Process Control & Instrumentation

02/01/17

- Process Control & Instrumentation (C&I / I&C)
- Define: Process, Control, Process control, Instrumentation, Process control + Instrumentation

03/01/17

- C&I: Front end & Back end
- Live & Non-live zero standards (V & I) → P = ?
- Actuation: Pneumatic, Hydraulic & Electric / Electronics type
- Instrumentation & Industrial Instrumentation

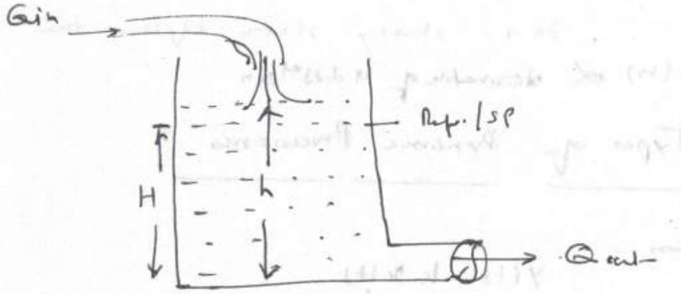
Process: A series of actions / steps taken in order to achieve a particular end / desired objective.

A C.S. manages, commands / directs / regulates the behaviour of process / device / system using closed loop control actions.

Process Control: Controller, Process.

04/01/17

- Process Control Principles



Work done = Qout = $K\sqrt{h}$

(flow $\propto \sqrt{\Delta P}$

flow out: Qout = $K\sqrt{\Delta P}$

here $\Delta P \propto h$

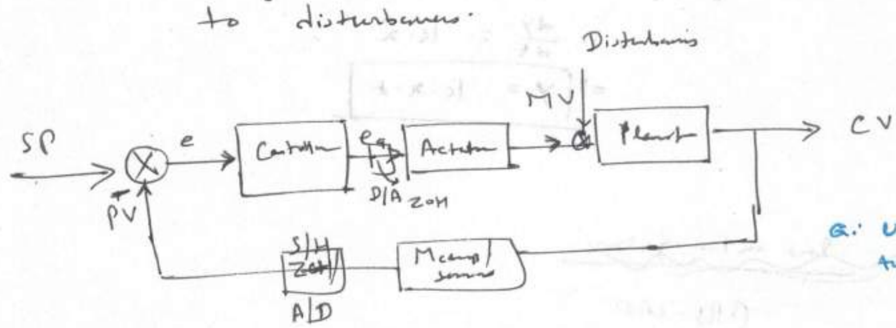
Qout = $K\sqrt{h}$

★ Q: develop a process control model for the shown tank level control without any sensors / actuators?

Q: Distinguish any sensor, actuator & transducer

→ Analog and Digital Signal Conditioning:

05/01/17 → Process dynamics: the time varying behaviour of a regulated / unregulated process ~~when~~ when it is subjected to disturbances.



Q: Use this model to neglect disturbance

09/01/17

→ Classification (Bharat)

1. Lumped parameter system: is described by ordinary differential (ODE) eqn's with the dependent variables as functions of any one independent variables i.e. time.
   Ex: mixing of hot water in a reservoir and settling temp. R, L, C.
2. Distributed parameter system: is described by partial differential eqns (PDE) with the dependent variables as functions of time as well as spaces.
   Ex: Temp. of a slab; stretch in a spring. comm^n cable, power cable

05/01/17 → 1. Lumped & Distributed param. system

2. Linear, stability & order

(a) Linearity: func of differential eqn.

A system is said to be linear if all the functs in eqns are linear funct.

∴ (L.S.): homogeneous + superposition

$$x(t) = a\, x_1(t) + b\, x_2(t)$$
$$y(t) = a\, y_1(t) + b\, y_2(t)$$

Stable: A system is said to be stable if it's controllable & observable both.

or

stable if the controlled variables (C.V.) converge to a steady state after the disturbances.

→ Order: system order (n) ∝ derivative of a diff eqn

Types of Dynamic Processes

① Instantaneous Process:

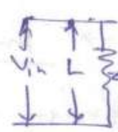
$$y(t) = k\, x(t)$$

output — static (sensitivity) gain — input

For unloaded potentiometer ∴ $E_0 = E_{ex} \left(x/L \right) \Rightarrow k = \frac{E_{ex}}{L}$ (V/m)

excitation

$\left(\frac{v_0}{v_{in}} = \frac{l}{L} \right)$



Potentiometer type - 0 order system

② Integral Process

$$\frac{dy}{dt} = k \cdot x$$
$$\Rightarrow \boxed{y = k \cdot x \cdot t}$$

③ 2nd order system.

RS-CAD
REDS
P-HDL

10/01/17

1st - order process

Ex: thermometers, RC/RL ckts

Any 1st order process can be defined by:

$$a_1 \dot{y}(t) + a_0 y(t) = x(t) \quad \text{---} (1)$$

$$\frac{a_1}{a_0}\dot{y}(t) + y(t) = \frac{x(t)}{a_0}$$

$$\Rightarrow \tau \dot{y}(t) + y(t) = K x(t) \quad \text{---} (2)$$

τ: dimension of time' is called time constant (τ)

K: steady state gain / static gain / static sensitivity

$$x(t) = 0 \quad \text{for } t \leq 0$$
$$x(t) = A \quad \text{for } t > 0 \quad \text{---} (3)$$

$\therefore$ for initial condition;

$$y = y_0 \quad \text{for } t = 0 \quad \text{---} (4)$$

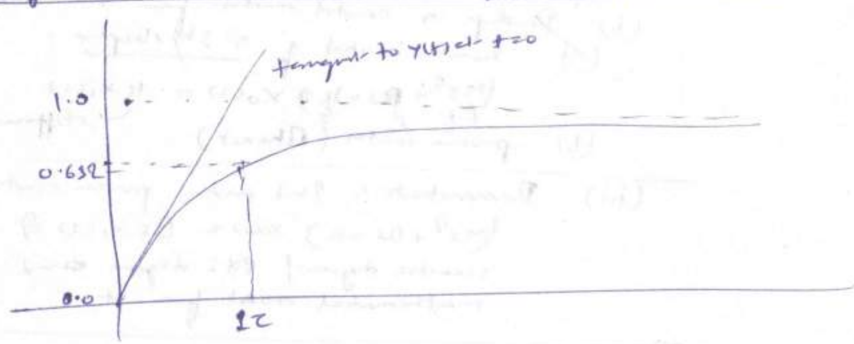
$\therefore$ soln of above eqn.

$$y(t) = \underbrace{\frac{A}{a_0}}_{\text{large value / steady state}} + \underbrace{\left(y_0 - \frac{A}{a_0}\right) e^{-t/\tau}}_{\text{transient response of system}}$$

$$\therefore \frac{y(t) - y_\infty}{y_0 - y_\infty} = e^{-t/\tau} \quad \text{---} (5)$$

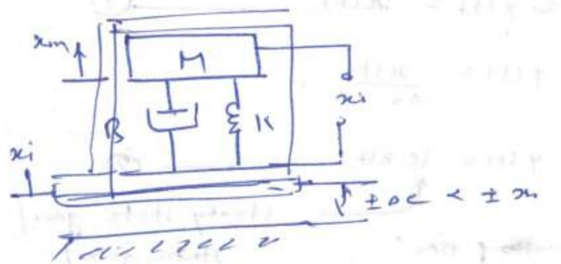
at $t = \tau$; $y(t) = 0.632$ (63.2%) of the step input.

time	τ	2τ	3τ	4τ	5τ
y(t), % chng.	63.2	86.5	95	98.2	99



11/01/17

2nd order system



Ex: Vibration sensors / Accelerometers / Vibration control / U-tube manometer, pneumatic valves / two liquid tanks in series, RLC ckt - etc.

$$M\ddot{x}_0 + B\dot{x}_0 + Kx_0 = M\ddot{x}_i$$

$$(Ms^2+Bs+K)\,X_0(s) = Ms^2 X_i(s)$$

$$\frac{X_0(s)}{X_i(s)} = \frac{Ms^2}{Ms^2+Bs+K}$$

relative displacement

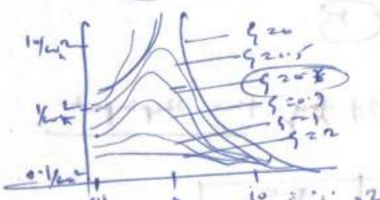
$$\frac{X_0(s)}{s^2 X_i(s)} = \frac{M}{Ms^2+Bs+K} = \frac{1}{s^2+B/M\,s+K/M} = \frac{1}{s^2+2\zeta\omega_n s+\omega_n^2}$$

abs. acceleration

$$= \frac{M/K}{M/K\,s^2+B/K\,s+1} \quad \text{at } s=j\omega$$

16/01/17

Q: Assignment (i) Derive an expression for the vibration control mechanism of APXL 150 ammeter.
$(Ms^2+Bs+K)\,X_0(s) = Ms^2 X_i(s)$



$\zeta = 0.6$, $\omega_n = 1$ kHz
$BW = 24 - 25$ kHz

(ii) Develop a control mechanism for the vibration control due to
(a) seismic control of a skyscraper.
$(Ms^2+Bs+K)\,X_0(s) = K\,X_i(s)$ → stiffness
(b) process control (Bhanot)

(iii) Demonstrate a 2nd order process control model of $(Ms^2+Bs+K)\,X_0(s) = Bs\,X_i(s)$ with a neat schematic diagram / P&I diagram and develop a mathematical model for it.

Refer (1) Bhanot by Oxford press
(2) P. Harriot by PHI

17/01/17

"Self Regulating Processes"

(5)

A process is said to be self-regulated if a ~~specified~~/ specific value of the CV (controlled variable) is adopted for a nominal load with no control action.

Ex: 1. Thermal system ✓ due to disturbance will not go out of control
2. Chemical reactor × (can go out of control)
3. a. Liquid level control × (outflow not depends on head/inflow)
b. Liquid level control through a resistance element – such that outflow depends on head. ✓

Note: Systems with self-regulation are often easier to control than systems without self-regulation; because the later have a tendency to overshoot/undershoot/or even oscillatory i.e. tends to ~~unstable~~ become unstable.

* FPLT

$\frac{}{(1-3)(2-5)(5-10)(10-20)}$

21/01/17

"Dead Time Elements"

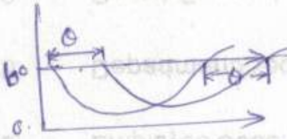
A dead time element is defined as a system in which the output is exactly of the same form as the input but follows the input after a (certain) delay of t_d seconds. The changes in the input are reproduced in the output after a time lag t_d.

$$\therefore \; y(t) = Kx(t - t_d) \quad \text{—— (1)}$$

for $x = A \sin \omega t$ (sinusoidal inputs)

$$y = KA \sin \omega(t - t_d) \quad \text{—— (2)}$$

$$= KA \sin(\omega t + \theta) \; ; \; \theta = -\omega t_d$$



$$\Rightarrow \frac{Y(s)}{X(s)} = K e^{-t_d s} \quad \text{—— (3)}$$

$$\text{or } \frac{Y}{KX}(j\omega) = 1\angle\theta = e^{-j\omega t_d} \quad \angle\theta = -\omega t_d \quad \text{—— (4)}$$

Ex: incompressible, non-reacting liquid flows through a pipe

θ_{in} → → θ_{out}

$$t_d = \frac{A \cdot L}{A \cdot U_{av}} = \frac{L}{U_{av}}$$

A ← area, L → length, U_{av} ← avg. velocity

insulated pipe, temp. drop, friction is zero

$$T_{out} = T_{in}(t - t_d)$$

↑ temp.

Taylor series approx.

$$e^{-\alpha s} = 1 - \alpha s + \frac{(\alpha s)^2}{L2} - \cdots$$

$$\Rightarrow e^{-\alpha s} \approx 1 - \alpha s$$

Pade's approx.

$$e^{-\alpha s} = \frac{1 - \frac{\alpha}{2} s}{1 + \frac{\alpha}{2} s}$$

FOPDT
SOPDT

$$\frac{Y(s)}{X(s)} = \frac{Ke^{-t_d s}}{(\tau s + 1)} = \frac{e^{-0.5s}}{4s+1}$$

(i) Taylor $= \frac{(1 - 0.5s)}{4s+1}$

(ii) Pade $= \frac{(1 - 0.25s)}{}$

Module-4

OPAMP based Robust PID Controller

$$P = K_P e_P + K_P K_I \int_0^t e\, dt + K_P K_D \frac{de}{dt} + P_I(0) \quad \text{--- (1)}$$

$\because$ $p = K_P e + P_0$

$p(t) = K_I \int_0^t e\,dt + p(0)$

$= K_D \frac{de}{dt}$

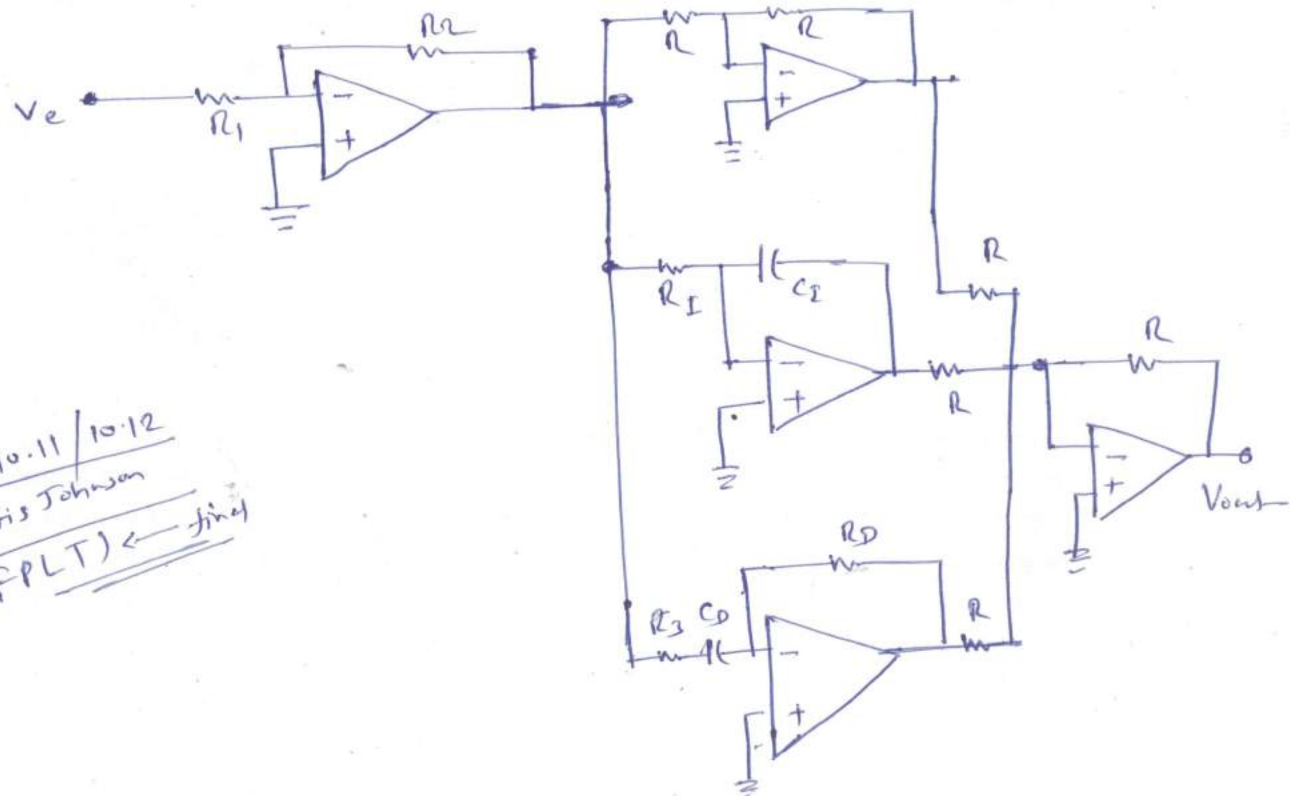
$P \rightarrow$ controller o/p in % full-scale

$e \rightarrow$ process error in percent (%) of the maximum

$K_P \rightarrow$ prop. gain, K_I - intg. gain, K_D - deriv. gain

$P_I(0) \rightarrow$ initial controller integral o/p

\# The zero-error term of the proportional mode is not necessary because the integral automatically accommodates for offset & nominal setting (static error).



*Ex 10.11 / 10.12
Curtis Johnson
A(FPLT) ← final

$$-V_{out} = \left(\frac{R_2}{R_1}\right) \cdot V_e + \left(\frac{R_2}{R_1}\right) \cdot \frac{1}{R_I C_I} \int V_e\, dt + \left(\frac{R_2}{R_1}\right) \cdot R_D C_D \frac{dV_e}{dt} + V_{out}(0) \quad \text{--- (2)}$$

where; R_3 has been chosen from
$2\pi f_{max} R_3 C_D = 0.1$ for stability

comparing with (1);

$$K_P = G_P = \frac{R_2}{R_1}, \quad K_D = G_D = R_D C_D, \quad K_I = G_I = \frac{1}{R_I C_I}$$

A/D ⇒ $\xrightarrow{CA,\,CT}$ (S) $\xrightarrow[DT]{CA}$ (Q) $\xrightarrow[DT]{DA}$ (Encoder) $\xrightarrow[DT]{DA}$ (binary coded data) (2)

& D/A ⇒ $\xrightarrow{binary/pulse}$ (Decoder) $\xrightarrow[DT]{DA}$ (ZOH) $\xrightarrow[CT]{CA}$ Analog signal,

LPF

$a_0 e(k) + a_1 e(k-1) + a_2 e(k-2) = b_0 e(k) + b_1 e(k-1) + \dots b_n e(k-n)$

A/D

Sampling ⟶ (i) instantaneous sampling

(a) through LPF:

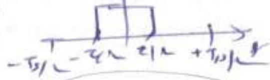
$$V_0(t) = f_s \sum_k m(kT_s)\, S_a[\omega_m(t-kT_s)]$$

(b) " BPF/ equalizer

$$V_0(t) = M(f)\, S_a\left(\frac{\omega T_s}{2}\right) e^{-j\omega T_s/2}$$

$$\therefore x = \frac{\omega T_s}{2}$$

(ii) Natural sampling



$$m_{ns}(t) = m(t) \cdot \left(V_n e^{jn\omega_s T}\right) \Rightarrow P^{\tau}_{T_s}(t)$$

$$\therefore V_n = \frac{\tau}{T_s} S_a\left(\frac{\omega\tau}{2}\right)$$

$$m_{ns}(t) \Rightarrow = \frac{\tau}{T_s} \sum_k m(t) \cdot S_a\left(\frac{\omega\tau}{2}\right) e^{jn\omega_s \tau}$$

d.c. array gain

$m_{ns}(t) \longrightarrow$ [LPF] $\longrightarrow d\,m(t)$

$k=0$

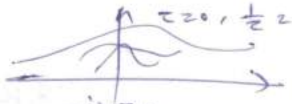
(iii) Flat top sampling

$m(t) = m(kT_s)$ $\longrightarrow (\times) \xrightarrow{m_s(kT_s)}$ [Hold τ] $\longrightarrow m_s(t)$

$\delta_{T_s}(t)$ $\qquad h^{\tau}(t)$

$\therefore \tau_h << T_s$

$\therefore \tau << T_s$



$\tau = 0,\ \frac{1}{\tau} = \infty$

$$m_{fs}(t) = m_s(t) * h^{\tau}(t)$$

$$\therefore M_{fs}(t) = \frac{\tau}{T_s} \sum_k m(f - kf_s) \cdot S_a\left(\frac{\omega\tau}{2}\right) e^{-j\omega\tau/2}$$

$$\boxed{V_0(t) = M_{fs}(t)\big|_{k=0} = \frac{\tau}{T_s} M(f)\, S_a\left(\frac{\omega\tau}{2}\right) e^{-j\omega\tau/2}}$$

what you get at Rx

D/A

$$\therefore R_x = \text{LPF + Equalizer ckt}\left(\frac{1}{S_a\left(\frac{\omega\tau}{2}\right) e^{-j\omega\tau/2}}\right)$$

$$\therefore V_R'(t) = d\,m(t)$$

Pneumatic Controller

Std. of Instrumentation

Power supply: 24 VDC

Std. I : 4-20 mA DC

Std. V : 1-5 VDC

= 3-15 psi

= 0.2-1 Bar

3 - 15 psi ⟷ 4 - 20 mA | 1-5 V DC

- Air is compressible
- Accuracy is poor ~~but~~ so performance is less.
- No return path is required.
- Pneumatic systems are fire & explosion proof.
- simple & easy to maintain

3 - 15 psi (std. pneumatic process control signal)

↕

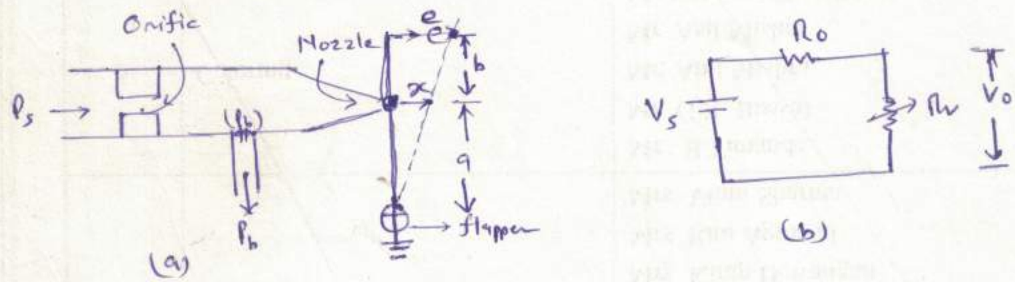
derived from 20-30 psi

↓

from SI unit (N/m^2 or pa)

20 - 100 kPa

Appl^n: flapper nozzle ; bellows.



P_s → supply pressure

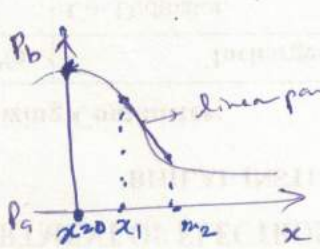
P_b → back pressure

e → nozzle flapper distance

$$\boxed{V_o = \frac{R_v}{R_o + R_v} \cdot V_s = \frac{V_s}{1 + \frac{R_o}{R_v}}}$$

if $R_v = 0$ i.e flapper is far away from nozzle, then $V_o = 0$ V

& if $R_v = \infty$ " " is covering the nozzle, then $V_o = V_s$



$$x = \frac{a}{a+b} \cdot e$$

$$\Rightarrow \frac{\Delta P_b(s)}{\Delta X(s)} = K \quad (\text{K is slope of linear part})$$

$$\boxed{\therefore \frac{P_b(s)}{E(s)} = \frac{a}{a+b} \cdot K}$$

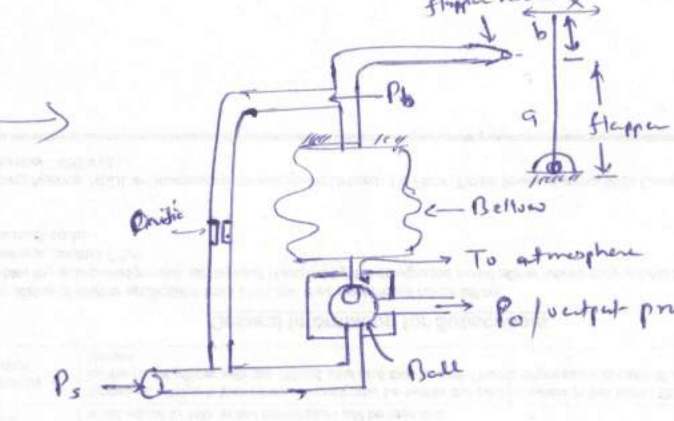
* if K < 0 ⇒ As error ↑es (flapper away from nozzle)

↕

controller o/p ↓es.

Pneumatic Relay (Power Booster) / Bellows

→ is a kind of pneumatic amp^r.



$\frac{\Delta P(s)}{\Delta X(s)} = K$; $K > 0$ so error ↓ ↔ controller i/p o/p

S. Bhanot

PP. 133 " Pneumatic Proportional Controller (P) "

PP. 135 " PD Controller

PP. 136 " PI "

PP. 137 " PID "

← Bellow

10.4 PNEUMATIC CONTROLLERS

Historically, the reason for using pneumatics in process control was probably that electronic methods were not yet competitive in cost or reliability. Safety was and still is a factor where the danger of explosion from electrical malfunctions exists. It is also true that the final control element is often pneumatically or hydraulically operated, which suggests that an all-pneumatic process-control loop might be advantageous. It appears that analog or digital electronic methods will eventually replace most pneumatic installations. But we will still have pneumatic equipment for many years until these are depreciated in industry. A good understanding of process-control principles can be applied to either electronic or pneumatic techniques, but it is necessary to consider some special features of pneumatic technology. This section provides a brief description of operations by which controller modes are pneumatically implemented.

10.4.1 General Features

The outward appearance of a pneumatic controller is typically the same as that for the electronic controller shown in Figure 10.1. The same readout of setpoint, error, and controller output appears, and adjustments of gain, rate, and reset are available. The working signal is most typically the 3- to 15-psi standard pneumatic process-control signal, usually derived from a regulated air supply of 20 to 30 psi. As usual, we use the English system unit of pressure because its use is so widespread in the process-control industry. Eventual conversion to the SI unit of N/m^2 or Pa will require some alteration in scale (of measurement) to a range of 20 to 100 kPa.

The pneumatic controller is based on the nozzle/flapper described in Section 7.3.3 as the basic mechanism of operation, much as the op amp is used in electronics. The schematic drawings of controller mode implementation are intended to convey the operating principles. Specific designs may vary considerably from the systems shown, however.

10.4.2 Mode Implementation

The following discussions present the essential features of controller-mode implementation using pneumatic techniques. The equations are stated in general form with units in SI, but the reader should be prepared to work with English units when necessary.

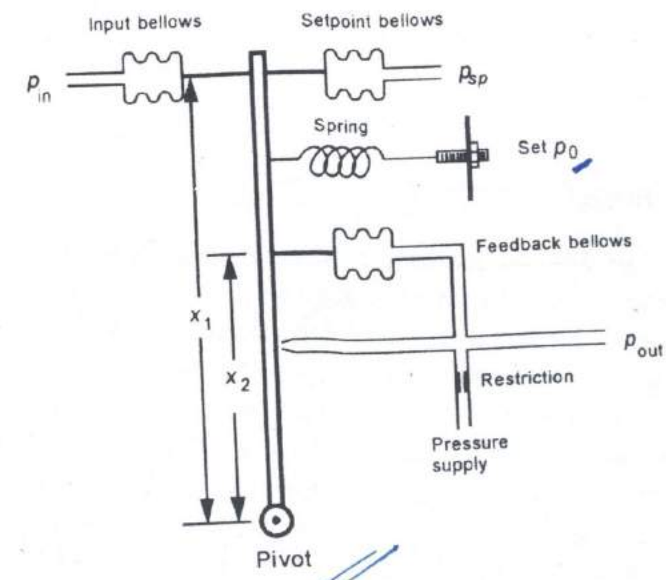
Proportional A proportional mode of operation can be achieved with the system shown in Figure 10.13. Operation is understood by noting that if the input pressure increases, then the input bellows forces the flapper to rotate to close off the nozzle. When this happens, the output pressure increases so that the feedback bellows exerts a force to balance that of the input bellows. A balance condition then occurs when torques exerted by each about the pivot are equal, or

$$(p_{\text{out}} - p_0)A_2x_2 = (p_{\text{in}} - p_{sp})A_1x_1$$

This equation is solved to find the output pressure

$$p_{\text{out}} = \underbrace{\frac{x_1}{x_2}\frac{A_1}{A_2}}_{K_p}(p_{\text{in}} - p_{sp}) + p_0 \tag{10.13}$$

URE 10.13
neumatic proportional-mode controller.



where
p_0 = pressure with no error
p_{in} = input pressure (Pa)
A_1 = input and setpoint bellows effective area (m^2)
x_1 = level arm of input (m)
p_{out} = output pressure (Pa)
A_2 = feedback bellows effective area (m^2)
x_2 = feedback lever arm (m)
p_{sp} = setpoint pressure

$A_1 = A_i + A_{sp}$

This relation is based on the notion of torque equaling force times lever arm, and the fact that a pressure in a bellows produces a force that is effectively the pressure times bellows area, much like a diaphragm. Equation (10.13) displays the standard response of a proportional mode in that output is directly proportional to input. The gain in this case is given by

$$K_p = \left(\frac{x_1}{x_2}\right)\left(\frac{A_1}{A_2}\right) \tag{10.14}$$

Because the bellows are usually of fixed geometry, the gain is varied by changing the lever arm length. In this simple representation, the gain is established by the distance between the bellows. If this separation is changed, the forces are no longer balanced, and for the same pressure a new controller output will be formed, corresponding to the new gain.

EXAMPLE 10.10

Suppose a proportional pneumatic controller has $A_1 = A_2 = 5\ \text{cm}^2$, $x_1 = 8$ cm, and $x_2 = 5$ cm. The input and output pressure ranges are 3 to 15 psi. Find the input pressures that will drive the output from 3 to 15 psi. The setpoint pressure is 8 psi, and $p_0 = 10$ psi. Find the proportional band.

Solution

First we find the gain from

$$K_p = \left(\frac{x_1}{x_2}\right)\left(\frac{A_1}{A_2}\right) = \left(\frac{8\ \text{cm}}{5\ \text{cm}}\right)\left(\frac{5\ \text{cm}^2}{5\ \text{cm}^2}\right)$$

$$K_p = 1.6$$

Now we have

$$p_{\text{out}} = K_p(p_{\text{in}} - p_{sp}) + p_0$$

$$p_{\text{out}} = 1.6(p_{\text{in}} - 8) + 10$$

The low input occurs when $p_{\text{out}} = 3$ psi, so

$$3 = 1.6(p_L - 8) + 10$$

which gives

$$p_L = \mathbf{3.625\ psi}$$

The high is found from

$$15 = 1.6(p_H - 8) + 10$$

which gives

$$p_H = \mathbf{11.125\ psi}$$

The proportional band (PB) is

$$PB = \left(\frac{11.125 - 3.625}{15 - 3}\right)100$$

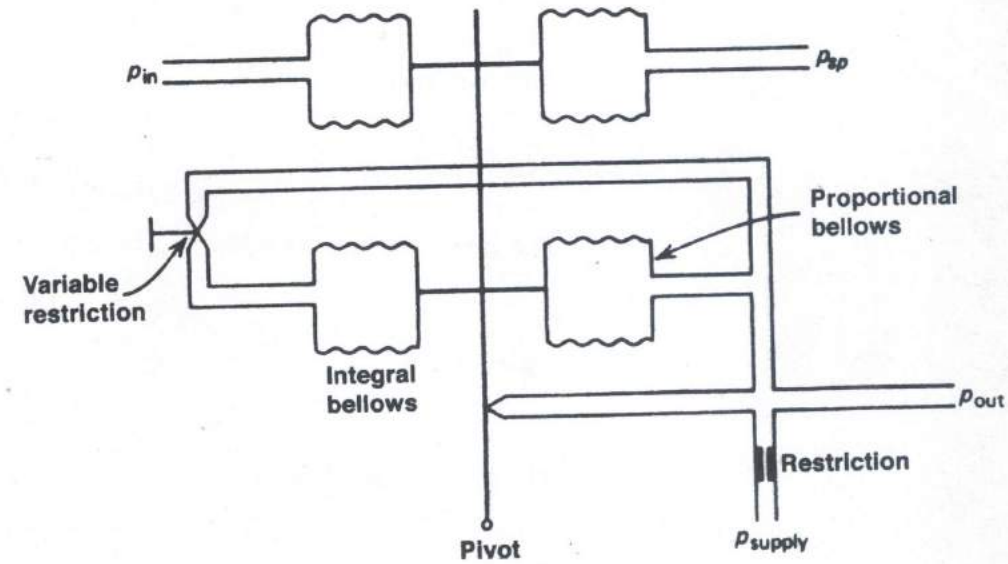
$$PB = \mathbf{62.5\%}$$

Note that this checks with

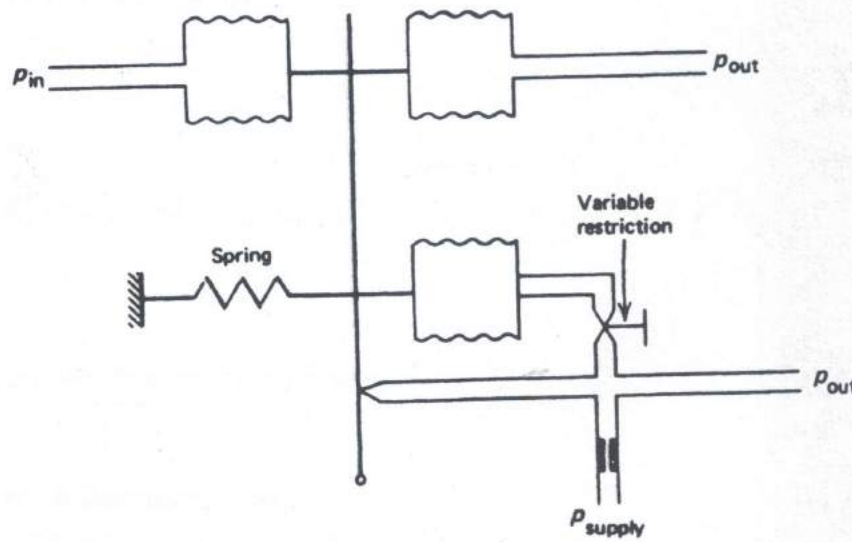
$$PB = \frac{100}{K_p} = \frac{100}{1.6} = 62.5\%$$

which could be used because the input and output ranges are the same.

Proportional-Integral This control mode is also implemented using pneumatics by the system shown in Figure 10.14. In this case, an extra bellows with a variable restriction is added to the proportional system. Suppose the input pressure shows a sudden increase. This drives the flapper toward the nozzle, increasing output pressure until the proportional bellows balances the input as in the previous case. The integral bellows is still at the original output pressure, because the restriction prevents pressure changes from being transmitted immediately. As the increased pressure on the output bleeds through the restriction, the integral bellows slowly moves the flapper closer to the nozzle, thereby causing a steady increase in output pressure (as dictated by the integral mode). The variable restriction allows for variation of the leakage rate, and hence the integration time.



URE 10.14
umatic proportional-
gral controller.



URE 10.15
umatic proportional-derivative
troller.

Proportional-Derivative This controller action can be accomplished pneumatically by the method shown in Figure 10.15. A variable restriction is placed on the line leading to the balance bellows. Thus, as the input pressure increases, the flapper is moved toward the nozzle with no impedance, because the restrictions prevent an immediate response of the balance bellows. Thus, the output pressure rises very fast and then, as the increased pressure leaks into the balance bellows, decreases as the balance bellows moves the flapper back away from the nozzle. Adjustment of the variable restriction allows for changing the derivative time constraint.

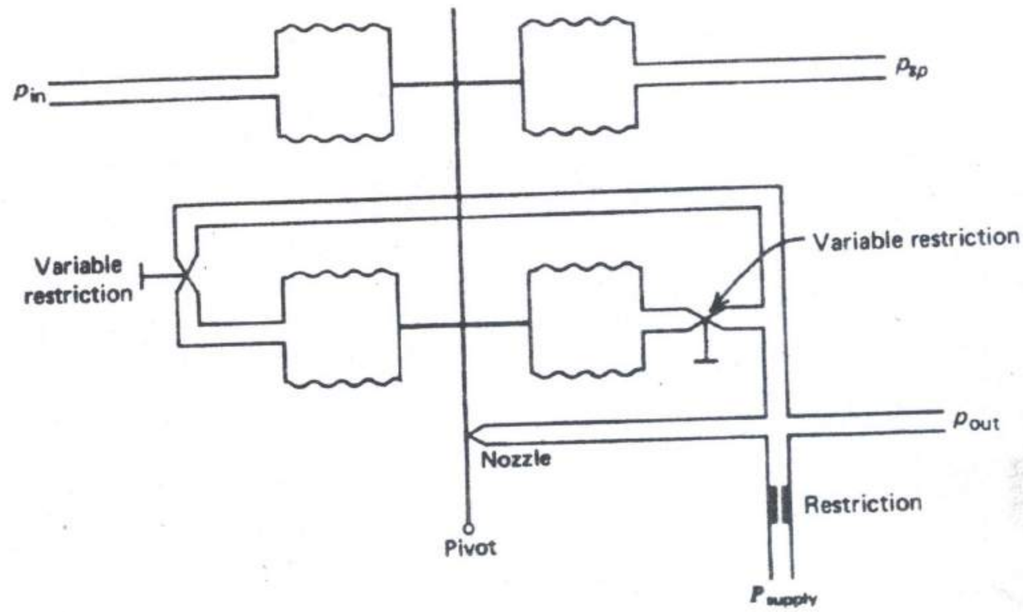


FIGURE 10.16
Pneumatic three-mode (PID) controller.

Three-Mode The three-mode controller is actually the most common ty[illegible] duced, because it can be used to accomplish any of the previous modes by setting [illegible] strictions. This device is shown in Figure 10.16, and, as can be seen, it is [illegible] combination of the three systems presented.

By opening or closing restrictions, the three-mode controller can be used [illegible] ment the other composite modes. Proportional gain, reset time, and rate are set by [illegible] ment of bellows separation and restriction size.

10.5 DESIGN CONSIDERATIONS

To illustrate some of the facets involved in setting up a process-control loop, [illegible] valuable to follow through some hypothetical examples. The following examples [illegible] that a process-control loop is required, and that the controller operation must [illegible] by electronic analog circuits.

EXAMPLE 10.11 Design a process-control system that regulates light level by outputting a 0–10 V [illegible] a lighting system that provides 30–180 lux. The sensor has a transfer [illegible] $-120\ \Omega/\text{lux}$ with a 10-kΩ resistance at 100 lux. The setpoint is to be 75 lux, and [illegible] tional control with a 75% proportional band has been selected.

Solution

We solve such problems by first establishing the characteristics of each part of the [illegible]

1. The illumination varies from 30 to 180 lux. We find the resistance [illegible] cording to

$$R = 10\ \text{k}\Omega - 0.12\ \text{k}\Omega(I - 100)$$

where I is the illumination in lux.