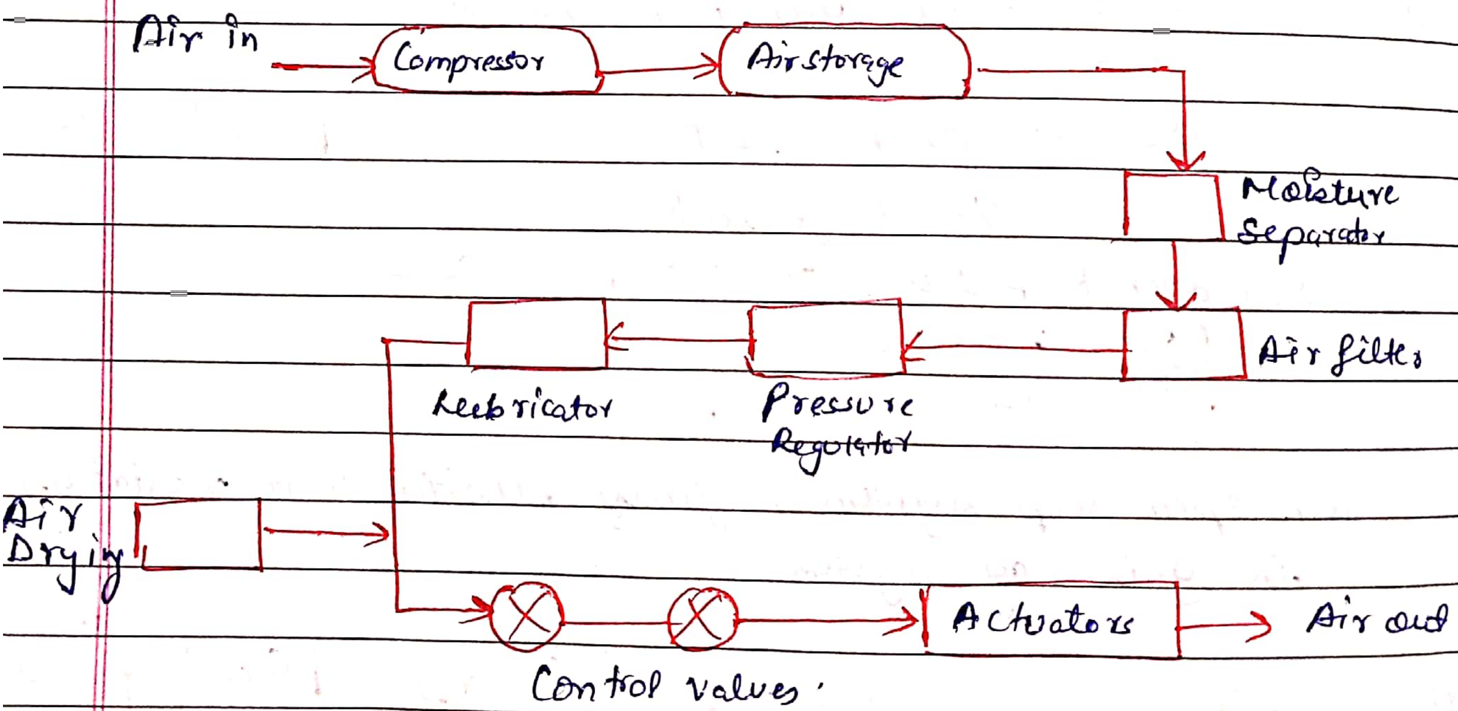


Fig: Block dig. of Pneumatic system

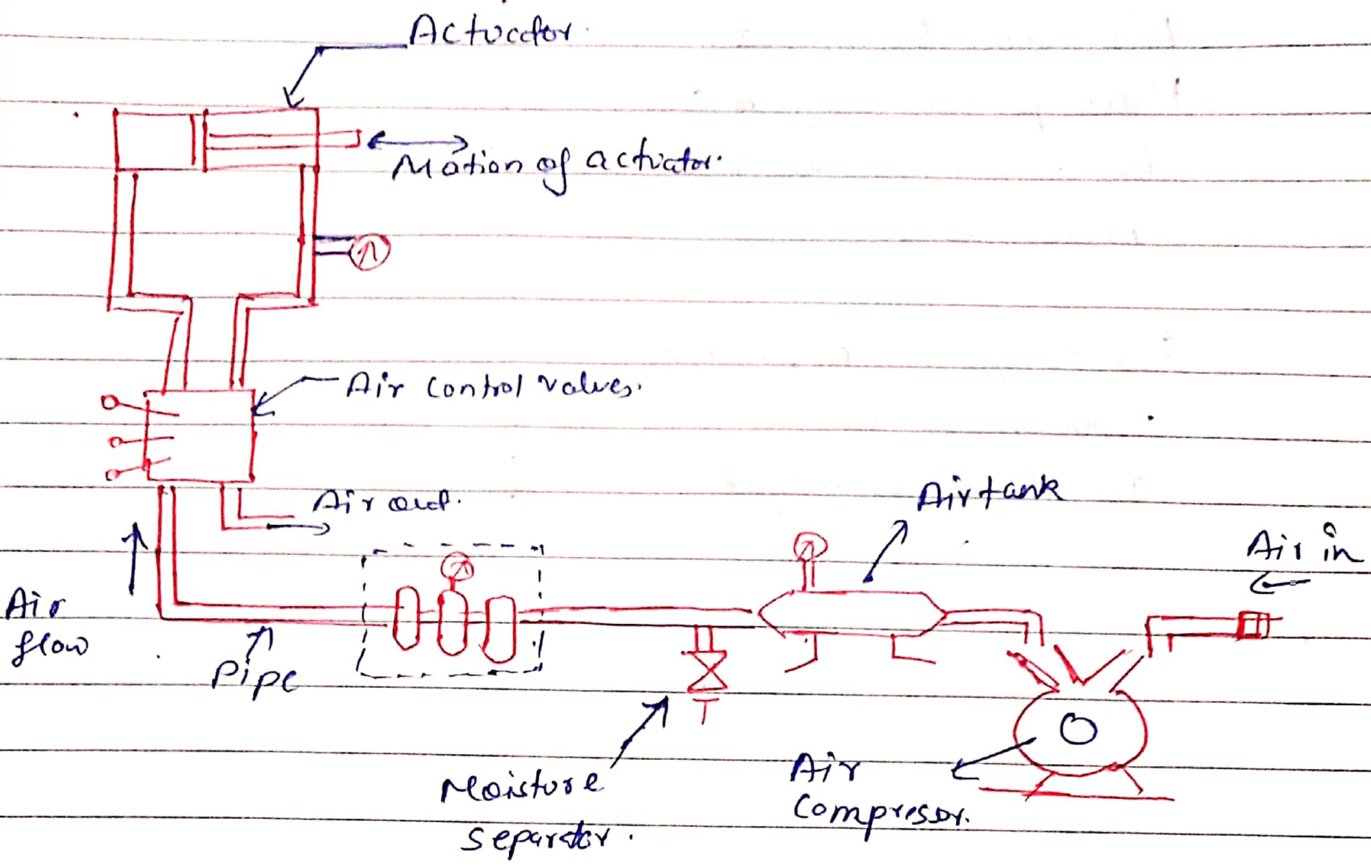


fig: Actual diagram of Pneumatic system.

Advantages:

1. The working medium of pneumatic system is air, which is easily and freely available.

2. Air is dry & hence pneumatic system is clean. Due to this property, this system are mostly widely used in the food industry automation & electronic industry automation.

Disadvantages

Suitable only for low pressure & hence low force application.

Generation of compressed air is expensive compared to electricity.

Weight to pressure ratio is ↑.

Exhaust air noise in unpleasant and silence has to be used.

1.37. PNEUMATIC SYSTEM

Consider the Fig. 1.126. In Fig. 1.126 a source is supplying air and the air is stored in vessel.

Let, P_i = Pressure of air of the source N/m^2

P_0 = Pressure of air in the vessel N/m^2

ΔP_i = Change in air pressure of source

ΔP_0 = Change in air pressure of vessel

R = Resistance to air flow into the vessel

C = Capacitance of the vessel

q = Rate of flow of air due to the differential pressure

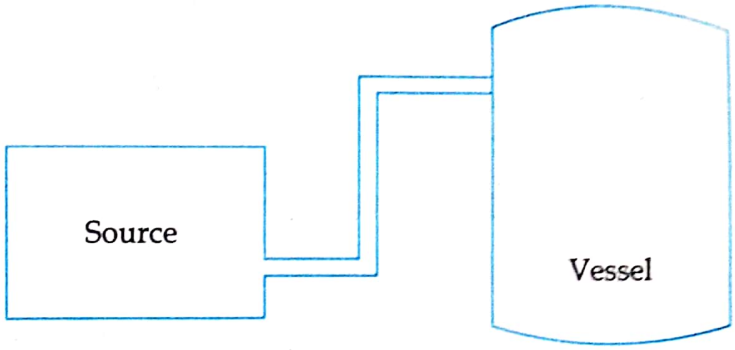


Fig. 1.126.

$$\therefore \qquad q = \frac{\Delta P_i - \Delta P_0}{R} \qquad \text{...(1.169)}$$

The volume of air stored in vessel increases the pressure inside the vessel.

$$\therefore \qquad \text{Volume } V = C\Delta P_0 \qquad \text{...(1.170)}$$

$$\therefore \qquad \text{Rate of storage in vessel} = \frac{dV}{dt} = C\frac{d\Delta P_0}{dt} \qquad \text{...(1.171)}$$

$$\text{Volume of air in flow } V = \int q\, dt = \int \frac{\Delta P_i - \Delta P_0}{R}\, dt \qquad \text{...(1.172)}$$

$$\text{Rate of air in flow} = \frac{dv}{dt} = \frac{\Delta P_i - \Delta P_0}{R} \qquad \text{...(1.173)}$$

Rate of air in flow = Rate of storage of air in vessel

$$C\frac{d\Delta P_0}{dt} = \frac{\Delta P_i - \Delta P_0}{R} \qquad \text{...(1.174)}$$

Take Laplace transform

$$sC\Delta P_0 = \frac{1}{R}[\Delta P_i(s) - \Delta P_0(s)]$$

$$\frac{\Delta P_0}{\Delta P_i} = \frac{1}{1+RCs} \qquad \text{...(1.175)}$$

Time constant = RC

11.3. CLASSIFICATION OF CONTROLLERS

Controllers are classified depending upon the type of controlling action used. Therefore, they can be classified as :

(i) Two-position or ON-OFF controllers
(ii) Proportional controllers
(iii) Integral controllers
(iv) Proportional-plus-integral controllers
(v) Proportional-plus-derivative controllers
(vi) Proportional-plus-integral-plus derivative controllers.

They can also be classified according to the power source used for actuating mechanisms, such as electrical, electronics pneumatic and hydraulic controllers. Hydraulic controllers are used for controlling heavy loads, pneumatic controllers are suitable for shop floor applications.

The selection of a particular type of controller depends on the nature of plant, operating conditions such as safety, cost, availability, accuracy, weight and size.

11.4. TWO POSITION CONTROL

This is also known as ON-OFF control or bang-bang control. This type of controllers are simple and inexpensive and are generally employed on home heating systems, domestic water heaters and industrial control systems.

In this type of control the output of the controller is quickly changed to either a maximum or minimum value depending upon whether the controlled variable (b) is greater or less than the set point or in other words depends upon the actuating error signal (e) The minimum value is usually zero.

Let, m = Output of the controller
M_1 = Maximum value of output of the controller
M_2 = Minimum value of output of the controller
e = Actuating error signal or deviation.

The equations for two-position control will be

$$m = M_1 \quad \text{when} \quad e > 0 \quad ...(11.\ )$$
$$m = M_2 \quad \text{when} \quad e < 0 \quad ...(11.\ )$$

The minimum value M_2 is usually either zero or $- M_1$

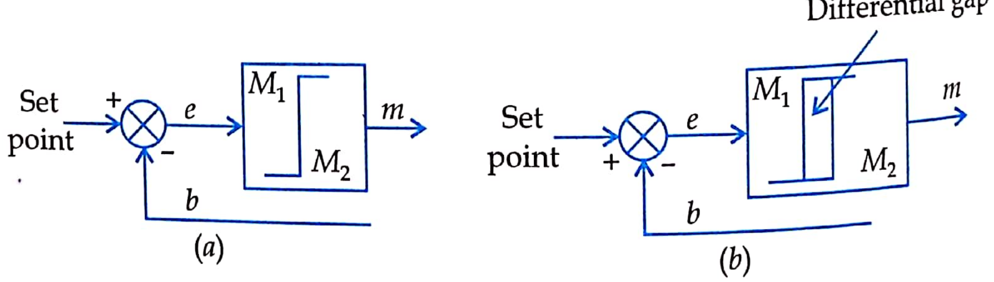


Fig. 11.2.

The block diagram of two position controllers are shown in Fig. 11.2. In ON-OFF controller there is an overlap as the error increases through zero or decreases through zero. This overlap creates a span of error. During this span of error, there is no change in the controller output. This span of error is known as *dead zone* or *dead band*. Dead band is shown in Fig. 11.3.

From Fig. 11.3, it is clear that till the error changes by Δe there is no change in the controller output. Similarly while decreasing the error must decrease beyond Δe below 0 to change the controller output. Hence, during $2\Delta e$ there is no change in the controller output. This zone is known as differential gap. The differential gap can also be defined as the range through which the actuating error signal must move before the switching occurs.

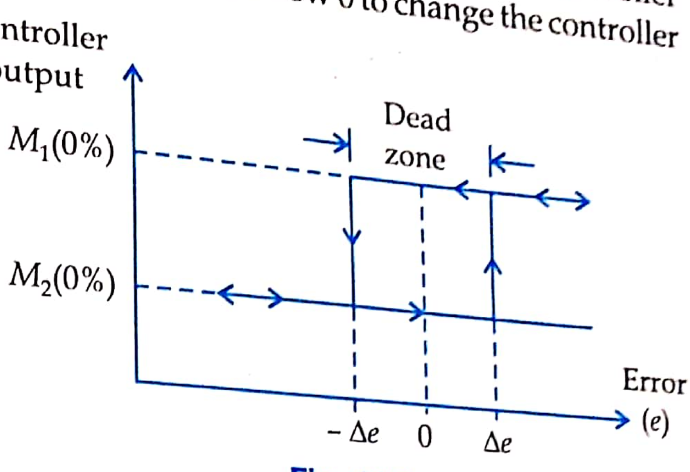


Fig. 11.3.

In this type of controller, the control variable always oscillates with a frequency which increase with decreasing width of the dead zone (differential gap). The decrease in dead zone, the number of ON-OFF switching of controller increases, hence therefore the useful life of the component decreases. Hence dead band should be designed to prevent the oscillations in ON-OFF controllers.

Two position control mode are used in room air conditioners, heaters, liquid level control in large volume tank.

The example of this type of controller is a room heater. Figure 11.4 shows the controlling of temperature. If the temperature drops below the set point, an error signal is produced by the error detector, this error signal energised the relay and the heater turned ON. Similarly, if the temperature increase above a set point, the heater is turned OFF.

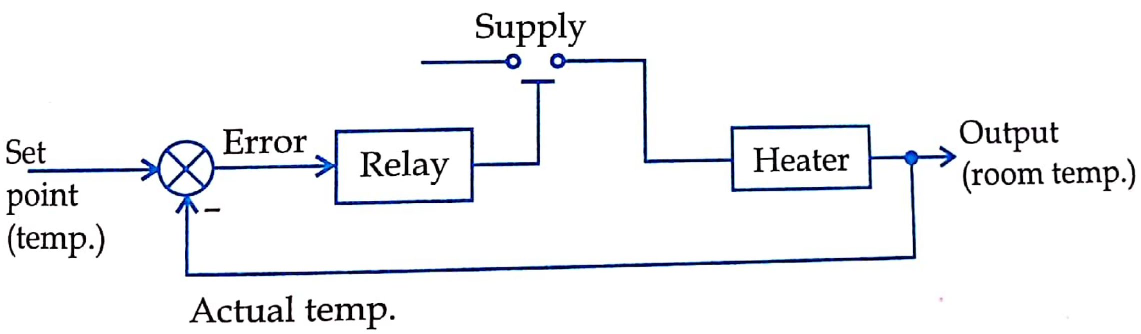


Fig. 11.4.

11.5. PROPORTIONAL CONTROL ACTION

In a controller with proportional control action, there is a continuous linear relation between the output of the controller m (manipulated variable) and actuating error signal e (deviation).

Mathematically

$$m(t) = K_p\, e(t) \qquad \text{...(11.4)}$$

or in terms of Laplace transform

$$M(s) = Kp\, E(s)$$

$$K_p = \frac{M(s)}{E(s)} \qquad \text{...(11.5)}$$

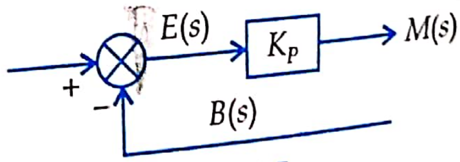


Fig. 11.5.

where K_p is known as proportional gain or proportional sensitivity. The block diagram of proportional controller is shown in Fig. 11.5.

Consider the liquid level system shown in Fig. 11.6. In this system the float lever is directly connected to the control value. When the level of the liquid rise, the valve close in proportionate amount this reduces the inflow to the vessel and vice versa. The inverse of proportional gain or proportional sensitivity is the proportional band and is defined as the change in level necessary to operate the valve through full stroke. Basically proportional controller is an amplifier with adjustable gain.

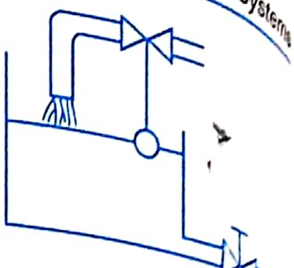


Fig. 11.6.

11.6. INTEGRAL CONTROL ACTION

In a controller with integral control action, the output of the controller is changed at a rate which is proportional to the actuating error signal $e(t)$.

Mathematically,

$$\frac{d}{dt} m(t) = K_i\, e(t) \quad \text{...(11.6)}$$

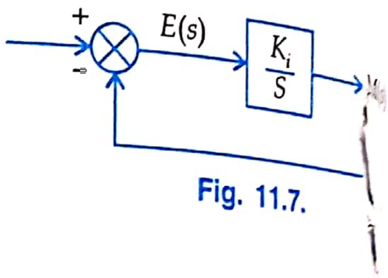


Fig. 11.7.

where K_i is a constant.

Equation (11.6) can also be written as

$$m(t) = K_i \int e(t) + m(0) \quad \text{...(11.7)}$$

where $m(0)$ = control output at $t = 0$.

Laplace transform of equation (11.6)

$$SM(s) = K_i\, E(s)$$

or

$$\frac{M(s)}{E(s)} = \frac{K_i}{s} \quad \text{...(11.8)}$$

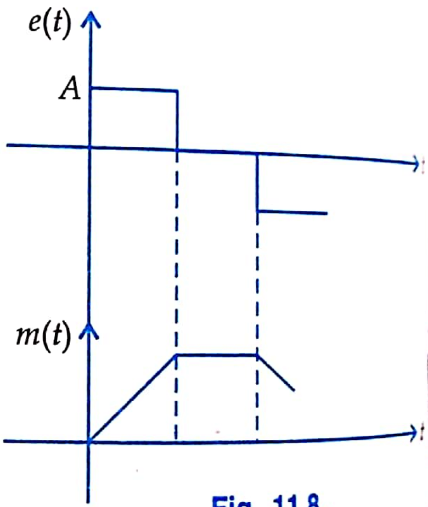


Fig. 11.8.

Equation (11.8) is the transfer function of integral controller. The block diagram of integral controller is shown in Fig. 11.7.

The inverse of K_i is called *integral time* T_i and defined as the time of change of output caused by a unit change of actuating error signal. The step response of integral controller is shown in Fig. 11.8.

From the Fig. 11.8 it is clear that for positive error, the output of the controller is ramp (positive), for zero error, there is no change in the output of the controller and for negative error the output of the controller is negative ramp. The integral control action is also known as *"Reset control"*.

11.7. DERIVATIVE CONTROL ACTION

In a controller with derivative control action the output of the controller depends on the rate of change of actuating error signal $e(t)$.

Mathematically,

$$m(t) = K_d \frac{d}{dt} e(t) \quad \text{...(11.9)}$$

where K_d is known as derivative gain constant

Laplace transform of Eqn. 11.9

$$M(s) = K_d\, SE(s)$$

or

$$\frac{M(s)}{E(s)} = sK_d \qquad ...(11.10)$$

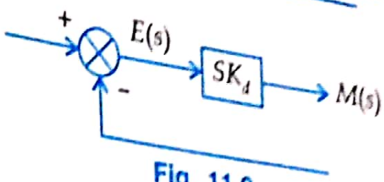


Fig. 11.9.

Equation 11.10 is the transfer function of the controller. The block diagram is shown in Fig. 11.9.

From equation 11.9 it is clear that when the error is zero or constant, the output of the controller will be zero. Therefore, this type of controller cannot be used alone. For this type of controller the gain should be small. The derivative control action also known as *rate control*.

11.8. PROPORTIONAL-PLUS-INTEGRAL CONTROL ACTION

This is the combination of proportional and integral control action. Mathematically it can be represented by equation (11.11).

$$m(t) = K_p\, e(t) + K_p\, K_i \int_0^t e(t)\, dt \qquad ...(11.11)$$

or

$$m(t) = K_p\, e(t) + K_p \frac{1}{T_i} \int_0^t e(t)\, dt \qquad ...(11.12)$$

Laplace transform of equation (11.12)

$$M(s) = K_p\, E(s) + \frac{K_p}{ST_i} E(s)$$

$$= E(s)\left[1+\frac{1}{ST_i}\right]K_p$$

$$\frac{M(s)}{E(s)} = K_p\left[1+\frac{1}{ST_i}\right] \qquad ...(11.13)$$

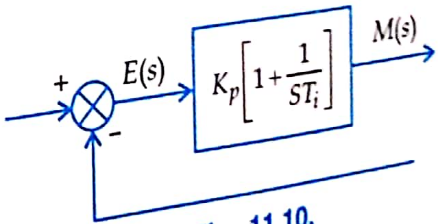


Fig. 11.10.

Block diagram is shown in Fig. 11.10.

In equation 11.13 both parameters K_p and T_i are adjustable. T_i is called *integral time*. The inverse of integral time is called *reset rate*. Reset rate is defined as the number of times per minute that the proportional part of the response is duplicated. Therefore, Reset rate is also known as *"repeats per minute."*

Consider the Fig. 11.11. The error varies at $t = t_1$. The output of the controller suddenly changes to m_p due to proportional action, after that controller output changes linearly with respect to time at a rate $\frac{K_p}{T_i}$.

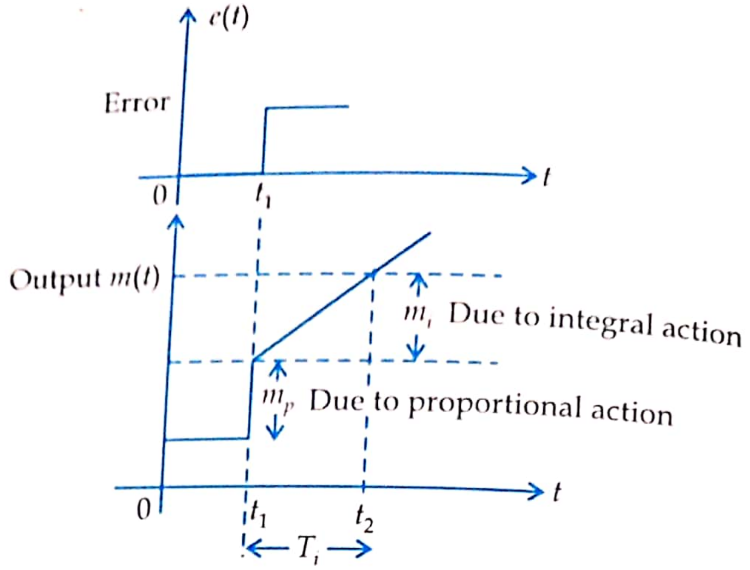


Fig. 11.11.

For unit step ($t_1 = 0$) the response is shown in Fig. 11.12.

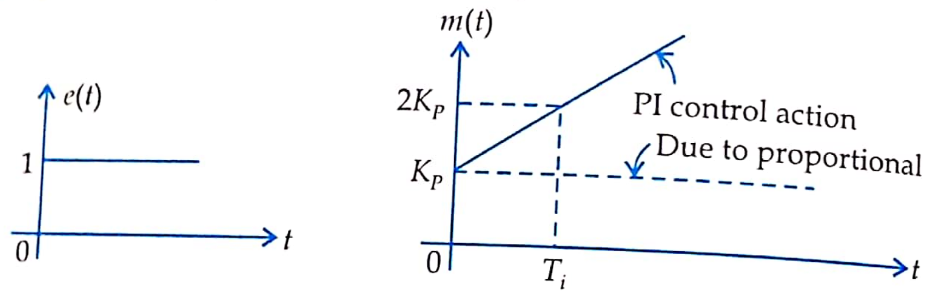


Fig. 11.12.

From the equation (11.12), it is clear that the proportional sensitivity K_p affects both the proportional and integral parts of the action.

11.9. PROPORTIONAL-PLUS-DERIVATIVE CONTROL ACTION

When a derivative control action is added in series to proportional control action, then this combination is termed as proportional-derivative control action. Mathematically it can be defined as

$$m(t) = K_p\, e(t) + K_p\, T_d \frac{d}{dt} e(t) \qquad \text{...(11.14)}$$

Laplace transform of equation (11.14)

$$M(s) = K_p\, E(s) + K_p\, T_d\, SE(s) = E(s)\,[1 + sT_d]\, K_p$$

$$\frac{M(s)}{E(s)} = K_p\,(1 + sT_d) \qquad \text{...(11.15)}$$

This is the transfer function.

The block diagram is shown in Fig. 11.13.

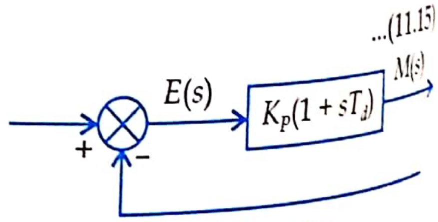


Fig. 11.13.

T_d is known as *derivative time*. Derivative time is defined as the time interval by which the rate action advances the effect of the proportional control action or in other words derivative time is defined as the amount of lead, expressed in units of time, that the control action is given.

If the actuating error signal $e(t)$ is a ramp function at $t = t_1$. The derivative mode causes a step m_d at t_1 and proportional mode causes a rise of m_p equal to m_d at t_2. This is for direct action PD control (Fig. 11.14).

PD control action reduces the rise time, faster response, improves the bandwidth and improves damping etc.

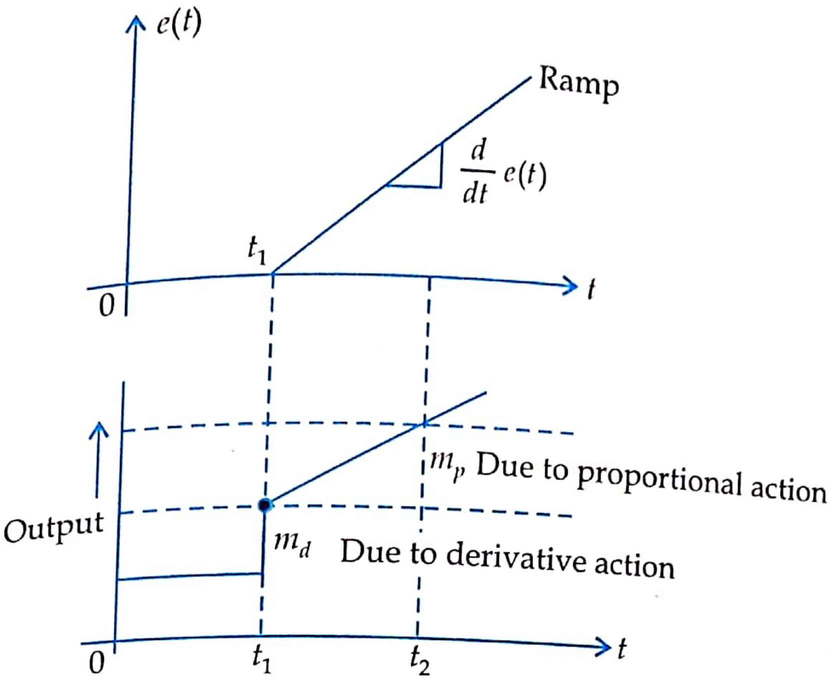


Fig. 11.14.

For unit ramp input.

If the actuating error signal is unit ramp then output of the controller is shown in Fig. 11.15.

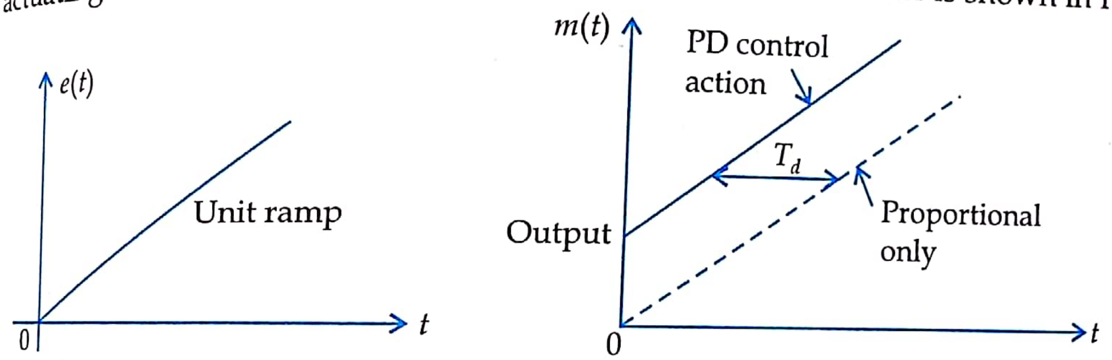


Fig. 11.15.

11.10. PROPORTIONAL-PLUS-INTEGRAL-PLUS-DERIVATIVE CONTROL ACTION

The combination of proportional, integral and derivative control action is called *PID control action* and the controller is called *three action controller*. Mathematically

$$m(t) = K_p\, e(t) + K_p \frac{1}{T_i}\int_0^t e(t)\, dt + K_p\, T_d \frac{d}{dt} e(t) \qquad ...(11.16)$$

Laplace transform

$$M(s) = K_p\, E(s) + \frac{K_p}{sT_i} E(s) + K_p\, T_d\, SE(s)$$

$$\frac{M(s)}{E(s)} = K_p\left(1+\frac{1}{sT_i}+sT_d\right) \qquad ...(11.17)$$

Equation (11.17) is the transfer function.

The block diagram is shown in Fig. 11.16.

K_p is the proportional gain, T_i is the integral time and T_d is the derivative time.

Let actuating error signal is given by $e = At$

where 'A' is a constant and 't' is time.

Put in equation (11.16)

$$m(t) = K_p At + \frac{K_p}{T_i}\int_0^t At\, dt + K_p T_d \frac{d}{dt} At$$

$$m(t) = K_p A \left[t + \frac{t^2}{2T_i} + T_d \right] \qquad ...(11.18)$$

From the above equation, the proportional part of the control action repeats the change of error (lower straight line) Fig. 11.17. The derivative part of the control action adds an increment of output so that proportional plus derivative action is shifted ahead in time (middle straight line). The integral part adds a further increment of output proportional to the area under the deviation line. The combination of proportional, integral and derivative action may be made in any sequence.

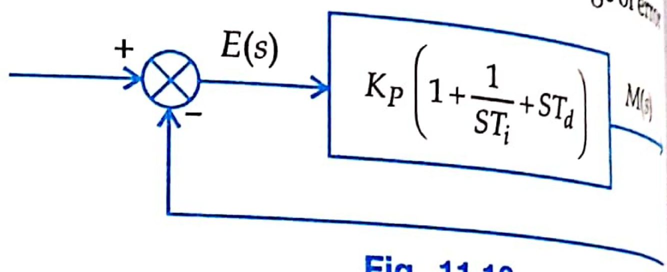


Fig. 11.16.

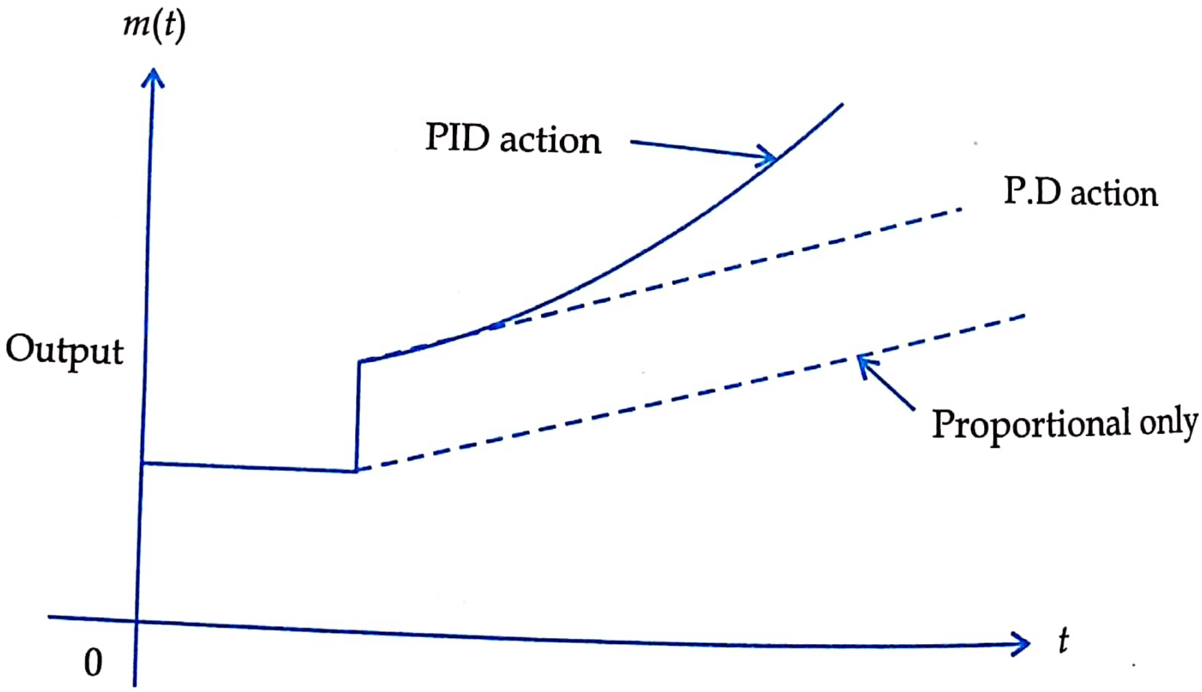


Fig. 11.17.

11.11. RESPONSE WITH P...

Motion Control of Hydraulic Cylinders

Element equations and interconnection equations:

Hydraulic system	Hydraulic-Mechanical	Mechanical system
$q_c = C\dfrac{d}{dt}p_{Lr}$	$f_c = Ap_{Lr}$	$M\dot{v} = f_c - Bv$
$q_{IN} = q_1 + q_c$	$q_1 = Av$	

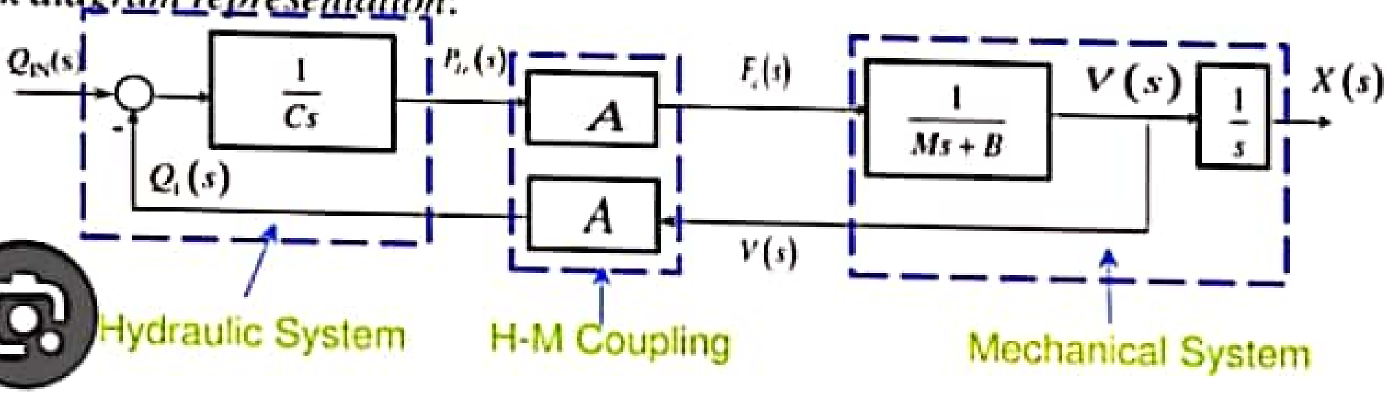
Take Laplace transforms:

$$Q_c(s) = CsP_{Lr}(s)$$
$$Q_{IN}(s) = Q_1(s) + Q_c(s)$$

$$F_c(s) = AP_{Lr}(s)$$
$$Q_1(s) = AV(s)$$

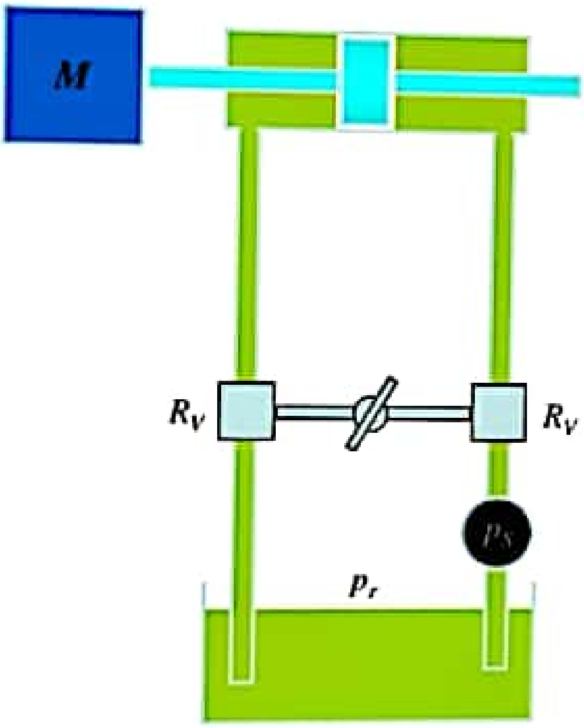
$$MsV(s) = F_c(s) - BV(s)$$

Block diagram representation:

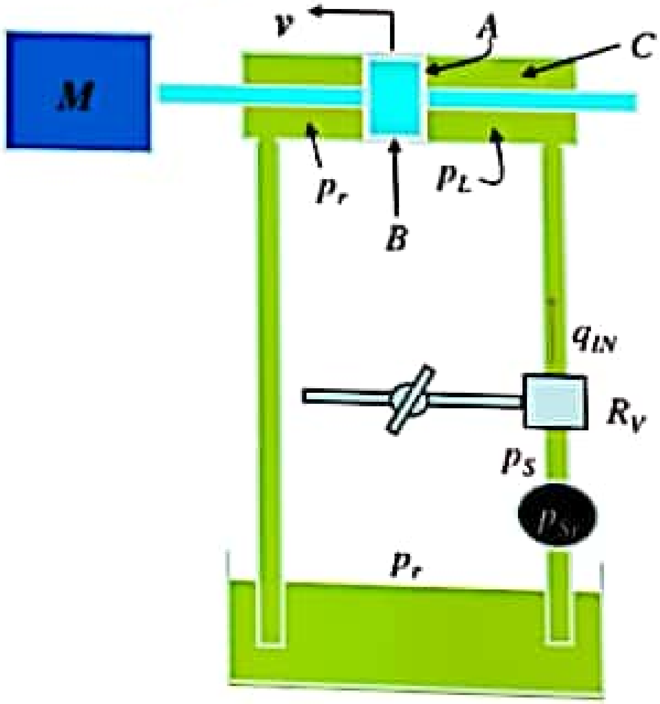


Motion Control of Hydraulic Cylinders

Hydraulic actuation is attractive for applications when large power is needed while maintaining a reasonable weight. Not counting the weight of the pump and reservoir, hydraulic actuation has the edge in power-to-weight ratio compared with other cost effective actuation sources. Earth moving applications (wheel loaders, excavators, mining equipment, ...) are typical examples where hydraulic actuators are used extensively. A typical motion application involves a hydraulic cylinder connected to certain mechanical linkages (inertia load). The motion of the cylinder is regulated via a valve that is used to regulate the flow rate to the cylinder. It is well known that such system chatters during sudden stop and start. Can you analyze the cause and propose solutions?



Motion Control of Hydraulic Cylinders



Let's look at a simplified problem:

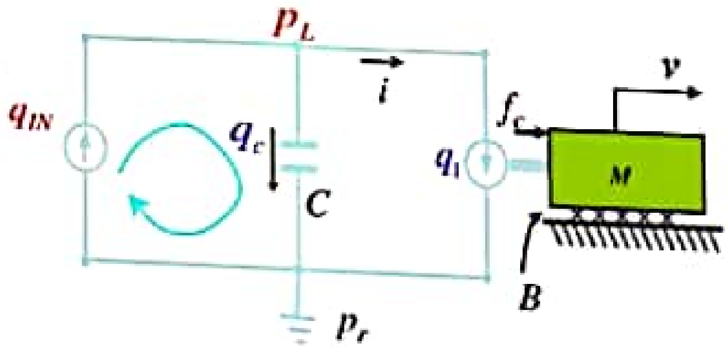
The input in the system to the right is the input flow rate q_{IN} and the output is the velocity of the mass, V.

A: Cylinder bore area

C: Cylinder chamber capacitance

B: Viscous friction coefficient between piston head and cylinder wall.

- *Derive the input/output model and transfer function between q_{IN} and V.*
- *Draw the block diagram of the system.*
- *Can this model explain the vibration when we suddenly close the valve?*



Motion Control of Hydraulic Cylinders

Element equations and interconnection equations:

Hydraulic system	Hydraulic-Mechanical	Mechanical system
$q_c = C\frac{d}{dt}p_{Lr}$	$f_c = Ap_{Lr}$	$M\dot{v} = f_c - Bv$
$q_{IN} = q_1 + q_c$	$q_1 = Av$	

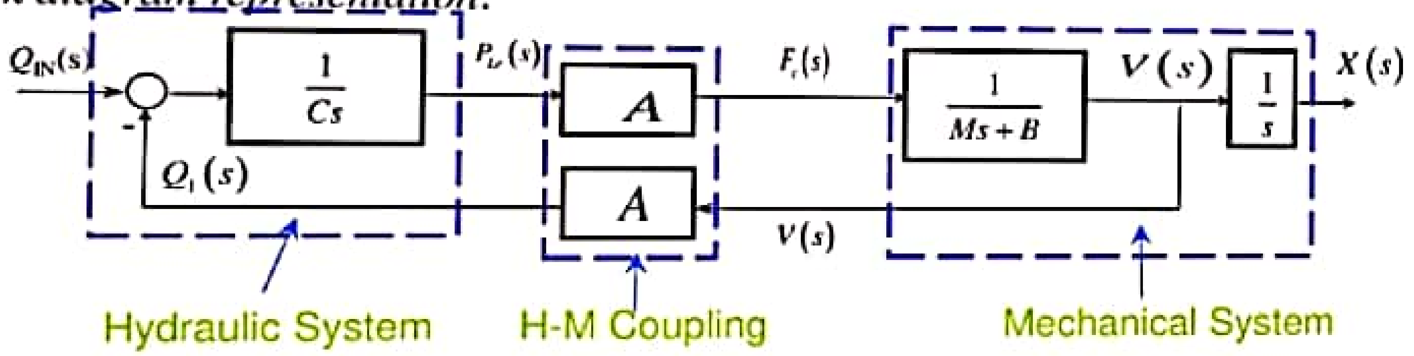
Take Laplace transforms:

$$Q_c(s) = CsP_{Lr}(s)$$
$$Q_{IN}(s) = Q_1(s) + Q_c(s)$$

$$F_c(s) = AP_{Lr}(s)$$
$$Q_1(s) = AV(s)$$

$$MsV(s) = F_c(s) - BV(s)$$

Block diagram representation:



Motion Control of Hydraulic Cylinders

Transfer function between q_{IN} and V:

$$G_{QV}=\frac{V(s)}{Q_{IN}(s)}=\frac{A}{MCs^2+BCs+A^2}$$

$$=\frac{A/MC}{s^2+\underbrace{B/M}_{2\varsigma\omega_n}\,s+\underbrace{A^2/MC}_{\omega_n^2}}$$

Analyze the transfer function:

Natural Frequency

$$\omega_n=\sqrt{A^2/MC}=\frac{A}{\sqrt{MC}}$$

Damping Ratio

$$\varsigma=\frac{B/M}{2\omega_n}=B/M\div\frac{2A}{\sqrt{MC}}=\frac{B}{2A}\sqrt{\frac{C}{M}}$$

Steady State Gain

$$K=\frac{A/MC}{A^2/MC}=\frac{1}{A}$$

How would the velocity response look like if we suddenly open the valve to reach constant input flow rate Q for some time T and suddenly close the valve to stop the flow?

In reality, large M, small C

reasonable value of natural frequency

very small damping ratio

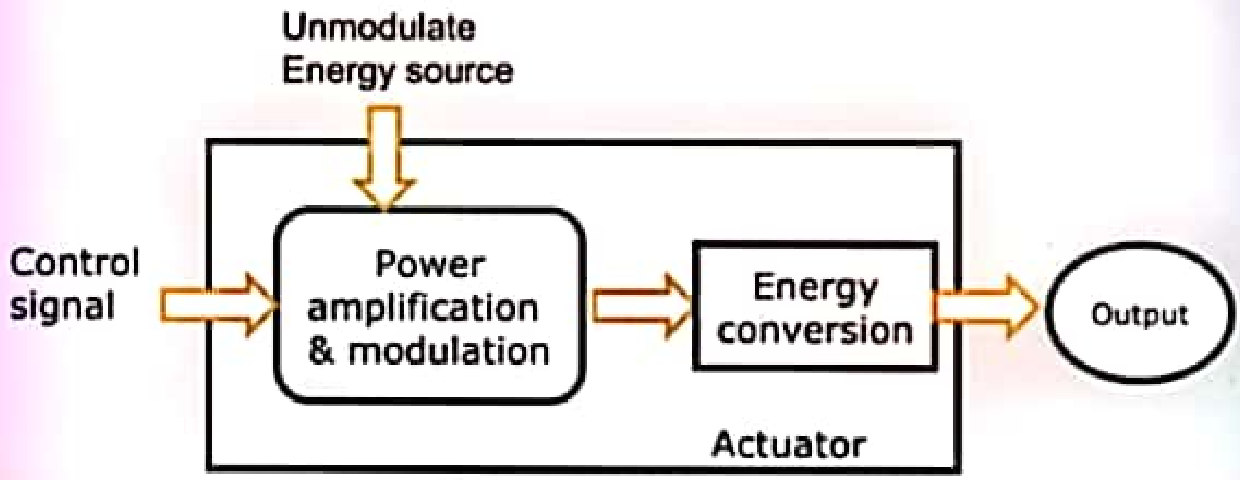
Oscillation cannot die out quickly

Chattering !!

What is an actuator?

- Actuators are devices used to produce action or motion.
- Input(mainly electrical signal , air, fluids)
- Electrical signal can be low power or high power.
- Actuators output can be position or rate i. e. linear displacement or velocity.
- Actuation can be from few microns to few meters

Actuator functional diagram



Types of actuators:

- ➢ **Hydraulic actuator.**
- ➢ **Pneumatic actuator.**
- ➢ **Mechanical actuator.**
- ➢ **Electrical actuator**

  - ➢ Linear actuator: solenoid, Hydraulic/Pneumatic.
  - ➢ Rotary actuator: motor, Hydraulic/Pneumatic.