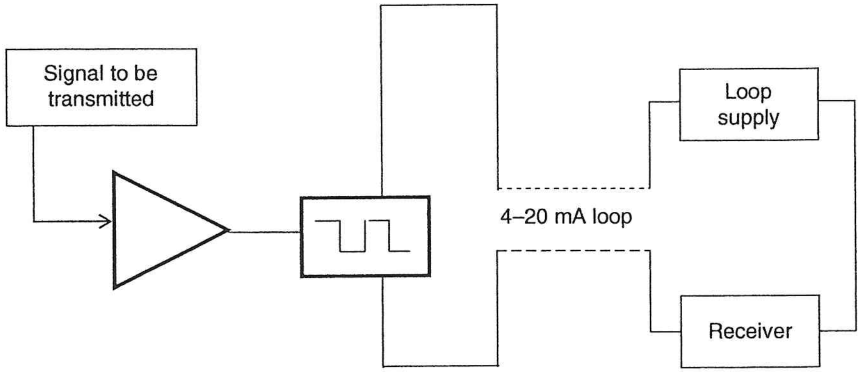
Current Transmission: 4–20 mA

Information is often transmitted with a full-scale span of 16 mA and an offset range of 4–20 mA. This approach is popular in process control as it offers the following benefits:

1. Some immunity to induced voltage noise.
2. Unaffected by line voltage drops.
3. Can differentiate between a value of zero and simple having no signal.
4. Not affected by stray thermocouple effects.
5. Not affected by contact resistances.
6. Can supply power to remote transducers.
7. Allows several components to be connected together in series as part of a process control loop.

An example of a typical application using an isolated 4–20 mA loop is shown in Figure 6.13.



▲ **Figure 6.13** *4–20 mA loop*

Test Examples

1. In a pneumatic telemetering system explain how the air flow through a nozzle in a transmitter is varied. How does this variation cause a change in the signal to the

2. Sketch and describe a variable inductance and a variable capacitance type of transducer. Discuss typical applications, with examples, of these devices in measuring or control systems.
3. Describe a remote telemetering system. Detail on a suitable diagram both the indicator and receiver unit and the connections between them.
4. Describe, with a suitable sketch, an electro-pneumatic converter. Explain the operation when subject to a change in input. State two applications of such a device.

7

ELECTRONIC DEVICES

The subject is specialised and extensive. A full presentation is available from a wide range of sources. For the purpose of this chapter an extreme rationalisation is necessary as follows:

1. Components described are only those active devices with a direct application to instrumentation and control and the basic introductory electronics theory is reduced to a minimum.
2. Description is related to semi-conductor devices only.

The contents of this chapter are given in five sections: semi-conductors, rectifiers, amplifiers, oscillators and other devices. It applies generally to linear integrated (analogue) circuits in the frequency domain, that is, concerned with sinusoidal (or similar) waveform and frequency analysis (current and voltage). Chapter 16 includes integrated digital circuits in the time domain, that is, concerned usually with square waveforms where the criteria is whether current or voltage is present or not, that is, logic devices, computers, etc.

Semi-Conductors

Atomic theory

and nucleus decides conductivity, for example, copper as a good conductor has many free electrons and mica as an insulator does not. Conventional current flow is positive to negative. When considering electron drift movement, which takes place from the negative terminal through the conductor to the positive terminal, it must be noted that the flow is opposite to the conventional.

Germanium and silicon in pure form have a diamond lattice formation, each of four valence (binding) electrons per atom, and electron flow is only possible by partial lattice breakdown due to thermal energy. Arsenic and antimony have a five valency shell readily fitting into the diamond lattice and leaving a surplus conduction electron. Boron or gallium have a three-valency shell and while bonding into the lattice occurs a missing electron creates a conduction hole.

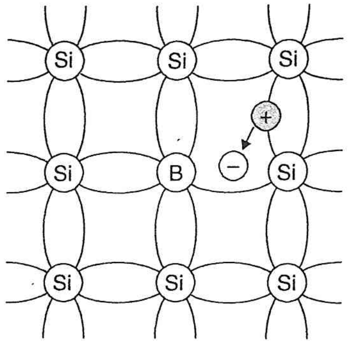
Electron conduction

With *conductors* the electrons, which constitute the current flow, are capable of drifting through the material. The electrons can be imagined to lie in a valance band and an energy supply, heat for example, is sufficient to excite the electrons sufficiently to allow them to jump across a narrow non-conducting band into the conducting drift band.

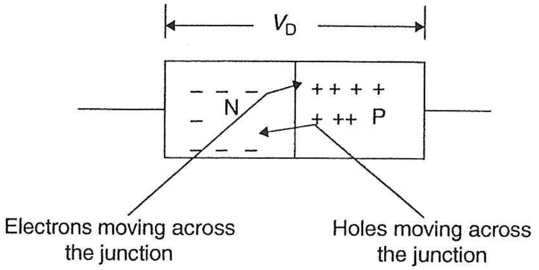
With *insulators* a non-conducting band is wider and electron jump does not readily occur, so that no current flows.

With intrinsic *semi-conductors*, such as germanium or silicon, the properties are midway between conductors and insulators. Some electrons can break from the crystal lattice bond structure, the gap created can then be filled by another electron, hence electron movement does occur and this increases with temperature increase. Extrinsic semi-conductor materials contain slightly impure or doped material, if arsenic (antimony, phosphorus) is added to germanium or silicon there is a surplus of electrons in the crystal lattice, such *donor* atoms give an *n*-type conductor. If boron (gallium, indium) is added there is a positive *gap* or *hole* in the crystal lattice, such *acceptor* atoms give a *p*-type conductor (Figure 7.1).

Conduction by electrons is similar to that in metals. For a *p*-type material, an electron moves through the lattice, being attracted by the positive hole, to fill the hole, this creates another hole, and so on. The hole then appears to move to the negative through the lattice, this can be regarded as causing the conduction. Majority carriers, electrons or holes in *n*-type and *p*-type impurities, greatly outnumber minority carriers



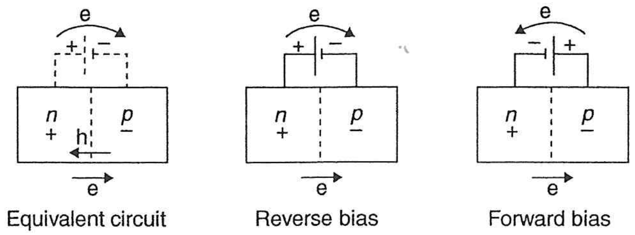
▲ **Figure 7.1** *Silicon crystal lattice doped with Boron*



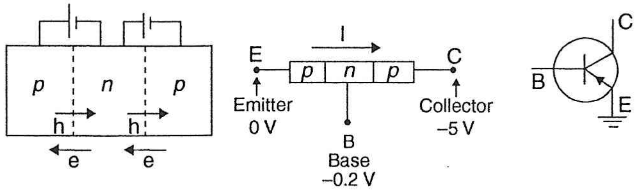
▲ **Figure 7.2** *The* n–p *junction as a rectifier*

The maximum junction temperature for solid state devices is usually fixed at about 125°C This restricts the case temperature to a lower figure depending on internal thermal resistance and junction to case thermal resistance. For most instrumentation applications power, levels are low and device failure is unlikely although temperature rise is likely to affect linearity. In some control applications thermal management can be essential to avoid failure.

When a *p*-type and an *n*-type material are made into a specific junction electron flow to the holes in the *p*-type occurs. A negative charge exists in the *p*-type and a positive charge in the *n*-type, thus giving a potential difference across the junction which stops further migration of electrons. This *n*–*p* junction can act for example as a rectifier, with the positive side connected to the *n*-type the potential difference is increased, as shown in Figure 7.2, with the negative side connected to the *n*-type the potential difference is reduced. A few random electrons (leakage current) can go against the bias. When reverse biased, the holes and electrons are drawn away from the junction leaving a depletion layer with virtually no current carriers.



Semiconductor diode



***pnp* bipolar transistor**

▲ **Figure 7.3** *Solid state junctions, examples*

Further consideration leads to transistors in which a *pnp* or *npn* sandwich exists. For *npn* the emitter emits electrons, the collector collects electrons, and the base controls the flow of electrons by controlling the charge concentration in the base region. For *pnp* the polarity is reversed and the flow is as shown in Figure 7.3. A relatively larger emitter-collector current can be controlled by a small base-collector current and voltage.

Current gain (collector to base current ratio) can easily be in the range 10–200. Power gain may be as high as 50,000.

Silicon planar technique (diffusion) is the basic process used in bipolar (two carriers e and h) solid state and integrated circuit chip technology for resistors, capacitors, diodes and transistors in circuit.

Rectifiers

Metal rectifiers, valve diodes and thyratrons have generally been superseded by the semi-conductor diode (*p*–*n* junction rectifier) and the thyristor (silicon controlled rectifier). More complex devices such as tunnel, variable capacitance, microwave and four-layer diodes are not considered in this book.

Semi-conductor diode

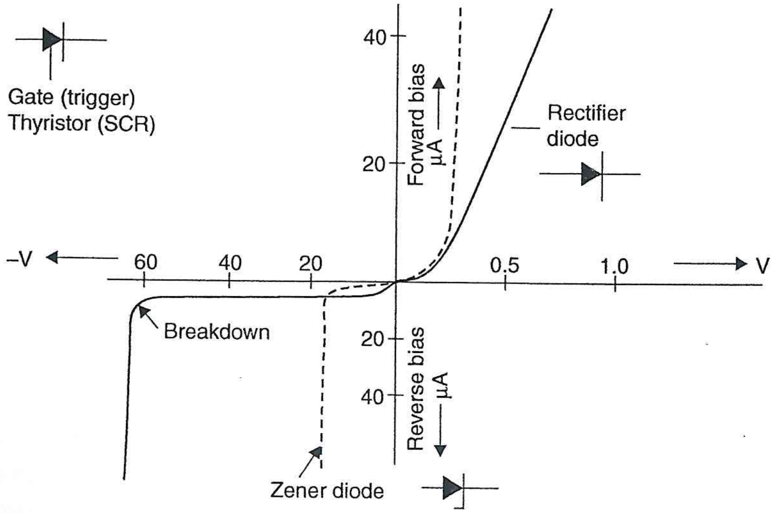
When ac current is applied to the *p–n* junction a large current will flow when forward biased polarity applies and conduction stops when reverse biased and the diode acts like any other rectifier. This is confirmed by the characteristic shown in Figure 7.4.

If the reverse bias is increased beyond a certain value, called the breakdown voltage, the reverse current will increase sharply and this is known as avalanche or zener current. Rectification diodes never operate in the breakdown region but the zener diode, used in voltage stabilisation and reference circuits, is operated in this region. Note in particular the symbols shown in Figure 7.4 to represent semi-conductor rectification, zener diodes, thyristor (silicon controlled rectifier) and the *different* scales on the axes. Current flow is in the direction of the arrow, the bar to indicate non-reversal (see also Figure 7.7, bridge rectifier circuit).

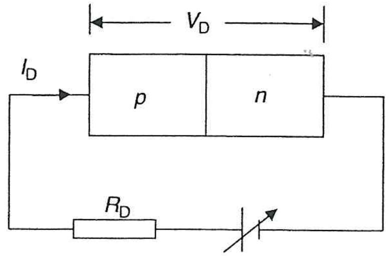
The diode is the simplest form of rectifier (Figures 7.5 and 7.6).

The bridge rectifier is shown in Figure 7.7.

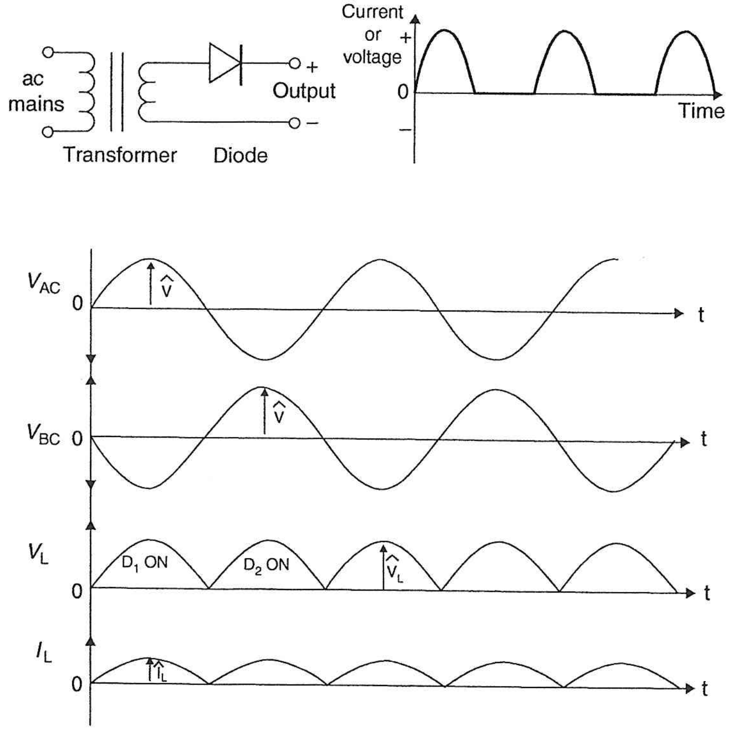
When A is positive with respect to B current flows through D_1 to the load and returns through D_3 to B. When B is positive with respect to A flow is through D_2 and returns through D_4.



▲ **Figure 7.4** p–p *junction characteristic*



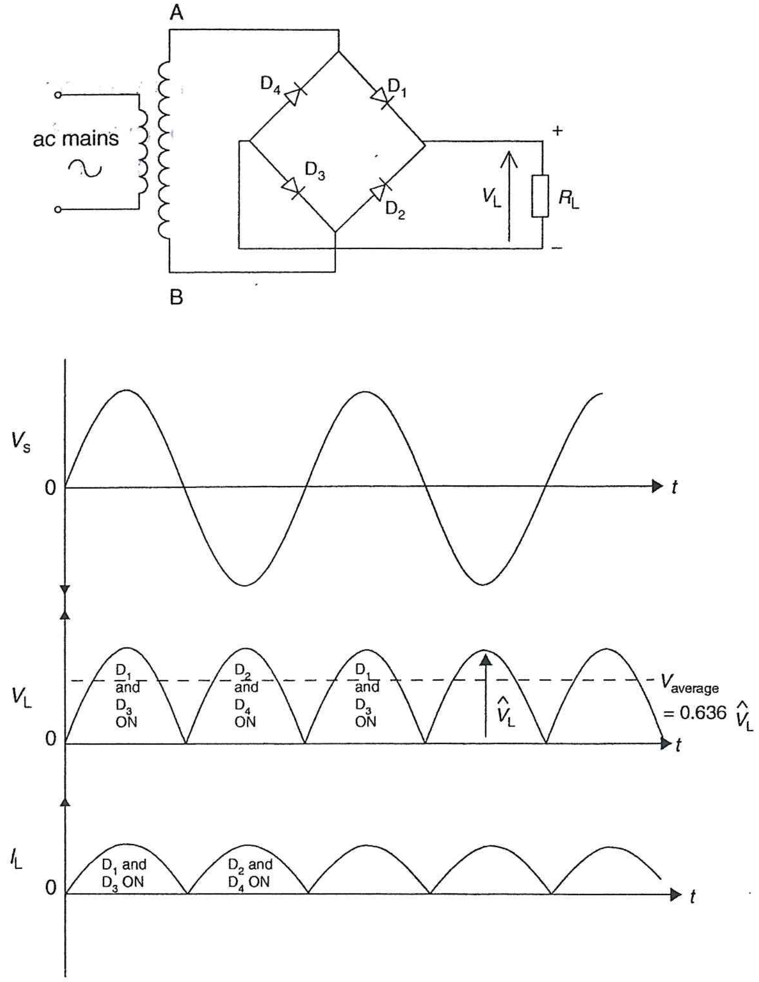
▲ **Figure 7.5** p–n *junction forward biased*



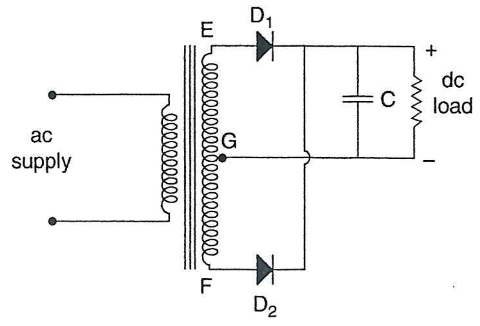
▲ **Figure 7.6** *Diode rectifier*

The centre tap transformer rectifier is shown in Figure 7.8.

When E is positive with respect to F current flows through D_1 to the load, returning to G, D_2 is reverse biased. When F is positive with respect to E flow is via D_2 to the load, returning to G, D_1 is reverse biased.



▲ **Figure 7.7** *Bridge rectifier*



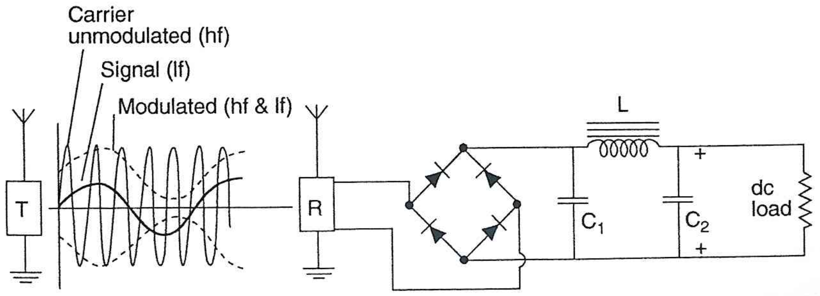
▲ **Figure 7.8** *Centre tap transformer rectifier*

The disadvantages of centre tap transformer rectifier are as follows.

1. Voltage across the load is only half of secondary voltage at a given instant of time.
2. 50% of the secondary power is used at a given instant, thus if you have a 23 VA transformer you can only have a 12.5 VA (not withstanding losses) dc power supply.

Applications

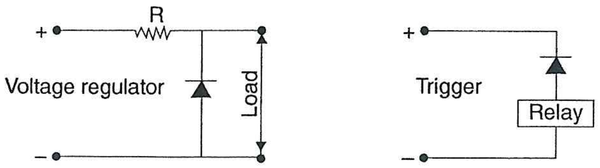
Low frequency (audio) signals cannot be efficiently radiated. A high frequency (radio) *carrier* has a low frequency signal impressed on it at the transmitter by varying or *modulating* the amplitude of the carrier wave in sympathy with the low frequency signal. At the receiver the signal information is recovered from the carrier wave by a process known as *demodulation* or detection. The wave at the receiver is first rectified (detected) and the signal information recovered by passive networks (resistance–capacitance–inductance). These networks are usually known as *smoothing* or *filter* circuits. Figure 7.9 shows a transmitter–receiver unit with fullwave bridge rectification-detection by semi-conductor diodes and a high frequency capacitor (C_1) filter with smoothing choke inductor (L) and filter capacitor (C_2). This is a capacitor input filter system, C_1 is often termed reservoir and C_2 smoothing capacitor. A capacitor provides high impedance to dc and an inductor high impedance to ac. The function of the filter may also be explained by regarding it as an integrating network. In general conversion between ac and dc is often required in instrument-control systems. Modulation, demodulation and re-modulation are frequently used in the electronic systems to utilise the best component for a particular duty of sensing, amplifying, control, etc. Low voltage supplies are often required for transistorised equipment. Typically a mains transformer, bridge rectifier, smoothing circuit and diode (zener) volts stabilisation is used.



Zener diode

Figure 7.10 shows two applications of zener diodes. As a voltage regulator (stabiliser) the reverse connected zener diode conducts if input voltage is above breakdown voltage and current from the supply is the sum of diode and load current. For input voltage increase then current increases through both R and the diode but the diode resistance decreases and current through the diode further increases. A larger volt drop across R will occur but output voltage across the diode remains reasonably constant. Variations of input or output cause shunt of more or less current through the diode resulting in constant voltage, that is, across the diode regulation circuit (see also Figure 11.9).

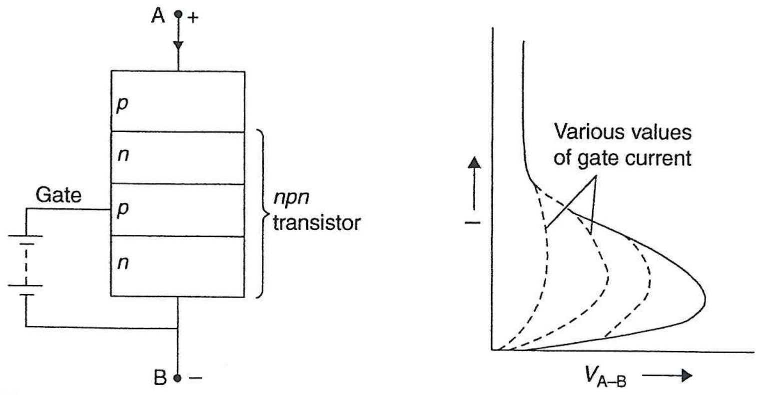
The second diagram illustrates use as a trigger safety device. The relay will be held and will not fire until a certain prescribed voltage is reached.



▲ **Figure 7.10** *Zener diode applications*

Thyristor (silicon controlled rectifier)

From Figure 7.11 it will be noted that this is a *pnpn* sandwich. Consider the section shown as an *npn* transistor which requires a base current from the gate to cause conduction from collector to emitter. With A negative both top and bottom junctions are reverse biased. With A positive and no gate voltage the middle junction is reverse biased. As shown in Figure 7.11, and with a pulse of positive current injected into the gate, then as the *p–n* junction (top) is already forward biased the device is turned on. When conduction exceeds about 10 mA an avalanche (zener) effect occurs and gate current is not required to maintain flow. To stop conduction, voltage has to be reduced to zero and the device requires another signal to fire. High currents can be controlled and the device is a very fast, high power gain, switch. Small gate current can switch a large load current or gate controlled halfwave rectifier. Applications include controlled rectification, inversion, stabilisation, regulation. Thyristor systems in excess of 10MW power rating are well established as the major power control element for electric (synchroconverter and cycloconverter) propulsion systems in ships. An application of the thyristor is given in Chapter 14.



Triac and diac

A triac has two SCRs back to back with one gate controlling conduction in either direction. A diac (no gate) builds up voltage to trigger pulse the triac gate current.

Gate turn-off device

Thyristors have become established as the preferred solid state switch for power levels in the order of megawatts. They have one main disadvantage in that they are not self-commutating, that is, they cannot be switched off by a command to the gate terminal. A thyristor type device which has been developed to overcome this problem is the gate turn-off (GTO) device. Reversal of pulse polarity at the gate terminal has the effect of turning off the device. GTOs tend not to be applied at the highest power levels and designers tend to rely instead upon the reverse bias effect of ac combined with power factor control techniques.

Insulated gate bipolar transistor

The insulated gate bipolar transistor (IGBT) combines the robust power handling characteristics of the bipolar transistor with the benefits of an insulated control terminal as in field effect devices. Power handling capability is not as great as the thyristor but is growing fast. Power converters of a few megawatts (MW) are now installed as the major control devices for electric (pulse width modulation) propulsion systems in ships.

Amplifiers

Amplifiers are an essential part of instrumentation and control. The pneumatic amplifier (relay) is described in Chapter 10. Feedback is an inherent addition but a detailed discussion on this topic is reserved until the end of this chapter. Devices are active, that is, utilising an external power source – as distinct from passive.

Rotating electrical amplifiers

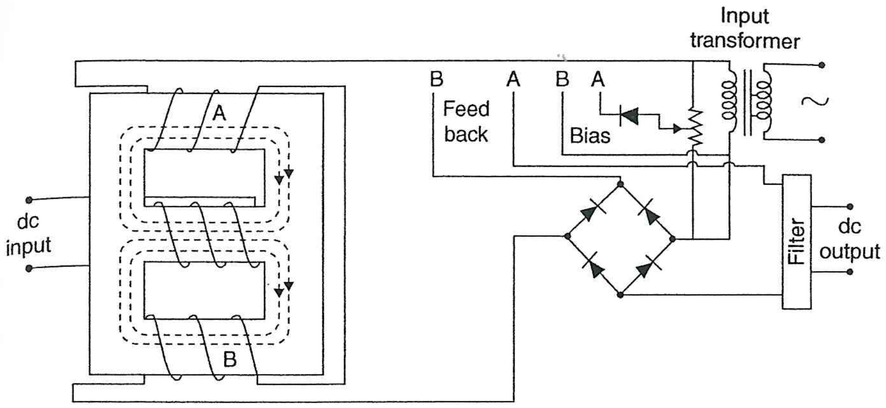
The separately excited generator is often used in control systems. The Ward Leonard type unit is generally well known and an application and description are given in Chapter 14.

Magnetic amplifier

The magnetic amplifier is of interest because of its use in electronic components, often in series with transistor amplifiers. A high permeability ferromagnetic core is wound with an ac current coil.

The inductance opposes increases of current until the induced magnetic flux saturates the core when the reactance now behaves as a resistor, that is, saturated reactor and large increases in current can occur. A dc-energised control winding on one limb of the core brings about, and varies, the degree of saturation and hence ac current flow in the gate limb. Bias and feedback windings are also incorporated on gates to improve flexibility and stability, and ac output can be rectified to dc which is filtered and appreciably amplified above the input. The typical unit is shown in Figure 7.12; ac input is from a transistorised oscillator and dc input is stabilised.

Flux due to dc is unidirectional through gate windings A and B but flux due to ac is, as shown, in opposite directions. The ac output can be passed through a bridge rectifier and filter. Positive feedback is utilised for gain adjustment without oscillation problems



▲ **Figure 7.12** *Magnetic amplifier*

because this unit is inherently very stable. The principle can also be used in a transducer with a sensor core to vary inductance by movement.

Classification

Generally this depends on duty. If frequency is the criterion, the range is from zf (zero frequency – dc amplifier) through lf (audio), rf, vhf to uhf (900 MHz). Generally the first two are of interest here (see Figure 7.26).

Another classification depends on the equipment to be controlled by the amplifier. Voltage types give undistorted voltage output and power amplifiers are to provide drive power. The latter is used to provide power to recorders, controllers, etc.

A third criterion depends on the position of the bias point in relation to the characteristic curve of the device. If operated near the middle of the linear characteristic there is no distortion and this is termed a Class A amplifier, which is ideal for voltage amplification but has a low power efficiency. If biased at or near cut off this is termed Class B and has a good power efficiency but severely distorted output – often halfwave. Two such amplifiers can be matched as a push-pull amplifier, which via a transformer gives undistorted output. Class C amplifiers are biased past cut off and have the highest efficiency and greatest distortion (reverse biasing).

With transistors the device is usually utilised in one of two modes *linear* and *non-linear*. In the former sinusoidal signals are amplified without distortion usually in two main types, that is, small signal voltage amplification and power amplification. The non-linear include: oscillators, that is, square (or saw) wave supply generators, bistable (flip-flop) devices used in counting circuits, etc.; static switching and hold (memory) circuits, logic devices, etc. These applications are described later in this chapter and in Chapter 16.

Analysis of Transistor Behaviour

Junction transistor

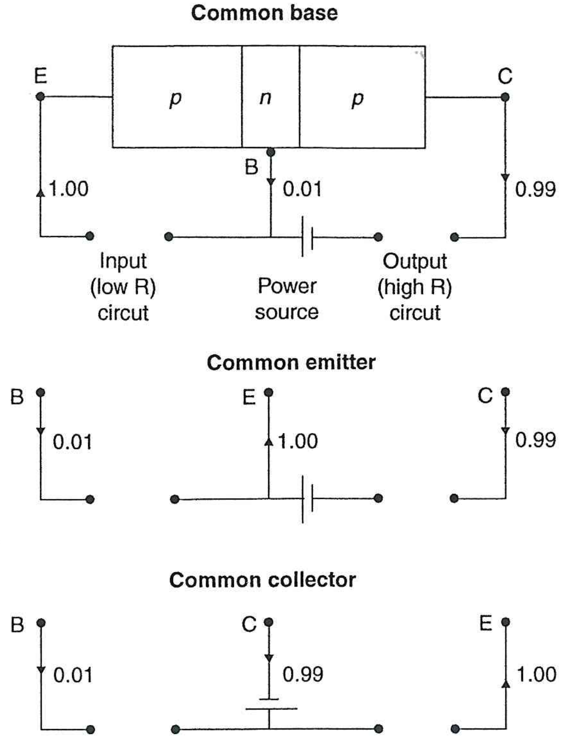
The *pnp* junction is shown in Figure 7.13. Due to initial diffusion, one junction (emitter-base) is forward biased and the other junction (base-collector) is reverse biased. The former conducts heavily and positive carriers (holes) diffuse across the *n* region. If this region is arranged to have few electrons little combination occurs and holes are attracted across the next junction by the bias voltage. Emitter current is the sum of collector current and base current. The collector current is much greater than the base current, and proportional to it over a wide range, so that collector current can be controlled by the base current. Power for emitter-collector current does not come from the amplifier input current, that is, base current, but from an external power source. This amplifier is an active device and in system terms can be treated as a 'black box', that is, input, output and power source relationships required without details of internal 'box' arrangements. (For *npn*, biasing voltages are reversed and conduction is mainly due to electrons). *pnp* is used in this text.

Factors of importance are transfer characteristic (function) (comparison of input and output), dynamic range (of power), efficiency (on power basis), amplification (gain) (magnitude of input and output voltages or currents) and frequency response (transit times).

The input circuit is biased to produce steady base current flow. Changes in input current cause much larger changes in output current, that is, current amplifier. It is a bipolar (utilises both charge carriers) device.

Circuit configurations

Means to connect input, to supply power and to make use of output are necessary. There are three ways to connect, differing in the way input and output are connected to the transistor, and each gives different characteristics which will depend on duty. Power must be consumed in the external circuit (load), usually by resistors, and the



▲ **Figure 7.13** *Circuit configurations*

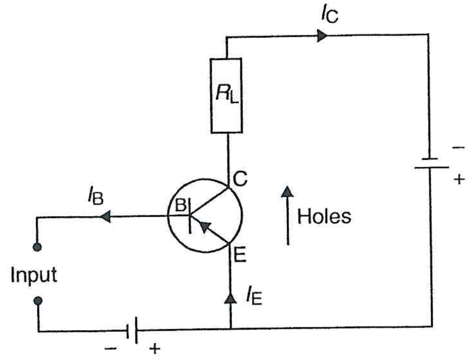
Configurations are as shown in Figure 7.13. These are common base, common emitter and common collector. This depends on the terminal which is common to the input and output signal; common emitter is the most often used. From Figure 7.13, for the common base connection, assuming an ac input of say 45 mV and 1 kΩ resistor in the collector circuit, then 990 mV will be developed across the resistor, that is, voltage gain 20. For the common emitter connection the input circuit has a much lower current, therefore the input resistance is about 100 times higher and without the resistor the current gain is 99. The common collector has similar characteristics to the latter. Currents shown in Figure 7.13, in mA, are illustrative.

Transfer characteristics

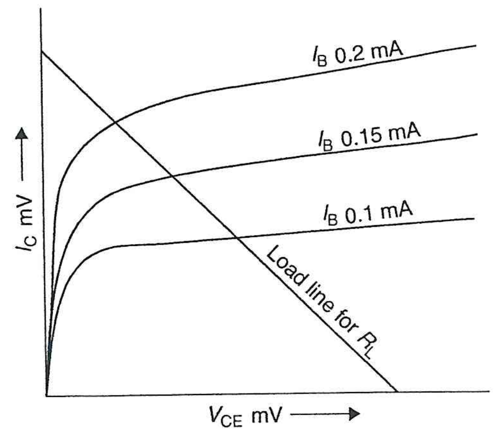
These depend on circuit arrangement adopted as well as upon the transistor itself. Consider the junction transistor as a current amplification device. The current transfer ratio (α) compares collector and emitter currents and is less than unity (due to leakage). Current gain (β) compares output and input currents, its value depends on the circuit expressing the result in terms of α. Current gain is less than unity for common base and typically between 10 and 200 for the other two configurations. Strictly current *changes* are compared. Transfer characteristic is preferably linear. Equivalent circuits and 'h' parameters are used in transfer analysis.

The *pnp* transistor circuit (common emitter) is shown in Figure 7.14. In practice the common junction is often earthed, output voltage tapped off after C to earth (via capacitor), bias battery replaced by RC circuits and supply is from voltage power lines not battery.

Characteristics are as shown in Figure 7.15 where variations of base current (at input) give variations of collector-emitter voltage projected down from the load line. For the load line – where it cuts baseline is supply voltage (cut off $I_B = 0$), saturation at crossing



▲ **Figure 7.14** *Transistor circuit (common emitter)*



with I_B = 0.2 mA here, operating point for voltage amplifier (requiring minimum distortion) at mid-length approximately. Class B amplifiers biased near cut off giving halfwave pulses.

Transistor voltage amplifier

It is necessary to include a high resistance in series with the collector and tap off voltage variations across it, and a gain of 250 can be achieved. If connected as a common emitter a positive pulse into the base makes it less negative and fewer holes flow from emitter to base. Collector current therefore decreases and the volt drop across the resistor decreases which causes collector voltage to increase. There is a 180° phase reversal between base input and collector output voltage signals. Voltage characteristic slopes down so collector voltages decrease for base voltage increase but it is the amplification, not the negative slope, that is important. If it is necessary not to have inverted output two amplifiers in series are used – inversion is useful for negative feedback. Common base connections are desirable for voltage amplification but are difficult to design so that common emitter configurations are usually found.

Parameters

The common emitter circuit gives medium input and output impedance, good current or voltage or power gain inversion. Common base gives low input and high output impedance, no current gain but good voltage and medium power gain in phase operation. Common collector gives high input and low output impedance, no voltage and power gain but good current gain in phase operation. The latter is often used for buffer stages connecting high impedance source to low impedance load (impedance matching). The common emitter mode, *pnp* or *npn*, is most frequently used for current amplification and especially for voltage amplification because a low input signal is required.

Equivalent T-circuit

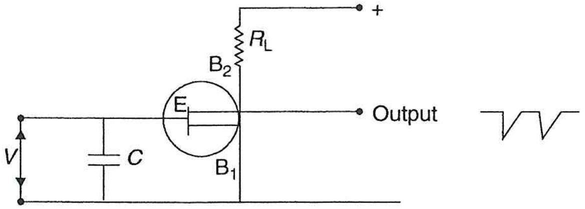
Presents a simple representation of the transistor to allow calculation of current, voltage and power gains. Such a circuit is shown in DTp – SCOTVEC Class One specimen examination question number 18 at the end of the book (common base configuration).

Unijunction transistor

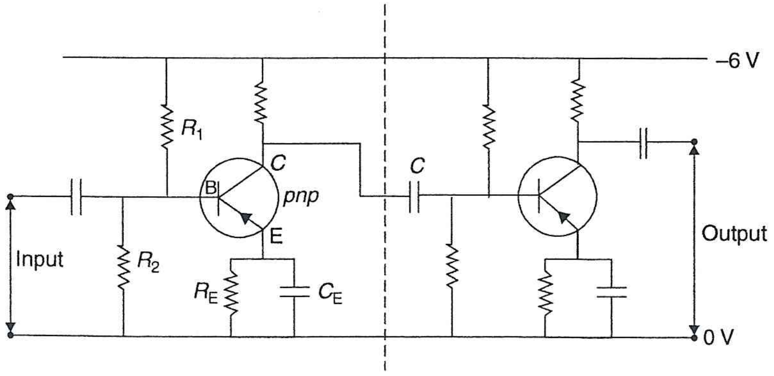
A bar of lightly doped *n* type material, with base connections B_1 and B_2 at each end, has a *p* type material contact (emitter) made between the two. If the emitter junction to drive an emitter current it flows in the B_1 emitter region. This decreases the region resistance and emitter voltage (negative resistance characteristic). The device is used for trigger operation, pulse oscillators, time delays and particularly for pulse generation to fire thyristors. In Figure 7.16, C charges until voltage can eject emitter current. At a certain value of this current the voltage V collapses giving a negative spike output pulse with rapid discharge of C. The capacitor recharges and oscillation continues. This device is therefore a simple relaxation oscillator but is described here in the general context of the transistor.

Small signal junction transistor amplifier

This is a linear mode device. Figure 7.17 shows a *pnp* common emitter configuration multi-(two) stage unit, the dotted line illustrates the staging, extension to more stages is achieved in the same additive way. In a triode valve auto grid bias is used and in transistors a similar principle is required. A suitable bias point which is stable with temperature variation is essential. Several ways, all dependant on feedback, can be used. In Figure 7.17, a resistor R_E in the emitter lead maintains a constant base voltage and any undue rise in the leakage (temperature induced) current causes the emitter voltage to fall. The emitter–base junction approaches reverse bias so reducing current through the unit. The potential divider $R_1 + R_2$ keeps base voltage constant when there is no input signal. Capacitor C_E acts as a bypass for ac components of emitter current. Circuits typify voltage amplifiers.



▲ **Figure 7.16** *Unijunction transistor (oscillator)*



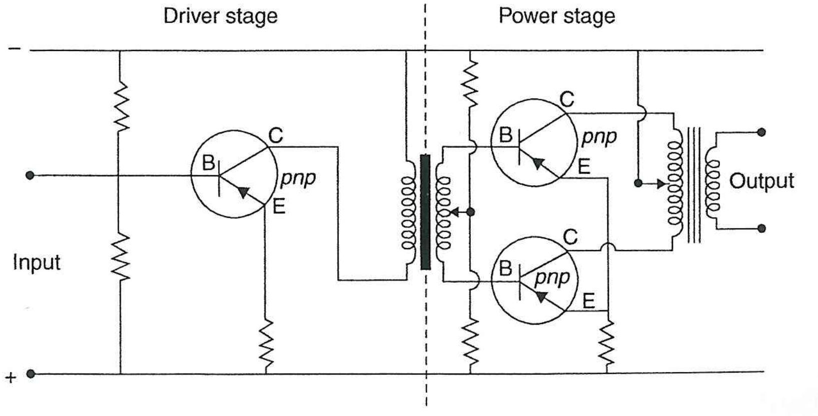
▲ **Figure 7.17** *Transistor two-stage amplifier (small signal)*

Coupling between stages can either be by a transformer method or, as shown, resistor-capacitor. Whilst current amplifier design is easily arranged, voltage amplification requires a high input impedance to the first stage. Essentially this needs increased feedback which can be achieved by omitting C_E and C the interstage capacitor (direct coupling). Other methods can be used such as emitter follower but this adds to complexity. For one stage current amplifier, omit C_E and take output across R_L, connect collector directly (no resistance) to the –6 V power supply.

Power amplifier

Power dissipation must be kept low so a high efficiency is important. Class B types are preferred but single transistors cannot be used because the operating characteristic range results in halfwave form outputs so that a push–pull twin arrangement is utilised. Such amplifiers require high input currents and a power (driver) stage is used, usually in Class A, the combination being classified as AB (linear mode). A typical arrangement is shown in Figure 7.18.

The driver transistor feeds to the transformer phase splitter. Inputs to the power stage are of equal amplitude and 180° out of phase. Each power transistor conducts for



▲ **Figure 7.18** *Push/pull power amplifier stage and driver* half a period and the complete waveform is restored in the output transformer. This transformer has its primary ends connected to the transistor collector leads and centre tap connected to the more negative lead. Signal flux is in the output transformer core throughout the whole period, with the complete waveform in the secondary winding. Power supplies are commonly ±6 V, as an order of magnitude.

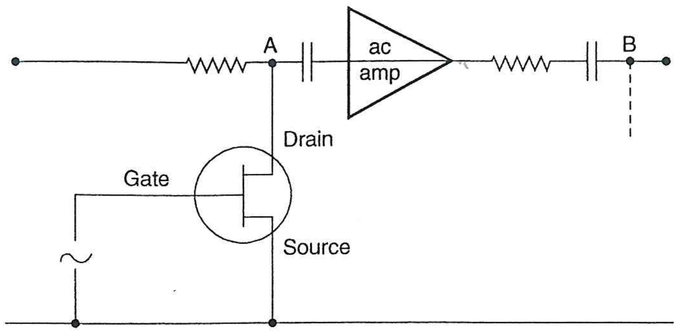
dc amplifier

Most instrument signals require dc amplification of low voltages. This is difficult to arrange as drift variation, largely caused by temperature variation in transistors, is amplified and passed on. With ac amplifiers the coupling capacitor excludes variations but with dc units the coupling is usually direct. Differential amplifiers have been used but perfect matching is difficult. Zener diode stabilisation and feedback circuits are also employed.

The solution often adopted is to use an inverter input to derive ac from dc, direct ac amplifiers and a converter output to give dc from ac. The converter is essentially a rectifier with smoother circuit, as described in the demodulation circuit of Figure 7.8, or a transistorised feedback integrator.

The inverter is called a chopper and converts steady input into square waves, height proportional to signal strength and easily amplified, by mechanical or transistor switching devices. When transistors are used voltage and temperature stabilisation are required. The transistor switch occupies four successive states, that is, off (voltage applied between *E* and *C* with leakage current only flowing), on-transition (*C* current rising and voltage falling), on (*C* current flowing and saturation voltage only between *E* and *C*), off-transition (*C* current falling and voltage rising). Rating conditions require careful design and a small offset voltage arises, temperature related, which causes problems. A field effect transistor is suited to chopping and a circuit is shown in Figure 7.19, such transistors have negligibly small voltage offset with the distinct advantage of a very high input impedance. Junctions (JFET) utilise *n* or *p* channels whilst metal oxide silicon (MOSFET) are n channel, either enhancement or depletion type.

One JFET is an *n* type bar (lightly doped) with electron input (source) and output (drain) at its ends. On both sides of the bar *p* type (heavily doped) material electrodes act as the gate (reverse biased relative to source). A narrow channel through the centre is controlled by the gate and impedance variation can arrange two conditions, saturation and 'pinch off' output voltage.



▲ **Figure 7.19** *FET chopper circuit*

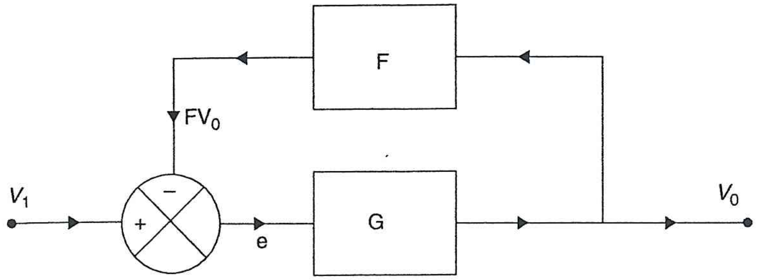
In Figure 7.19 the FET varies its drain and source resistance according to voltage level and polarity of the input signal. Essentially it is working as a make and break to produce square waveform. Output, in the absence of any restoring mechanism, would be symmetrical about a OV line as dc level is lost in the ac amplifier. The output can be periodically shorted at B with another FET as at A, so that negative going portions are removed and dc level restored. A smoothing circuit would be fitted at output. Source line could well be earthed. A FET can also give large current variations for small changes in gate voltage, that is, amplifier operation, if required. It is a unipolar device. Linear and digital MOS integrated circuits are used in microprocessors in preference to bipolar types. They use variation in gate voltage to vary current source-drain, utilise one carrier and have high input impedance.

Operational amplifier

A combination of a high gain dc amplifier, that is, chopped, ac, smoothed, together with feedback and input impedance is required in control systems. The complete amplifier (with a gain of –A) is usually diagrammatically represented as a triangle. Such devices are described in detail in Chapter 11. They are essentially voltage amplifiers, in cascade multi-stage form, gain 10^5 – as an integrated circuit on a silicon chip, used in analogue computation and digital logic.

Feedback analysis

This aspect has been mentioned previously but it is now necessary to consider a more detailed analysis before concluding the work of this section. Consider Figure 7.20 of



▲ **Figure 7.20** *Closed loop (feedback amplifier block diagram)*

fraction F of output fed back. Voltages are taken as the variables, V_1 input, e error, V_0 output (the more general terminology would be θ_1, θ, θ_0). Subtraction of V_0 from V_1 is arranged with an odd number of amplifier stages, giving 180° phase shift, and adding V_0 to V_1; this is *negative feedback*. Also see page 265.

$$
\begin{aligned}
V_0 &= Ge \\
e &= V_1 - FV_0 \\
V_0 &= G(V_1 - FV_0) \\
\frac{V_0}{V_1} &= G\left(1 - F\frac{V_0}{V_1}\right) \\
\frac{V_0}{V_1}(1+GF) &= G \\
\frac{V_0}{V_1} &= \frac{G}{1+FG}
\end{aligned}
$$

Now if the 'open loop' gain FG is high compared to 1 (i.e. for a high value of amplifier gain G):

$$\text{Overall gain} = \frac{1}{F}$$

This is independent of G, which can vary, and only dependent on F which is fixed by accurate stable resistors. The resistive input impedance is increased by a factor of $1 + FG$. The marked improvement in performance over the open loop amplifier is at the expense of additional amplifier stages made necessary by increasing G to make FG much greater than unity.

Consider an amplifier with a gain of 10^4 and negative feedback fraction F one-hundredth, that is, 10^{-2}

$$\text{Overall gain} = \frac{10^4}{1+10^{-2}\times 10^4} = 99$$

Assume a change in G due to say variation of supply voltage, ageing of transistors, etc. of as much as 50% reduction.

$$\text{Overall gain} = \frac{5\times 10^3}{1+10^{-2}\times 5\times 10^3} = 98$$

That is, fall of 50% amplifier gain results in about 1% fall in overall gain. Negative feedback gives stability and accurate control.

Consider now the case of *positive feedback*.

$$
\begin{aligned}
V_0 &= Ge \\
e &= V_1 + FV_0
\end{aligned}
$$

This, for electrical, is feedback voltage in phase with input voltage.

$$\frac{V_0}{V_1} = \frac{G}{1-FG}$$

Again there is increase of overall gain compared to 'open loop' gain. However there is a marked disadvantage in that a small change in G causes a much greater change in overall gain and also overall gain increases rapidly as FG increases so that when $FG = 1$ the overall gain is infinite. Output is available with no input, that is, the amplifier is an oscillator. Positive feedback use therefore causes instability and self oscillation. Oscillators are very useful in instrumentation electronics but oscillatory situations in control systems must be avoided. Instability and oscillation shows as practical hunting or cycling on the control system which is most unsatisfactory.

Oscillators

An oscillator is an instrument for producing voltages that vary in a regular fashion. The output may be sinusoidal, that is, a sinewave generator (harmonic oscillator) or important in control system equipment. A wide range of harmonic oscillators exist from high frequency (LC types) to low frequency (RC types) but apart from basic principles only the relaxation oscillator will be described because of its practical application.

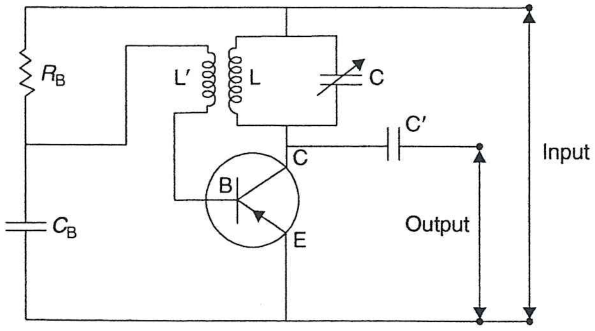
Basic theory

An *LC* parallel circuit in which inductive reactance equals capacitive reactance is resonant oscillatory, resonant frequency equals 1/2 π √*LC*, negligible supply current and appreciable loop current (for an *LC* series circuit maximum supply current at this frequency). In practice resistance is present and oscillations would diminish. If sufficient energy, correctly timed, is supplied to the *LC* circuit utilising a transistor to make up losses the oscillation can be maintained indefinitely. This energy is supplied as correct phase and magnitude positive feedback.

Referring to Figure 7.21, *LC* is the frequency determining tuned circuit and the remainder is oscillation maintaining. By mutual induction at *L′* positive feedback is arranged from the transistor.

Harmonic oscillators

An amplifier providing its own input functions as an oscillator and if the feedback is small is a pure sinewave generator. Typical refinements for high frequency harmonic work include Hartley and Colpitts oscillators. For lower frequency work in harmonic generation the principle is similar to that above but the feedback line includes resistors and capacitors. A three RC section input gives 180° phase shift and as a collector voltage in a transistor is 180° out of phase with base voltage this technique gives in

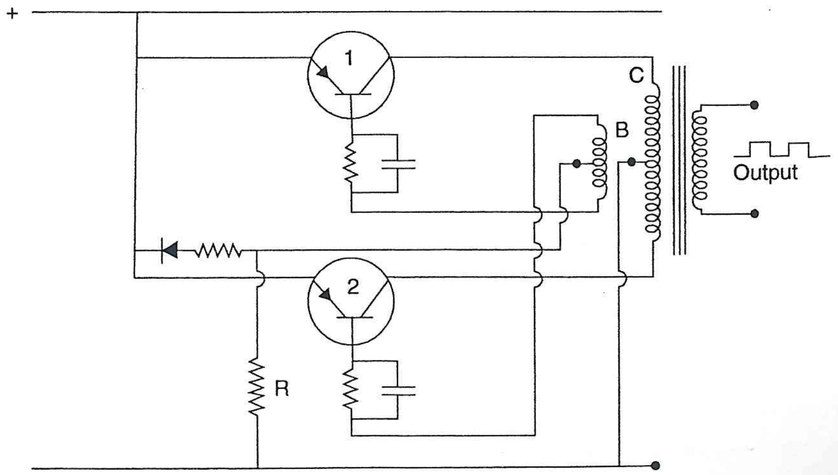


phase between the two. A phase shift oscillator or Wien bridge network is regularly used. Linear mode signal generators are of two types namely constant voltage which is a low impedance source and constant current which is a high impedance source.

Relaxation oscillators

Such oscillators are used in the non-linear mode where rapid switching of transistors from off to saturated (bottomed) is arranged. For sawtooth waveform a unijunction transistor, as previously described and illustrated in Figure 7.16, can be used. Alternatively a gas discharge tube with RC circuit is suitable usually with a thyratron (or thyristor) controlling time base strike voltage. A more sophisticated method is to use a single amplifier connected as an integrator (see Chapter 11). High current pulses of short duration can be obtained from a blocking oscillator.

For rectangular waveform generators a push–pull blocking oscillator can be used as shown in Figure 7.22. The transformer core material has a square form hysterisis loop. When the supply is switched on (high starting resistance *R*) assume transistor 1 starts conduction so that a voltage is developed across the collector winding (*C*) and induced across base winding (*B*). Polarity is such that 1 is forward and 2 reverse biased so that the positive feedback turns 1 full on and 2 is off. Collector current from 1 rapidly builds up and the core of *C* saturates and voltage collapses which cuts off base drive to 1 and collector current starts to fall. A voltage is now induced in B to try and maintain this current but reversed in sense; 2 is now biased on and 1 off and the half cycle is repeated.



Two state circuits, with abrupt transition from one state to the other, can be arranged with RC coupled amplifiers in place of the transformer coupling described. The basic circuit has the output of one transistor connected to the input of another and vice versa. Such devices are called free running (astable) multivibrators. If instead of two unstable states only one is arranged, the circuit is called a monostable triggered multivibrator or univibrator (flip-flop). The effect of a pulse is to flip the circuit into the unstable state whereupon normal multivibrator action allows flop back into the stable state. A flip-flop circuit is described in Chapter 16. Another method is to 'clip' sinusoidal waves using zener diodes. Power supplies often ± 6 V, that is, of this order of magnitude.

Other Devices

Electronic digital devices are greatly used in logic circuits and computing, typical applications are considered in Chapter 16. The speed of response and reliability of transistor switching greatly enhance its use in annunciator and control circuits.

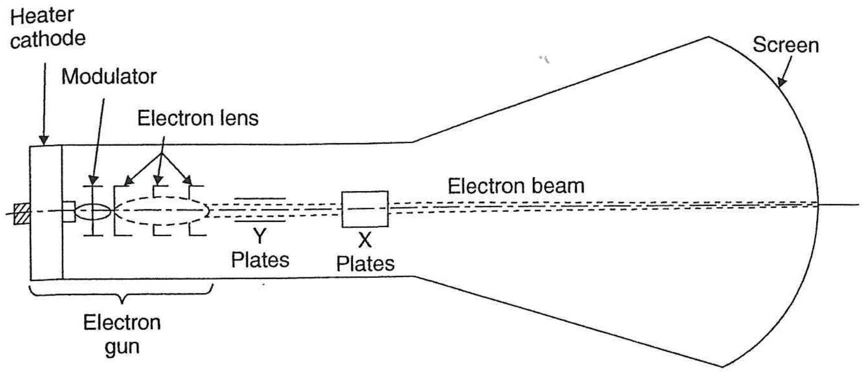
Certain specialist equipment, mainly used in analysis, such as ultra violet recorders, wave and transfer function analysers etc. is best described from specialist literature if required. Perhaps the most important in this respect is the oscilloscope, originally known as the cathode ray oscilloscope (CRO).

Oscilloscope

The oscilloscope is shown in Figure 7.23. The full circuit includes power supply packs and amplifiers. In addition a relaxation oscillator timebase (multivibrator saw tooth generator) is required.

In Figure 7.23, the electron beam from the gun is focussed on to a fluorescent screen and the glass tube is under high vacuum (pressure 10^{-6} mmHg). Input signals represented as voltages are connected to the Y plates and deflections produced are shown on the vertical axis of the screen. The timebase circuit is connected to the X plates and the beam is deflected horizontally from the left to right with uniform speed and then returned in almost zero time.

Although computer monitors are now used to perform many of the applications now associated with measurement of electrical waveforms the oscilloscope is still heavily



▲ **Figure 7.23** *Oscilloscope*

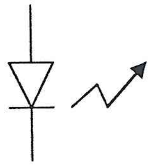
scopes have exceptional ability to detect spurious events and for some applications cathode ray devices are preferred for their inherent responsiveness.

Other applications in analysis are numerous. A relevant practical application of the scope is display of a pressure volume diagram from an IC engine. Screen scales can be calibrated directly in the required units and the application of integration gives power and torque characteristic on display.

Light emitting diode

The light emitting diode (LED) emits light when forward biased. Gallium arsenide gives out energy as infra red radiation; phosphides and indium give green and yellow. LEDs are well established as on-off or fault indicators and can be used in arrays, etc. Their low power consumption makes them ideal for intrinsic safety applications.

LED technology continues to develop. Blue and white LEDs are now established as options for low energy luminaries.



▲ **Figure 7.24** *LED*

Common applications in control are in optics whereby an electrical signal may be converted to light for signalling purposes. The common symbol for the LED is shown in Figure 7.24.

Photo-transistor

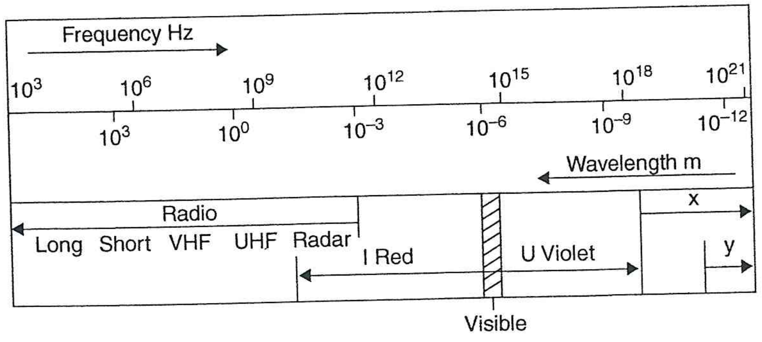
Photo-transistors have a base (or gate) connection which is light sensitive. The collector and emitter arrangement may be as for a bipolar device so that a light signal may be used to control electrical current. Photo-transistors and LEDs find extensive applications in digital transmission of data.

Opto-coupler

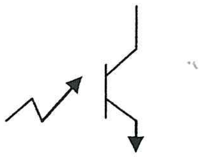
Multi-channel devices combining the properties of LEDs and photo-transistors are now used in digital instrumentation and control systems. They offer the benefit assisting separation between low energy signals and electrical interference often generated by electrical power systems.

Radio communication

The production, transmission and detection of sound or picture information is by electromagnetic waves – the range and spectrum of such radiation is given in Figure 7.26 (see also Figure 7.8).



▲ **Figure 7.25** *Photo-transistor*



▲ **Figure 7.26** *Electromagnetic radiation spectrum*

Fibre optics

Modulated emitted light (diode/laser) is pulsed at high frequency through optical glass fibre cable then converted to electrical signal. Advantages – easy multiplexing, no interference or hazards.

Test Examples

1. Explain why electronic devices are inherently suitable for display systems and generally unsuitable for actuating systems. Describe any method by which a small electrical signal may be amplified.
2. State the purpose served by transistors. Sketch the circuit diagram for an *npn* voltage amplifier. Explain the precautions which should be taken regarding care, handing and operating environment for transistorised devices.
3. Describe a halfwave rectifier. Sketch the output waveform: (i) without, (ii) with a capacitor across the purely resistive load terminals. What modifications are necessary to give fullwave rectification?
4. Draw a circuit diagram of a single-stage common emitter transistor amplifier. Indicate the type of transistor and the supply polarities. Give details of one cause of distortion that can arise in the circuit.

8

FINAL CONTROLLING ELEMENTS

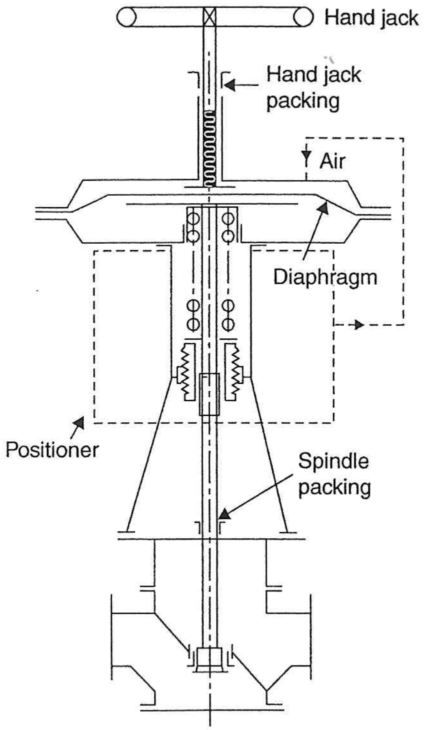
Final controlling elements act directly on the controlled body, process or machine. In a servo-mechanism this is a servo-motor, rectilinear or rotary, receiving amplifier output and driving the load. Correcting unit (motor and correcting element) is applicable to process control systems. An actuator is a motor with limited rotary or rectilinear motion.

Correcting Units

Such devices may be pneumatically, hydraulically or electrically operated or a combination and the word motor is applicable to all.

Diaphragm operated control valve

This unit, as described, is pneumatically operated and can be described in three parts: motor, valve and positioner. Figure 8.1 refers to a fuel variable but is applicable to any similar variable. Ring gland seals of Teflon, Neoprene bonding or aluminium foil



▲ **Figure 8.1** *Fuel oil control valve with positioner*

Motor element

Air pressure acts on top of a synthetic rubber diaphragm and is opposed by upward spring force, oil flow is right to left, hand regulation is possible and the fail-safe position is shut (up). The pressure-stroke characteristic is based on linear which requires a large constant area diaphragm, minimum friction and a linear spring force-deflection characteristic. A limited travel motor-actuator-*reverse* action.

Correcting element (valve)

The valve can be single seated reverse action as shown, or direct action single seated, or double seated (direct or reverse) which give balanced valve forces and less operating energy and are widely used. Materials for all components depend on the medium being controlled. The overall flow characteristic requires to be assessed for the piping system as a whole, as well as for the valve, to achieve design conditions. In general valves may be simplified into *three* types of variable % flow–% valve lift characteristics. Mitre valves with wings (bevel or poppet) usually give inverted near parabola characteristics best suited to on-off operation. Vee port (in wings) high lift or modified parabolic contoured valve plugs can be designed for proportional control. Characteristics are then a true linear relation between flow and valve travel for the former and near parabolic equal percentage, that is, equal increments of valve travel give equal percentage change in existing flow, for the latter. These three types are sometimes defined as quick opening, linear and semi-logarithmic.

$$\text{Turn Down Ratio} = \frac{\text{Maximum controllable flow \%}}{\text{Minimum controllable flow\%}}$$

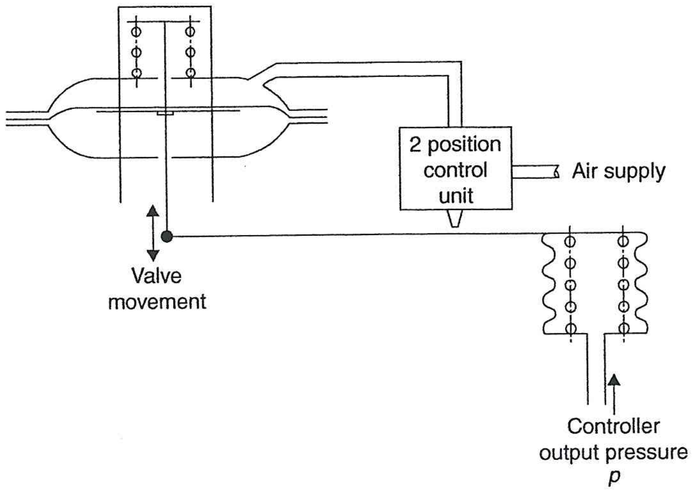
That is, each a percentage of the theoretical (100%) flow.

Positioner

Such devices are necessary when:

a. there is a high pressure drop across the valve,
b. the valve is remote from the controller,
c. the medium being controlled is viscous,
d. there are high gland pressures required.

Essentially each of the above effectively increase friction, hysteresis or unbalanced forces acting on the valve spindle. The positioner provides extra power to position the valve accurately and speedily to offset these effects (Figure 8.2).



▲ **Figure 8.2** *Valve positioner*

A motion feedback device from the valve spindle senses deviation between the desired value position input signal and the actual valve position and supplies extra correcting power. A flapper is connected at one end to the valve spindle and to a pressure bellows at the other, with the nozzle between the two. Increase of *p* increases pressure on the diaphragm until valve movement restores the flapper to the throttle position and equilibrium is restored. Further speed boost can be added, as shown, by inserting a pneumatic relay to apply full air pressure to the diaphragm. Both positioner and relay (as described in Chapter 10) act as pneumatic amplifiers. Valve positioners are very often used in sequence operation of valves in a system, that is, split range control (Chapter 13). Double seated valves (two inlets through ends, outlet at centre) are often used giving three way mixing and bypass arrangements on engine coolant systems.

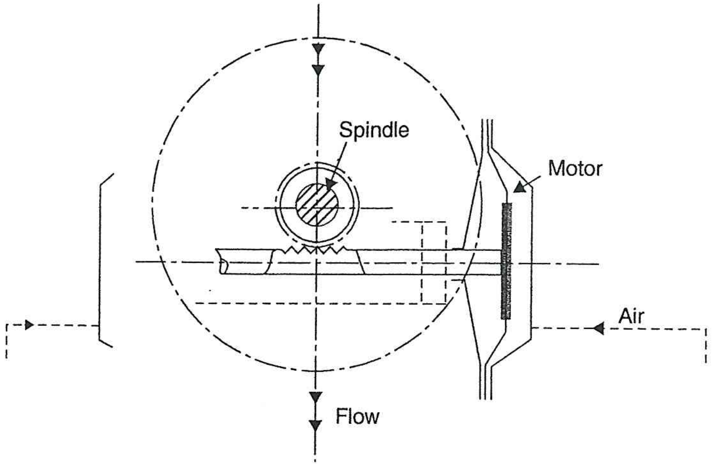
Piston operated control valve

Double seated valves with balanced valve forces are invariably utilised with diaphragm control valves because of the characteristics of this actuator. However the piston type actuator gives powerful valve forces, long stroke and accurate positioning so that single seated valves can be used which often have a more desirable flow pattern and require less maintenance. In the *direct* acting type a loading pressure on top of a piston (down force) is maintained constant (supply air via combined reducing-relief valve). Actuating air on the bottom of the piston (up force) is controlled in pressure by a small relay pilot valve, diaphragm operated from input signal, and connecting to supply (open up) or vent (close down).

Torque actuated control valve

There are two air motors, one for each direction of rotation of the valve spindle. Motors are transverse to spindle and rotate the spindle by a ratchet and toothed wheel. Motors are standard diaphragm or piston mechanisms. High torques for large valve forces can be achieved by multiple diaphragms or duplication of motors. A diagrammatic sketch is shown in Figure 8.3.

An alternative design utilises electric motor gear drive to the spindle by a similar arrangement. The motor must be reversible, variable speed and fitted with limit switches.



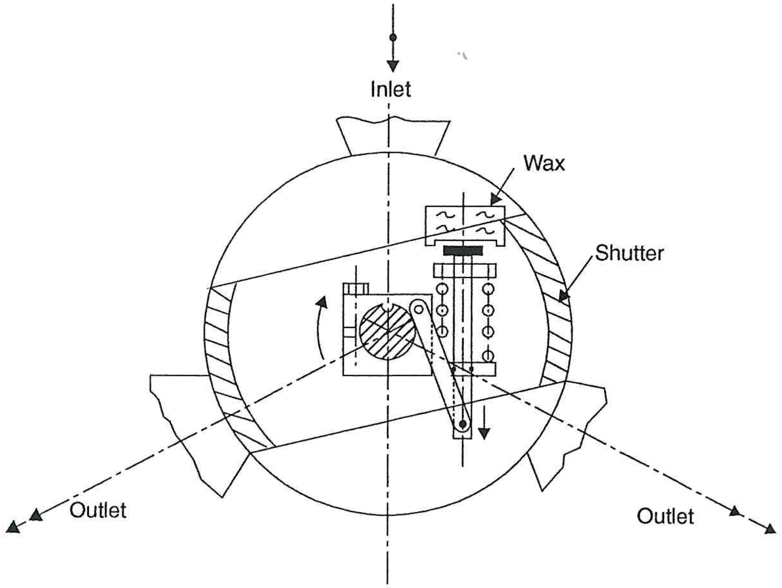
▲ **Figure 8.3** *Torque actuated valve*

Rotary cylinder control valve

The valve consists of a semi-rotary shutter operating in the square throat section of the valve passage. Operating torque is transmitted to the shutter gate via a spindle perpendicular to flow direction. The 'swing through' design of butterfly valve requires a good spindle seal and tight shut off is best arranged by closure of shutter against a flexible disc. Such valves are best suited to throttling operation between about 15° and 60° for reasonable turn down ratios. Torque requirement is not high and linear actuators of any design are suitable. It is characterised by equal % flow.

Wax element temperature control valve

This type has a copper capsule containing wax whose expansion varies with temperature. Movement is transmitted via a diaphragm, plunger and linkage to vary the position of a shutter which rotates in the valve body. The valve is best suited to mixing or bypass conditions, control normally being limited to a range of temperature of about 10°C, fail-safe inherent in design. While the self-contained simple design is attractive for many duties it is a fixed control. Figure 8.4 is a diagrammatic representation. Temperature rise causing down-movement of the plunger, clockwise rotation, closing right and opening left outlet connection. The basic three-port valve body can be designed with the shutter operated by an external pneumatic cylinder operated from a remote pressure



▲ **Figure 8.4** *Wax element actuated valve*

Servo-Motors

May be rectilinear or rotary; operated by air, fluid or electricity; applied in either process or kinetic control systems.

Electric motors dc

Essentially the servo-motor is a conventional motor, series, shunt or compound, with control of field current or armature voltage by the controlling device. High torque and low inertia is required so that armatures are reduced in diameter and lengthened. Good commutation over a wide range of speeds is necessary and design must allow for peak transient changes. Performance is limited by heating caused by high armature currents and magnetic saturation of iron paths. Reversal is arranged by reversing the current through the field or armature via the controlling device, which is generally satisfactory, although split field motors can be used.

Electric motors ac

The three-phase cage rotor induction motor is a desirable machine in electrical work, being low cost, robust and reliable. Unfortunately starting torque is low and the torque-speed characteristic is non-linear so that control is difficult. Through most of the twentieth century for servo use the torque characteristic had to be improved by using high resistance rotors which unfortunately generate extra heat and cost. Commutator motors are available but add to complexity and cost. However, toward the end of the century variable frequency (and voltage) drives based on thyristor and then transistor systems became commercially viable.

The two-phase induction motor is used in low power systems especially for position control. Applications include instrument potentiometers, bridges and pen recorders. Such a motor has two stator coils wound at right angles, which are fed with alternating currents 90° out of phase, to produce the rotating magnetic field. For reasonable modulation, torque is proportional to the two currents. If a fixed voltage and frequency is applied to one reference winding, then torque is proportional to the voltage of the other winding, which is connected to represent the amplitude of the control signal. Characteristics, especially with a high resistance rotor, are reasonably linear over a limited range. Heat generation at reference field and rotor are high.

Single-phase motors for servo systems are unsatisfactory except for on-off control and special starting arrangements, such as split phase, are required.

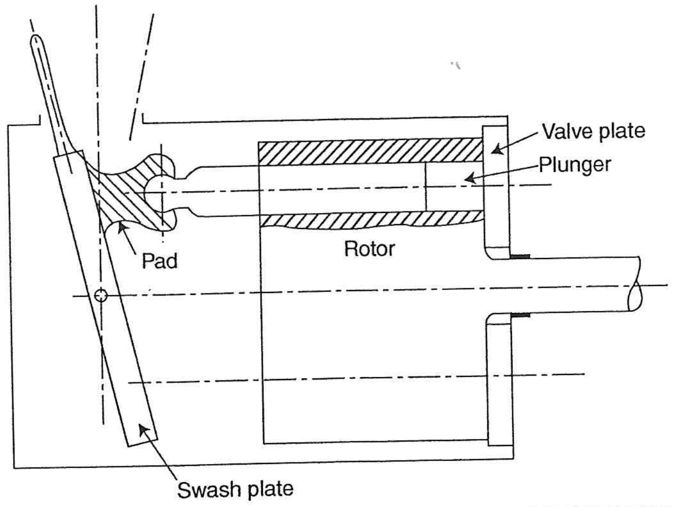
Synchronous motors can be used for low power drives such as pen recorders, etc. where synchronism of timing is required.

Hydraulic ram servo

Used for linear actuation, that is, ram or jack type, but can be utilised as a torque device with multiple rams. Generally a medium control performance system used in position devices. Normally short stroke but can operate with long stroke and high pressures (ship steering gear). There is little in the construction calling for special attention.

Hydraulic variable delivery pump

Not strictly a final controlling element but has important applications in hydraulic



▲ **Figure 8.5** *Variable delivery pump*

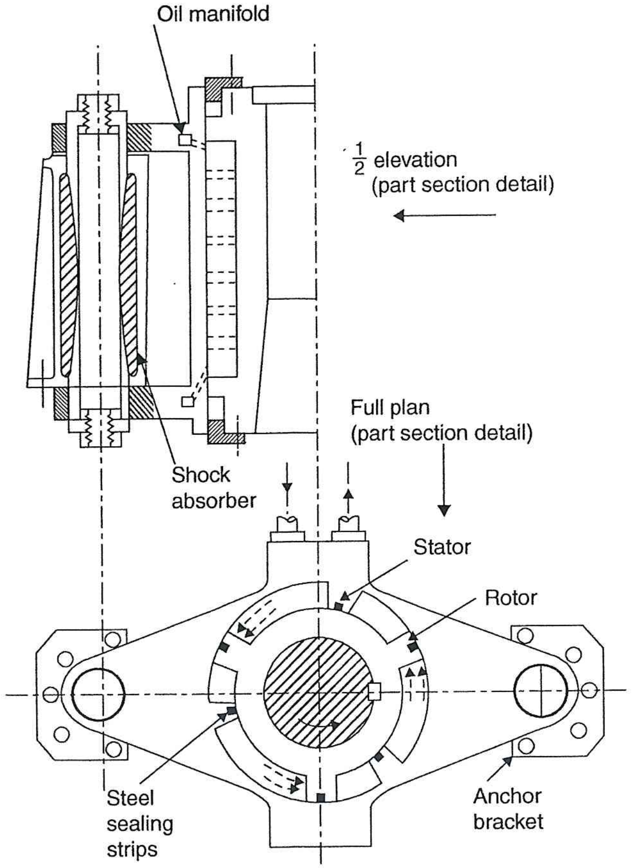
trunnion, cam operated ball piston, etc. The hydraulic motor is virtually a reverse pump and has similar construction. Consider Figure 8.5 illustrating the swash plate type.

Slipper pads bear against the swash plate face and plungers are driven in and out axially for each revolution of the rotor. The swash plate movement varies effective stroke and can reverse the flow. A number of axial plungers are used in the rotor. Delivery can be to an identical motor with fixed swash plate.

Other types, particularly using a booster supply pump, have a similar design and can give discharge pressures over 140 bar. Higher pressures give smaller components and very positive action.

Hydraulic rotary vane servo

Details are as sketched in Figure 8.6. Rotation depends on which side of the vane is connected to the pump pressure feed, this should be clear from the plan view as sketched. The large rotary vane unit is normally designed for a maximum pressure of about 90 bar as distortion and leakage are liable to occur at higher pressures. The design is simple and effective. In fact the apparent space and weight saving is not as great as may be imagined due to the higher pressures and integrated construction utilised in modern hydraulic ram designs. There is, however, a definite space saving but the first cost is higher. Absorption and transmission of torque relief is essential to avoid excess radial loading of vanes. The three-vane type is used for rudder angles to

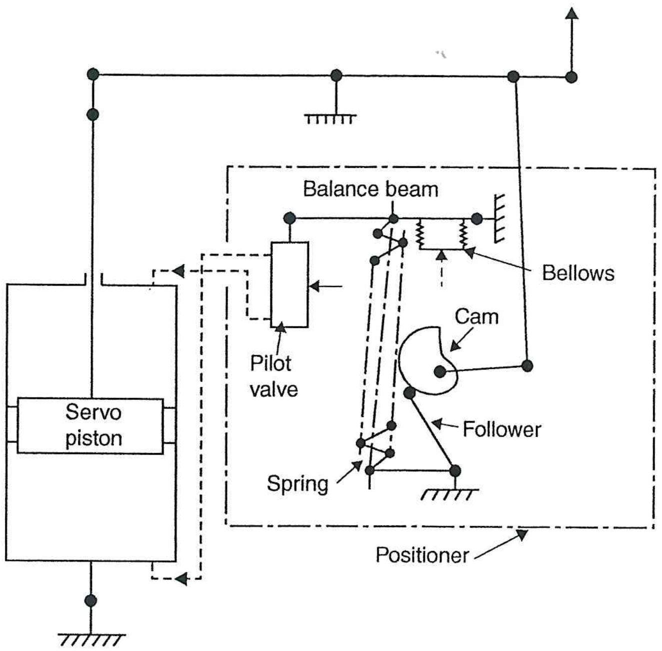


▲ **Figure 8.6** *Hydraulic rotary vane servo*

Pneumatic piston servo

Refer to Figure 8.7. The pilot valve has two outlets, one to the top and one to the bottom of the servo-piston. If the valve is displaced from its neutral position then pressure at one port increases while at the other port it decreases, so causing piston movement. The movement of the piston is arranged, via linkage gear and cam, to vary the tension on a spring giving an opposing moment to the signal pressure on the bellows. When these two moments balance the pilot valve is at middle or neutral position and the pressures on each side of the servo-piston balance, thus locking the piston.

(In the case of a diaphragm valve the pilot valve would only have one outlet to the diaphragm top, the valve stem movement via the gear linkage and cam would alter the



▲ **Figure 8.7** *Pneumatic piston servo and positioner*

the bellows causing the balance beam to pivot about the right-hand end and operate the pilot valve. This produces a second air signal whose relationship to the first signal is dependent on the tension in the spring attached to the beam end point.

The mechanical movement of the valve, or other control device being operated, is transmitted by a driving rod to the cam and linkage, thereby adjusting the tension in the spring. By using a suitably shaped cam the position of the regulating unit to which the positioner is attached may be given a predetermined relationship with the incoming air signal.

1/120 bar change in signal pressure will give full travel to the pilot valve which could give 1 1/3 bar variation in output pressure.

Other servo-motors

Variable couplings and clutches can be used, either hydraulic or electric, for rotary speed control. Electromagnetic solenoid devices, linear and rotary, are available for many purposes including electrical contact and relay operation and incremental digital

Test Examples

1. Make a detailed sketch of a simple diaphragm-operated control valve, such as a reducing valve, although any other type of a similar control valve will be accepted. Analyse the action of the interconnecting elements, that is, those parts affecting control. Explain how load changes are sensed and the command signals are transmitted to the actuator.
2. An air damper is controlled in position by variable air pressure to a pneumatic actuator. Sketch and describe the system, describe the actuator and explain its mode of operation.
3. Sketch and describe a control valve of the wax element type and show how it is incorporated into a coolant system.
4. With the aid of simple sketches explain briefly what is meant by:
    - (i) a direct-acting diaphragm-operated valve;
    - (ii) a reverse-acting diaphragm-operated valve;
    - (iii) a linear characteristic valve;
    - (iv) an equal percentage characteristic valve.

    Make a diagrammatic sketch of a valve positioner and explain its action.

9

PROCESS CONTROL THEORY

Terminology

The following definitions should be considered in relation to Figure 9.1, which refers to the loop system. Other definitions of terms are given at the appropriate place in the text to cover and clarify essential points. Process control is concerned with physical quantities involving variables such as temperature, pressure, flow, level, etc.

Accuracy

Accuracy is the conformity of an indicated value to an accepted standard value, or true value. It is usually measured in terms of inaccuracy and expressed as accuracy.

It is a number or quantity which defines the limit that errors will not exceed, when the device is used under reference operating conditions. The units to be used must be stated explicitly. Typically a + and – sign precede the number or quantity. The absence of a sign infers both signs (±).

Accuracy can be expressed in a number of forms:

Accuracy expressed in percentage of span, for example, ±1.5%.

Accuracy expressed in terms of the measured variable units, for example, ±1°C.

Accuracy expressed in percentage of the maximum range value.

Accuracy expressed in percentage of actual reading.

Accuracy for a system with three elements:

A sensor with an accuracy of 1%.

A transmitter with an accuracy of 0.5%.

An indicator with an accuracy of 1%.

Absolute accuracy: + or −1 + or −0.5+ or −1 = + or −2.5%.

Most likely accuracy (Root Mean Square) = SQRT[(±1)2 ±(0.5)2±(1)2] = 1.5%.

Ambient

This is the surrounding environment with reference to the subject.

Attenuation

Attenuation is a decrease in signal magnitude over a period of time.

Automatic controller (*Automatic regulator*)

A portion of an automatic controlling or regulating system in which a signal representing the controlled condition is compared with a signal representing the command signal and which operates in such a way as to reduce the deviation.

Note. The two functions of an automatic controller or regulator, namely to determine the deviation and to generate the control signal dependent on the deviation, are in many devices carried out by two separate parts, the comparing element and the controlling element respectively.

Calibration

The procedure of comparing and determining the performance accuracy is called calibration. To configure a device so that the required output represents (to a defined degree of accuracy) the respective input.

Cascade control system

A control system in which one controller provides the command signal to one or more other controllers.

Closed loop

Relates to a control loop where the process variable is used to calculate the controller output. In a closed loop system the control action is independent of desired output.

Controller

This is a device which operates automatically to regulate the control of a process with a control variable.

Control system

An arrangement of elements (amplifiers, converters, human operators, etc.) interconnected and interacting in such a way as to maintain or affect, in a prescribed manner, some condition of a body, process or machine which forms part of the system.

Command signal

The quantity or signal which is set or varied by some device or human agent external to and independent of the control system and which is intended to determine the value of the controlled condition. Symbol γ_i.

Converted command signal

A physical quantity related only to the command signal, and normally proportional to it, but of a different physical kind suitable for operating the comparing element or the coordinating element. Symbol θ_i.

Note. In definitions where there is no ambiguity the term 'command signal' will be used to imply the command signal itself or the converted command signal.

Comparing element

The element which accepts, in physically similar form, the command signal and the controlled condition, or their equivalents, and determines the deviation or the converted deviation.

Converted deviation

A physical quantity related only to the deviation, and normally proportional to it, but of a different physical kind suitable for operating the amplifier element. It may also be used for operating other elements in the system. Symbol $\theta = \theta_0 - \theta_i$.

Author's note: Often written as $\theta = \theta_i - \theta_o$, $\gamma = \gamma_i - \gamma_0$.

Controlled condition

The physical quantity or condition of the controlled body, process or machine which it is the purpose of the system to control. Symbol γ_0.

Converted controlled condition

A physical quantity related only to the controlled condition and normally proportional to it, but of a different physical kind suitable for operating the comparing element or the co-ordinating element. Symbol θ_0.

Note. In definitions where there is no ambiguity the term controlled condition will be used to imply the controlled condition itself or the converted controlled condition.

Correcting unit

Of a process control system. The single unit containing the motor element and correcting element in a process control system.

Correcting element

The final controlling element in a process control system.

Dead time

The time interval between a change in a signal and the initiation of a perceptible response to that change (a dead band region may exist on a controller).

Desired value

The value of the controlled condition which the operator desires to obtain.

Detecting element

The element which responds directly to the value of the controlled condition.

Deviation

The difference between the measured value of the controlled condition and the command signal. Symbol $\gamma = \gamma_0 - \gamma_i$.

Distance velocity lag

That time interval between an alteration in the value of a signal and its manifestation unchanged at a later stage arising solely from the finite speed of propagation of the signal.

For example, the time it takes for a heating effect to travel with the fluid from heat source to detection element along a lagged pipeline. Lag = Distance/Velocity. Causes phase lag. Theoretically no magnitude change.

Error (absolute)

Algebraic difference between the indication and the true value of a quantity to be measured. Absolute error = indication − true value. $\Delta X = X' - X$.

Input element

The element which is included, when necessary, to convert the actual command signal into a converted command signal suitable for operating the comparing element.

Note. In some systems there is no input element as the command signal is taken, without conversion, direct to the comparing element.

Load

The rate at which material or energy is fed into, or removed from, the plant (*on a process control or regulating system*). (1) The controlled device. (2) The properties (e.g. inertia, friction) of the controlled device that affect the operation of the system (*of a kinetic control system*).

Measuring element

The element which responds to the signal from the detecting element and gives a signal representing the controlled condition.

Measuring unit

A unit which gives a signal representing the controlled condition. It comprises a detecting element and measuring element.

Note. Such a unit is used as the monitoring element of a process control system.

Measured variable

Monitoring feedback

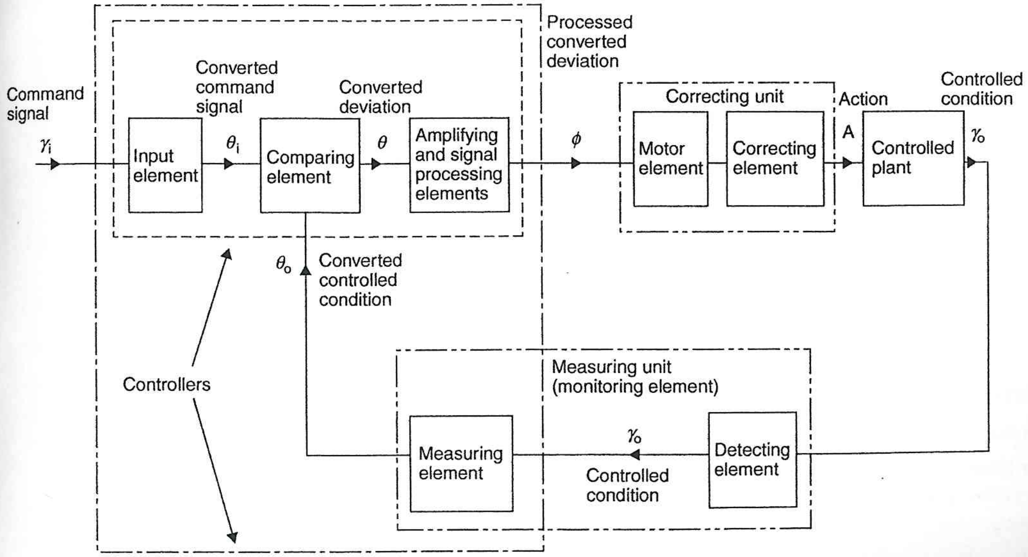
The feedback of a signal representing the controlled condition along a separate path provided for that purpose, for comparison with a signal representing the command signal to form a signal representing the deviation (see Figure 9.1).

Motor element

The element which adjusts the correcting element in response to a signal from an automatic controller.

Offset (*droop*)

Sustained deviation.



▲ **Figure 9.1** *Simple automatic control system showing some combinations of elements*

Overshoot

The difference between the maximum instantaneous value of the step function response and its steady state value.

Process

The act of physically or chemically changing, including combining, matter or of converting energy.

Process control system

A control system which is used to control some physical quantity or condition of a process.

Set value (*set point*)

This is the command signal to a process system.

Settling time

The time taken to approach a final steady state within specified limits.

Note. The settling time depends on the limits specified and is meaningless unless these limits are specified.

Example. In the particular case of a series LR circuit subject to a step function of voltage, the settling time of the current to within 1% of its final value is approximately five times the time constant L/R.

Signal processing

The processing of the information contained in a signal by modulating, demodulating

Transfer lag

That part of the transmission characteristic, exclusive of distance-velocity lag, which modifies the time-amplitude relationship of a signal and thus delays the full manifestation of its influence.

For example the measure lag for the detection element, which is dependent on *R* and *C*, causes phase lag and reduces amplitude.

The aim is to keep inherent lags as small as possible, together with reducing inertia and increasing stiffness (or their equivalents) for the system. The alternative is to increase system gain but this can create instability.

Response of Detection Elements

Time lags obviously occur in a plant due to the individual lags of components and transmission of signal lags. The lags must be fully evaluated before the control design can be established. As an illustration the lag of a temperature detector element can be considered:

Consider a detector element which is directly inserted in a pipeline. The fluid flowing increases in temperature at a uniform rate of say 10°C in 1 min.

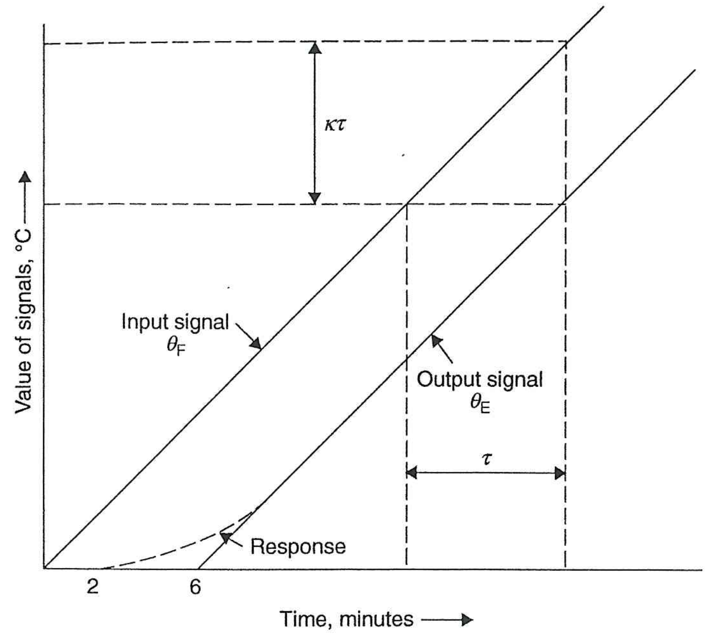
Refer to Figure 9.2. The first indication of temperature change at the detector element may be after about say 2 min and there may be a constant lag at a given reading of about 6 min (ramp input).

If θ_F is the fluid temperature and θ_E is the element temperature:

$$\theta_F - \theta_E \, \alpha C_E R_F$$

C_E is thermal capacity of element (mass times specific heat), R_F is liquid to element thermal resistance to heat flow

$$\theta_F - \theta_E = kC_E R_F$$



▲ **Figure 9.2** *Linear response of detector element*

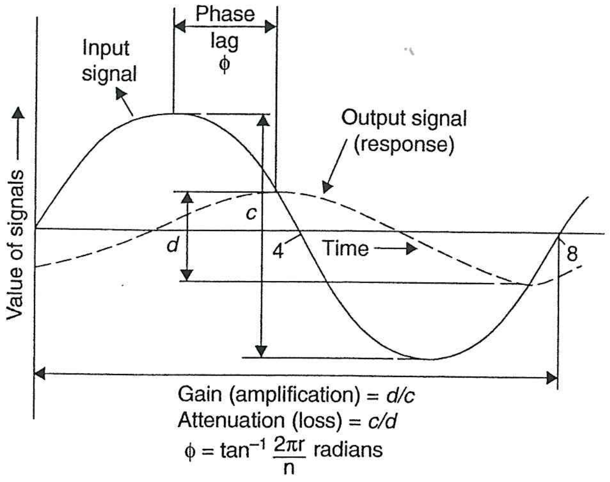
Measuring lag is $\theta_F - \theta_E$ (say °C), C_E R_F *is* the time constant τ (say minutes)

$$\theta_F - \theta_E = k\tau$$

This lag consideration is based on linear variation: if the variation was exponential then the measure lag is usually arbitrarily defined in terms of the time it takes for the output signal amplitude to reach 63.2% of the input signal amplitude. The lag time on the sketch is given in minutes but should preferably be reduced to seconds in practice. Figure 9.2 assumes fairly heavily damped response. Under-damped response would show in oscillation curves about the line θ_E.

If the disturbance causing the variation is a continuous sine form variation the appearance would be as in Figure 9.3, note that the response has a reduced amplitude and has a phase lag. τ is the time lag of detecting element, *n* is the period of process disturbance, attenuation applies as gain is less than unity.

Considering the case of a temperature detector element in a pocket then to reduce lags the time constant (CR) must be reduced to give quick response and the following would be aimed at:



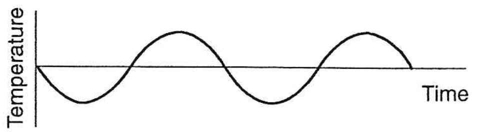
▲ **Figure 9.3** *Steady state response to sinusoidal signal*

1. A close fitting thermometer in a pocket with immersion in a high conductivity fluid.
2. Clean fittings and a high velocity for the fluid to be measured (turbulent flow).
3. Light, good conductivity pocket material using deep immersion into the flow of fluid.
4. Reduced piping distances, friction and inertia effects.

Types of control action

Can be illustrated by any variable; level is selected for this chapter.

Two-step controller action (on/off control)



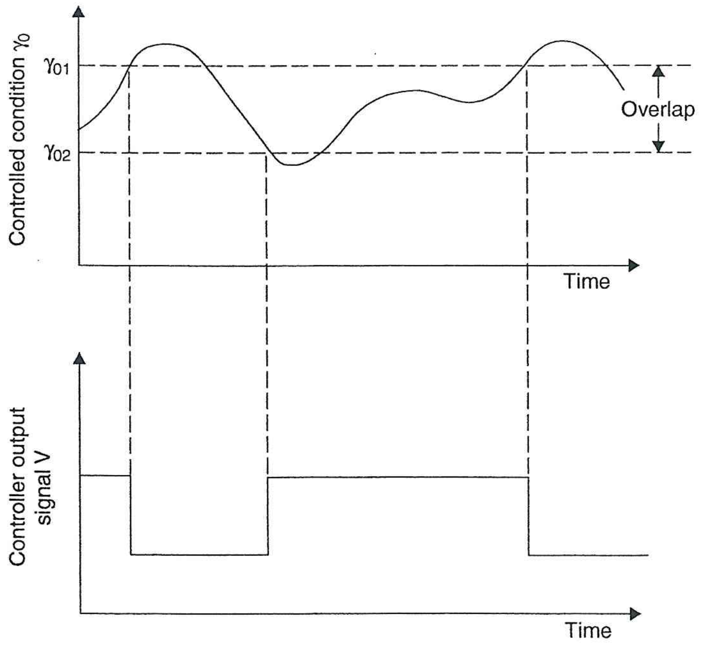
This is the action of a controller whose output signal changes from one predetermined value to another when the deviation changes sign.

It should be noted that the limits are not necessarily on-off although this is often used (see Figure 9.4), especially in digital systems (Chapter 16).

A typical example of two-step controller action would be liquid-level control in a tank with a varying supply and a required continuous and steady outflow. Overlap, which could be adjustable, allows working between predetermined limits (differential gap or overlap) and gives less irregular action; this would be suitable, as another example, for refrigeration motor cut in and out control by room temperature.

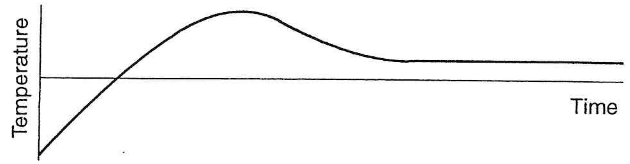
Lag tends to allow overshoot and this should normally be reduced to reasonable limits. The closeness of control is influenced by the capacity of the system and also that property of an uncontrolled system to reach equilibrium for a fixed set of conditions (inherent regulation).

Such action of two-step control is a simple but most useful method with numerous applications in practice. By arranging more chosen values and corresponding correcting signal steps the control can be made much closer with less overshoot, this method is termed multi-step controller action.



▲ **Figure 9.4** *The action of a two-step controller with overlap*

Proportional control action (*P*)



The action of a controller whose output signal V (or Φ) is proportionate to the deviation θ.

θ is the difference between the measured value of the controlled condition θ_0 and the command signal θ_i.

$$V \alpha -\theta$$
$$V = -K_1\theta$$

The negative sign denotes that the correction signal is opposite in direction to the deviation. K_1 a constant depending on the *controller characteristic* is called the proportional action factor.

Potential correction Φ (*change* of *actual* controlled condition γ_0) is proportional to the movement of the correcting unit (which depends on V).

$$\Phi \alpha V$$
$$\Phi = C_1 V$$

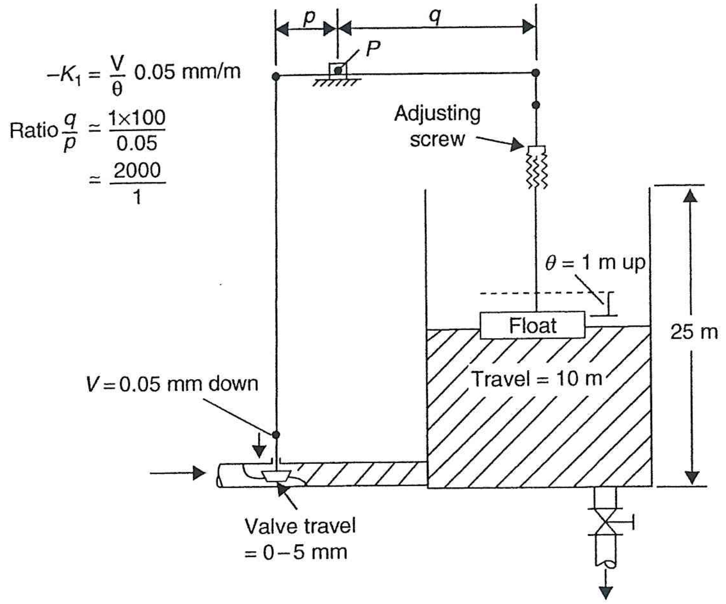
where C_1 is a constant depending on the *correcting unit characteristic.*

Now

$$V = -K_1\theta$$
$$\Phi = -K_1 C_1 \theta$$
$$\Phi = -\mu\theta$$

$\mu = \Phi/\theta$ and is numerically the proportional control factor, or simply the controller gain, a typical value, in pneumatics, may be about 15.

Referring to Figure 9.5 and assuming linear characteristics, it is desired to maintain a fixed height h in the tank while the outflow demand varies. As this is self operating



▲ **Figure 9.5** *Liquid level control by self-operating controller*

If h is set for 10 m, assume the valve is then 0.25 mm from the seat, K_1 = 0.05 mm/m (decided by leverage), then if h increases to 11 m the valve movement to shut in is 0.05 (11 − 10) = 0.05 mm, that is, the new valve position is 0.3 mm from the seat. There is no controller gain here, much the *reverse* in fact.

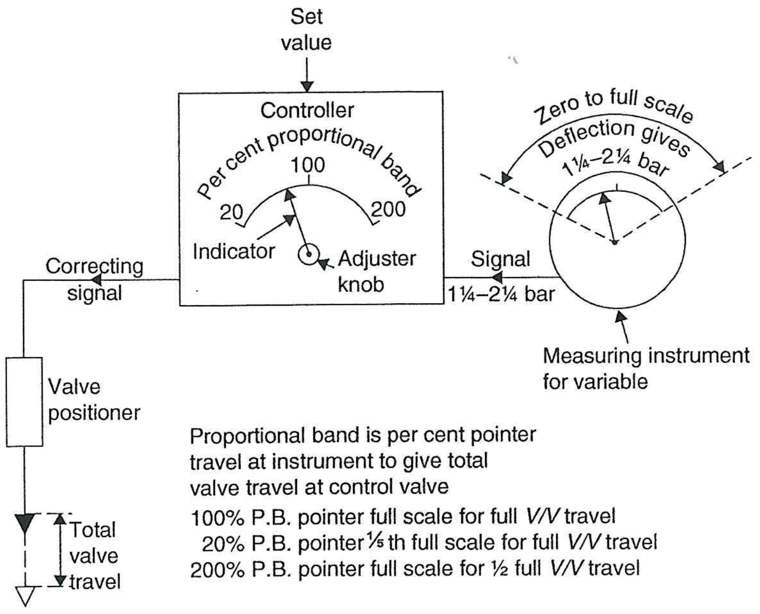
Proportional band

That range of values of deviation corresponding to the full operating range of output signal of the controlling unit, from proportional action only.

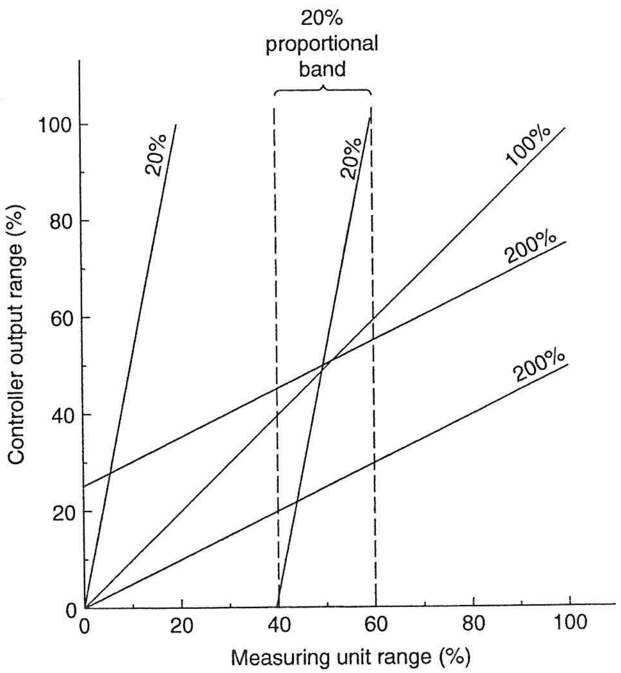
This band can be expressed as a percentage of the range of values of the controlled condition which the measuring unit of the controller is designed to measure (see Figures 9.6 and 9.7).

$$\text{Proportional band} = \frac{(\text{Total valve span})}{(\text{Total measure span}) \times K_1} \times 100$$

For the example for the given level controller, if the full measurement scale is from 0 to 20 m head, that is, 100%, and the full valve stroke is 0.5 mm, that is, 100% then 10 m fully strokes the valve (i.e. 0.05 × 10 = 0.5).



▲ **Figure 9.6** *Proportional band (not to scale)*



▲ **Figure 9.7** *Proportional band*

Alternatively:

$$\text{Proportional band} = \frac{0.5}{0.05 \times 20} \times 100 = 50\%$$

If the proportional bandwidth is narrow then a big controlling movement is required for a small deviation, and the control is sensitive, that is, high value of K_1 and a small offset results (see later). Too narrow a proportional bandwidth can however cause instability and hunting. The practical result is a compromise, the set value must of course be within the band.

Note: For good control the following are essential.

1. A high deviation reduction factor (hence high μ), that is, small deviation from set value after a disturbance. High μ, means high K_1 highly sensitive, narrow proportional band, etc.
2. Minimum offset.
3. Low value of subsidence ratio at short oscillating period, that is, quick return to set value after a disturbance.

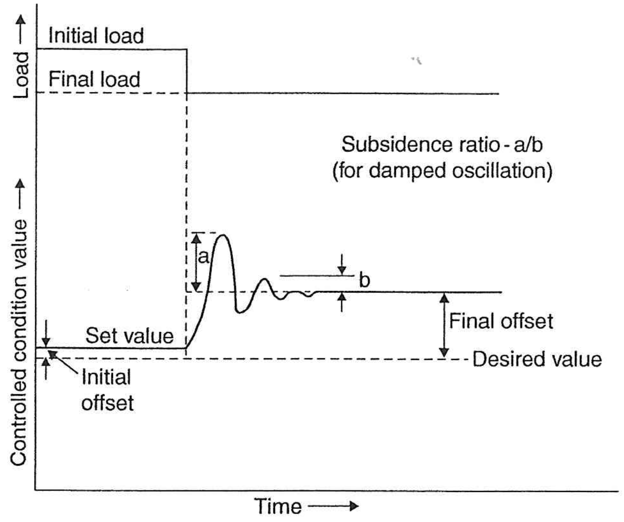
These are achieved by plant analysis. Widening a proportional band causes an increase of offset, of damping and of period of oscillation.

Offset

This is the sustained deviation due to an inherent characteristic of proportional control action. (It should be noted that with all proportional controllers the *set value* differs from the *desired value* by varying amounts depending on the given load conditions.) If K_1 is large, for a given deviation, the offset will be small; K_1 is dependent on the proportional band of the controller (see Figure 9.8). Consider the following analogy (as shown in Figure 10.4).

A spring hanging from a support, with a mass of say 10 kg on the end, will have a certain extension and the mass will be at a certain vertical position *X*. If the mass is pulled down and released it will oscillate but will finally return to *X*. This is an example of proportional action in that the spring restoring force is proportional to the extension (also opposite in direction). The desired value position *X* is always reached.

Now if the mass is changed to say 20 kg, then after oscillation it *will not* return to *X* but *will* return to a new position of equilibrium *Y*. Offset will be the difference between the

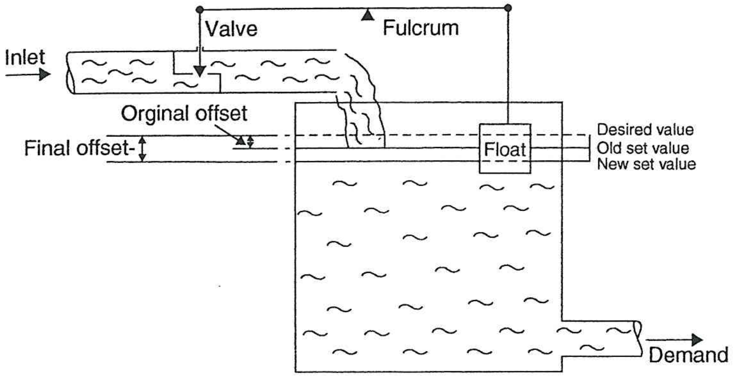


▲ **Figure 9.8** *Proportional controller action*

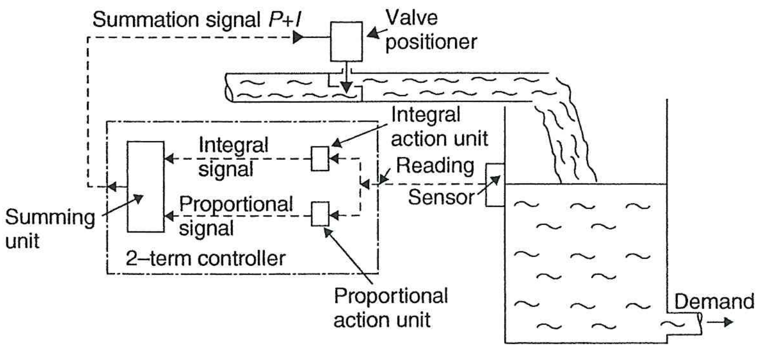
This means, with proportional control, where a set value (the command signal to a process control system) at a given load occurs it will *only give coincidence with the desired value at that load.* At any other load offset exists. If this offset is acceptable to a plant the proportional controller is satisfactory. If the offset is too great additional refinements have to be incorporated into the controller (see Figures 9.10, 9.11 and integral action later). *In many cases of practical description in this book and elsewhere, for simplicity, desired value, set value or set point, etc., are all used for the same thing and no distinction is made on a fine point of principle.*

Figure 9.9 illustrates another analogy using level control, that is, equilibrium before and after a demand change with two different heads and valve settings.

Example of a *human control loop*. A man regulates the water inlet valve to a tank to maintain gauge level with variable outflow demand. He is told the level required (desired value), will see the level (measured value), after a change will compare the two and decide on adjustment (correcting action), and finally there is amplification for muscle action to operate the valve (correcting element). Proportional control will arrest the change and hold it steady but at a point different from the original set value due to the load change. The human operator would bring the level back to the desired value after arresting the level, that is, he would apply re-set (integral) action to remove offset. Overshoot would not occur because the operator would not, while adjusting for offset, go on altering the valve right up until offset was gone. He would ease down valve adjustment rate as desired value was approached, that is, *apply a damping action,*



▲ **Figure 9.9** *Simple proportional action control loop*



▲ **Figure 9.10** *Proportional plus integral control loop*

Integral control action (*I*)

This is the action of a controller whose output signal changes at a rate which is proportional to the deviation.

Note: The object of integral control action is to reduce offset to zero.

$$\frac{dV}{dt} \propto -\theta$$

by the definition given above *dt*

$$\frac{dV}{} = -K_2\theta$$

K_2 is called the integral action factor.

$$\Phi = C_1 V$$
$$\Phi = -C_1 K_2 \int \theta dt$$
$$\Phi = -p \int \theta dt$$

ρ is called the integral control factor.

Thus the potential correction Φ at a given time *t* is proportional to the area between the desired and recorded values ${}_0\int^1 \theta dt$ is a mathematical way of writing that area. Rate of change of potential correction with respect to time is proportional to the deviation {*$d\Phi/dt$ expresses mathematically rate of change of Φ with respect to t*}.

Now

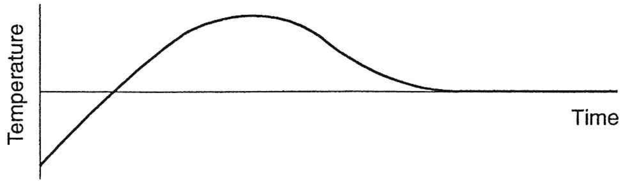
$$\mu = C_1 K_1$$
$$\rho = C_1 K_2$$

and

$$\therefore \frac{K_1}{K_2} = \frac{\mu}{\rho} = S$$

Integral action time (*S*)

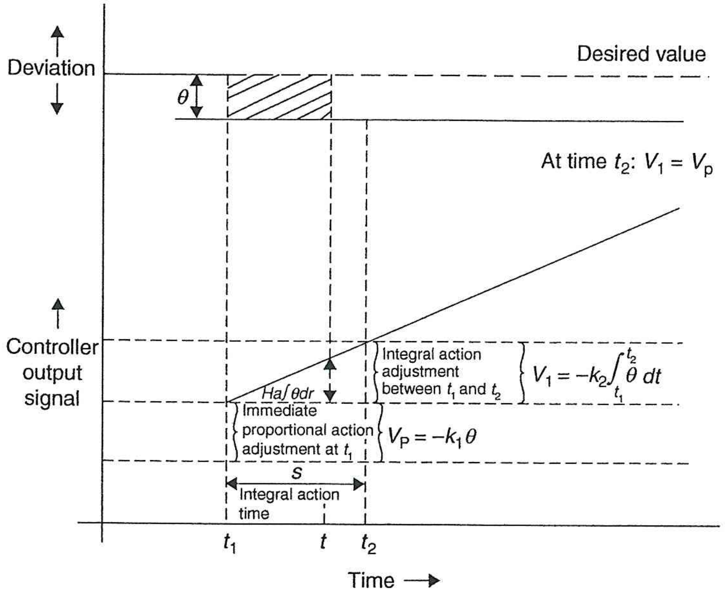
By definition: In a controller having proportional plus integral action, the time interval in which the part of the output signal due to integral action increases by an amount equal to the part of the output signal due to proportional action, when the deviation is unchanging.



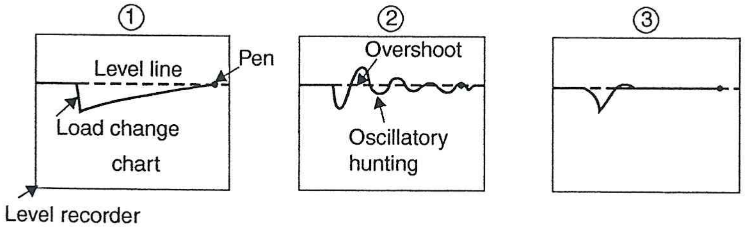
After time *S* then $V_p = V_1$ and the controller output change equals $2V_p$. Note that $S = \mu/\rho$, that is, integral action reduces controller gain. The *larger* the *S* time setting the

Figure 9.11 is given assuming an instantaneous deviation change. This change is referred to as *step function input.* Deviation under proportional action alone would constantly increase, giving bigger offset, but the addition of integral action maintains a constant deviation.

A *more likely* short-term action would give integral action until deviation ceased, that is, no offset. Integral action reduces a previously fixed controller gain μ and introduces extra lag, so is undesirable, it should not be used unless the use of a wide proportional band gives too big offsets. See Figure 9.12.



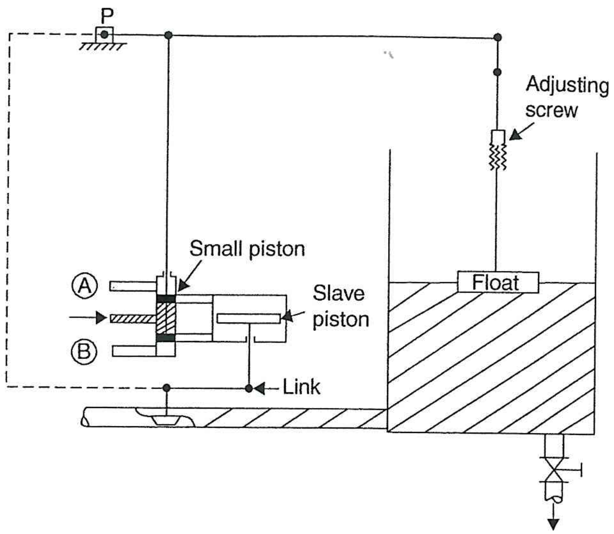
▲ **Figure 9.11** *Proportional and integral controller action*



Too little integral action effect, i.e. reset takes a long time

Too much integral action effect, i.e. overshoot and long time to damp out

Correction integral action effect, i.e. verv slight overshoot and quick damping



▲ **Figure 9.13** *Integral action on liquid-level control*

Referring to Figure 9.13. If the level rises, the small piston moves up and high-pressure fluid flows through the top port and returns through port B, this action via the link closes the valve to reduce the inflow. This movement will always continue as long as a deviation exists and the rate of travel depends on the area of the top port opening, which is proportional to the deviation. Conversely fall in level causes oil to flow in at the bottom port and return through port A. The only time the valve is not moving is at the desired value, offset will never be possible.

Note: Proportional plus integral ($P + I$) can be applied by including the link shown dotted in Figure 9.13. For a rising float, above set point, both act in the same direction downwards to close the valve, pivot P can be moved to vary the individual actions. For a falling float *above* set point the actions are in opposition. For a falling float *below* set point both act to open the valve. Integral action *always* tends to reduce offset. Integral action is *not* used alone; if it was the characteristic would be similar to two-step action. Note the use here of a hydraulic controller (small and slave piston) for the integral action itself. Proportionally controlled first-order open loop systems, with an inherent integration characteristic (e.g. shaped lavatory cisterns), respond exponentially to a stop function when the loop is closed.

Derivative control action (D) (Basic action 4)

Note: The object of derivative control action is to give quicker response and supplement inadequate proportional control damping.

$$V \propto -\frac{d\theta}{dt} \quad \text{by definition above}$$

$$V = -K_a \frac{d\theta}{dt}$$

K_3 is called the derivative action factor.

$$\Phi = C_1 V$$

$$\Phi = -C_1 K_3 \frac{d\theta}{dt}$$

$$\Phi = -\eta \frac{d\theta}{dt}$$

η is called the derivative control factor.

Now

$$\mu = C_1 K_1$$

$$\eta = C_1 K_a$$

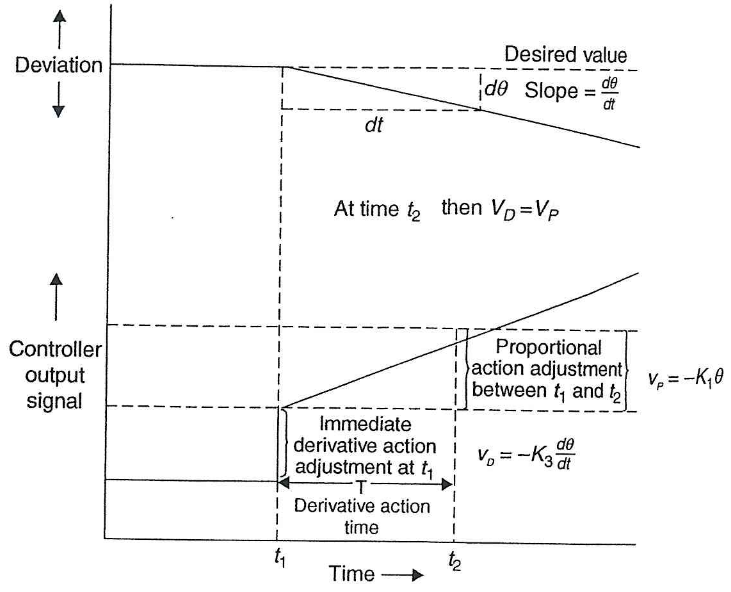
$$\therefore \frac{K_1}{K_3} = \frac{\mu}{\eta} = \frac{1}{T}$$

Derivative action time (*T*)

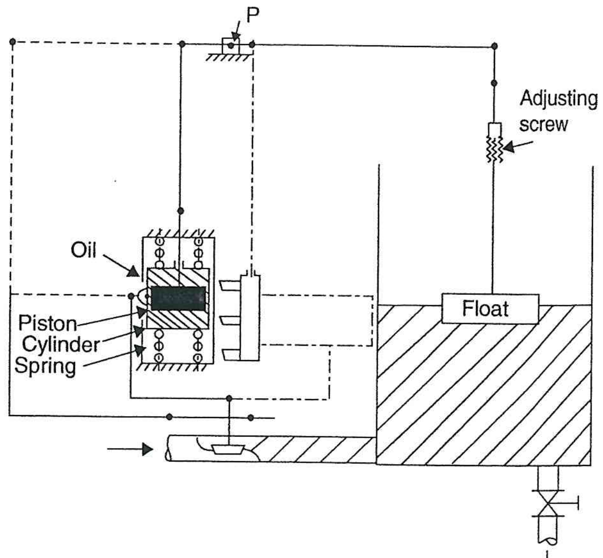
By definition: In a controller having proportional plus derivative action, the time interval in which the part of the output signal due to proportional action increases by an amount equal to the part of the signal due to derivative action, when the deviation is changing at a constant rate. Such deviation change is referred to as *ramp function input*.

In Figure 9.14 the derivative action is assumed instantaneous. After time *T* then $V_D = V_p$ and total controller output signal change equals $2V_p$. Use of derivative action increases μ and gives phase lead, which are desirable, but *T* is limited as too much derivative action may cause instability and hunting. Note that $T = K_3/K_1$ the *larger* the *T* setting the *greater* the derivative action contribution to the potential correction (increased by increasing resistance).

Referring to Figure 9.15. Now from mechanics, rate of change of displacement with



▲ **Figure 9.14** *Proportional and derivative controller action*



▲ **Figure 9.15** *Derivative action on liquid-level control* to velocity, so one would expect some form of damping device in this rate response action.

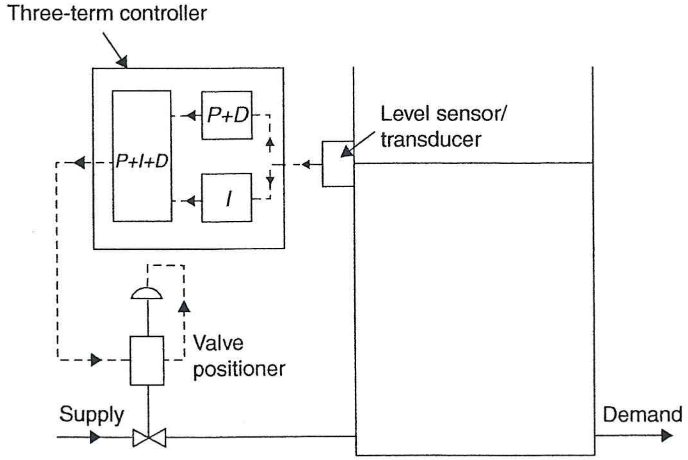
Derivative control is *not* used alone, it is a transient condition which must be combined with proportional control.

If the level rises at a certain rate the piston (in the dashpot) moves down at a certain velocity; proportional to this velocity is a down force on the cylinder which acts to close the valve in, the cylinder motion is resisted by a spring. Valve displacement is proportional to down force. Whenever the float stops changing position the down force ceases and the springs return the cylinder to its original position.

Note: Proportional plus derivative ($P + D$), the two terms can be applied by including the link shown dotted; proportional plus derivative plus integral ($P + D + I$), the three terms can be applied by including the link shown dotted and the link shown chain dotted. For a rising float, for ($P + D + I$) with the arrangement shown, above set point, all act in the same direction downward to close the valve, pivot P can be moved to affect the value of all control factors.

Three-term controller

$P + I + D$ actions, combined, are illustrated for level control in Figure 9.16.

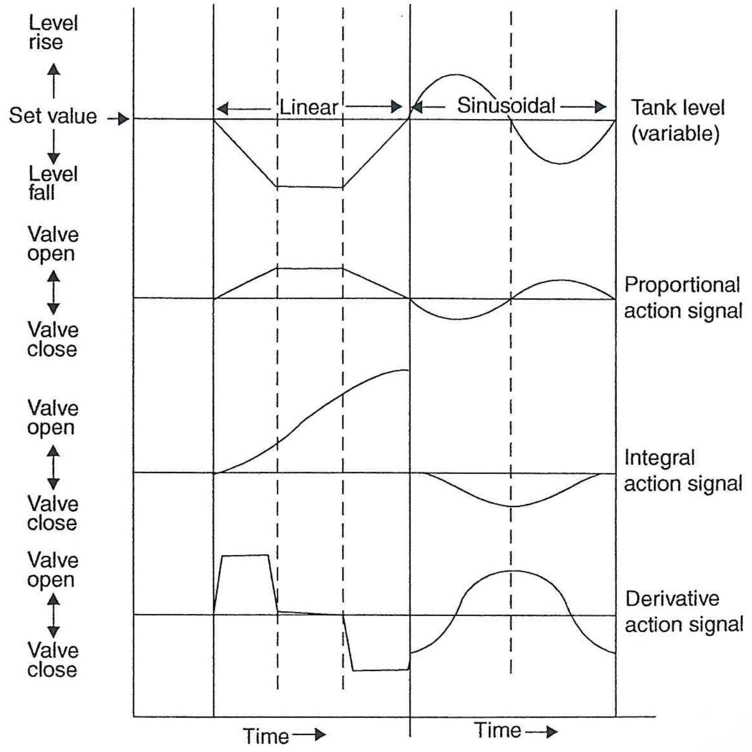


▲ **Figure 9.16** *Three-term controller*

Distance time graphs of control actions

Refer to Figure 9.17. Such analysis gives a clear pictorial representation. Slope of a distance time graph is velocity; an inclined straight line is constant velocity as the slope is constant, a curve of decreasing slope represents deceleration. The top two diagrams should be self-explanatory, relative heights depend on proportionality factor. For integral action note that whenever the variable is away from desired value the integral effect is always moving to correct. For the value at any instant on the integral sketch think of the characteristic at that instant on the first sketch, applied on the opposite side of the axis, and to a suitable scaled factor. For derivative action note that it opposes the motion of the variable irrespective of the desired value.

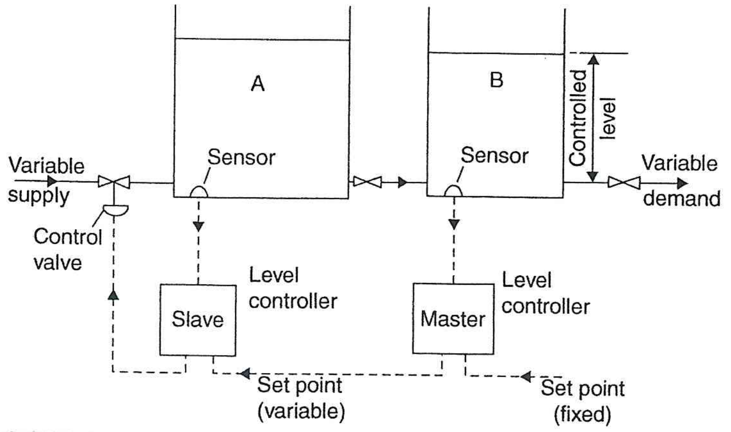
The value of the signal on the fourth sketch is the change of slope of the first sketch, again on the opposite side of axis, that is, slope only changes at four points on sketch one and at such points the derivative effect is acting almost instantaneously.



Cascade control

Consider a multiple capacity system for level control, the two capacitor tank system illustrated in Figure 9.18 is an example. Single capacitor systems respond quickly to load changes and are easy to control utilising correct proportional band and reset action but interaction occurs with multiple systems. Tank A acts as a lag effect on the controlled process from tank B so the combination is less sensitive, especially to supply variations. This is an inherent problem with large inertia (mass, heat capacity, etc.) systems as, for example, in IC engine coolant circuits.

Consider Figure 9.18. There are two variables, supply and output demand, affecting the controlled variable which is level in tank B. The slave controller with level sensing from tank A controls the input supply control valve according to the set point and is a single capacitor control loop for tank A. The master controller with level sensing from tank B (the controlled variable) controls the input supply quantity to tank B, that is, the level in tank A, and is a single capacitor control loop for tank B. This is achieved because the master controller signal controls the set point of the slave controller. A two capacitor system has therefore been simplified to two single capacitor systems which are more easily controlled. Alternatively sensing for the slave could be flow rate at supply rather than tank A level. The process can be extended to multi-capacity systems with control of any desired variable. The principle is utilised very often in practice, for example, IC engine coolant and Butterworth heating, as described in Chapter 13. If a certain pressure range of controller output is divided up by relays or controllers for different functions, in, for example, a sequence, this may be termed *split range control*. This is also utilised in practice, for example, exhaust range pressure control (Chapter 13).

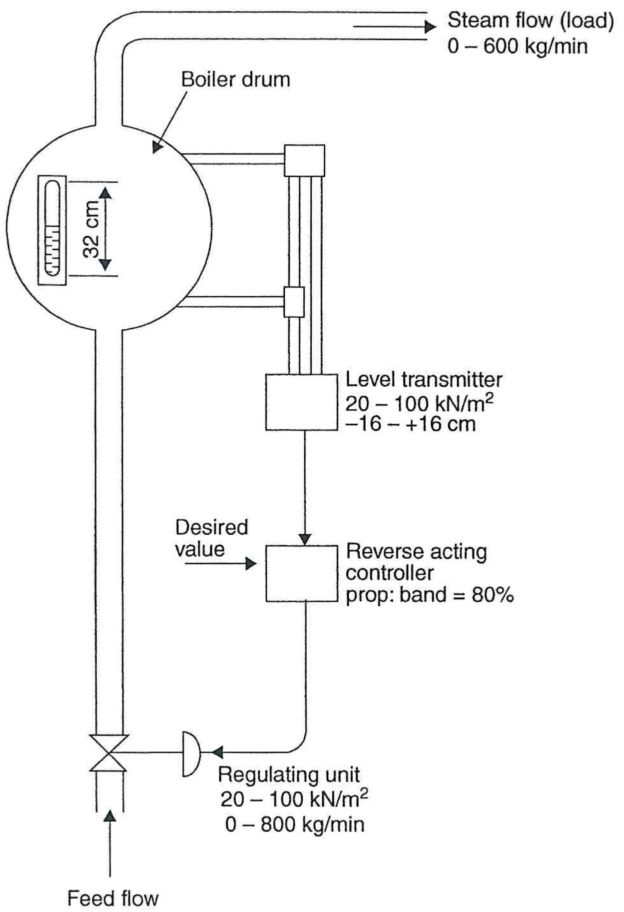


▲ Figure 9.18

Example – level control

When considering numerical questions it is often best to utilise a tabular approach as the following example illustrates:

The sketch (Figure 9.19) shows a single element boiler water level control system. Assuming that the system has been adjusted so that the level is at the desired value of 16 cm ('half glass') when the load is 500 kg/min, determine:



a. the offset if the load is reduced to zero,

b. the proportional band setting required such that the offset is limited to 8 cm if the load changes from 500 to 100 kg/min,

Steam flow load (kg/min)	500	0	100
Level (cm)	16	32	24
Controller input (kN/m^2)	60	100	80
Range change (kN/m^2)		40	20
Controller output (kN/m^2)	70	20	30
Range change (kN/m^2)		50	40

that is, offset 16 cm, proportional band 50%. Unless stated to the contrary, a linear proportionality is assumed between the indicator/controller variable scale ranges in such cases. A similar question is included at the end of the book – specimen examination question number 15, HND (BTEC & SCOTVEC). An alternative solution to the previous is: System proportional control factor μ equals multiple of proportionality characteristics/coefficients, that is, $31.25 = 2.5 \times 1.25 \times 10$ when $\Phi = -\mu\theta$ and as $\Phi = -500$ kg/min so $\theta = +16$ cm. Similarly working in the reverse direction from $\mu\theta = +8$ cm the controller characteristic/coefficient, or proportional action factor K_1 is now 2 (gain), proportional band is 50%.

Similar questions are included at the end of the book, including those requiring graph plots of controller signals – after analysis by a method such as just described. When the controller includes integral action the approach is similar but it must be remembered that integral action time (S) elapses while the signal changes (by integral action) by an equal amount to the immediate proportional action signal. See HNC (BTEC & SCOTVEC) specimen examination questions number 16 and number 18 HND (BTEC & SCOTVEC).

Test Examples

1. Explain the meaning of the following terms relating to process control:
   (a) desired value,
   (b) error signal,
   (c) detecting element

   (d) feedback,
   (e) reset action,
   (f) servo-motor.

2. Explain the meaning of the following terms using suitable diagrams where appropriate:
   (a) potential correction,
   (b) proportional control,
   (c) integral control,
   (d) integral action time,
   (e) derivative control,
   (f) derivative action time.

3. Draw simple diagrams showing the response of a detecting element suffering from a distance velocity lag equivalent to 5 s and a single transfer lag, when subjected to disturbances in the form of:
   (a) a step,
   (b) a ramp.

   Illustrate, on two simple diagrams, the effect of an increase in frequency on 'phase lag' and 'attenuation' for a detecting element suffering from transfer lag.

4. A temperature measuring device suffers a distance-velocity lag of 15 s and also exhibits a simple transfer lag with a time constant of 40 s. If the temperature being monitored jumps suddenly from 30°C to 35°C, what temperature does the device indicate 55 s after this step change? (33.16°C)

10

PNEUMATIC CONTROL PRINCIPLES

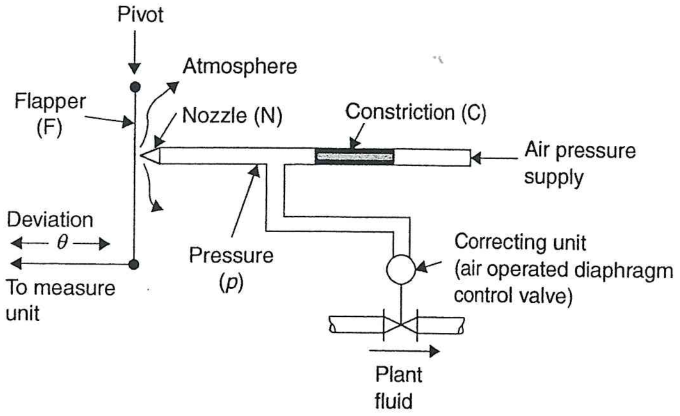
Note: The bar is used as the unit of pressure in this section. 1 bar = 10^5 Pa = 10^5 N/m^2.

Pneumatic Two-Step Control Technique

Refer to Figure 10.1. The constriction may be about 0.2 mm bore and the nozzle about 0.75 mm outlet bore; these sizes are largely fixed by air purity condition, that is, particle filtration size.

With the flapper, or baffle, moved away from the nozzle, full nozzle pressure drop occurs, pressure *p* may be about 1.2 bar or less. With the flapper almost closing the nozzle, pressure *p* may be near 2 bar, that is, almost supply pressure. Two values of pressure *p* can be arranged, which will depend on the flapper position, which is in turn decided by the measure signal movement. An on-off operation or low-rate and high-rate operation can be utilised with these two pressures.

Average flapper travel between two limits is often less than 0.05 mm. The nearer the flapper to the nozzle the stronger the measure signal force required; this is a limitation.

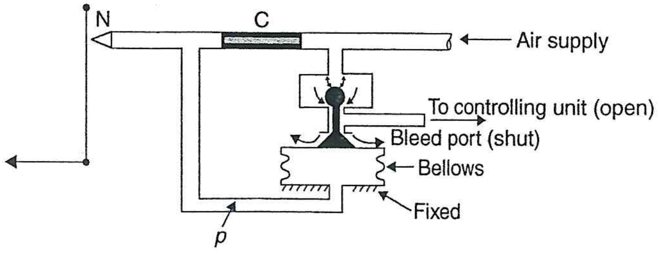


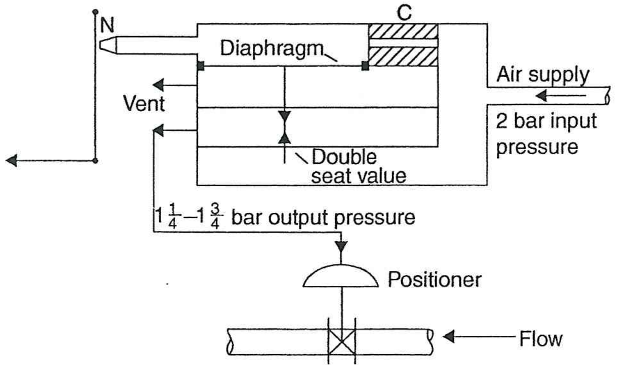
▲ **Figure 10.1** *Two-step pneumatic control*

of flapper travel do not give equal increments of pressure *p*, but over a fairly wide range of travel, say 30–70%, the relation is *reasonably linear*, that is, linear between 0.015 and 0.033 mm in 0.05 mm travel.

The Relay

Provides pneumatic amplification, proportional movement and reduced time lag. It is equivalent in action to an electronic amplifier.If *p* increases (see Figure 10.2) then the bellows act to close the bleed port and supply air passes, and conversely if *p* decreases a continuous bleed to atmosphere occurs. Amplification by a fraction of 16 can easily be arranged, for example, a flapper travel of 0.01 mm causing a change of *p* on the bellows of 0.05 bar could give output from 1.2 to 2 bars. Flapper travel is approximately proportional, by a *linear* relation, to output signal in *this* throttle position of 0.05 bar bellows pressure range. An alternative type of relay is given in Figure 10.3 for comparison.





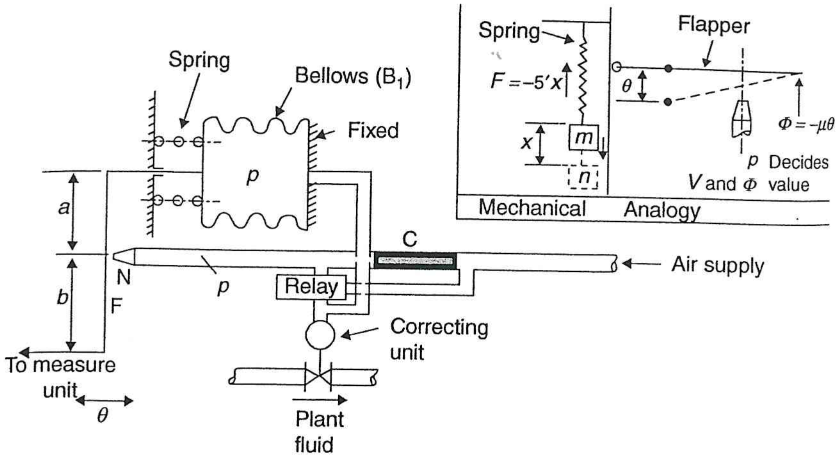
▲ **Figure 10.3** *Alternative design of relay valve*

Various alternatives and refinements can be added, for example, a bellows connected to the relay output will give action proportional to output utilising negative feedback, etc. The relay could introduce further non-linearity if not properly matched in design.

Pneumatic Proportional Control Technique

This utilises adjustable (negative) feedback due to the bellows and flapper linkage. Input (from the measure signal) is compared to output (from the relay signal) and the action is to reduce this difference, so matching input to output. Any desired ratio between input and output can be achieved by adjusting the linkage ratio *a* : *b* shown in Figure 10.4. For a 50% proportional band then the measurement change is 50% of scale for full valve stroke, that is, under ideal conditions the control should operate to maintain measured value and desired value together at 50% valve stroke. Varying load means the controller keeps conditions stable within the proportional band, but not at the desired value; maximum offset cannot exceed half band width.

Refer to Figure 10.4. Consider the measure link moving right, this decreases the nozzle escape and pressure *p* increases. Pressure *p* acts, via the relay, on the bellows so tending to act in the opposite direction to the initial movement with proportional action against the spring (just as for the simple spring analogy p. 148 earlier). This decreases the sensitivity (flapper travel near nozzle). The ratio *a* : *b* (which is adjustable) decides the bandwidth, this action is the simple lever principle (feedback can never exceed deviation).



▲ **Figure 10.4** *Pneumatic proportional control with negative feedback*

This cancellation whereby a pressure increase moves the flapper to lower the pressure means that a greater movement of the measure unit, for a given change in control line pressure, is required so ensuring proportional action. This also gives a wider proportional band without increasing mechanical linkages which would reduce accuracy. The relay shown in all sketches is not in practice necessarily fitted to all controllers. Without the bellows the proportional flapper travel region is very small.

Bellows movement is proportional to pressure *p*.

$$x = m\theta - np$$

where *x* is movement of flapper next to the nozzle, *m* and *n* are proportionality constants (including the adjustments *a* and *b*) for the deviation θ and the negative feedback pressure *p* (which also decides *V* and Φ).

x is negligible compared to other movements.

$$\therefore np = m\theta$$

$$\therefore p = -\frac{m}{n}\theta$$

$$\therefore \Phi = -\mu\theta$$

That is, potential correction is *proportional* to the deviation and *equals* the proportional control factor multiplied by the deviation. The negative sign indicates opposite direction.

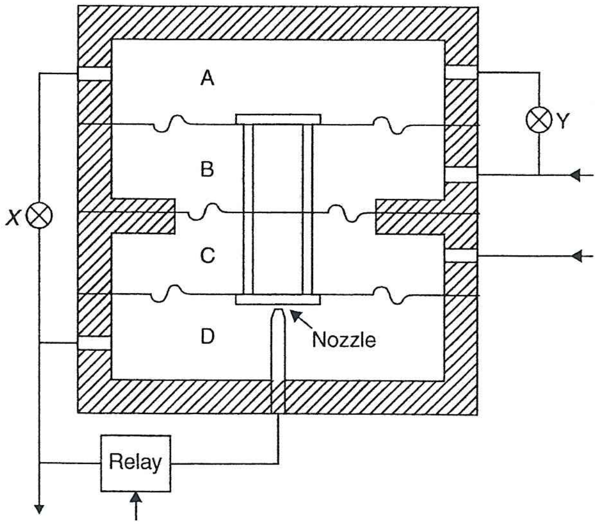
Stack Type Controller Principle (P Action)

Refer to Figure 10.5. The construction is of air chambers stacked on top of each other, separated by diaphragms and incorporating relay valves, nozzles and restrictor control valves.

The measured value (controlled condition) enters at chamber C and the set value (command signal) set up at the reducing valve enters at chamber B. Variations between these two values causes the diaphragm arrangement to move up or down vertically so that air flow through the nozzle to the chamber D controls cancellation of the deviation caused by the pressure variation.

Pressures at A and B would be equal if control valve X were closed, hence pressures at C and D would equalise as D pressure (controller output signal) changed, this means 100% proportional band.

Conversely if X were opened fully pressures at A and D would be equal so that deviation from set value would cause the nozzle to be fully opened or closed. This is two-step control action. Valve Y can act as an adjustment but essentially it prevents direct connection between output and set value air lines.



▲ Figure 10.5 *Stack type controller principle (P action)*

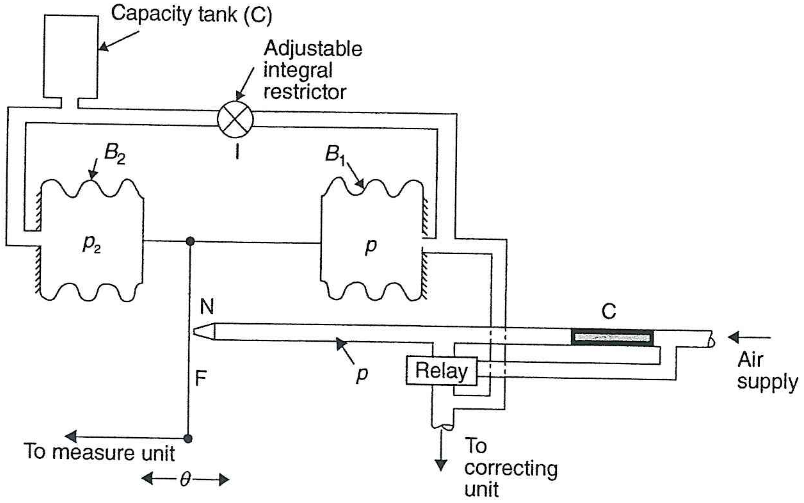
Variation of the setting of X between open and closed gives proportional band variation between 0% and 100%.

By utilising different stacking arrangements, for example, capacity bellows, different connections to control valves (restrictors), variable bellows areas, etc. then the correct proportional, derivative or integral actions can be incorporated as required. *P, P + D, P + I* actions separately generated and combined in an addition unit give three-term action without interaction problems.

Pneumatic Proportional Plus Integral Control Technique

Integral (reset) action can be regarded as a slow cancellation of the sensitivity reduction provided by the negative feedback of the proportional system.

Refer to Figure 10.6. *Without* the needle value adjustable restrictor I, the proportional negative feedback bellows B, the effect would be completely cancelled by the proportional positive feedback bellows B_2 effect (assuming equal bellows sizes and form), simulated two-step or near proportional action for limited flapper travel would result (depending on flapper travel utilised). Similarly in the steady state *with* the needle value as there would be zero pressure difference across it.



▲ Fi

When a disturbance causes a deviation to occur (say p increases) then the rate of p_2 change is proportional to the deviation effect $p - p_2$.

If the measure unit moves right under a constant deviation increase then p increases giving near proportional action V_p *immediately. Negative feedback to bellows* B_1 reduces sensitivity giving wider proportional band and true proportional action.

Deviation, under proportional action alone, would become greater, more offset would occur. However bellows B_2 exerts positive feedback to raise pressure p_2 at a rate dependent on the deviation, and this maintains constant deviation. Integral action would continue until deviation ceased and there would be no offset, that is, restoration to desired value. A repeat is accomplished when the amount of change in air pressure in the reset (integral or floating) bellows equals the amount of original change in output pressure to the proportional bellows.

$$x = m\theta - n(p - p_2)$$

That is, negative feedback due to p and positive feedback due to p_2. Again taking $x = 0$:

$$p - p_2 = \frac{m}{n}\theta \quad \text{for whole action}$$

now

$$\frac{dp_2}{dt} \propto p - p_2 \quad \text{for integral action}$$

that is, rate of change of pressure p_2 is proportional to the difference of pressure.

$$\frac{dp_2}{dt} = \frac{1}{CR}(p - p_2)$$

CR is a time constant dependent on the capacity C of the tank and the resistance R of the restrictor I, CR is the integral action time S.

$$S\frac{dp_2}{dt} = \frac{m}{n}\theta$$

integrating

$$Sp_2 = \frac{m}{n}\int \theta dt$$

$$p_2 = \frac{m}{nS}\int \theta dt$$

Thus for the whole action

$$p = \frac{m}{n}\theta + \frac{m}{nS}\int \theta dt$$

applying negative direction sign, with p equivalent to Φ

$$\Phi = -\mu\left(1 + \frac{1}{S}\int \theta dt\right) \quad \text{for } (P + I)$$

Note: Consider the distinct analogies.

$$\text{Pressure: } \frac{dp_2}{dt} = \frac{1}{CR}(p - p_2)$$

where rate of pressure p_2 with respect to time is proportional to excess pressure $p - p_2$. CR time constant, C tank capacity and R restrictor flow resistance.

$$\text{Electrical: } \frac{dV_2}{dt} = \frac{1}{CR}(V - V_2)$$

where rate of change of voltage V_2 with respect to time across a condenser is proportional to excess voltage $V - V_2$. CR time constant, C capacitance of the condenser and R current resistor resistance, the latter often negligibly small.

$$\text{Temperature: } \frac{d\theta_E}{dt} = \frac{1}{CR}(\theta_F - \theta_E)$$

where rate of change of temperature θ_E across a detector element with respect to time is proportional to excess temperature $\theta_E - \theta_F$. CR time constant, C is thermal capacity of element and R thermal resistance to heat flow.

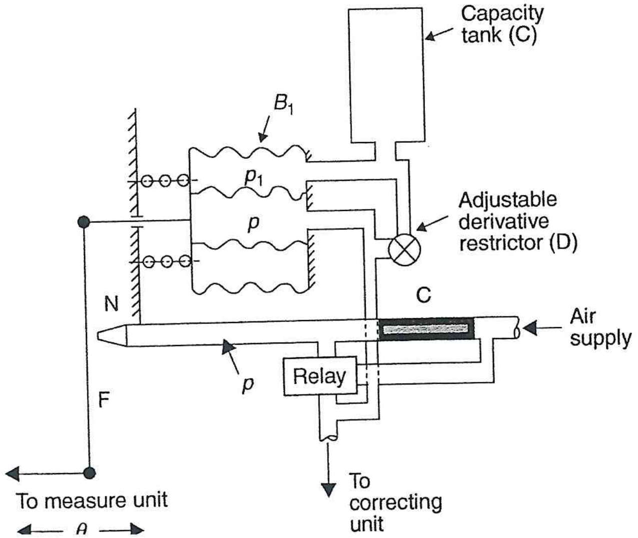
Pneumatic Proportional Plus Derivative Control Technique

Derivative (rate) action increases sensitivity by restricting the negative feedback provided by the proportional system so that during the change high speed sensitivity occurs but when the change ceases ordinary proportional action occurs.

Refer to Figure 10.7. *Without* the needle valve adjustable restrictor D, proportional action results, similarly for the steady state with the needle valve. When a disturbance causes a deviation to occur (say p increases) then the *rate* of p_1 change is proportional to the deviation effect $p - p_1$. Derivative action stabilises more quickly after a change. Considering the inner bellows, the smaller area gives less force per unit pressure change of p, a narrower proportional band, higher sensitivity and less feedback occurs than if the same pressure effect acted on the larger outer bellows.

If the effective area of the inner bellows was one quarter of that of the outer bellows then an instantaneous deviation produces a finite response equivalent to four times the normal proportional action with negative feedback for the same actuating signal applied to the outer bellows.

Considering the outer bellows which gives the derivative action then the change of pressure via the relay across the resistance and tank (D and C) gives a pressure drop proportional to the rate of chance of activating signal deviation. This means the sensitivity reduction due to negative feedback is adjusted in line with the rate of change of the deviation.



The combination bellows means that when movement starts (say to the right) to increase, the narrow proportional band, caused by p only on the small bellows, gives high output relay signal pressure. Such exaggerated output is then amended for derivative action by p_1 on the large bellows until the measure movement ceases and pressure in the outer bellows equals pressure in the inner bellows (no pressure drop). This means the control valve operates sooner for the same rate of change from the measure unit.

Double bellows are *not* always utilised, strictly the derivative action is on the outer bellows only. This arrangement has disadvantages as phase lag to the derivative action occurs (see compound controllers later).

The inner bellows gives proportional action only, for simplicity regard this bellows as omitted.

$$x = m\theta - np_1$$

negative derivative action feedback due *to* p_1.

Taking $x = 0$ as previously:

$$p_1 = \frac{m}{n}\theta \text{ for whole action}$$

Now

$$\frac{dp_1}{dt} = \frac{1}{CR}(p - p_1) \text{ for derivative action only}$$

CR is the time constant, dependent on capacity *C* of the tank and resistance *R* of the restrictor *D*, *CR* is derivative action time *T*.

Rearrange the last expression:

$$p = p_1\left(T\frac{d}{dt} + 1\right)$$

$$p = \frac{m}{n}\theta\left(T\frac{d}{dt} + 1\right)$$

$$p = \frac{m}{n}\left(T\frac{d\theta}{dt} + \theta\right)$$

where m_1 and n_1 are new proportionality constants to allow for the proportionality feedback effect of the combined bellows.

Now applying the negative sign to indicate the opposite direction and with p equivalent to potential correction Φ.

$$\Phi = -\mu\left(\theta + T\frac{d\theta}{dt}\right) \text{ for } (P + D)$$

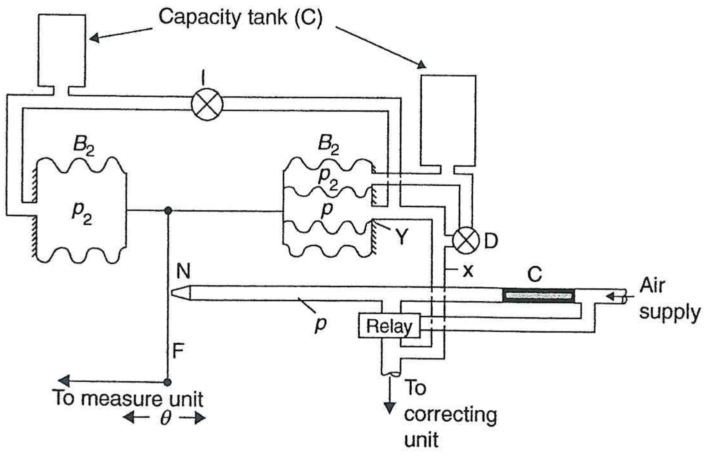
Pneumatic Compound Controller (*P* + *I* + *D*)

Three term ($P + I + D$) or two term ($P + I$ or $P + D$). A controller action in which the output signal from the controller is the result of more than one operation on the deviation.

$$V = -K_1\left(1 + \frac{K_2}{K_1}\int \theta dt + \frac{K_d d\theta}{K_1 dt}\right) \text{ for three term}$$

$$\Phi = -\mu\left(\theta + \frac{1}{S}\int \theta dt + T\frac{d\theta}{dt}\right) \text{ for three term}$$

Figure 10.8 shows the compound pneumatic controller, the action should be clear from previous diagrams.



▲ Figure 10.8 Compound (P + I + D)

Interaction

With the pneumatic arrangement shown in Figure 10.8, but *D* at X, adjustment of either *I* or *D* affects each of the three actions. Thus the effective action times (*S* and *T*) differ from the nominal (dial set) action times. *D* can be moved from X to Y which may improve performance but still gives interaction. For truly independent adjustments then derivative and integral actions should be generated separately based on proportional action and combined in a relay (see also Chapter 15).

Air Supplies

An adequate supply of clean, dry compressed air is required with well-designed, installed and maintained air line systems.

Quantity is defined under standard intake conditions, that is, 15°C and 1 bar, which relate size, capacity and consumption.

Quality requires that filtration removes solid particles, oil and water. If dew point can be reduced at high temperature, below any likely ambient temperature of the system, the installation can be kept dry. High compression, with interstage and after cooling is effective especially when large delivery receivers allow cooling under pressure. Absorber filters such as silica gel or activated alumina should be fitted at low level system points to act as moisture traps – such traps should also be fitted adjacent to reducing valves.

Compressors are either arranged to run continuously, fitted with unloading devices to allow running light when pressure supply is reached, or have pre-set cut in and cut out pressure switches. Machine capacity should be such that 50% time loading only is required; a 3 kW unit (4 bar) would meet this criteria when delivering output of one cubic metre (referred to standard conditions) for up to ten instruments.

Air lines should have a gradient of at least 1 : 50, with moisture traps at lowest points, and instrument tappings are taken from the top of headers. Final stage filters are often of the ceramic type and silicone impregnation makes them water repellant. Annealed seamless copper tubing, pickled inside and out, is often used – especially for single instrument loads. Polythene and PVC tubing is resistant to corrosive atmospheres and is also much cheaper for larger installations. For the supply to say ten instruments the hp line (4–7 bar) would be about 12 mm bore, delivery through 18 mm reducing valve

Test Examples

1. Describe the operating principle of a pneumatic controller. Explain what is meant by the term 'proportional action'. Show by means of a simple sketch how the controller functions to maintain a particular system in equilibrium.
2. (a) Make a diagrammatic sketch of a two-term ($P + I$) pneumatic controller of a nozzle-flapper type and briefly describe its operation.
   (b) With reference to the diagram describe briefly how the controller could be set before commissioning.
   (c) With reference to the diagram describe briefly how the proportional band adjustment could be calibrated.
3. (a) Sketch a three-term nozzle flapper controller which has provision for receiving pneumatic desired value and measured variable signals.
   (b) Explain how the proportional action is generated and how the gain may be varied.
   (c) Describe how the integral action is generated and how the degree of integral action may be varied.
   (d) Describe how the derivative action is generated and how the degree of derivative action may be varied.
   (e) Explain why a relay valve is necessary and what additional benefits may result from its use.
4. Describe, with the aid of a suitable sketch, the construction of a $P + D$ controller. Explain, using a graph, the open-loop response to a ramp change in measured value. How can the controller be changed from direct-acting to reverse-acting?

11

ELECTRONIC CONTROL PRINCIPLES

Operational Amplifiers

Operational amplifiers (op-amps) have become an essential building block in many instrumentation systems being used to amplify tiny electrical signals from sensors to more robust levels suitable for processing and transmission, which in turn use op-amps.

The basic op-amp has two inputs, an inverting input (–) and a non-inverting input (+) and one output.

Op amps are considered to have very high input impedance and low output impedance. This means that they do not become an unnecessary load on the signal source but do not in turn become overloaded by whatever they are driving. Furthermore, the open-loop gain of the op-amp is extremely high.

A signal applied to the inverting input will have its polarity reversed on the output. A signal applied to the non-inverting input will retain its polarity on the output.

The closed-loop gain or amplification of the signal is determined by a feedback input. Whole textbooks have been written on the subject of the op-amp, so in this chapter a review is made of the common applications which are relevant to control and instrumentation.

Most op-amps need a bipolar power supply of at least ±5 V with sophisticated high performance devices requiring higher values. This is indicated in the following examples as $\pm V_s$.

The inverting amplifier

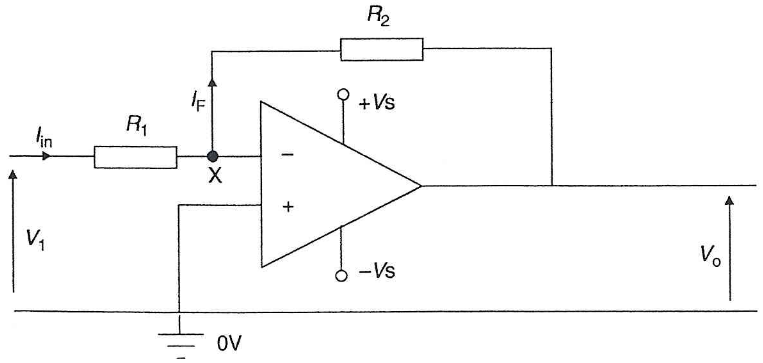
The inverting op-amp is the most basic application. Figure 11.1 represents the op-amp as a triangle with two inputs (–, +) and one output. External resistors R_1 and R_2 establish the inverting configuration.

Virtual Earth concept

To understand the operation of this and other op-amp arrangements it is helpful to consider the Virtual Earth concept.

Due to the high input impedance of the IC the current drawn by the (−) input is negligible and since the open-loop gain (A) is very high, a change in the output voltage is brought about by a change in the (−) input terminal of negligible magnitude.

Point 'X' is therefore held at Virtual Earth potential.



$$\text{Hence } I_{in} = \frac{V_1}{R_1} = I_f = \frac{-V_o}{R_2}$$

$$\frac{V_o}{R_2} = \frac{V_1}{R_1}$$

$$\text{Therefore } V_o = \frac{-R_2}{R_1} \times V_1$$

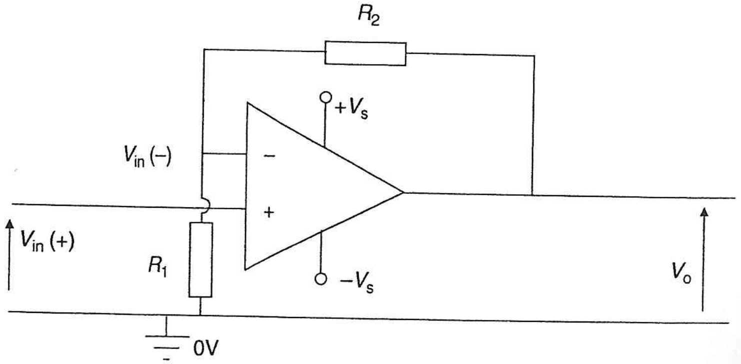
and voltage gain of amplifier, $\frac{V_o}{V_1}\; A_V = \frac{-R_2}{R_1}$

Although the input resistance of the IC can be very high the input resistance of this amplifier $= R_1$.

The non-inverting amplifier

$V_{in}(+) = V_{in}(-) = V_o\left[\frac{R_1}{R_1 + R_2}\right]$ by potential divider action (Figure 11.2)

$$\text{Therefore } V_o = \left[\frac{R_1 + R_2}{R_1}\right] \times V_{in} = +\left[1 + \frac{R_2}{R_1}\right] V_{in}$$



▲ **Figure 11.2** *Non-inverting amplifier* and voltage gain of amplifier, $A_V = \frac{1 + R_2}{R_1}$

The inverting summing amplifier (Figure 11.3)

$$I_1 + I_2 + I_3 = I_F$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = \frac{-V_o}{R_F}$$

that is, $V_o = -\left[\frac{R_F V_1}{R_1} + \frac{R_F V_2}{R_2} + \frac{R_F V_3}{R_3}\right]$

and if all resistances are the same value, for example, $R_1 = R_2 = R_3 = R$

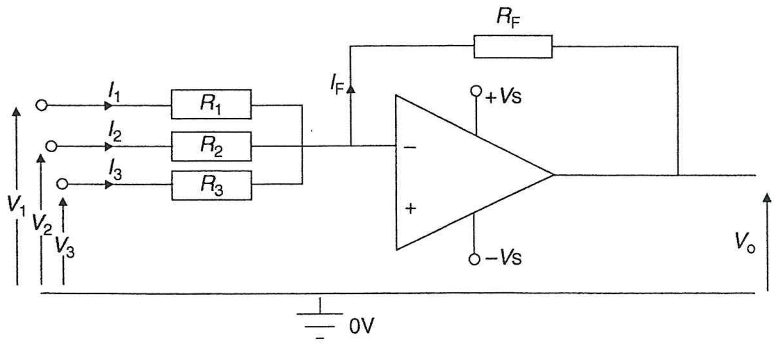
then

$$V_o = -\frac{R_F}{R}[V_1 + V_2 + V_3]$$

The difference amplifier (subtractor)

The aim of the subtractor amp (Figure 11.4) is to provide an output which is equal to the difference of the two input signals or proportional to their difference.

Make resistor $R_1 = R_2$ and $R_F = R_3$



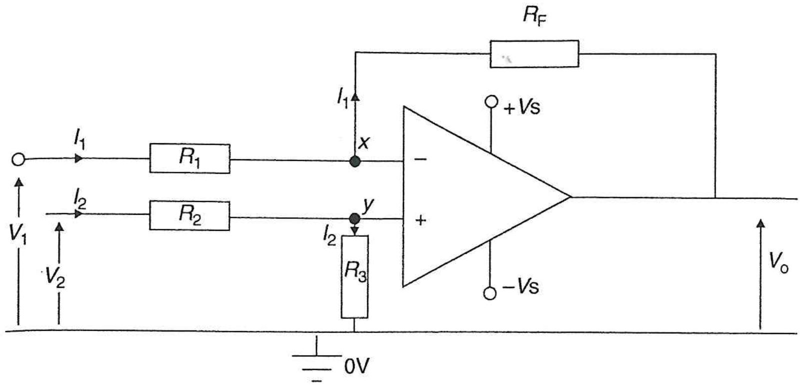


Figure 11.4 *Difference amplifier (subtractor)*

now $V_x = V_y$

$$\text{Current } I_1 = \left[\frac{V_1 - V_x}{R_1}\right] - \left[\frac{V_x - V_o}{R_F}\right] \tag{i}$$

and

$$\text{Current } I_2 = \left[\frac{V_2 - V_y}{R_2}\right] - \left[\frac{V_y}{R_3}\right] \tag{ii}$$

Therefore from equation (i)

$$\left[\frac{V_1}{R_1} - \frac{V_x}{R_1}\right] = \left[\frac{V_x}{R_f} - \frac{V_o}{R_f}\right]$$

$$\left[\frac{V_1}{R_1} - \frac{V_o}{R_f}\right] = \left[\frac{V_x}{R_f} - \frac{V_x}{R_1}\right]$$

On substituting $V_x = V_y\, R_1 = R_2$ and $R_f = R_3$ into equation (ii)

$$\left[\frac{V_2 - V_x}{R_1}\right] = \frac{V_x}{R_f}$$

$$\left[\frac{V_2}{} - \frac{V_x}{}\right] = \frac{V_x}{} \tag{iii}$$

$$\frac{V_2}{R_1}=\left[\frac{V_x}{R_f}+\frac{V_x}{R_1}\right] \qquad \text{(iv)}$$

On equating (iii) and (iv)

$$\frac{V_2}{R_1}=\left[\frac{V_1}{R_1}+\frac{V_o}{R_f}\right] \text{therefore} \left[\frac{V_1}{R_1}+\frac{V_o}{R_f}\right]=\frac{V_2}{R_f}$$

therefore

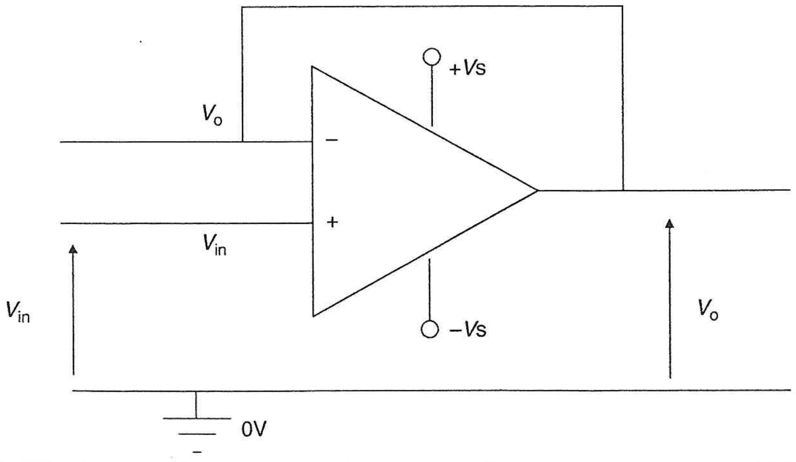
$$\frac{V_o}{R_f}=\left[\frac{V_2}{R_1}-\frac{V_1}{R_1}\right]=\frac{V_2-V_1}{R_1}$$

$$V_o=\frac{R_f}{R_1}(V_2-V_1)$$

The unity gain follower (buffer amplifier) (Figure 11.5)

From the non-inverting amplifier we have deduced that the output voltage (V_o) can be calculated.

Therefore $V_o=+\left[1+\frac{R_2}{R_1}\right]V_{in}$ … if we extract R_2 and R_1



so $V_o = V_{in}$

and voltage gain, $A_v=\frac{V_o}{V_{in}}=1$

The circuit has a voltage gain of unity, a very high input resistance (e.g. 100 MΩ) and a very low output resistance (e.g. <1 Ω).

It is used to 'match' a high resistance source to a low resistance load and is connected between the source and load.

The comparator

In the configuration two voltages are compared and the difference is amplified

This is one of the few applications where the op-amp is used in *open-loop* mode (i.e. no negative feedback applied), as opposed to the closed-loop mode.

The open-loop voltage gain for the 741 op-amp = 200,000 therefore if $V_{supply} = \pm 5$ V

then $V_{in}(\text{Sat})=\left[\frac{\pm 5}{200000}\right]=\pm 25\mu V$

The differential comparator

This circuit (Figure 11.6) compares one voltage with another of the same polarity.

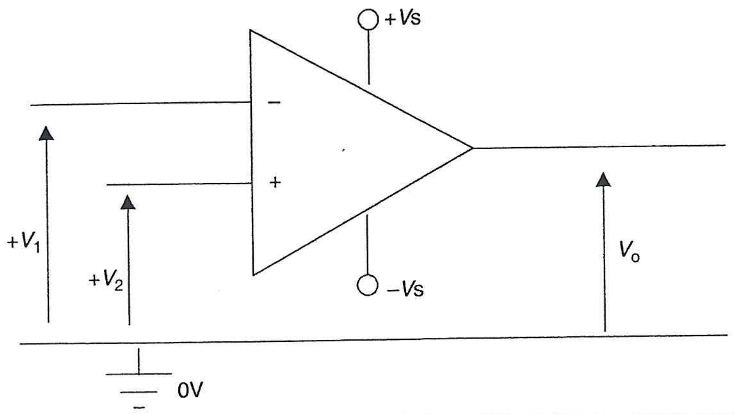
If $+V_1 = +V_2$ then $V_o = 0$ V

Now for a very small difference between V_1 and V_2 the op-amp 'saturates'

that is,

if $V_1 > V_2$ by 25 μV, V_o will be at $-V_o$ (sat) … approx 90% of $-V_s$

if $V_2 > V_1$ by 25 μV, V_o will be at $+V_o$ (sat) … approx 90% of $+V_s$



▲ **Figure 11.6** *Differential comparator*

Application of the comparator

The Schmitt trigger circuit (Figure 11.7)

This is a regenerative (positive feedback) comparator. The circuit is used for voltage level detection, reshaping pulses with poorly defined (leading and trailing) edges and 'squaring' sine wave signals.

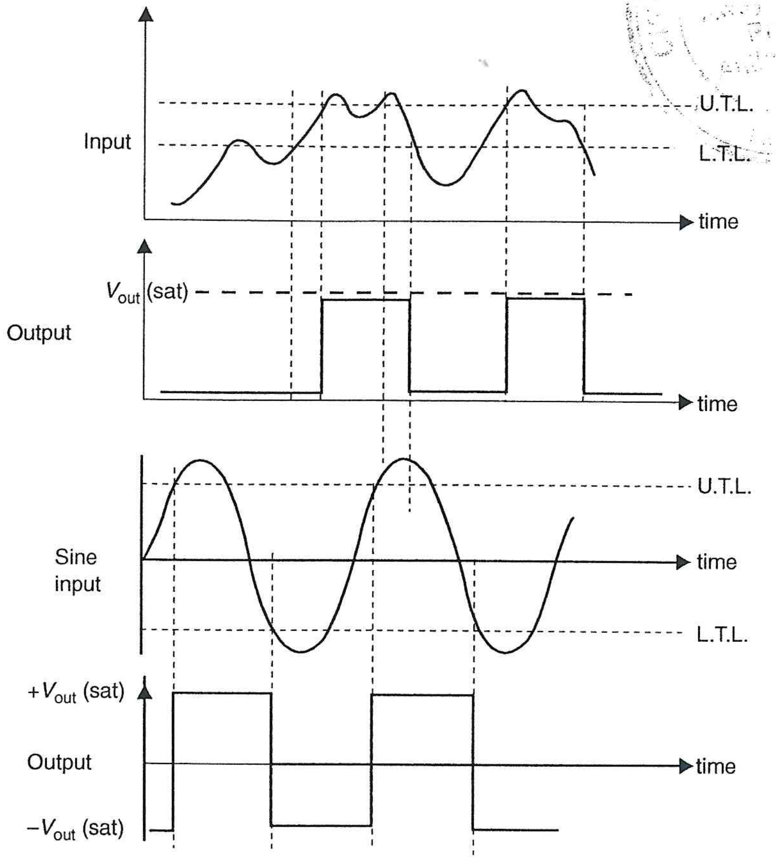
The Schmitt trigger is basically a fast acting electronic switch that changes state at a specific voltage trip point (UTL, i.e. upper trip or threshold level). A feature of the Schmitt is that the circuit does *not* switch back immediately once the input signal is reduced to just below the input upper threshold level, but at a specifically designed lower input level (i.e. lower trip or threshold level). Because there is a distinct difference between upper and lower trip voltage levels, the circuit is said to possess *hysteris* (or backlash).

This is useful in eliminating noise superimposed upon the input signal.

The Schmitt trigger can be constructed using various electronic technologies:

a. Discrete components
b. An operational amplifier
c. Be available as ready constructed integrated circuit devices

Only (b) is considered in detail here.



▲ **Figure 11.7** *Schmitt trigger circuit*

The non-inverting Schmitt trigger (Figure 11.8)

Another common way that op-amps are used are in comparator circuits. A comparator circuit will compare the voltage on the two inputs and then make the output high or low. This is accomplished by having one input the voltage reference (V_{ref}) and the other input is the voltage input (V_{in}). Shown below are the two ways to hook up a comparator circuit.

Note: *V* has been mainly used previously as the symbol for controller output signal. In this chapter, *V* is used as a general symbol for voltage, suffix i or 1, etc. for input (alternative E or e, for V, sometimes used elsewhere).

Electronic two-step control technique

On-off devices find a wide range of application using this simple switching technique. A typical example is room temperature control in which a bi-metallic strip closes or opens electrical connections leading to energy input. Small permanent magnets ensure snap action and differential gap is adjustable. Digital devices are often used.

Electronic proportional control technique

Apply Ohm's law to the circuit of Figures 11.1–11.8.

$$I_1 = \frac{V_1 - V_x}{R_1} = \frac{V_1}{R_1} \quad \text{as } V_x \text{ is zero}$$

$$I_F = \frac{V_o - V_x}{R_F} = \frac{V_o}{R_F} \quad \text{as } V_x \text{ is zero}$$

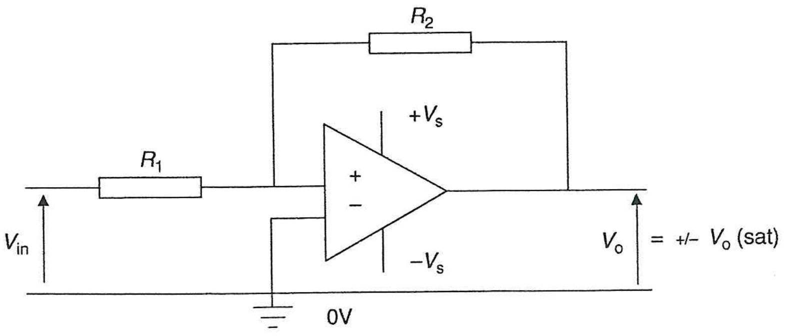
$$I_1 = -I_F$$

because the amplifier input current is considered to be zero.

This is Kirchhoff s law for currents at a point.

$$-V_o = \frac{R_F}{R_1} V_1$$

Action is *scalar multiplication* (V_o proportional to V_1) with the multiplying factor R_F/R_1 and the negative sign indicating *inversion*. Adjustable circuit gain (proportional band) is achieved by altering R_F with R_1 fixed ($R_F/R_1 = 1$ is 100% bandwidth). For multiplying factors below unity an adjustable potentiometer (attenuator) can be used. $V_o = tV_1$ where $t = r/R$ the tapping ratio. Removal of the minus sign can be achieved by using two amplifiers in series. $G = R_F/R_1$ is commonly 1 or 10, gain.



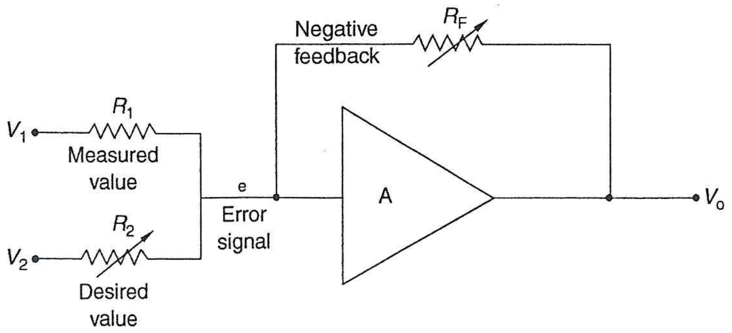
Consider now two inputs as shown in Figure 11.9.

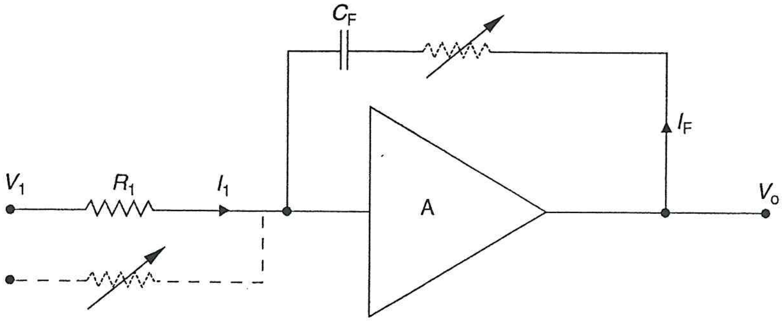
$$V_o = -R_F\left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right)$$

where V_1 and V_2 are negative inputs. This is essentially a *summer* (and scalar) action which can be extended to further inputs as required. If $R_1 = R_2 = R_3 = \text{etc.} = R_F$ then $V_o = -(V_1 + V_2 + V_3 + \text{etc.})$, that is, summation only. *Ratio* control of inputs can be achieved by adjustment of the respective input resistances. A controller must produce an output signal proportional to the *deviation* between desired and measured values. The two signals can be compared (comparing element), perhaps elsewhere, by opposition flow through a common resistor, the voltage across which now represents deviation (error) signal for transmission to the amplifier input. If one input voltage is applied as negative to a summer the result is effectively *subtraction*. For Figure 11.9 if V_1 and V_2 are regarded as measured value and desired value (in opposition) this gives error input and *proportional to deviation* control action, bandwidth adjustment at R_F. Amplifier power supplies and earth lines are omitted for simplicity.

Electronic integral (reset) control technique

Consider the circuit of Figure 11.10: By placing a capacitor C_F in the feedback circuit a limit is placed on the amplifier response rate to change of input signal.





▲ **Figure 11.10** *Electronic integral (reset) control*

For a capacitor

$$C = Q/V$$
$$\therefore Q_F = C_F V_o$$
$$I_F = \frac{dQ_F}{dt} = C_F \frac{dV_o}{dt}$$
$$\int dV_o = \frac{1}{C_F}\int I_F dt$$

but

$$I_1 = -I_F \quad \text{and} \quad I_1 = \frac{V_1}{R_1}$$
$$V_o = -\frac{1}{C_F R_1}\int V_1 dt$$

That is, output voltage is the integral voltage with the time constant (reset rate) dependent on C_F and R_1. If, as for the two previous sketches, there is a modification to two inputs, via resistors representing measured and desired values, then amplifier input voltage corresponds to error voltage, that is, output voltage is the integral of error input voltage. A feedback resistor R_F is necessary to give proportional addition and make adjustment more easy, with a fixed capacitor, alternatively potentiometer adjustment could be provided. Integral action is essentially rate control in the feedback network of the circuit by capacitance. R_F and R_2 additions shown dotted. Integral action is very rarely applied on its own.

Electronic derivative (rate) control technique

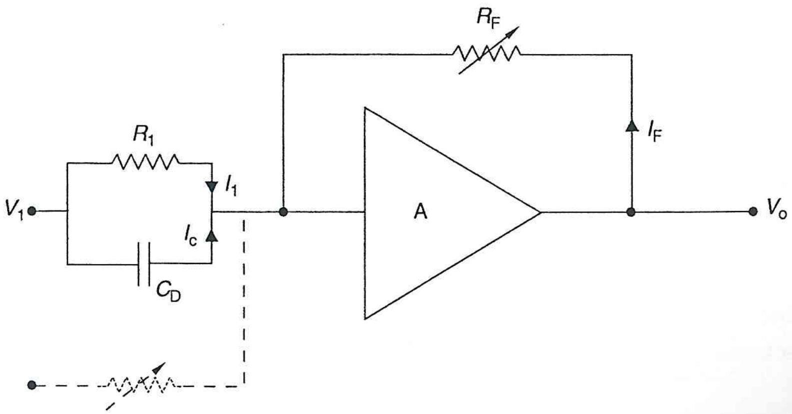
Consider the circuit of Figure 11.11 in which it is necessary to consider $P + D$ combinations: A capacitor C_D is in the input circuit, together with a resistor R_1, to produce a rate of change component.

In the steady state there is no current through C_D.

$$I_1 = -I_F$$
$$V_o = -\frac{R_F}{R_1}V_1$$

In the transient (changing) state:

$$I_1 = \frac{V_1}{R_1}$$
$$I_c = C_D\frac{dV_1}{dt}$$
$$I_1 + I_c = -I_F$$
$$I_1 + I_c = -\frac{V_o}{R_F}$$
$$V_o = -R_F(I_1 + I_c)$$
$$V_o = -R_F\left(\frac{V_1}{R_1} + C_D\frac{dV_1}{dt}\right)$$



The output voltage therefore has two desired components, that is, proportional to input and proportional to rate of change of input. The feedback resistor is necessary to give proportional addition and adjustment. If, as before, measured value and desired value inputs through resistors are applied then input voltage is deviation error signal and output voltage is signal to final control element. The phase advance network ahead of the amplifier gives attenuation across the CR circuit which requires compensation with increased gain at the amplifier. The R_2 desired value resistor is shown dotted. Derivative action is never applied on its own.

Electronic compound controller (*P* + *I* + *D*)

A controller action in which the output signal from the controller is the result of more than one operation on the deviation (error signal), in this case three, that is, three-term controller.

$$V_o = -R_F\left(\frac{V_1}{R_1} + \frac{1}{C_F R_1}\int V_1 dt + C_D \frac{dV_1}{dt}\right)$$

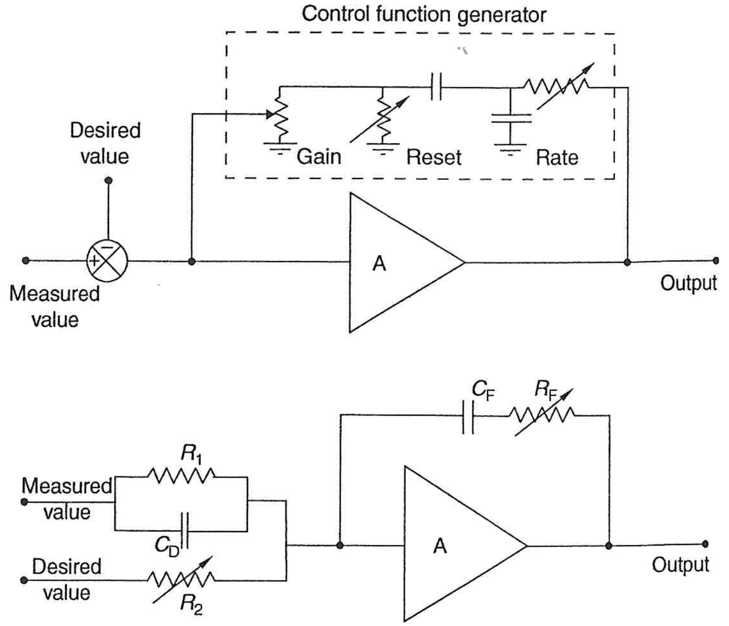
leading to:

$$V_o = -\frac{R_F}{R_1}\left(V_1 + \frac{1}{C_F}\int V_1 dt + R_1 C_D \frac{dV_1}{dt}\right)$$

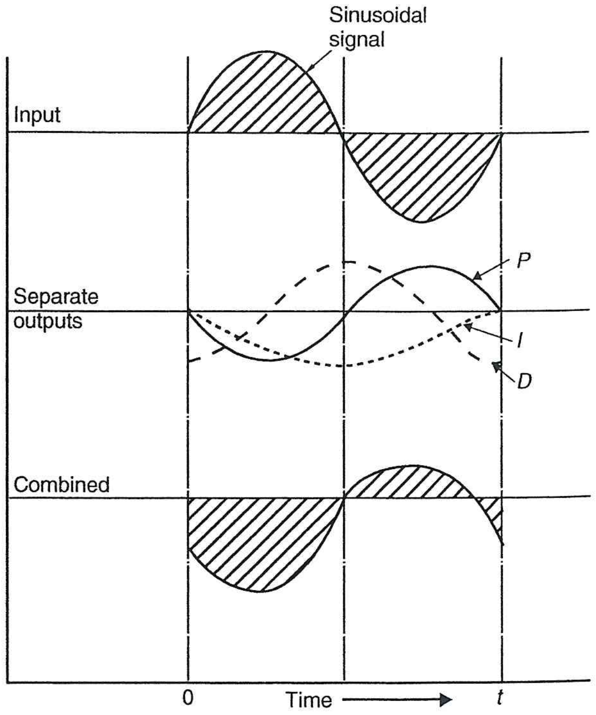
The relation with the proportional, integral and derivative factors given previously and equations relating to Figure 10.8 are obvious.

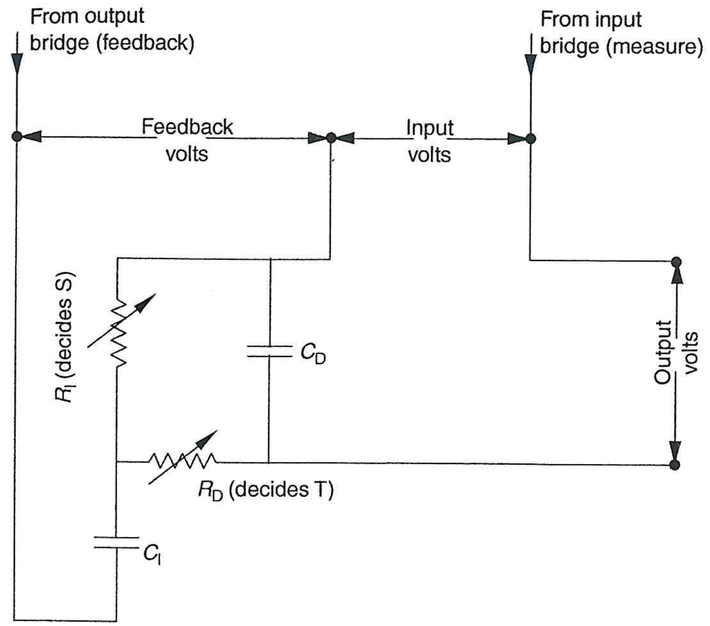
Referring to Figure 11.12: The sketch shows the compound electronic controller, the action should be clear from previous diagrams and should be compared with Figure 10.8. Similar remarks about interaction apply as for the pneumatic case. The upper sketch illustrates grouping to controller (note the summer, and the potentiometer gain adjustment) while the lower sketch is basic operational amplifier configuration.

Figure 11.13 is a typical response curve for (*P* + *I* + *D*) action. Figure 11.14 is a simplified form of electrical circuit which can be compared with the previous sketch and to the complete electronic controller diagram given later in Chapter 12.



▲ **Figure 11.12** *Electronic controller (compound P + I + D)*





▲ **Figure 11.14** *Electronic controller circuit (compound P + I + D)*

Note: With electric-electronic controllers:

1. For output voltage to be proportional to input voltage it is necessary to add a resistor (R_1) in the feedforward path to the amplifier (i.e. in series) and a resistor (R_F, adjustable) in the feedback path (i.e. in parallel).
2. If output volts are to be proportional to deviation, represented by error input volts (*e*), then error signal is applied as input to the circuit of 1.
3. For the addition of integral action to 2 above it is necessary to include a capacitor (C_F) in the feedback circuit in series with resistor R_F.
4. For the addition of derivative action to 2 above it is necessary to include a capacitor (C_D) in the feedforward circuit to the amplifier in parallel with the resistor R_1.
5. If $P + I + D$ action is required to combine 2, 3, 4, above, then

$$V_o = -\left(\frac{R_F}{R_1}e + \frac{R_F}{R_1 C_F}\int e\,dt + R_F C_D \frac{de}{dt}\right)$$

Black box analysis

It is useful to summarise some of the preceding work in this chapter utilising this analysis approach, concerned with external relationships and not internal circuitry (which includes operational amplifier with negative feedback loop). Amplifier power supplies and earthing are important and actual voltage used depends on the amplifier and conditions of working.

Refer to Figure 11.15 for illustrative connections:

A	is null offset	B	amplifier inverting input (–)
C	amplifier non-inverting input (+)	D	supply (–6 V)
E	spare terminal	F	supply (+6 V)
G	output (feedback to B)	H	null offset

Only two input signals (maximum), are considered to either B or C for simplicity of illustrations. Terminology for Figure 11.15 should be clear except for null offset, which needs elaboration. In derivation of equations the input current to the operational amplifier is assumed negligibly small, and where resistances are specified equal that these are exactly so. This is practically not possible. To balance input resistances, and reduce such offset, terminal C (when not in use) is earthed through a resistance (R_E) of magnitude equal to the equivalent resistance of feedback and input circuits in parallel. To balance any remaining offset, and this is particularly important for integrating