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INSTRUMENTATION AND CONTROL SYSTEMS

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REEDS MARINE ENGINEERING AND TECHNOLOGY

INSTRUMENTATION AND CONTROL SYSTEMS

Revised by Gordon Boyd

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PREFACE

This book aims to bridge the gap between the mathematical treatment often used by the specialist control engineer and the descriptive literature of a particular manufacturer.

It is written primarily for those with a general engineering background who have had little experience in instrumentation and control.

The work favours marine engineering but students and engineers in other industries should find it a useful book as the subject has a common basis. Text and examples cover the requirements of Department for Transport (Maritime and Coastguard Agency) for examinations as administered by the Scottish Qualifications Authority – and all Business and Technician Education Council (BTEC) and SCOTVEC – syllabuses and examinations for all marine engineer officers and cadets as defined by STCW 95 REG. III/2 & 3. Requirements for content of B. Eng. in Marine Engineering are also covered.

Some examples are included for purposes of analysis and understanding and it should be noted that although some represent long-established practices they can still be found in service.

Full use has been made of simplified diagrams and the work is presented from basic principles, using analogues where appropriate.

The introduction is followed by Chapters 1–5 on variable measurement in instrumentation. Chapters 6–8 on telemetering, electronic devices and final controlling elements link instrumentation to control. Chapters 9–14 cover theory, practice and components of process and kinetic control systems. Chapters 15 and 16 are intended to develop a broader knowledge of the subject and, by necessity, have a more analytic and mathematical approach.

A selection of test examples are included at the end of each chapter and specimen examination questions are added at the end of the book.

The reader should refer to manufacturers' instruction manuals to obtain a full and detailed description of a specific or particular component.

INTRODUCTION

Historical

Instrumentation has always been an integral part of technology. Development from simple level indicators, Bourdon tubes, moving iron and moving coil meters, etc. has been rapid. Progress in electrics and electronics has led to centralised recording and display stations with associated data processing, computing and control systems. Application to control with the requirement of accurate measuring (sensors), variable converting (transducers) and remote signal transmission (telemetering) has involved a close relation between measuring, processing and control systems. The advantage of electrical signal transmission is apparent in the development of instrumentation. Modular designs and interchangeable plug-in sub-assemblies have improved servicing of electronic units. Digital operation has replaced analogue operation in many applications.

The Watt governor (1788) was one of the first practical applications. Instability was recognised in the nineteenth century in hunting of steam engine speed and ship steering gears, and much analysis followed. Development in engineering plant and bridge equipment is likely to remain in a state of continuous improvement.

The third quarter of the twentieth century saw more complex systems which were mainly pneumatic and hydraulic, being replaced by development in electronics. Accelerated progress in digital electronics meant that the final quarter of that century saw the establishment of computer control.

These developments led to much greater unmanned operations of many shipboard activities to the extent that prolonged operation of sophisticated vessels could not be achieved with current manning levels without computer-based automation. They have also enabled more sophisticated operations from entertainment systems, to process plant control, survey processes, electric propulsion and dynamic positioning

Systems are generally classified by their field of operation. Process control such as temperature, flow, level and pressure; kinetic control such as displacement, velocity and acceleration, etc.

Utilisation

The degree of utilisation in marine practice varies a great deal. Individual control loops, from simple to fairly complex, have been in use for many years. Centralised data handling has been a relatively recent innovation. Ship's controls have developed rapidly with improved reliability. There are many links between localised instrumentation and control, the centralised data handling system and an integrated central control system. This requires that computer technology is involved in the interface between measurement and control. Computer control has developed from small programmed functions to quite sophisticated, direct, digitally controlled processes. A modern computer can be programmed not only to control machinery under all conditions but also to have start up, emergency and shutdown procedures.

Economy

Automation results in more efficient operation and reduced manpower in every case. There is increased initial cost due to specialised equipment provision which leads to increased insurance requirements and some increase in certain running costs, for example, staff training, skilled maintenance, etc. Overall running costs are reduced because of large cost savings in fuel and general maintenance, due to efficient operation and close supervision, as well as staff reductions. The annual savings, taking all factors into account, is well proven for controlled plants and the factor increases with increasing size of plant and machinery.

Safety

In most cases safety is improved by monitoring and control.

Essential requirements for any UMS ship to sail at sea are enumerated in the SOLAS 1974 Chapter II-1, regulations 46 to regulation 53. The main points discussed in this chapter are as follows:

1. **Bridge control of propulsion machinery**

   The bridge watchkeeper must be able to take emergency control action. Control and instrumentation must be as simple as possible.

2. **Centralised control and instruments are required in machinery space**

   Engineers may be called to the machinery space in an emergency and controls must be easily reached and fully comprehensive.

3. **Automatic fire detection system**

   Arrangement should be provided on an UMS ship to detect and give alarm in case of fire.

   Alarm and detection system must operate very rapidly. Numerous well-sited and quick-response detectors must be fitted.

4. **Fire extinguishing system**

   In addition to conventional hand extinguishers a control fire station remote from the machinery space is essential. The station must give control of emergency pumps, generators, valves, ventilators, extinguishing media, etc.

5. **Alarm system**

   A comprehensive machinery alarm system must be provided for control and accommodation areas.

6. **Automatic bilge high-level fluid alarms and pumping units**

   Sensing devices in bilges with alarms and hand or automatic pump cut in devices must be provided.

7. **Automatic start emergency generator**

   Such a generator is best connected to separate emergency bus bars. The primary function is to give protection from electrical blackout conditions. Local hand control of essential machinery. Adequate settling tank storage capacity. Regular testing and maintenance of instrumentation.

Terminology

The *detecting element* responds directly to the value of the variable. A *measuring element* responds to the signal from the detecting element and gives a signal representing the variable value. For example pressure (variable), Bourdon tube (detecting element) and linkage pointer, scale, that is, pressure gauge (*measuring element*). *The measuring unit* comprises detecting element and measuring element. Such a unit is used as a *monitoring element* (to convert, when necessary, the actual variable value into a converted variable value) of a process control system

Sensor is a term used for the detecting element. This is, by its very nature, essentially a *transducer.*

Transducer is a device to convert a signal (representing a physical quantity) of one form into a corresponding signal of another form, retaining the amplitude variations of energy being converted. For example, a microphone is a sound transducer (acoustic to electrical) and a loud speaker an electrical transducer (electrical to acoustic). A transducer may be an integral part of the measuring unit, for example pressure to displacement in a Bourdon pressure gauge. It may also be a separate unit converter especially suitable to change the signal to a better form for remote transmissions, for example, displacement to electrical in a differential transformer.

Telemetering may be defined as signal transmission over a considerable distance. In measurement this involves information transfer from detecting element to a central recording-display station. In control this involves control operating devices and related signal transfers. In telemetering systems the measuring unit is often called the *transmitter,* usually incorporating a transducer, and the recording unit some distance away is then referred to as the *receiver* which may have an associated transducer if required.

The terminology involved further to the above and especially related to control systems is now fairly extensive. Such terminology is covered in some detail at the start of Chapter 9.

In this book, instrumentation is generally confined to dynamic systems related to recording and control. Obviously the range is much wider if extended to include static-laboratory type instrument devices.

Comparison of Systems

Hydraulic systems are generally more restricted in application. Basically the technique is as for pneumatics but fluid cannot be allowed to escape and a recovery-storage system is required. General use is in the higher pressure range.

A combination of electronic measure-record instrumentation and pneumatic final power control element is very effective. Controllers may be either pneumatic or electronic. The former have generally been used because of proven reliability and ease of application to final power transmission. Electronic controllers are increasingly being used and electronic-electric systems have many obvious advantages.

The advantages of pneumatic systems are:

1. No heat generation and safe in an explosive atmosphere.
2. Less susceptible to power supply variation, but do have appreciable time lags.
3. Direct application, without transducers, to large final power actuators.
4. Immune to electrical interference.

The advantages of an electronic system are:

1. Small and adaptable with cheap flexible transmission lines.
2. No moving parts; can however generate heat.
3. Stable, generally accurate and very short time lags.
4. Low power consumption, direct application to computers, but often need final element transducers.
5. Flexible, upgradeable and adaptable to innovation.

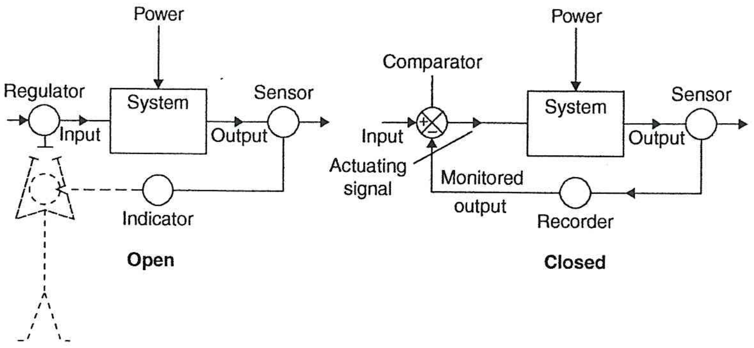
In every case equipment must be robust, reliable, interchangeable, simple and resistant to the environment. Appropriate commissioning time should be applied and regular skilled maintenance is required. Signal dc transmission is usually preferred although ac signals are essential for certain variables and easy amplification of ac is an inherent advantage.

Control Loops

An open loop system has no feedback and controller action is not related to final result.

will be maintained at a reasonable value related to outside conditions. However room temperature does not control fuel supply so that this is open loop.

Now to the open loop shown, add human operator, so closing the loop (dotted lines on Figure 0.1). This is a manually controlled closed-loop system.



▲ **Figure 0.1** *Control loops*

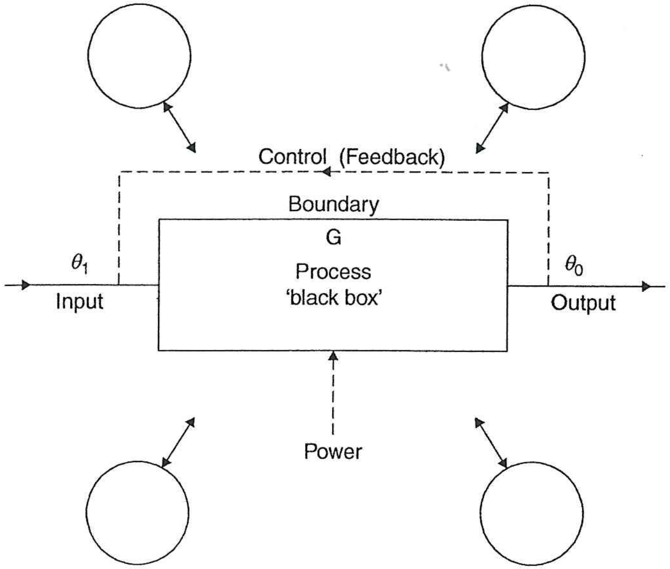
The automatically controlled closed-loop system is actuated by a signal dependent upon deviation (error) between input (set) and output values. Deviation only exists when monitored output (negative feedback) differs from input and this signal controls power supplied to output. For a closed-loop system, as sketched, output power is only controlled by, and not supplied by, the actuating signal. Closed loops have a self-regulating property.

System

This may be regarded as an assembly of linked components within a boundary. A system may have one input and a related output dependent on the effect of that system (transfer function *G*).

$$\theta_0 = G\theta_i$$

The boundary, represented as a 'black box', may include a complex system which need not be analysed if *G* is provided. More complex systems have interconnecting links to



▲ **Figure 0.2** *Systems*

Analogue

Many different physical phenomena behave in a similar way, that is, are analogues of each other. Two examples are air escape from a storage vessel and electrical charge loss from a capacitor.

Rate of change of pressure α pressure

Rate of change of charge α voltage

That is, rate of change of variable $x = -kx$

$$\frac{dx}{dt} = -kx$$

A solution, where *C* is the *x* value when time is zero, is:

$$kt = l_n \frac{C}{x}$$

Voltage (or current) can readily be made analogous to physical phenomena.

Digital

A digital device manipulates 'bits', that is, discrete items of information – illustrated by the digital clock representation. States are on/off, equal/unequal, etc. and the binary digit system is utilised.

Computers

Electronic analogue computers are essentially simulators on which electrical analogues of various systems can be analysed and illustrated.

The digital computer is a machine for routine, high-speed repetitive arithmetic.

Microprocessors and Microcomputers

First-generation mainframe computers (approx. room size) were often, for the same capacity, replaced by minicomputers (say desk size) and in turn by microcomputers (hand size and smaller) following the silicon chip and integrated circuit (IC) development.

A microprocessor (μP) – component product – may be a single chip unit or a collection of unassembled processor-related components such as central processor unit (CPU), timers, memories, interfaces, etc.

A microcomputer (μCP) – board product – assembly of μP components mounted on a printed circuit board is sufficient to make up a working computer.

Beside the microprocessor other critical functions are input/output buffers, random access memory (RAM) and read only memory (ROM).

While the μP, consisting of arithmetic logic units plus sets of registers and control circuits, cannot be used by itself to create a system it can, with support from a dedicated controller or μCP. The μP is applied to Instrumentation and Control in the form of the

1

TEMPERATURE MEASUREMENT

This chapter discusses the practical aspects of temperature measurement (thermometry). No consideration is applied to absolute standards or to the consideration of special techniques related to extreme temperatures, etc.

Mechanical Thermometry

Mechanical thermometry is the measurement of temperature using mechanical means. The techniques are therefore well established.

Liquid in glass thermometers

Mercury can be used from −38°C (its freezing point) to about 600°C. For the higher temperatures an inert gas at high pressure is introduced as the boiling point of mercury is about 360°C at atmospheric pressure; special glass is also required.

Alcohol is used in the range −80°C to 70°C (or toluene) and pentane can be used to −196°C.

Total immersion types are most accurate, especially when the fluid is coloured and magnification is used. In many cases only the temperature *differential* is required so

Health and safety concerns preclude the application of substances such as mercury and toluene in most commercial applications.

Filled-system thermometers

These thermometers are filled with liquid, vapour or gas. All utilise a bulb, connecting capillary and usually a Bourdon tube mechanism, responding to pressure change from volume variation (liquid), for pointer or pen operation. Some systems incorporate a compensating capillary and bourdon tube to allow for changes of ambient temperature. Alternatively a bi-metallic link for compensation can be incorporated into the mechanism.

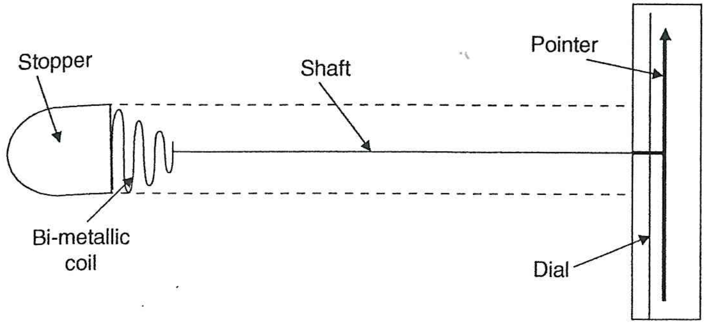
A common type of liquid-filled system utilises mercury in steel which can be pressurised for high temperature duty to 600°C. Such devices are most useful for remote sensing and telemetering back to a central instrumentation panel. The capillary bore is about 0.02 mm and the scale is generally linear but calibration must allow for heat variation. Power is sufficient for pointer, pen or transducer operation.

Vapour pressure thermometers commonly use freon, alcohol or ether which partly fills the system as liquid, and the remainder is vapour filled. Measurement of vapour pressure gives an indication of liquid surface temperature and is usually used in the range −50°C to 260°C, with the upper limit fixed by the critical temperature of the liquid which must have a low boiling point (high vapour pressure). The scale is non-linear; ambient variations can be neglected but there can be appreciable time lags and the device is not well suited to remote indication.

Gas-filled thermometers usually employ nitrogen or helium under high pressure; pressure is proportional to absolute temperature at constant volume. The usual temperature range is −50°C to 430°C and the scale is linear. Compensation for ambient temperature variation is difficult. When used as a sensor linked to a pneumatic transducer it is a very effective device.

Bi-metallic thermometers

The principle of operation of bi-metallic devices is that of differential expansion of two different materials rigidly joined together, one on the other, as a strip of bi-metallic



▲ **Figure 1.1** *Mechanical thermometer (bi-metallic type)*

a Ni–Mo alloy gives a good bimetallic strip. The helix coils or uncoils with temperature variation and as one end is fixed the movement rotates shaft and pointer. The range of the instrument is fixed by the materials used.

Electrical Thermometry

Resistance thermometer

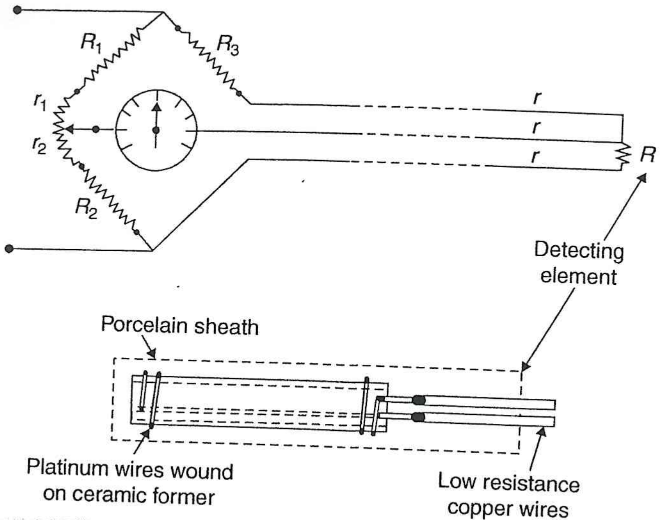
The electrical resistance of a metal varies with temperature and this relationship is usually expressed as $\rho_\theta = \rho_0(1 + \alpha\theta)$, where ρ_θ is the specific resistance at temperature θ°C, ρ_0 is the specific resistance at temperature 0°C and α is a constant which depends upon the metal and is called the temperature coefficient of resistance.

Figure 1.2 shows diagrammatically a resistance type of temperature measuring unit using the well-known Wheatstone bridge principle. $r_1 r_2$ is a variable resistance used for balance purposes; at balance we have:

$$\frac{R_1 + r_1}{R_2 + r_2} = \frac{R_3 + r}{R_4 + r}$$

r is the resistance of each of the wires and since each wire will be subjected to the same temperature variation along its length their resistances will always be equal.

When the temperature detecting element is subjected to temperature alteration its



▲ **Figure 1.2** *Resistance thermometer*

is being done another pointer can be moved simultaneously and automatically to give the temperature – this is known as the null balance method Alternatively, the galvanometer can give the temperature reading directly, in this case no variable resistance r_1 r_2 would be required.

For the measurement of ambient temperature conditions the resistances, apart from the temperature measuring resistance, would have to be made of a metal whose resistance does not vary with temperature. A metal which nearly fulfils this requirement is constantan.

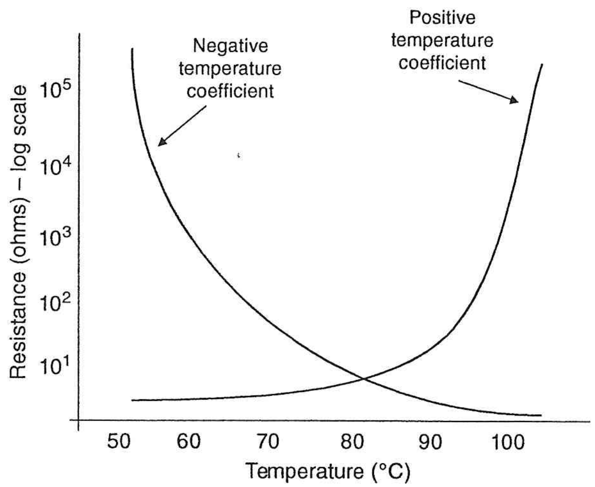
Resistance thermometers can be exceedingly accurate. Platinum is the most suitable sensing wire element but copper and nickel wire are used in the range −100°C to 200°C and tungsten, molybdenum and tantalum are used to 1200°C, in protective atmospheres. The platinum element usually has a resistance of 100 ohms at 0°C (hence the term *PT100*), in which case resistance of wires is limited to about 3 ohms. Use up to 600°C with twin wires is often acceptable with the three-wire method used for higher accuracy; measurement is by Wheatstone, Kelvin or Mueller bridges or potentiometric methods.

Thermistor (Thermally sensitive resistor)

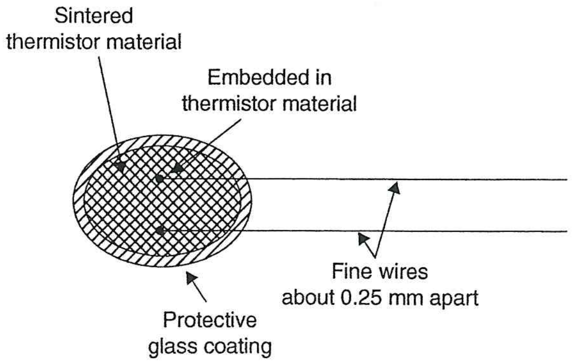
Thermistor or thermally sensitive resistor devices are among

a characteristic of a resistance change with temperature change. Included in this category are carbon resistors and doped germanium units (see Figure 1.3).

Thermistors are made of semi-conducting materials manufactured by sintering (i.e. heating under pressure) powder mixtures of metallic oxides such as manganese, nickel, cobalt, copper, iron or uranium. The size and configuration can be controlled so that rods, beads, discs and washer shapes can be produced as desired. Figure 1.4 shows an ellipsoid of thermistor material, with wires about 0.25 mm apart firmly embedded in the material making good electrical contact. The whole assembly may be coated with glass to give strength and protection.



▲ **Figure 1.3** *Thermistor resistance to temperature characteristics*



Washer-shaped thermistors may be fitted over bolts or studs. Beads or rods of thermistor material are suitable for use as probes.

The advantages of thermistors are as follows:

1. Relatively small and compact, the bead arrangement shown could have a diameter up to 2.5 mm with a resistance up to about 100 megaohms.
2. Low specific heat, hence the thermistor does not take away too much heat.
3. Physically strong and rugged.
4. Relatively high temperature coefficient of resistance, it could be as high as ten times that of some metals.
5. They can be used for extremely low temperature measurement with great accuracy.

The mathematical relationship for thermistors is given by:

$$\rho_\theta = \rho_0 e\beta(1/\theta - 1/\theta_0)$$

where ρ_θ is the specific resistance at temperature θ, ρ_0 is the specific resistance at temperature θ_0 and β is a constant which depends upon the material used in the construction ($\beta \simeq 4000$). The characteristic is shown in Figure 1.3.

The large negative temperature coefficient of resistance of NTC thermistors may be explained by considering the number of electrons available for carrying current.

Few electrons are available at low temperatures, but as the temperature increases the kinetic energy of the electrons increases and this enables them to move from inner tightly bound orbitals to the outer conduction bands of the atom. With more free electrons available to carry current the resistance to current flow reduces.

In metals, where there are many free electrons, increase in temperature leads to 'traffic jams' of electrons and hence the resistance to current flow increases.

Positive temperature coefficient (PTC) thermistors have a less linear characteristic and tend to be less suited to measurement applications. They may be configured to have a 'knee' in their characteristic curve at a particular temperature. In the characteristic shown in Figure 1.3 resistance increases rapidly at above 90°C so that detection of temperatures likely to be damaging, to, say, thermoplastic insulators, is highly reliable.

high as 1600°C. The small thermal mass can lead to self-heating and coupled with high sensitivity and exponential characteristic means instability must be carefully watched. The thermistor merely replaces the resistance element on one limb of a bridge circuit in the measuring unit.

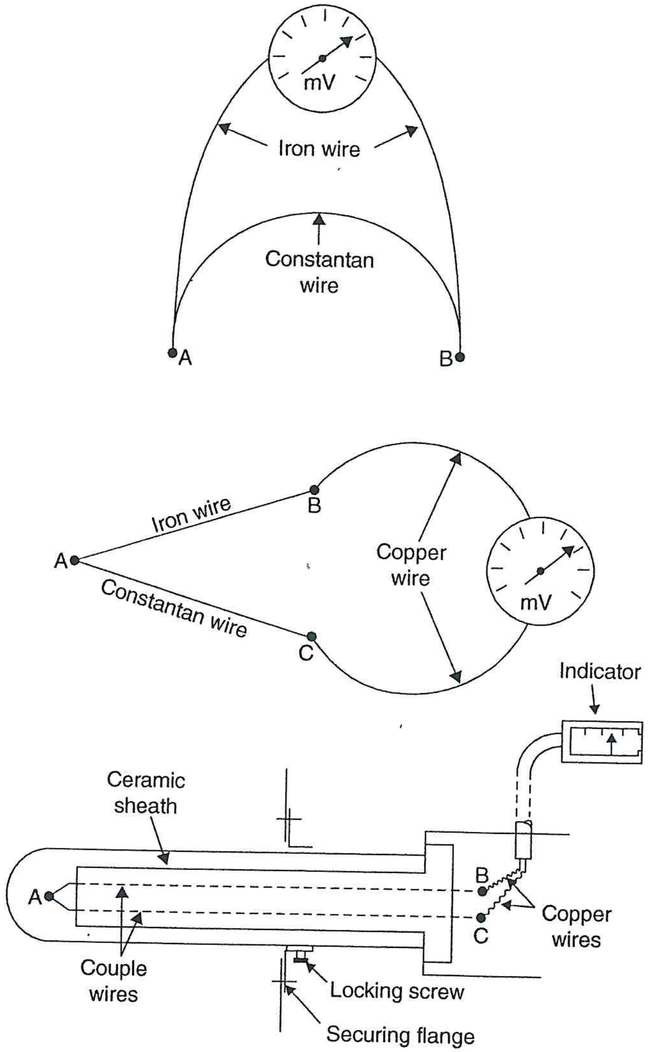
Thermocouple

Whenever a junction formed between two dissimilar homogeneous materials is exposed to a temperature difference, an emf will be generated which is dependent on that temperature difference and also on the temperature level and the materials involved. This thermoelectric emf is called the Seebeck effect (Seebeck discovered it in 1821) and is an algebraic sum of two other effects discovered by Peltier and Thomson. The two materials, usually metals, form the thermocouple.

Figure 1.5 shows a thermocouple consisting of two wires, one iron and one constantan (i.e. a copper–nickel alloy), with a millivoltmeter coupled to the iron wire. If the junctions A and B are maintained at the same temperature no current will flow around the circuit since the emfs in the circuit will be equal and opposite. If, however, A is heated to a higher temperature than B then current will flow since the emf at one junction will be greater than the opposing emf at the other junction.

A third wire can be introduced as shown in Figure 1.5, where AB and AC form the couple wires. Providing the junctions B and C are maintained at the same temperature, the introduction of the third wire BC will not affect the emf generated. Hence A will be the hot junction and B with C will form the cold junction. Couple wires AB and AC shown as iron and constantan respectively can be made of various metals and alloys, the choice depending upon temperature of operation; the wire BC would generally be longer than the couple wires and could be made of copper. Figure 1.5 shows the device in detail.

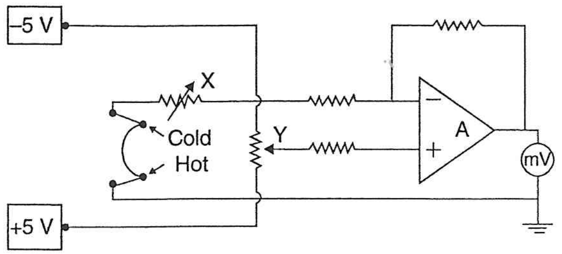
In a practical thermocouple system the cold junction B and C may be at a relatively high temperature due to the environment. This would mean that the temperature difference between the hot and cold junctions would be small and therefore in millivolts. The indicator itself could then become the cold junction if the wires from terminals B and C to the indicators are of the same material, or material with similar characteristics, to the couple wires. The wires are then called compensating wires and the cold junction temperature would be reasonably constant if the indicator is within an air-conditioned



▲ **Figure 1.5** *Thermocouple*

A copper (+) constantan (–) couple is used up to about 350°C, constantan being a 40% Ni 60% Cu alloy. Up to 850°C an iron-constantan couple is used with a chromel (90% Ni 10% Cr) and alumel (94% Ni 2% Al) couple up to 1200°C. Average emf is 0.05 mV/°C, which compares with about 18 mV/°C for a thermistor. Platinum–platinum plus 10% rhodium couples have been used to 1400°C.

The emf generated is usually given by an expression of the form:



▲ **Figure 1.6** *Electronic thermocouple*

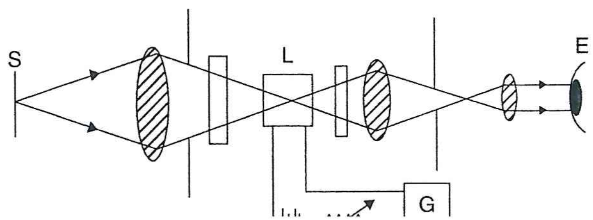
where θ is the temperature and A, B, C, D, are constants of diminishing order. Figure 1.6 shows an electronic thermocouple with operational amplifier (A) giving 0.1 V/°C. Y is for calibration at cold junction temperature and X for other temperature calibrations.

Radiation pyrometers

When temperatures are above the practical range of thermocouples, or the 'target' is not accessible, or an average temperature of a large surface is required then radiation pyrometers are used. It is generally based on black body radiation and the work of Stefan, Boltzmann and Planck with amended factors of emissivity to allow for variation from the ideal black body radiator. Types of radiation pyrometers are optical, radiation and two colour. The former will be considered.

Optical pyrometers

Referring to Figure 1.7, S is the source and rays enter lamp box L after passing through the lens, aperture and absorption filter. The lamp is electric and current and voltage are measured at G. Rays leaving L pass through a red filter, lens and aperture to eye E.



The device is often known as a disappearing filament unit. Both source and reference, the latter being the filament of a small vacuum lamp, are observed through the microscope. Power to the lamp is adjusted until the reference source disappears into the main source. Power is calibrated to give a temperature reading directly. Correction factors apply for the filters used and the device is a selective radiation pyrometer as only a narrow band of radiation wavelength is utilised. Radiation pyrometry is particularly useful for evaluation of temperature in furnaces, molten metals, process controls, etc. Non-contact infrared measurement devices are used extensively for condition monitoring and for fault finding in bearings, gearboxes and electrical plants.

Photo-electric pyrometers

There are three types of photo-electric cells: photo-emissive, photo-conductive and photo-voltaic. Photo-voltaic pyrometers are discussed here.

Incident light falls on p-type silicon layered on to n-type silicon backed with a metallic strip. The emf generated is measured, after calibration, by a galvanometer or self-balancing potentiometer connected across the p-type and the backing.

Such pyrometers are best suited to measuring small radiation sources and are stable and accurate with a very quick response time, which makes them suitable for distance remote control systems.

Note: Many of the measuring devices for temperature considered previously, particularly electrical types, could also be classified as telemetering or transmitting units as the signal is readily conveyed over considerable distances to a remote measuring, recording or display station. This applies in many cases to other such devices in the following chapters. The detecting element (sensor) is inherently a transducer in operation for many instrument units.

Test Examples

1. Describe, with the aid of simple sketches, three types of temperature measuring devices. State how they are graduated and where they are used.
2. Sketch and describe an electrical instrument used for reading temperature at a remote distance. State the

3. Explain with reasons how Wheatstone bridge networks are employed in circuits of electrical resistance thermometers, explosive gas sampling devices, or any similar application. Sketch the circuit for such a device indicating the function of the Wheatstone bridge.
4. Sketch and describe a temperature measuring system employing a thermocouple.
5. Explain why an NTC thermistor is likely to be more useful as a measuring device than a PTC thermistor.

2

PRESSURE MEASUREMENT

When a fluid is in contact with a boundary it exerts a force at right angles to that boundary. This force is the pressure exerted by the fluid.

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}\ \text{N/m}^2$$

There are three categories of pressure:

1. *Absolute pressure*: Measurement of pressure related to a datum of absolute (complete) vacuum.
2. *Gauge pressure*: Measurement of pressure related to a datum of local atmospheric pressure.
3. *Differential pressure*: Measurement of the difference between two unknown pressures neither of which is atmospheric nor complete vacuum.

Atmospheric Pressure

A barometer is an instrument for measuring atmospheric pressure. It is affected by seasonal changes of temperature. Barometers are therefore used tor the measurement of altitude and also as one of the aids in weather forecasting. The value of atmospheric

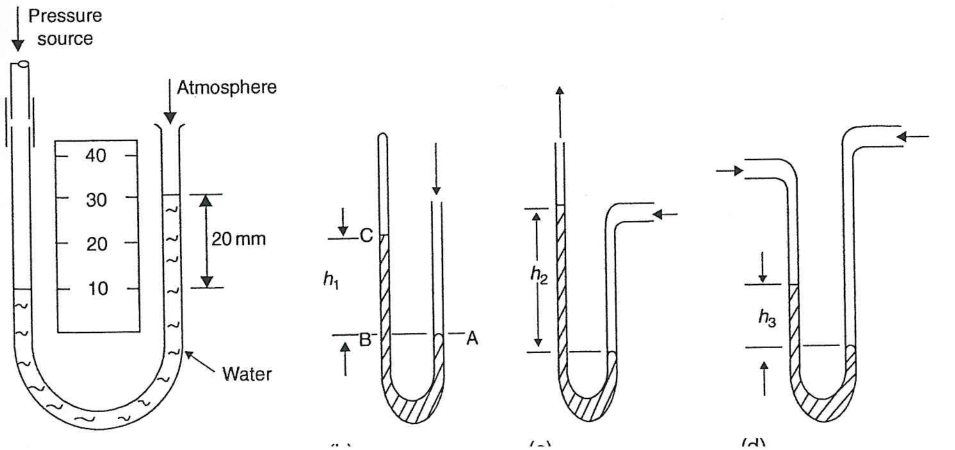
Construction and principle of operation

A simple barometer consists of a glass tube, less than 1 m in length, sealed at one end, filled with mercury and then inverted into a trough containing more mercury. Such a barometer is shown in Figure 2.1 and it is seen that the level of the mercury column falls leaving a vacuum. Atmospheric pressure acts on the surface of the mercury in the trough and this pressure is equal to the pressure at the base of the mercury column in the inverted tube, that is, the pressure of the atmosphere is supporting the column of mercury. If the atmospheric pressure falls the barometer height h decreases. Similarly if the atmospheric pressure rises then h increases. Thus atmospheric pressure can be measured in terms of the height of the mercury column.

It may be shown that for mercury the height h is 760 mm at standard atmospheric pressure, that is, a vertical column of mercury 760 mm high exerts pressure equal to the *standard value of atmospheric pressure.*

There are thus several ways in which atmospheric pressure can be expressed:

$$\begin{aligned}\text{Standard atmospheric pressure} &= 101\,325\ \text{Pa or } 101.325\ \text{kPa}\\ &= 101\,325\ \text{N/m}^2 \text{ or } 101.325\ \text{kN/m}^2\\ &= 1.01325\ \text{bars or } 1013.25\ \text{mbars}\\ &= 760\ \text{mm of mercury}\end{aligned}$$



Pressure measurement methods

Liquid balance

The measured pressure is balanced by the pressure exerted by a column of liquid, for example, a manometer.

Commonly used fluids are water for low pressure and mercury for higher pressure.

It is limited in use because of size:

$$1\text{ bar} = 750\text{mm Hg}$$
$$1\text{ bar} = 10\text{m water}$$

It is useful for measuring low differential pressures, for example, the pressure drop across a main engine air cooler or other fan pressures (see Figure 2.1). Absolute pressure measurement: h_1 mmHg

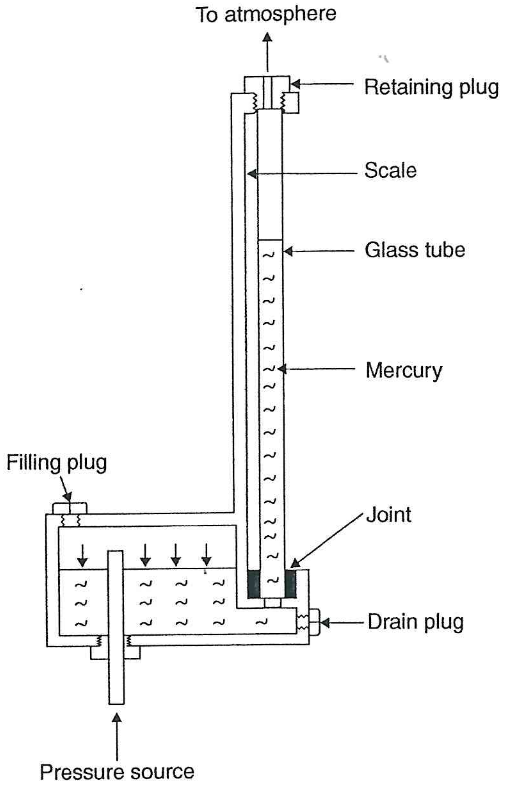
Gauge pressure measurement: h_2 mmHg

Differential pressure measurement: h_3 mmHg

Mercury Manometer

A well type mercury manometer is shown in Figure 2.2.

This instrument measures pressure of a higher order than that measured by the water manometer, such as scavenge or supercharge air pressure for IC engines. The uniform bore glass tube is small in diameter so that when mercury is displaced from the well into the tube, the fall in level of mercury in the well is so small it can be neglected. Hence the pressure reading is indicated directly by the level of mercury in the glass tube. The relative density of mercury is 13.6 hence 1 mm of mercury is equivalent to a pressure of 9.81 × 13.6 N/m^2, that is, 134 N/m^2 or 0.134 kN/m^2. A special application is the vacuum gauge (kenotometer), which is a combined barometer and manometer, with the scale on the right hand side calibrated in absolute pressure.



▲ **Figure 2.2** *Mercury manometer (well type)*

Mercury Barometer

This instrument resembles the mercury manometer in Figure 2.2 but the top of the glass tube is sealed at a vacuum and the pressure source would be the atmosphere.

If we assume the atmospheric pressure is supporting 760 mm of mercury in the tube, then:

$$\begin{aligned}\text{Atmospheric pressure} &= 760 \times 0.134\\ &= 102\text{ kN/m}^2\\ &= 1.02 \times 10^5\text{N/m}^2\\ &= 1.02\text{ bar}\end{aligned}$$

The value of the atmospheric pressure varies slightly with climatic conditions. Hence to ascertain true absolute pressures the barometer reading should be taken at the same time as that of the gauge pressure.

If for example we wish to obtain the absolute pressure in a container and the readings were:

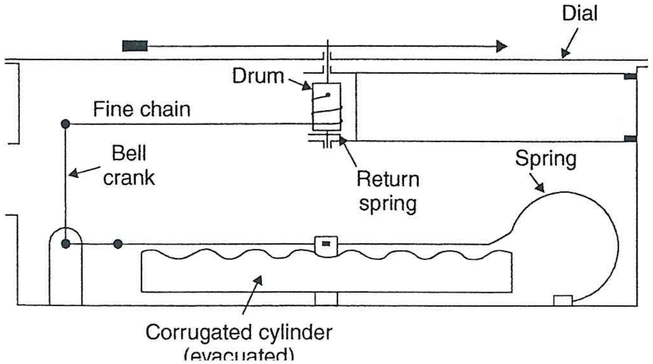
Condenser gauge reading 742 mm
Barometer gauge reading 762 mm

then, condensed pressure is

$$
\begin{aligned}
&= (762 - 742) \times 0{\cdot}134 \\
&= 2.68\ \text{kN/m}^2
\end{aligned}
$$

Aneroid Barometer

The aneroid barometer is shown in Figure 2.3. It consists of a corrugated cylinder (detecting element) made of phosphor bronze or other similar material, a steel spring, bell crank, pointer, dial and case (measuring element). The corrugated cylinder is completely evacuated and hence the pressure of the atmosphere tends to collapse it. The centre of the corrugated cylinder deflects downwards if atmospheric pressure increases and the spring causes deflection upwards if atmospheric pressure decreases. Cylinder motion is transmitted to the instrument pointer.



Displacement of an Elastic Sensing Element

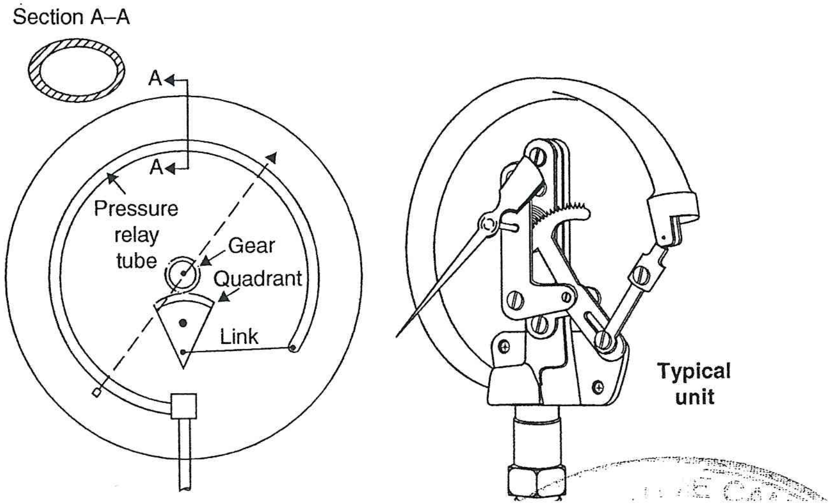
Elastic sensing elements are, commonly, one of the following.

Bourdon tube

A pressure relay tube is the principal working component (detecting element). This tube which is semi-elliptical in cross section is connected to the pressure source. When the tube is subjected to a pressure increase it tends to unwind or straighten out and the motion is transmitted to the gauge pointer through the linkage, quadrant and gear (measuring element). If the tube is subjected to a pressure decrease it winds, or coils, up and the motion is again transmitted to the pointer. This gauge is therefore suitable for measuring pressures above or below atmospheric pressure. A diagrammatic sketch is shown in Figure 2.4.

Materials used in the construction of the gauge are solid drawn phosphor bronze or stainless steel for the pressure relay tube. Bronze or stainless steel is used for the quadrant, gear and linkage.

The Bourdon movement is frequently used in transducers and controllers to vary output signals in pneumatic or electrical form.



Pressure gauge (Schaffer)

This type utilises a strong flexible metal diaphragm (detecting element) which moves up as pressure increases. The device is shown in Figure 2.5. Again this device can also be used as a transducer (pneumatic or electric) in telemetering or control with an output signal proportional to diaphragm movement. Similar remarks apply to most detecting (sensing) devices (as detailed in Chapter 6).

Diaphragm

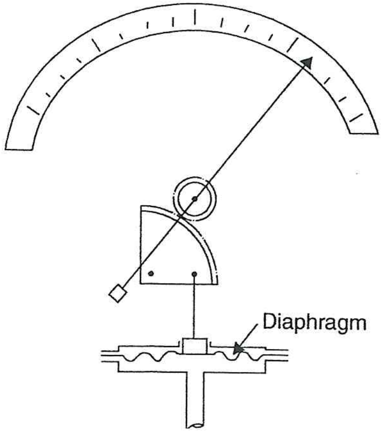
Pressure is measured as the amount of deformation of a flexible membrane.

A modified version of this is used when a general-purpose gauge is not suitable due to the corrosive or viscous nature of the liquid being measured.

This type of gauge should not be used with liquids that solidify under normal conditions, which would clog the gauge and may make it difficult to remove from the pipeline.

Bellows

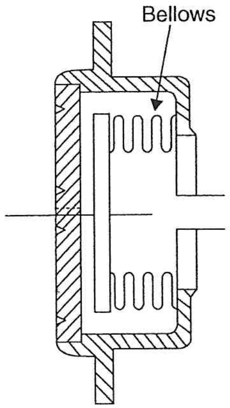
Pressure is measured by the amount of elongation of a bellows.



The bellows is used extensively in pneumatic instrumentation for precise control and/or fine movement

All pressure-measuring devices work on the force balance principle.

Measured pressure = Pressure exerted by a column of liquid
= Force exerted by an elastic membrane

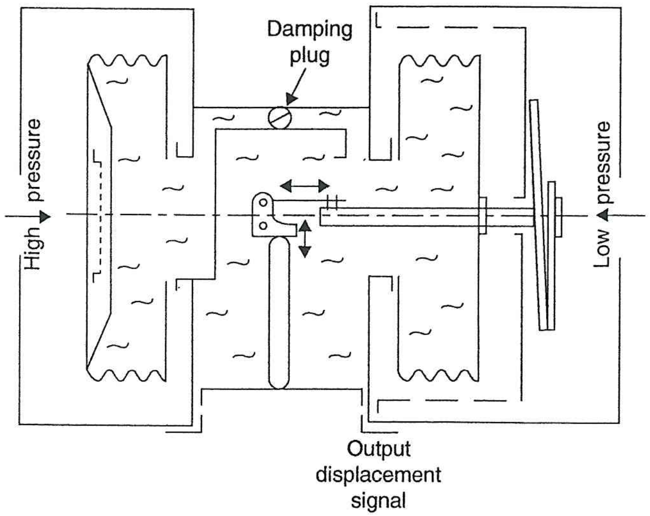


Differential Pressure Cell (D/P Cell)

Figure 2.5 illustrates a single diaphragm subject to differential pressure (D/P). The D/P cell is often used in direct D/P recording as well as flow and level applications. The detecting element of the cell is a bellows, or diaphragm, whose mechanical movement is used to indicate, or transduced to, electrical or pneumatic signal output. Low pressure will result in a slack diaphragm.

As an alternative to a one-membrane diaphragm, a sealed capsule (twin membrane) can be inserted in the cell body and secured so that different pressures are applied at each side. The capsule can be filled with a constant viscosity fluid (for a fairly wide temperature range) which also damps oscillation. Silicone is such a fluid. Again mechanical movement of the capsule is proportional to D/P. Capsule stacks are also used.

Another type of D/P cell utilises two separate bellows. Such a design, often called a



▲ **Figure 2.6** *Differential pressure cell*

the horizontal spindle, one end of which has a flexure strip and the other end is fastened to flat plate springs. Equilibrium exists when spring force equals D/P. Mechanical travel is via the flexure strip, lower seal diaphragm and vertical spindles to indicator or transducer. A bi-metallic strip adjusts bellows fluid capacity to allow for volumetric expansion. This device is shown dotted within the left-hand bellows. The bellows are often made of welded stainless steel discs and inner faces to protect it if excess pressure s applied

Piezoelectric Pressure Transducer

Piezoelectric effect

When a force acts on certain crystals an electrostatic charge is formed on the surface of the crystals. The charge is proportional to the applied force (Figure 2.7).

Crystals used are:

- Quartz (natural)
- Lithium sulphate (synthetic)

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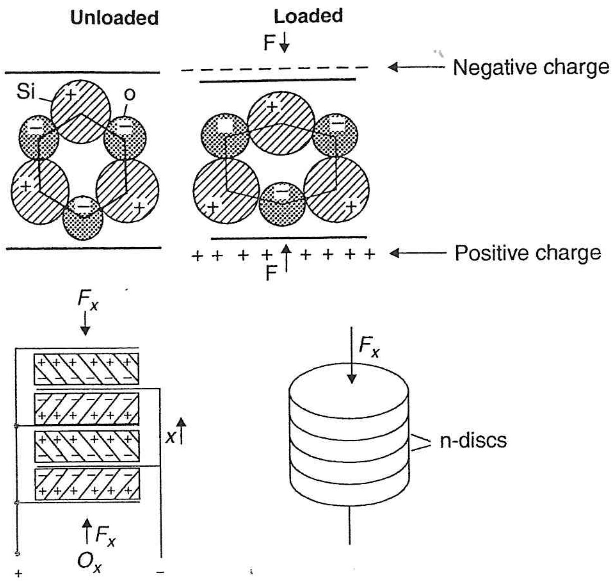


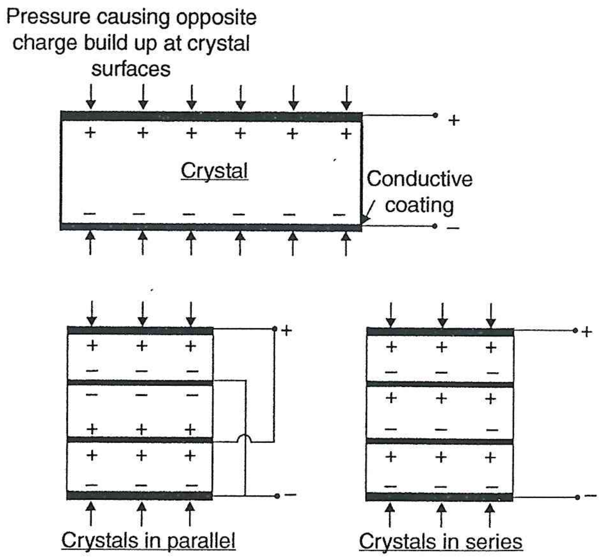
▲ **Figure 2.7** *Piezoelectric crystals – crystal structure (simplified)*

With *certain* solid crystals having an asymmetrical electric charge distribution, any deformation of the crystal produces equal external unlike electric charges on the opposite faces of the crystal. This is known as the piezoelectric effect.

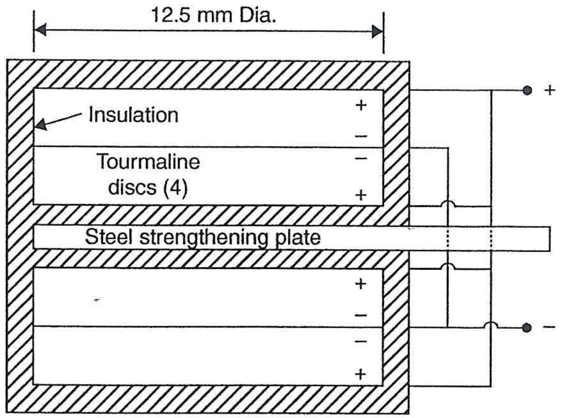
Deformation of the crystal can be caused by pressure and the charges produced can be measured by means of electrodes attached to the opposite surfaces of the crystal.

Crystal materials can be naturally occurring or man made. Quartz (i.e. SiO_2) is a material that can be used in temperature environment up to 550°C; it is stable mechanically and thermally. Barium titanate, a ceramic produced commercially, is also used but tourmaline is principally used because of its good electrical properties. The output voltage from tourmaline crystal, acting as a detecting element (sensor) and transducer, is a linear function of the pressure applied and the charge sensitivity is approximately 2×10^{-10} coulomb/bar; it can be used for pressures varying from 1.03 to 800 bar. The only drawbacks are (1) its sensitivity to temperature change (i.e. its pyroelectric effect), hence ideally it should be used only under controlled temperature conditions and (2) it is more suited to pressure variations than to static pressure.

Figure 2.8 shows crystals in series and parallel. The series arrangement gives a higher output voltage for the same pressure applied whereas the parallel arrangement reduces



▲ **Figure 2.8** *Piezoelectric crystals*

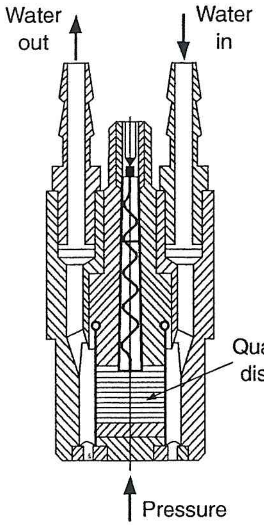


▲ **Figure 2.9** *Piezoelectric sensor*

coated with insulating material to help minimise the effects of temperature variation in the medium whose pressure is being measured.

Pyroelectricity, like piezoelectricity, makes use of the spontaneous polarisation of materials such as ferro-electrics. Temperature variations causing changes in polarisation can be utilised in very accurate calorimetric recordings.

Design



▲ **Figure 2.10** *Design of Piezoelectric transducer*

Operation

The Piezoelectric transducer has to be used with what is known as a charge amplifier. The Piezoelectric effect is static electricity and any measuring instrument will tend to discharge the static charge.

A charge amplifier has high input impedance, which makes it, in effect, an open circuit thus preventing discharge. The charge amplifier gives an output voltage proportional to the input charge.

Piezoelectric transducers are used for measuring high pressures that are constantly varying. They are not particularly suitable for measuring pressures that are static. The devices lend themselves ideally for use in a diesel engine combustion pressure measurement system.

Strain Gauge

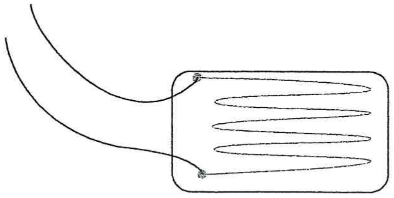
A strain gauge can be used to measure the elastic deformation of a material due to the pressure acting on the material.

In the elastic range metals have a proportional relationship between stress (force or pressure) and strain (elongation). When the stress acting on a material increases then the material elongates with a corresponding decrease in cross-sectional area (Poisson's ratio). As resistance = $\rho\ l/A$ (ρ = resistivity, l = length, A = cross-sectional area). Then increasing stress, or pressure, gives a proportional increase in resistance. Common materials for strain gauges are Nichrome (Nickel–Chromium) and Constantan (Copper–Nickel).

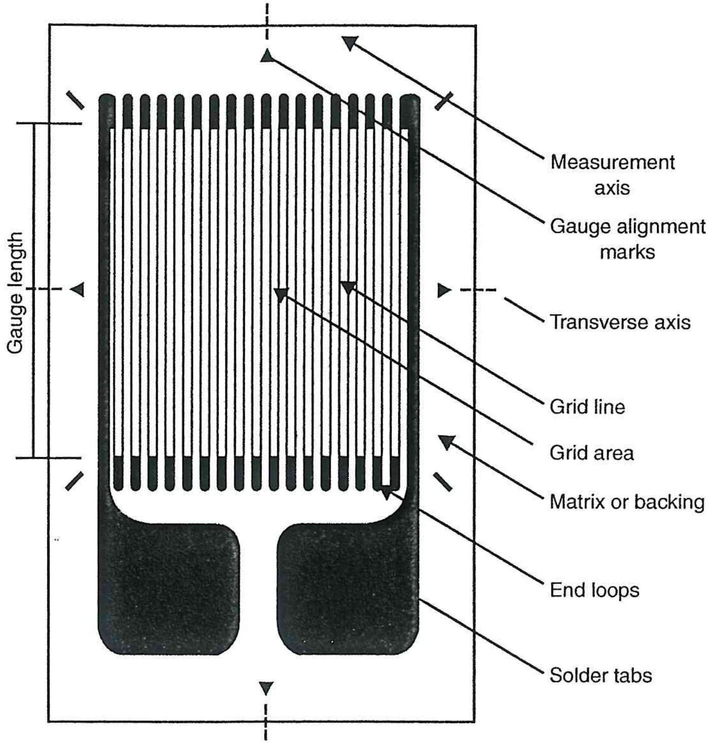
Very fine wires are bonded to an insulator – usually an epoxy resin – and are then securely bonded to the surface of the material that is deforming by the pressure. The wire gauge deforms as much as the parent material and its change in resistance is measured.

Typically the foil wire is about 4 μm (0.004 mm) thick and using the looped layout the total length of wire is increased for the size of the sensor. This gives a greater resistance and correspondingly greater changes in resistance. The wire is fixed to a flexible backing material such as paper, resin or plastic which is glued to the surface under test; wires are soldered or spot welded. One alternative is the foil type where the grid is etched from thin metal foil using printed circuit techniques. Another alternative is a *p* or *n* doped silicon semi-conductor which can be very small and is extremely sensitive. The concept is shown in Figure 2.11.

The range is up to 700 bar with an accuracy of 0.01–1.0%. It can be temperature limited due to the adverse effect on the bonding cement. A maximum temperature of 150°C is typically quoted.

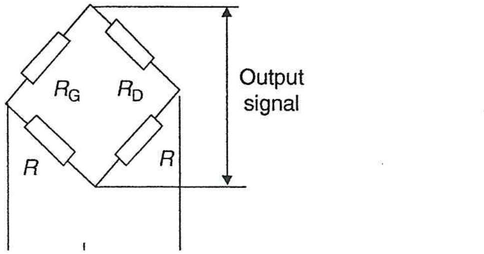


Design



▲ **Figure 2.12** *Foil strain gauge terminology*

Operation



The strain gauge is typically used as one leg of a Wheatstone bridge arrangement with a second (dummy) gauge used as a temperature compensator.

Uses

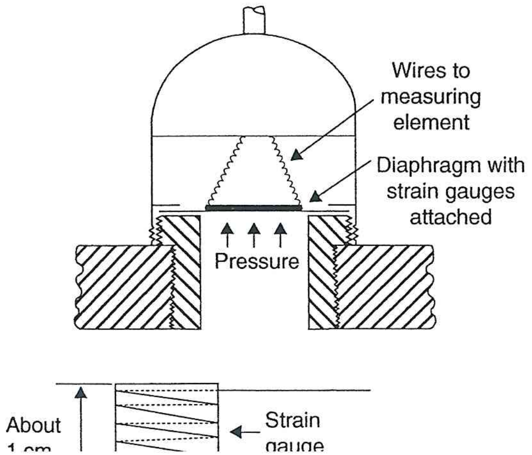
The strain gauge can be attached to practically any material and can measure the pressure inside a vessel simply by detecting the deformation of the vessel shell. No openings in the vessel are required therefore using a strain gauge for high-pressure vessels means that no access to the vessel, and thus no weakening, occurs.

The *unbonded* strain gauge is essentially a pressure sensor and a typical design is shown in Figure 2.14.

The detecting (sensing) element can be fastened directly to the diaphragm as shown, or alternatively, a central force rod can transmit diaphragm movement to the detecting (sensing) element consisting of plate springs with posts on the periphery upon which the strain gauge wire is wound.

In all strain gauges, to minimise resistance change due to temperature effects, it is usual to employ materials with a low temperature coefficient of resistance for the wire, such as constantan. Alternatively a second compensating wire loop can be incorporated.

The measuring element for strain gauges is generally a Wheatstone bridge circuit with temperature compensating resistance and strain gauge resistance arranged as two, of the four, resistances and a central galvanometer and constant dc voltage source. Null balance methods can also be used, or for high sensitivity the bridge may be fed by ac voltage and the galvanometer replaced by a transistor amplifier and detector. The measuring unit is effectively a transducer, that is, displacement-electrical.



Test Examples

1. Sketch and briefly describe three types of pressure-measuring devices.
2. Sketch and describe a Bourdon-type pressure gauge. State the materials used in construction. Discuss briefly how the Bourdon movement can be utilised for telemetering devices.
3. Describe, with the aid of a sketch, any type of D/P cell. Detail three applications in instrumentation on using the D/P cell.
4. Explain the operation of a foil strain gauge and describe a bridge method to achieve an output voltage proportional to the strain.

3

LEVEL MEASUREMENT

Liquid-level sensors are usually classified under two headings: direct methods and inferential methods.

Direct Methods

Float operated

The float is generally a hollow cylinder or ball working on direct action or displacement principles. Level variation is transmitted by tape or wire and pulley or torque tube (usually with counterweights fitted) to the indicator. High or low level alarm contacts are easily arranged. Pulley movement can also be arranged to operate a contact arm over an electrical resistance so varying current or voltage to indicator or receiver.

These instruments have been the main stay of the petroleum automatic tank gauging market for most of the twentieth century.

Changes in the liquid level inside the tank raise or lower a large stainless steel float. The float is attached to a powerful negator spring sometimes via a perforated tape. The negator spring provides constant tension, which balances the float on the liquid level. The perforated tape engages pins on a sprocket wheel that, in turn, drives the counter

Float gauges can accurately and continuously measure liquid levels in the refrigerated tanks of liquefied gas carriers. The gauge can operate in tanks up to 50 m deep, and at temperatures as low as −200°C.

When the gauge is not in use the float can be securely stored beneath the gauge head using the lockup mechanism. A transmitter may be fitted to the unit allowing total integration into the shipboard cargo and control system.

Sight glasses

Various types are in use depending on working conditions. The simple boiler water glass gauge with toughened glass and the plate type of water gauge for high pressures are typical.

Probe elements

Floatless types of level sensors can be arranged where the liquid is a conductor. Sensing electrodes, rods or discs, vary electrical circuits when they are in contact with liquids. A typical example is detection of the fluid level in a tank by capacitive techniques (see Figure 3.1). This technique is used in oil–water interface detection in oil–water separators (see Chapter 13 in this volume).

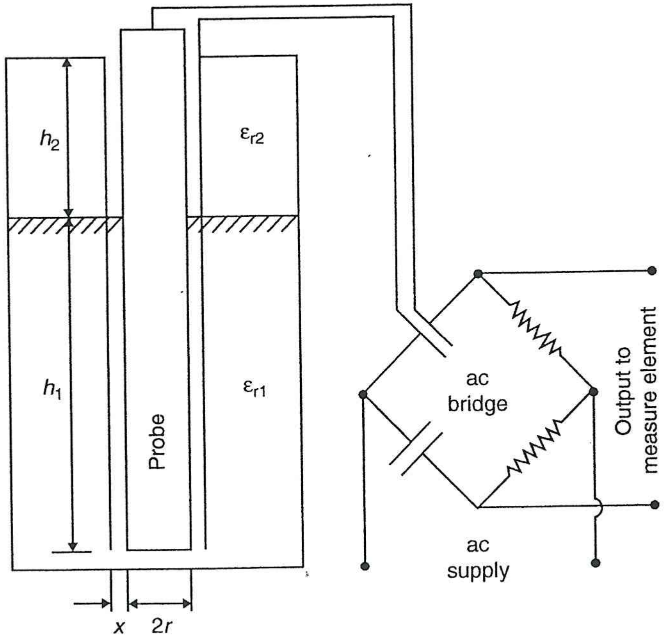
Detection of level is measured by variation of capacitance, which is accomplished by alteration in dielectric strength. One plate of the capacitor is a probe, possibly made of stainless steel, the other is the shell and both are connected to an ac bridge which is supplied with high frequency, low voltage alternating current. As the interface moves the dielectric strength (relative permittivity ε_T) alters.

An approximate expression for the capacitance in an ac bridge circuit (Figure 3.1) is:

$$C = \frac{\varepsilon_0[\varepsilon_{r1}h_1 + \varepsilon_{r2}h_2]}{2l_n[1 + x/r]}$$

and since ε_{r2} is approximately unity for air ($\varepsilon_{rl} > 1$)

$$C = \frac{\varepsilon_0[\varepsilon_{r1}h_1 + h_2]}{2l\ [1 + x/r]}$$



▲ **Figure 3.1** *Level sensor (capacitive)*

where ε_0 is the permittivity of free space, ε_r is the relative permittivity, h_1 is the head of fluid being measured, h_2 is the distance from fluid surface to tank top, 2_r is the diameter of the probe, x is the separation between the circular plates and l_n is the natural logarithm.

Inferential Methods

Pressure elements

The static-pressure method is extensively used.

$$p = \rho g h$$

Where p is pressure, ρ density of fluid, g gravitational acceleration, h fluid head. Any of the sensing and measuring devices described in Chapter 2 are therefore applicable to

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inside or outside the vessel with suitable correction factors applied for correct datum and density of fluid. The differential pressure cell is often used in level measurement. Telemetering for remote reading is readily applied, pneumatically or electrically, to the displacement movement of the level (pressure) sensor.

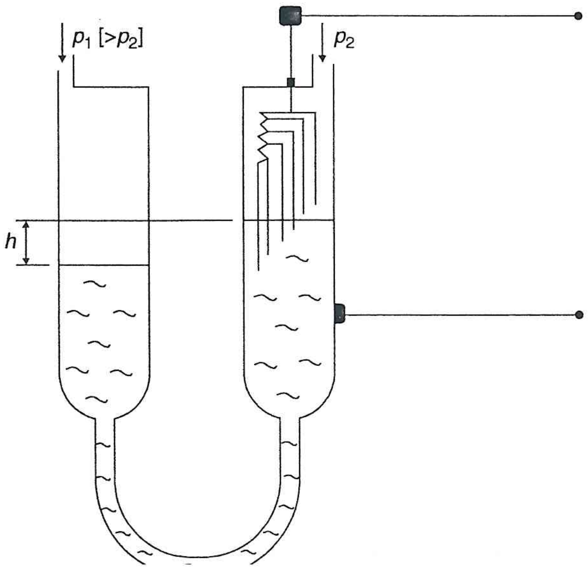
Manometer types

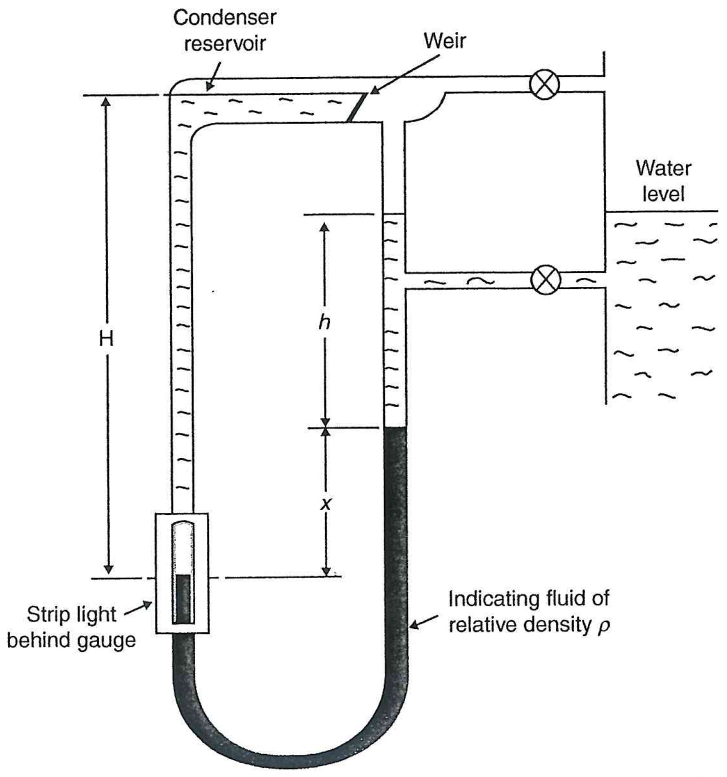
The static pressure equation is applicable and devices have been described in Chapter 2. Three types of remote level indicators are now described.

For the Electroflo electrical type as sketched in Figure 3.2 the difference in level h is directly proportional to the difference between the level of the liquid in the tank and a datum. The transducer element contains resistances immersed in mercury to form an electrical circuit with transmission to remote indicator receivers.

Figure 3.3 is a diagrammatic arrangement of the Igema remote water-level indicator. The lower portion of the U tube contains a coloured indicating fluid which does not mix with water and has a density greater than that of water.

The equilibrium condition for the gauge is $H = h + \rho x$ where ρ is the relative density of the indicating fluid. H, h and x are variables.





▲ **Figure 3.3** *Igema remote water level indicator*

If the water level in the boiler falls, h will be reduced, x will be increased and H must therefore be increased. The level of the water in the condenser reservoir is being maintained by condensing steam.

If the water level in the boiler rises, h will be increased, x will be reduced and H must therefore be reduced. Water will therefore flow over the weir in the condenser reservoir in order to maintain the level constant.

A strip light is fitted behind the gauge which increases the brightness of the (red) indicating fluid, which enables the operator to observe at a glance, from a considerable distance, whether the gauge is full or empty.

Figure 3.4 is another type of remote water-level indicator. In this case the operating fluid is the boiler water itself. The operation of the gauge is as follows.

If we consider a falling water level in the boiler, the pressure difference across the

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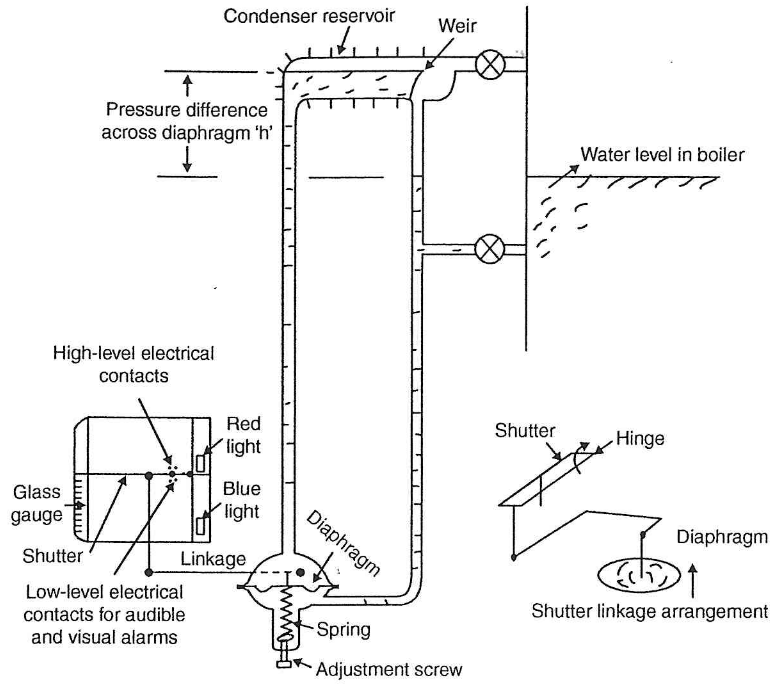


▲ **Figure 3.4** *Remote water-level indicator*

shutter which in turn moves down pivoting about its hinge, causing an increase in the amount of (red) colour and a decrease in the amount of (blue) colour seen at the glass gauge. It will be clearly understood that if the water level now rises then the (red) will be reduced and the (blue) increased.

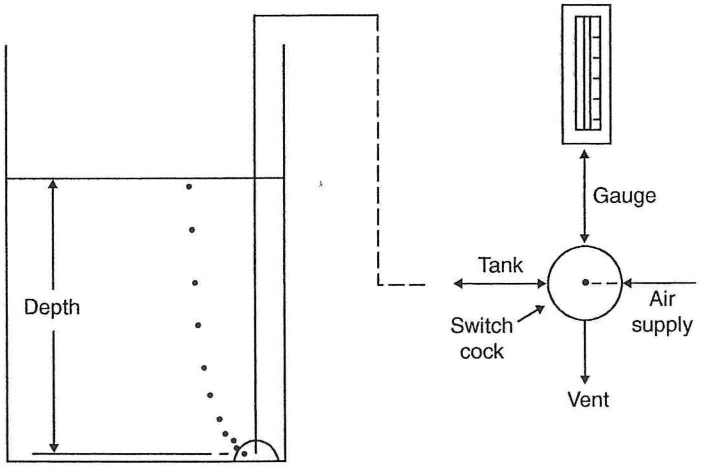
Separating the (blue) and (red) colours, which are distinctive and can clearly be seen from a considerable distance, is a loose fitting black band which moves with the shutter, giving a distinct separation of the two colours.

An adjustment screw and spring are provided to enable the difference in diaphragm load to be adjusted. Hence correct positioning of the shutter and band in relation to the reading of a glass water gauge fitted directly to the boiler is possible.

Both devices shown in Figures 3.3 and 3.4 are also capable of being observed by closed circuit television systems to extend the distance between transmission and reception. Alternatively telemetering by pneumatic or electrical transmitters is readily arranged. A D/P cell would be suitable for the former and any displacement transducer, such as a differential transformer, could be used for the latter.

Purge systems

For small air-flow rate, about one bubble per second, a pressure equal to that in the dip tube will be applied to the indicator as shown in Figure 3.5. This simple bubbler device is an arrangement that is similar to the *pneumercator* used for determining depths of water and oil in tanks. Air supply to the open-ended pipe in the tank will have a pressure which is directly proportional to the depth of liquid in the tank.



▲ **Figure 3.5** *Pneumercator level indicator*

Ultrasonic and nucleonic devices

An *ultrasonic* transmitter and receiver (utilising piezoelectric crystals) are located above the tank so that two echoes are received, one from the liquid surface and one from the tank bottom. The time separation between the two signal echoes is proportional to liquid depth – which can be displayed and measured by an oscilloscope or edge-triggered digital timer.

Nucleonic units have a shielded radioactive strip source from which gamma radiation is picked up by a detector on the opposite side of the storage vessel.

Non-contact Level Measurement

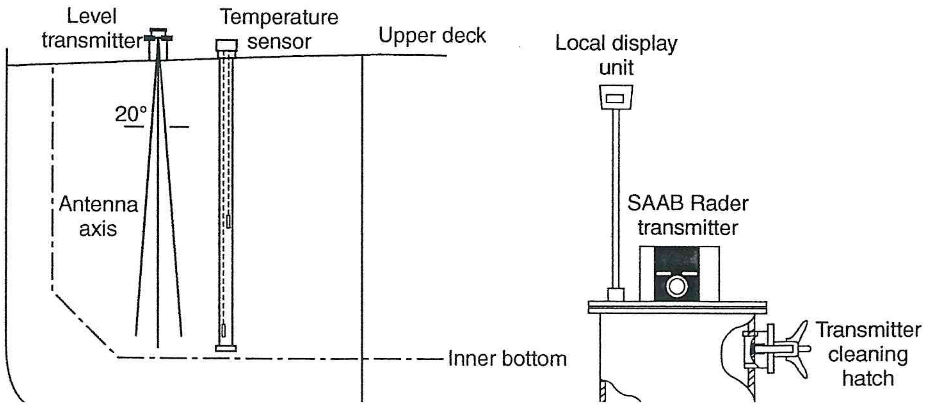
Radar tank gauging

Radar tank gauges are a 'downward-looking measuring system' installed on the tank deck-head. Operating on the time-of-flight method, they measure the distance from the reference point (process connection) to the product surface. Radar impulses are emitted by an antenna, reflected off the product surface and received again by the radar system. The distance to the product surface is proportional to the travel time of the impulse. Due to the nature of the microwave, radar tank gauges need to be equipped with functions to suppress interference echoes (e.g. from edges and weld seams) in the tank so they are not interpreted as level measurement. Radar technology is suitable for measuring a wide range of petroleum products with dielectric constants of 1.4 and higher (Figure 3.6).

Integrated radar together with other devices, such as pressure or temperature sensors, can be read locally and/or communicated to the cargo control room, providing a completely integrated system on some modern instillations.

Advantages claimed for these installations are as follows:

- Non-contact measurement: No moving parts hence low maintenance
- High (±1 mm) accuracy



Intrinsically safe 2- or 4-wire, low-cost installation

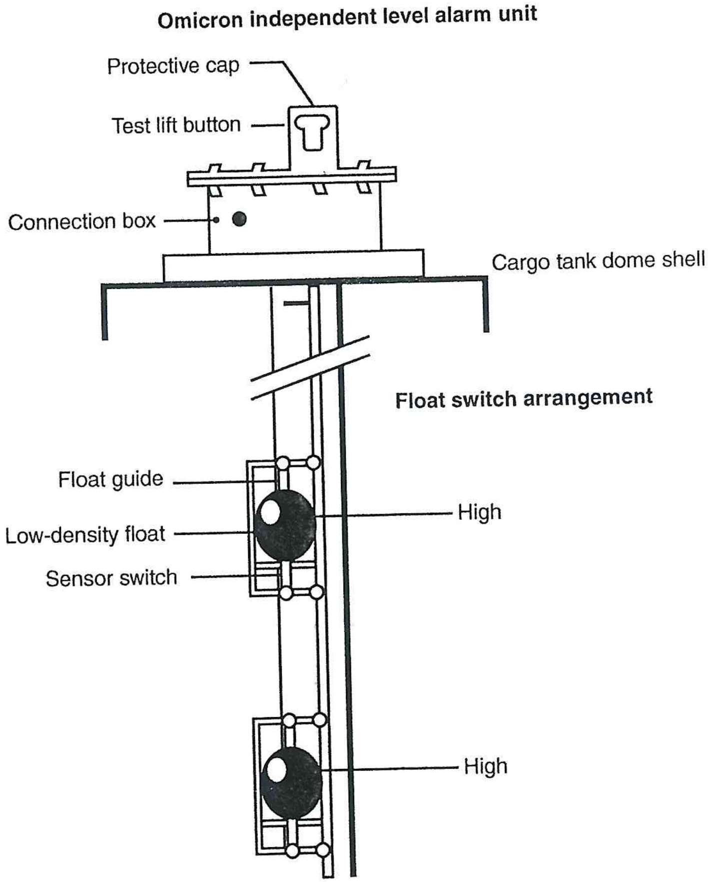
Standalone instrument or integrated tank gauging system

Easy onsite operation via menu-driven alphanumeric display

Gas-tight process connection.

nkers systems are usually hardwired for safety and security reasons.

ometimes additional high-level alarms can be set lower than normal and this can be sed for topping off purposes as shown in Figure 3.7.



▲ **Figure 3.7** *High-level alarm system*

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Test Examples

1. Sketch and describe a distant-reading boiler water-level gauge. Explain its principle of operation.
   Give two ways in which the gauge would give incorrect readings. State the routine maintenance necessary to ensure maximum reliability at all times.
2. Sketch and describe any type of level sensor. Discuss the modifications necessary to utilise the device as a transmitter in a telemetering system.
3. Describe, with a sketch, an instrument used to indicate the level of liquid in a tank. Can the result be used to determine pressure above a given datum? If so, state the other variables likely to be involved.
4. Describe the arrangement of an air-purge tank system.

4

FLOW MEASUREMENT

Many of the techniques utilised in flow measurement employ principles also used in pressure and level measurements. Flowmeters are generally divided into two fundamental types, that is, quantity meters and rate of flow meters; flowmeter generally implies the latter.

Quantity Meters

These devices measure the *quantity* of fluid that has passed a certain point. *No time is involved.* Types are usually classified as *positive* or *semi-positive.* A typical positive type utilises the flow to drive a reciprocating piston and a counter is attached. The meter acts like a conventional engine with fluid pressure supplying motive power. Stroke length and cylinder dimensions fix the quantity delivered per cycle. Semi-positive types are usually rotary. A form of gear pump, or eccentrically constrained rotor, can be used which is driven by the fluid. Quantity is measured by number of rotations (cycles) and fluid per cycle.

Rate of Flow Meters

of passage. They are therefore classified as *inferential*, that is, volume inferred from velocity. There are two fundamental components of the rate of flow meter. The *primary element* is that portion of the instrument which converts the quantity being measured into a variable to operate the secondary element, for example, orifice and pressure tappings from a venturi. The *secondary* element measures the variable created by the primary element, for example, a differential pressure (D/P) cell.

Integrators

Quantity meters are more expensive and less suited to deal with large fluid quantities than rate of flow meters. Rate of flow meters are often used as quantity meters by fitting an integrator. As a simple example consider variable flow. The rate of flow can be measured at set time intervals and a graph plotted, the area of which gives quantity over the time period required. In practice this is performed mechanically or electrically by an integrator. One type is based on the planimeter principle and another type (escapement) utilises mid-ordinate techniques from a heart-shaped cam drive. Flat-faced cam drive, or worm and wheel designs, can be used with a turbine wheel or helix type of primary element having a counting mechanism secondary element, incorporating the integrator to interpret quantity. The integrator is often included within the receiving unit of telemetering systems and a typical device is illustrated and described in Chapter 6. Integration is readily performed electrically by use of a conventional watt-hour meter. It should be understood that integration is a general instrumentation operation whose use is not restricted only to flowmeters.

Square Root Extraction

When inferential devices are used, with velocity sensors utilising D/P techniques, the velocity is not directly proportional to pressure difference, or head. Velocity is related to the square root of pressure, or head, that is, a curve of flow rate plotted against pressure, or head, is of parabolic form.

This means that if a pressure difference is used in a sensor device connected to a manometer or pointer through a linear mechanism, the rate of flow scale on the characteristic is not an embarrassment. If, however, the D/P has to be used in a control system the square root is usually extracted to give a signal which is directly proportional to the fluid flow rate. Square root extraction is described later in this chapter under D/P inferential devices. It is difficult to integrate readings of a system when the square root extraction is not applied.

Inferential-Rotational

These can be considered as mechanical or electrical.

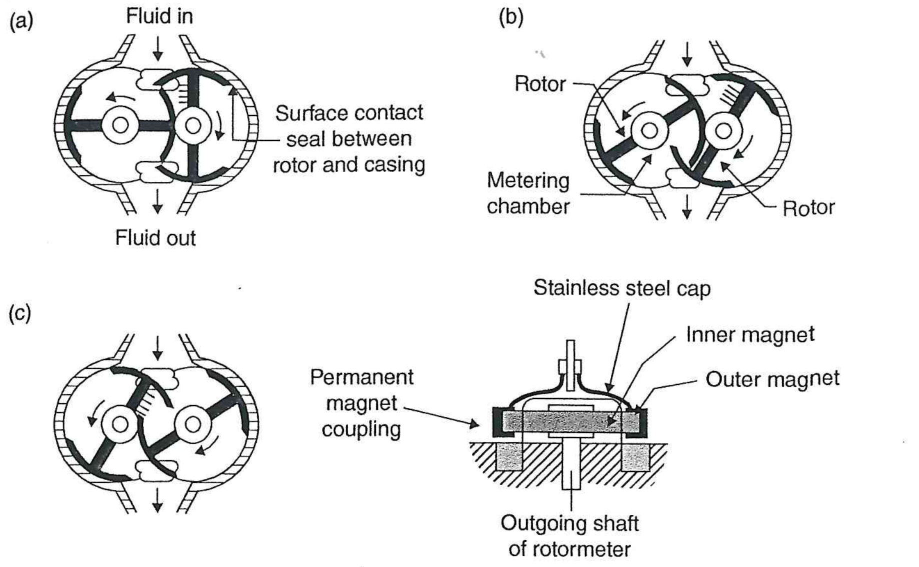
Mechanical-type flowmeter

Designs are usually of the 'turbine wheel' type with speed of rotation directly proportional to linear flow velocity and, with area of passage fixed, the volume rate is inferred. A wheel, fan or helix is inserted in the pipe or duct, mounted vertically or horizontally, gear trains are used to interpret the movement. This is the principle of vane anemometers.

Rotormeter

The measuring principle is illustrated in Figure 4.1 where the meter, of the duplex rotor positive displacement type, is shown in three specific positions. This rotary flowmeter operates on the displacement principle, the measuring system consisting of a casing with two rotors. Bearing bushes are provided on either side of each rotor so that the rotor runs clear of the casing and spindle in a radial direction. The rotor is located in an axial direction by means of end bearings so that it runs clear of the bearing plates. Both the end bearings and the spindle are fixed to the shaft while the bearing bushes are fixed to the rotor and rotate relative to the end bearings and the shaft. Each rotor carries a gear wheel at the rear through which the rotors are coupled together. The rotary movement of the rotors is transmitted to the outgoing shaft of the meter through a gearwheel fitted at the front of one of the rotors. Consider Figure 4.1.

In position 'A', the left-hand rotor is fully relieved from load while the liquid pressure acts on one side of the right-hand rotor causing this rotor to rotate in clockwise direction.



▲ **Figure 4.1** *Flowmeter (mechanical)*

In position 'B', the liquid in the displacement chamber is pressed by the right-hand rotor to the outlet.

In position 'C', the right-hand rotor is entirely relieved from load while the liquid pressure now acts on one side of the left-hand rotor so that it takes over the task of the right-hand rotor.

To reduce leakage losses to a minimum, it is essential to provide for effective sealing between inlet and outlet. To this end, the rotors seal off against the casing by surface contact.

In the rotormeter, the motion of the rotors is transmitted to the external parts by the attraction between two permanent magnets, an inner and outer magnet. The maximum torque transmitted by this system is 0.4 Nm. This arrangement offers the following practical advantages.

Leakproof transmission, which means that it is impossible for corrosive or hazardous liquids to leave the meter.

Protection of attached parts or instruments. If the mechanism of external parts or instruments should be blocked for whatever reason, the permanent magnetic coupling unning at constant speed. Hence, at ambient temperature the magnetic coupling has n eight-fold safety margin which will, in most instances, be amply sufficient to take ccelerations and decelerations (which are the most frequent operating conditions) ithout slipping of the coupling.

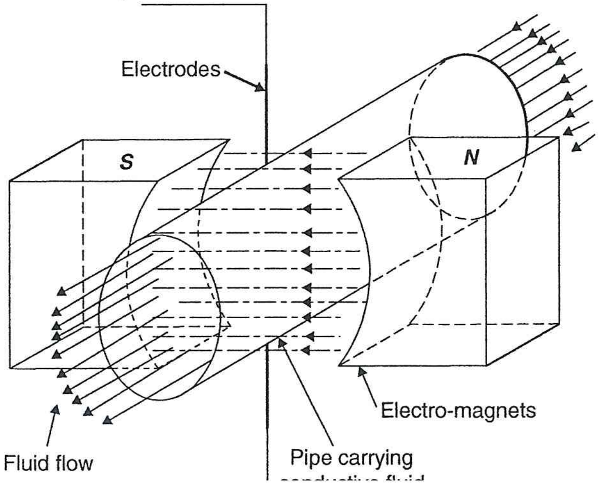
lthough the torque transmitted by the magnets decreases with rising temperature, xperience has shown that even with a liquid temperature of up to 250°C the available orque is still amply sufficient.

Electrical-type flowmeter

ne type utilises rotating vanes with a small magnet attached to one vane and a coil in he pipe wall. The electrical impulse can be counted on a digital tachometer calibrated flow rate. The design now described has no moving parts.

lectro-magnetic flowmeter

his type is shown in Figure 4.2. The principle utilised is that of a moving conductor (the quid) in a magnetic field generating a potential difference. In the simple arrangement hown, the two electro-magnets are supplied with current (ac is preferred to dc to educe polarisation of the dielectric). There are two sensor electrodes. If B is the flux lensity of the field, v, velocity of flow, d, pipe diameter, then in suitable units the emf enerated at any instant is given by:

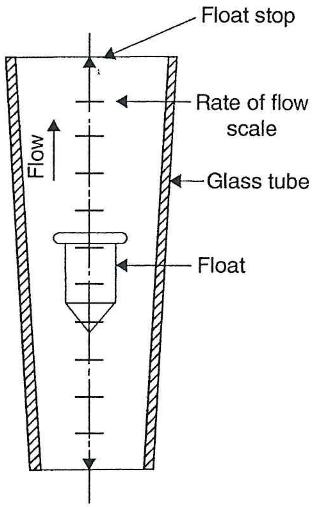


$$e = Bvd$$

For constant B and d, e is directly proportional to v.

This type does not strictly fit into the classifications given but a brief description is appropriate at this stage. A sketch is given in Figure 4.3.

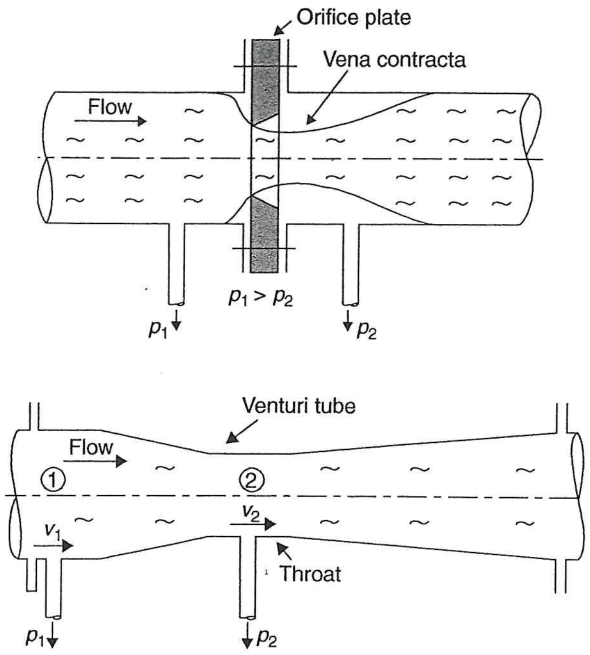
This is a variable-area meter. A long taper tube is graduated on its vertical axis. The float moves freely in the tube and by an arrangement of shaped flutes in the float it slowly rotates. As flow rate increases the float rises in the tube, so that the annular area increases, which means that the D/P across the tube is at a constant value. The float can be arranged with a magnet attachment and a follower magnet outside will transmit motion to a pointer via linkage if required.



▲ **Figure 4.3** *Rotameter*

Inferential-Differential Pressure

Primary elements



▲ **Figure 4.4** *Flow sensors*

both the orifice plate and venturi sensors using energy conversion to produce a pressure difference which can be utilised by the secondary element to provide a signal for direct reading, telemetering or control.

Using the venturi flow sensor as an example the theory involved is as follows:

Assuming unit mass, and energy at points 1 and 2 being the same, that is, neglecting friction and shock losses as small, then from Bernoulli for incompressible flow of fluid of density ρ:

$$\text{KE at 1} + \text{PE at 1} = \text{KE at 2} + \text{PE at 2}$$
$$\tfrac{1}{2}v_1^2 + p_1/\rho = \tfrac{1}{2}v_2^2 + p_2/\rho$$

where KE is kinetic and PE is pressure energy.

The equation for continuity of flow for area A is:

$$v_1 A_1 = v_2 A_2$$

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$$\dot{m} = k\sqrt{p}$$

where p is the pressure difference $(p_1 - p_2)$ and k is a meter constant in terms of areas and density, which includes a discharge coefficient factor. Frictional losses are greater for orifice than for venturi meters. Seal pots protect sensor leads.

Secondary elements

Any D/P device can be used as a secondary element including the manometer, diaphragm and D/P cell as described in Chapter 2. The measure scale will be non-linear for direct recorders due to the square root relation and telemetering, control and integration will be generally unsatisfactory unless a correcting unit is fitted. When manometers are used various compensations can be used. The simple manometer can utilise a curved measuring limb and the well-type manometer can be arranged with a shaped chamber or may include a parallel tube and a shaped displacer. Other direct measuring devices utilise a cam incorporated in the mechanism, an example is the ring balance. In the electrical resistive sensor described in Chapter 3 (Figure 3.2), when used for flow measurement, the electrode tips immersed in mercury are arranged in a parabolic curve with each other which gives the compensation. Three flow sensor square root extraction devices are now considered in more detail.

Square root extractors

Figure 4.5 is one type of square root extractor using a parabola shaped bell which can be connected through linkage to mechanical, pneumatic or electrical display and control systems.

The D/P is applied with the high pressure inside and the low pressure outside the bell.

(a) With its changing cross-sectional area and buoyancy, due to change in D/P, the bell movement is made to be directly proportional to the square root of the D/P. Hence the bell movement is directly proportional to the fluid flow being sensed by the orifice plate or venturi sensor.

This device is often called a Ledoux Bell. For air flow measurement, instead of the bell
(b) being shaped, a shaped displacer is arranged in a separate chamber. The displacer is

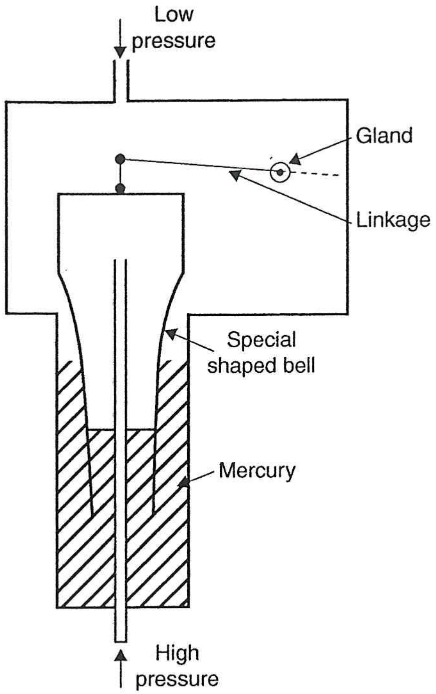

Figure 4.5 *Square root extractor (mechanical)*

igure 4.6 is a diagrammatic sketch of another type of square root extractor utilising ıe pneumatic flapper nozzle position balance principle (as described in Chapter 6).

efer to Figure 4.6. The D/P from a flow sensor acts on a horizontal lever B, this effects ıe amount of air escaping from the nozzle and hence the pressure in the bellows ressure alteration in the bellows causes movement of the vertical lever A. The very nall relative motion between levers A and B provides square root extraction. The utput air signal is directed to the measure element (recorder) or controller.

igure 4.7 shows a square root extraction technique using electrical force balance (as escribed in Chapter 6). The D/P, in electrical signal form represented as variable ıput, is applied to the left-hand side. With the force balance beam in equilibrium ıe output signal is variable $\sqrt{x}$. Variation in input signal, causing unbalance, can be rranged to be re-balanced by suitable adjustment to output signal. This can be done ı various ways; one method could be to connect the right hand of the beam to ifferential capacitor in the output circuit (see Figure 6.6). This is a closed loop but ithout electrical connection between input detected signal and output measured

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Figure 4.8 root extra used in th operation.
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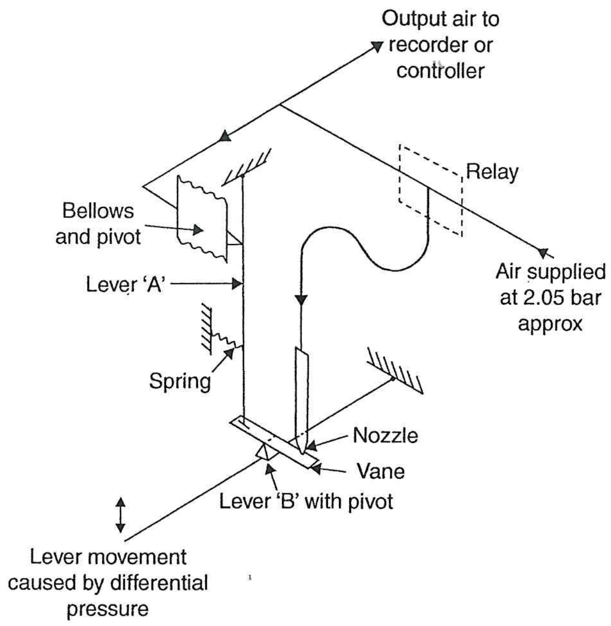
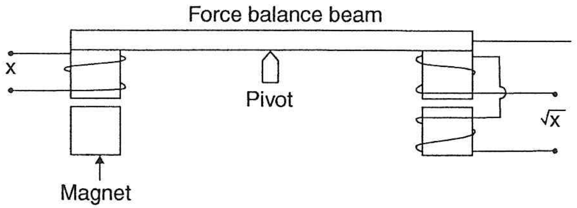


▲ Figure 4.6 *Square root extractor (pneumatic)*

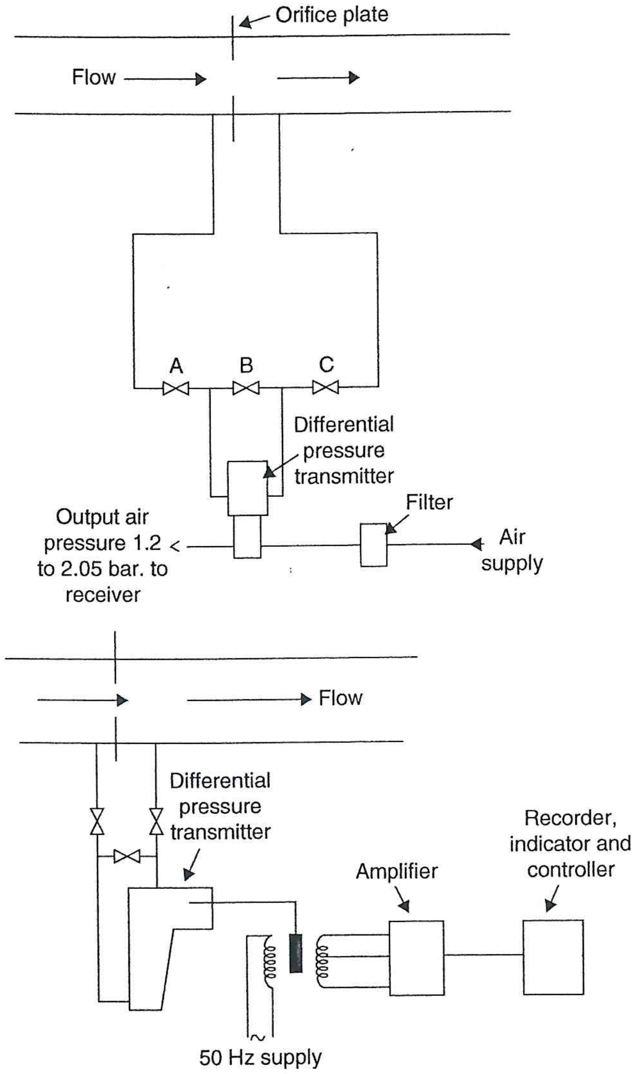


▲ Figure 4.7 *Square root extractor (electrical)*

Figure 4.8 shows two arrangements of flow sensor/transducer units, each with square root extraction. For the pneumatic system the valves marked A, B and C would be used in the sequence, open B, close A and C, when taking the D/P transmitter out of operation. This valve sequence would also apply to the electric system.

With steam flow measurement, the pressure tappings from the flow sensor are led to cooling reservoirs wherein the steam condenses. Water only then acts on the square root eliminator or recorder thus preventing damage.

The pneumatic system would utilise square root extraction as shown in Figure 4.6 (the



▲ **Figure 4.8** *Flow sensors/transducers*

The electrical system can utilise mechanical movement (from a device such as Figure 4.5) as shown to give square root extraction. Variation of the position of the soft iron core of the inductor unit governs output signal to the amplifier. Alternatively direct signals to the amplifier can be taken from electrical devices shown in Figures 3.2 and 4.7.

Ultrasonic and Nucleonic

Ultrasonic flowmeters utilise an oscillator transmitter and receiver timer to measure apparent sound velocity in the fluid, which is proportional to the velocity of the fluid, across a diametral path inclined at an angle with the flow direction. Calibration is required to allow for the velocity profile.

Nuclear types employ a radioactive tracer injected into the fluid to measure the flow time, for a known volume, between two points by two detectors and a recorder. Normal protection against ionising radiation is required for the sample measure.

Test Examples

1. Sketch the apparatus and describe the method of measuring steam flow through a pipe.
   Explain why results obtained using this apparatus may differ from theoretical results.
2. Describe, utilising a sketch, any type of flowmeter. For inferential types of device how is the measured variable related to flow rate?
3. Inferential flowmeter devices using differential pressure techniques for velocity sensing exhibit non-linear characteristics. Discuss these characteristics and describe a device to restore linear characteristic to measure or control output signal.
4. Sketch an orifice plate installation showing the flow pattern and pressure variation. To what is the flow rate proportional?

5

OTHER MEASUREMENTS

Advances in various technical areas have enabled development of new sensor designs and data handling methods. It is likely that this process will continue at a pace with systems based on substances such as graphene and the application of nanotechnology. However, this chapter attempts to discuss measurements which are available but have not yet been covered by earlier chapters.

Speed-Tachogenerator

The dc tachogenerator is a small precision generator driven by the shaft whose rotational speed is required. Output voltage is directly proportional to speed. The tacho is best geared to run at maximum speed so giving maximum output signal and improved signal to noise ratio.

When used as a *tachometer* in measuring systems the output voltage from the tachogenerator is measured on a conventional voltmeter calibrated in terms of rotational speed.

Mechanical type tachometers are based on centrifugal action, linked to product lateral travel.

A conventional ac generator for use as a tachogenerator or tachometer is generally

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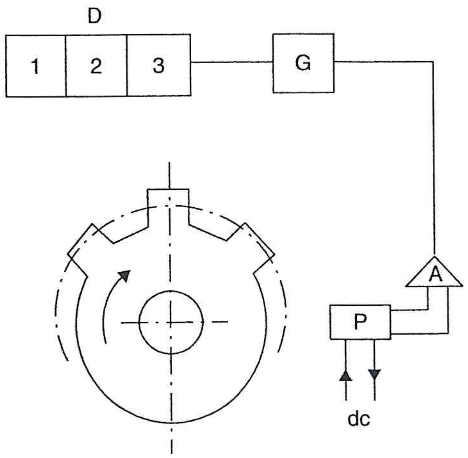
thin aluminium cup rotating around a fixed iron core. The stator is wound with two coils at right angles, one ac supply the other ac output. With the cup stationary there will be no output as the windings are at right angles. An emf is induced with cup rotation, due to cutting of flux of supply winding. This links with the output winding so giving a signal proportional to rotational speed; frequency and phase being that of input signal. The device can be used for rate of change detection. With dc supply at constant speed no emf is induced in the output coils but angular acceleration or deceleration induces a voltage proportional to this change in the output coils. A 'velocity voltage' applied to a differentiation (rate of change) circuit (CR series) will give a voltage across the resistor which is approximately proportional to acceleration (especially with a small time constant). Electronic amplifiers configured as differentiators are used to improve accuracy. Alternatively as force is proportional to acceleration a simple spring accelerometer can be used.

A digital tachometer (counter) is shown in Figure 5.1.

As the (ferrous) toothed wheel rotates each tooth alters the air gap and flux in a pick up coil (P) whose output pulses are amplified (A). Pulses pass through a timing gate (G), with a, say, a one-second opening period, and are counted on a digital counter (D) which scales (related to number of number per revolution) and displays as revolutions per second.



▲ **Figure 5.1** *Digital tachometer*

Torque-Power

dicated power can be measured by a conventional mechanical indicator although odern practice is tending towards digital display techniques with integration for ower. Shaft power of engines is measured by a torsionmeter in conjunction with a chometer (power proportional to product of torque and rotational speed). Specific el consumption is readily achieved from these readings with a flowmeter calibration r fuel consumption. Various types of torsionmeter are available but those giving a ontinuous reading are usually of the electrical type. One design in common use is ased on differential transformer operation (Chapter 6) which is illustrated in Figure G f the specimen questions at the end of the book. Another design is based on magnetic tress sensitivity and is termed a *torque inductor* – *torductor* – and is now described.

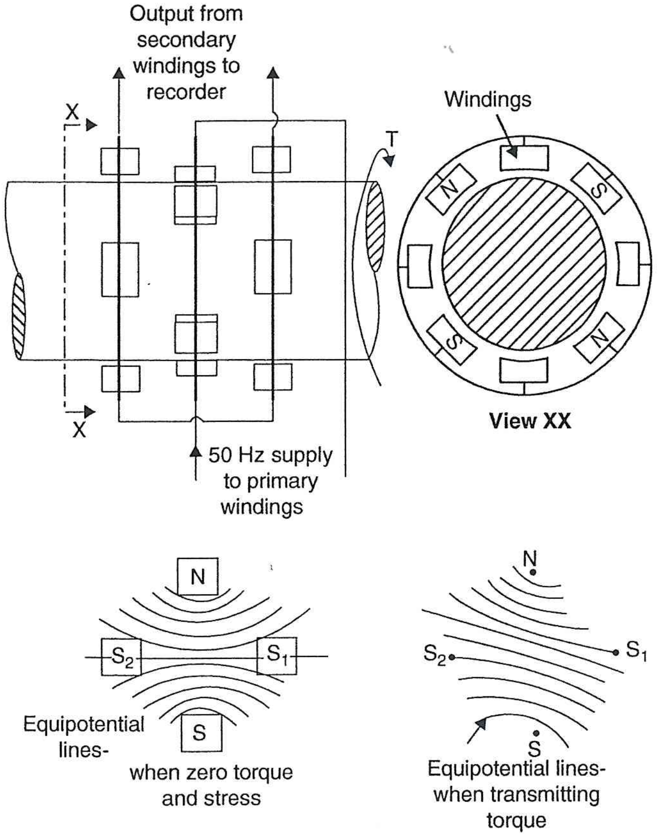
he torductor is, as the name implies, a *torque inductor,* it is a stress transducer that is minently suited to the measuring of torque in rotating shafts. It gives a high power utput and requires no slip rings or other shaft attachments since it operates without ny contact. Figure 5.2 shows a ring torductor. It consists of one primary ring which arries four poles, marked N, S, that is supplied with (50 Hz) alternating current. Two uter secondary rings have four poles each, arranged at 45° to the primaries, all of vhich are connected in series with mutually reversed windings.

o contact exists between the poles and the shaft, there being a 2–3 mm air gap rovided to ensure this.

Vhen no torque is applied to the shaft there are no stresses in the shaft and the magnetic ields between NS poles induced in the shaft will be symmetrical, the equipotential ines are then situated symmetrically under the secondary poles S_1, S_2, as shown and econdary flux and voltage will then be zero.

Vhen a torque is being transmitted the equipotential lines form an asymmetrical attern, as shown, due to the mutually perpendicular unlike stresses, acting at 45° to the haft axis, causing increased permeability in one direction and decreased permeability t 90° in the other direction. This causes the S_1 pole to become magnetically slightly ositive and the S_2 pole slightly negative.

The output from the secondaries of the ring torductor is of the order of a few milliwatts, vhich is large enough to be used without any amplification. If this signal is now married



▲ **Figure 5.2** *Ring torductor*

Viscometer

Newton investigated the viscosity of fluids and postulated, for most fluids under prescribed conditions, that flow rate is proportional to applied stress, more exactly that applied shear stress is proportional to velocity gradient.

$$\frac{F}{A} = \eta\frac{dv}{dx}$$

where η is a constant called the coefficient of viscosity. Applying this equation to the

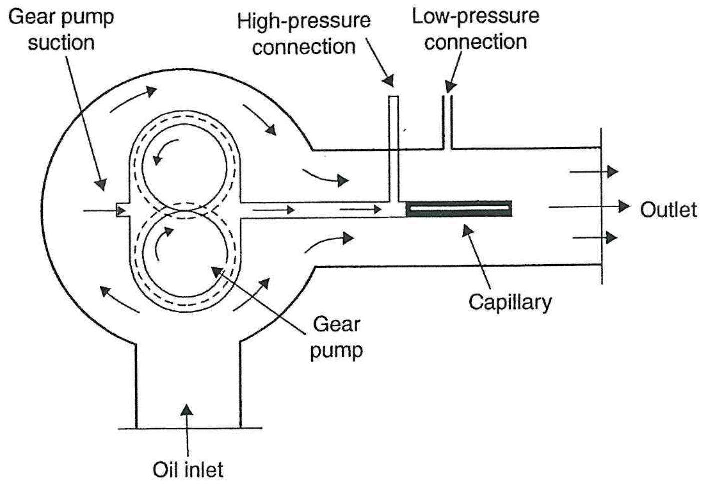


Figure 5.3 *Operational arrangement of the sensor*

$$\eta = \frac{\pi p r^4}{8 l \dot{V}}$$

or a constant flow rate ($\dot{V}$):

$$\eta = p \times \text{a constant}$$

vhere p is differential pressure (D/P).

igure 5.3 shows the operational arrangement of the sensor element of a viscometer see Figure 12.12). A small gear pump driven at constant speed, by an electric motor hrough a reduction gear, forces a *constant* fluid quantity from the housing through a mall-bore tube (capillary). Fluid flows through the capillary without turbulence, that s, streamlined (laminar) flow prevails and D/P is proportional to viscosity of fluid. The /P can be measured by any of the means previously described. The device, within a ontrol system, is described in Chapter 13 (Figure 13.19).

Photo-Electric Cells

with a thin layer of semi-conductor material

many situations such as oil–water content, smoke density, oil mist, flame indicator, etc. detection as described later in this chapter.

Photo-emissive cells rely on light energy to release electrons from a metallic cathode.

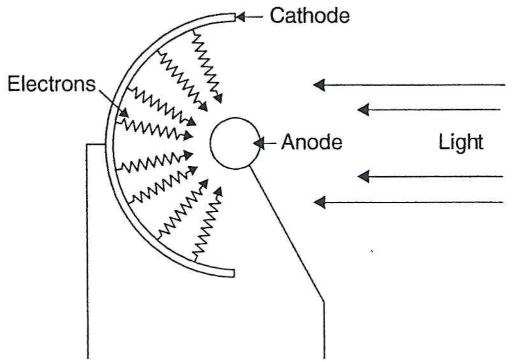
If visible light, which is radiation and hence energy, falls upon certain alkali metals – such as caesium – electrons will be emitted from the surface of the metal. Metals in general exhibit this characteristic, but for most materials the light required has a threshold wavelength in the ultraviolet region so that visible light does not cause electron emission.

Light energy comes in packages called *photons* and the energy of the photons is used in doing work to remove the electrons and to give the electrons kinetic energy after escape from the metal.

Figure 5.4 shows a simple photocell; visible light falls on the metal cathode from which electrons are emitted, they collect at the anode and in this way create a potential V which can then be amplified and used for alarms and control, etc.

In the vacuum cell all current is carried by photo electrons to the positive anode. In the gas-filled cell emitted electrons ionise the gas, producing further electrons, so giving amplification. Secondary-emission (photo-multiplier) cells utilise a series of increasingly positive anodes and give high amplification.

Photo-transistors exhibit similar characteristics and small size and high amplification make their use particularly attractive especially when applied to counting systems, that is, digital tachometry. This device is shown in Figure 5.5. Optical focus incident light on the base increases the base current, hence collector current and output voltage falls. This device is discussed further in Chapter 7.



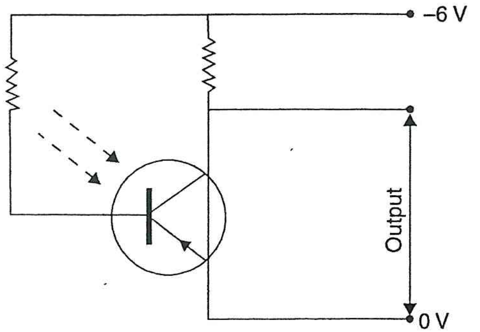


Figure 5.5 *Photo-transistor*

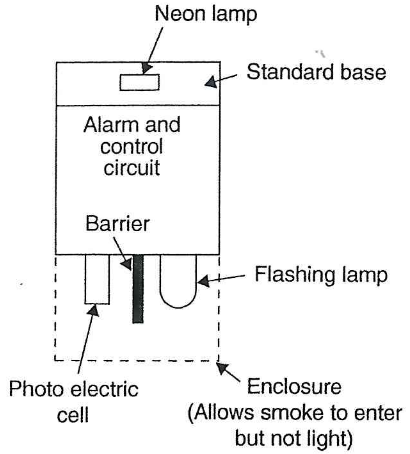
Oil in Water Sensor

useful application of photocells is in detection of oil–water interface (as an alternative the method described in Chapters 3 and 13). Fluid passing through glass is exposed long wavelength light from an ultra-violet lamp, which causes fluorescence if oil rticles are present. This light can be detected by the secondary element photocell unit hich produces a signal for amplification. The amount of fluorescent light is dependent the amount of oil in the oil–water mixture and this affects the amount of visible light tected by the photocell. An ultrasonic beam between piezoelectrical crystals across e interface is also used, sometimes utilising beam reflection or refraction across the terface.

Smoke Density Detector

r fire warning and exhaust gas indication a photocell in conjunction with an amplifier d alarm or indicator is used. Three types are in use: operated by light scatter, by light scuration and by a combination of the two.

light scatter photocell separated from a semi-conductor intermittently flashing ht source is shown in Figure 5.6. The housing enclosure allows smoke but not light side. With smoke present in the container, light is scattered around the barrier on to e photocell and an alarm is triggered. The light obscuration type is used in oil mist

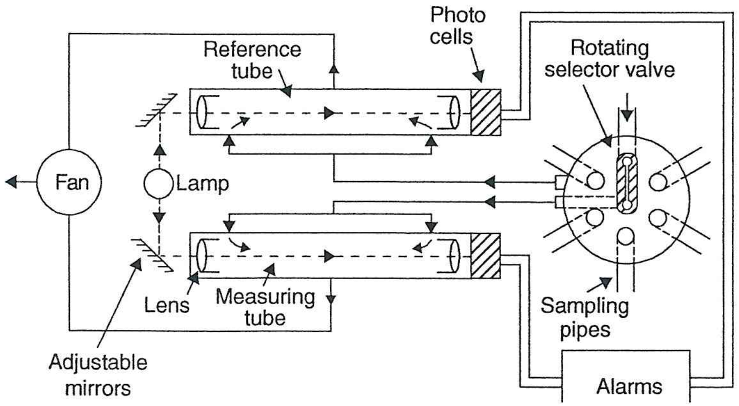


▲ **Figure 5.6** *Smoke density detector*

Oil Mist Detector

The photocells of Figure 5.7 are normally in a state of electric balance, that is, measure and reference tube mist content in equilibrium. Out of balance current due to rise of crankcase mist density can be arranged to indicate on a galvanometer which can be connected to continuous chart recording and auto visual or audible alarms.

The suction fan draws a large volume of slow moving oil–air vapour mixture in turn from various crankcase selection points. Oil mist near the lower critical density region

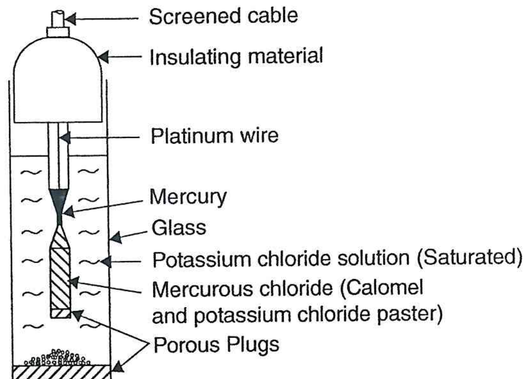


s a very high optical density. The alarm is normally arranged to operate at 2.5% of e lower critical point, that is, assuming 50 mg/l as the lower explosive limit then the rning will be at 1.25 mg/l.

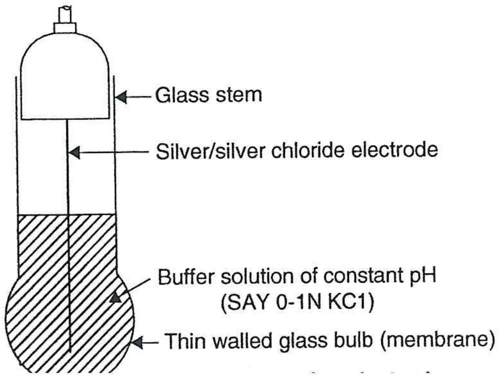
H Sensor

e pH value of a solution is the logarithm of the reciprocal of the hydrogen ion ncentration in the solution. Its value ranges between 0 and 14; neutrality being 7 ything from 7 to 14 is alkaline and from 0 to 7 is acidic. pH measurement and control extremely important, being primarily used for feed water analysis.

e method of pH measurement is by means of a conductivity cell consisting of two ectrodes and a temperature sensor; pH value varies with temperature hence it is



Reference electrode

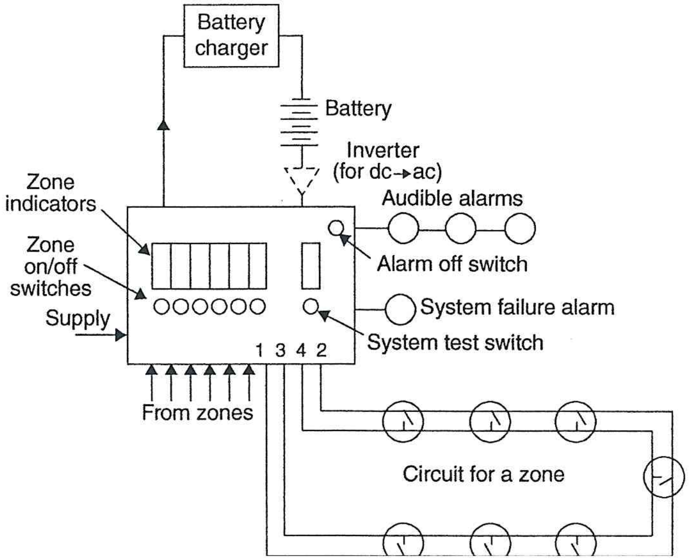


important that this be controlled by means of a sensor/compensator. One of the electrodes is a reference electrode which has a fixed potential irrespective of the variation of hydrogen ion concentration of the solution. The other electrode produces a potential dependent mainly upon the difference in hydrogen ion concentrations between the buffer solution and the solution whose pH has to be measured (across the membrane). In this way the potential difference between the glass measuring electrode and reference electrode is a measure of the pH value of the solution. Electrodes, with sensor/compensator, are inserted in the fluid flow path.

Figure 5.8 shows the two types of electrode used in the conductivity cell.

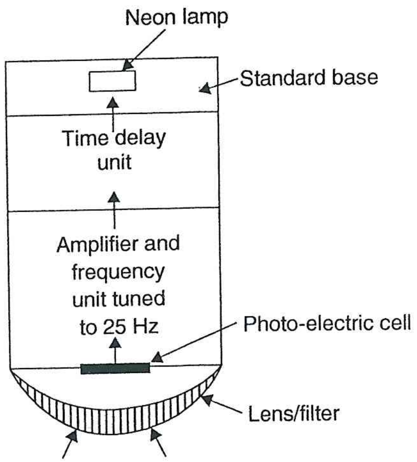
Heat (Fire) Detector

Detector heads are generally one of three types. At a set heat (temperature) condition the increasing pressure on the bulb-type pneumatic diaphragm closes electrical alarm contacts; increased differential temperature on the bi-metallic type activates alarms; increased heat fractures a quartzoid bulb (containing a highly expansive fluid) releasing the water sprinkler supply and pressure alarm. A simple fire detection-alarm circuit is shown in Figure 5.9.



Flame Detector

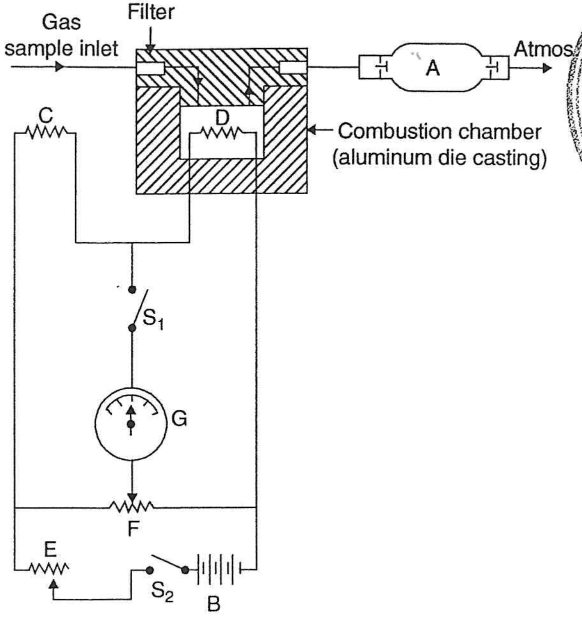
igure 5.10 illustrates the infrared type of device. Flame has a characteristic flicker equency of about 25 Hz and use is made of this fact to trigger an alarm. Flickering adiation from flames reaches the detector lens/filter unit, which only allows infrared ays to pass and be focused upon the cell. The signal from the cell goes into the selective mplifier, which is tuned to 25 Hz, then into a time delay unit (to minimise incidence f false alarms, fire has to be present for a pre-determined period), trigger and alarm ircuits.



▲ **Figure 5.10** *Flame detector*

Gas Explosion – Detector Meter

The instrument illustrated in Figure 5.11 is first charged with fresh air from the atmosphere using the rubber aspirator bulb (A). On-off switch (S_2) is closed together with check switch (S_1) and the compensatory filament (C) and detector filament (D) are



▲ **Figure 5.11** *Gas explosion – detector meter*

The instrument is now charged from the suspect gas space and while operating the bulb, the switch S_2 is again closed. If a flammable or explosive gas is present it will cause the detector filament to increase in temperature. This disturbs the bridge balance and a current flows. Galvanometer G can be calibrated so that the scale is marked to read '% of Lower Limit of Explosive Concentration of Gas'.

An alternative design has two ionising chambers, one reference (air) and the other sample, each containing a radioactive ionising source. Combustion particles when ionised are more bulky and less mobile than normal gas molecules so they are readily neutralised. This results in higher resistance and voltage change at the sample chamber – which activates alarms.

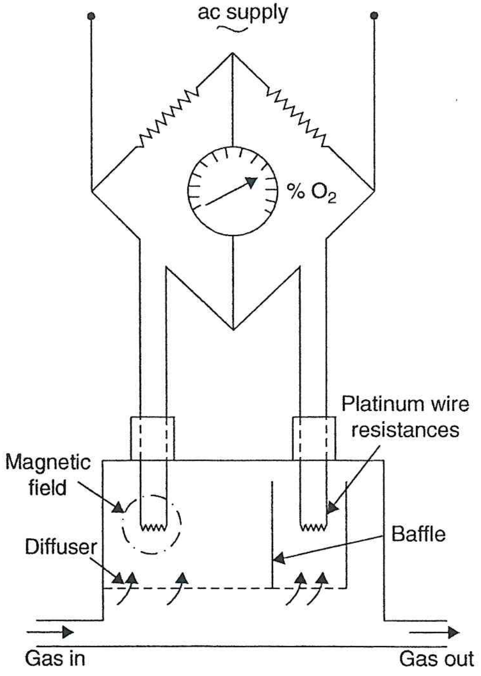
Gas Analysis

For detailed gas analysis an Orsat apparatus is used. However, a number of measurements require to be continuously recorded. Two representative examples can be considered:

Oxygen analyser

Gases can generally be classified as either diamagnetic or paramagnetic, the former seek the weakest part of a magnetic field and the latter the strongest. Most of the common gases are diamagnetic but oxygen is paramagnetic and use is made of this in the oxygen analyser shown in Figure 5.12.

Two platinum wire resistances are heated by current from an ac bridge and the gas to be measured enters the resistance chamber via a diffuser. One of the resistance wires is placed in a magnetic field hence oxygen is drawn towards this resistance, thus convection currents are set up around this resistance which is then cooled relatively to the other resistance. The bridge is then unbalanced; the amount of unbalance is a measure of the oxygen content and this is displayed on the galvanometer.



▲ **Figure 5.12** *Oxygen analyser*

CO_2 analyser

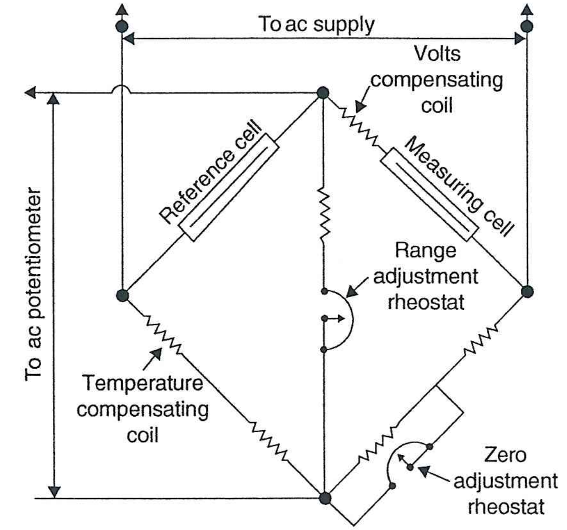
Refer Figure 5.13. Approximate thermal conductivities are in proportion:

$$CO_2 = 1, H_2O = 1, CO = 4, O_2 = 2, N_2 = 2$$

The sample enters via a filter and drier; water vapour is removed as it has the same conductivity as CO_2. The wire cell resistance is proportional to heat dissipation, proportional to thermal conductivity of gas in the cell, proportional therefore to CO_2 content. Air is used in the reference cell. Thus the only difference between gas sample and air, from the thermal conductivity viewpoint is CO_2 (as H_2O removed and O_2 and N_2 have the same value). This assumes no CO or H_2; if these are present (normally only very small proportions) they will be registered as CO_2 unless the sample is first passed over a burner and these two gases burned off before the reading.

Thus the Wheatstone bridge electrical unbalance is dependent on CO_2 content and the unbalance electrical current is measured by the potentiometer.

Chemical absorption and mechanical types are also used.



▲ **Figure 5.13** *Thermal conductivity type CO_2 recorder*

Relative Humidity

A hair element will react to changes of humidity and provide a linear movement, with negligible force, which can be converted to electrical or pneumatic signal and amplified as required.

Water Analysis

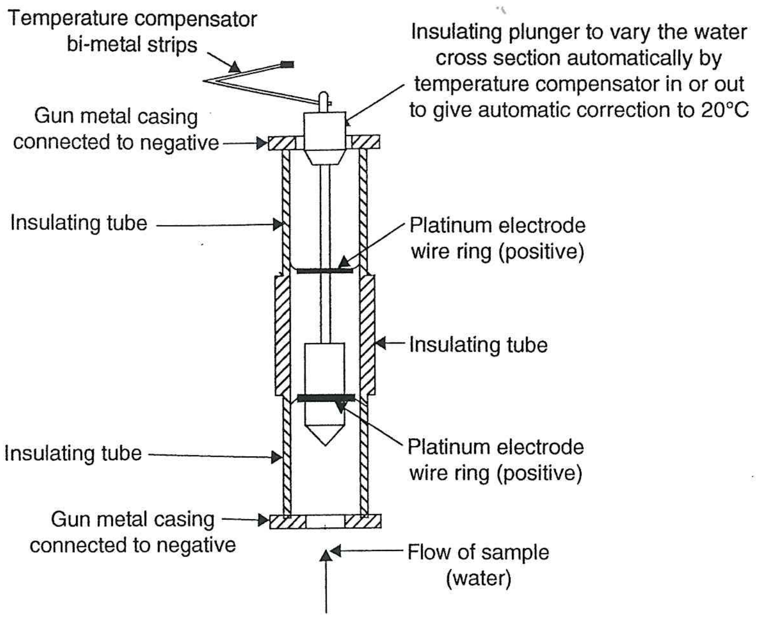
The measurement of pH has been considered previously. Two other measurements are commonly required, that is, electrical conductivity meter for dissolved solid assessment and dissolved oxygen meter.

'Dionic' water purity meter

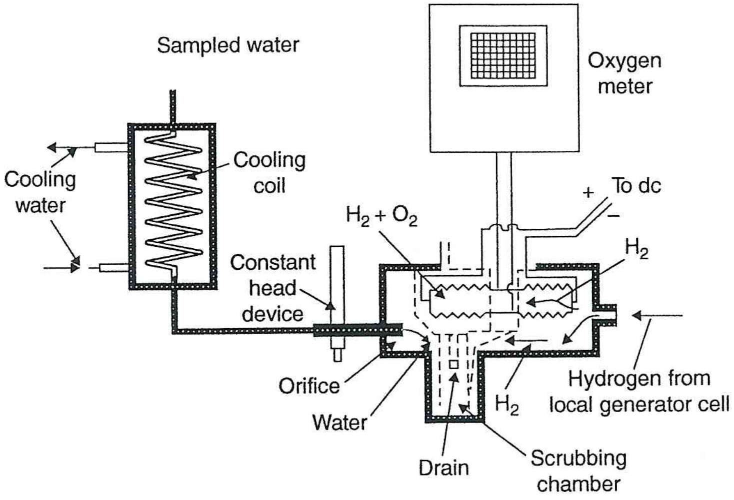
Specific conductivity mho/cm^3 is the conductance of a column of mercury 1 cm^2 cross-sectional area and 1 cm long. This is a large unit and micromho/cm^3 (reciprocal megohm) is used and when corrected to 20°C is called a dionic unit. Conductivity of pure distilled water is about 0.5, fresh water about 500 dionic units. The sensor, shown in Figure 5.14, measures conductivity of two water columns in parallel, that is, between positive platinum rings and negative gunmetal collars. The insulating plunger, operated by bi-metallic strip, varies cross-sectional area for automatic correction to 20°C. The measurement is by conventional ohmeter. The device should be used with de-gassifying units to avoid errors due to occlusion of carbon dioxide.

Dissolved oxygen meter

The unit is shown in Figure 5.15. The sample water flows via a chamber which surrounds the katharometer (Wheatstone bridge circuit) and receives pure hydrogen. Some hydrogen is taken into solution and this releases some dissolved oxygen (in air). This mixture passes to the atmosphere across one side of the bridge while the other side is in pure hydrogen. The cooling effect differs on the two sides of the katharometer



▲ **Figure 5.14** *Dionic water purity meter*

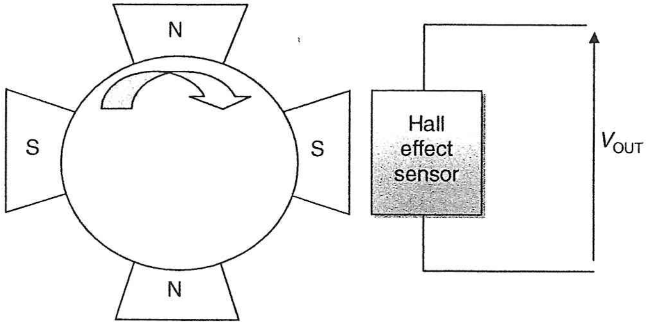


▲ **Figure 5.15** *Dissolved oxygen meter*

Hall Effect Sensor

The Hall effect sensor is a semi-conductor crystal that produces a voltage output proportional to the presence and direction of magnetic flux. Applications include measurement of shaft speed as shown in Figure 5.16. Here the ouput voltage will be an ac signal whose frequency is directly proportional to shaft speed.

Hall effect sensors are also used for dc current measurement where the jaws of a clamp meter (tong tester) are clamped around a cable. The magnetic field around the cable is proportional to the current to be measured and the instrument will produce an output proportional to the flux.

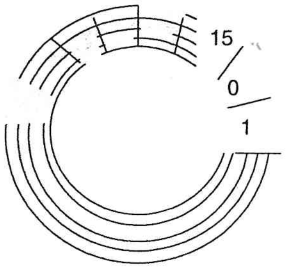


▲ **Figure 5.16** *Hall effect sensor*

Other Encoders

Various other methods exist for measurement of speed or position on rotating shafts and for measurement of linear position. Besides the Hall effect, encoders use inductive, capacitive and optical techniques.

Accuracy is enhanced by means of using multiple tracks with optical sensors as shown in Figure 5.17. The tracks are arranged such that each of the 16 segments has a unique binary value. Standard codes such as Gray code or Angular Pure Binary are used both



▲ **Figure 5.17** *Optical sensors*

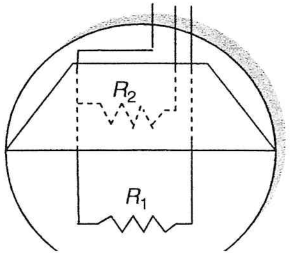
Mass Air-Flow Measurement

Although akin to flow measurement, this technique measures the mass of air flow as opposed to volume. This is essential for optimal performance of fuel injected engines.

There are two common methods, both of which rely on measurement of ambient air temperature.

The traditional approach is the Vane Meter, in which an air flap door operates a potentiometer which yields a resistance change proportional to mass air-flow.

More recently hot wire sensors have become common. In this method a platinum resistance wire is suspended in the air intake. A fixed voltage source drives a current through the wire. When air flows past the wire it cools and so reduces wire resistance leading to an increase in current which is internally measured and used to determine the mass of air flowing past the wire. Figure 5.18 shows an arrangement where R1 is the measuring sensor and R2 is shielded from the air flow but gives a background measure of temperature.



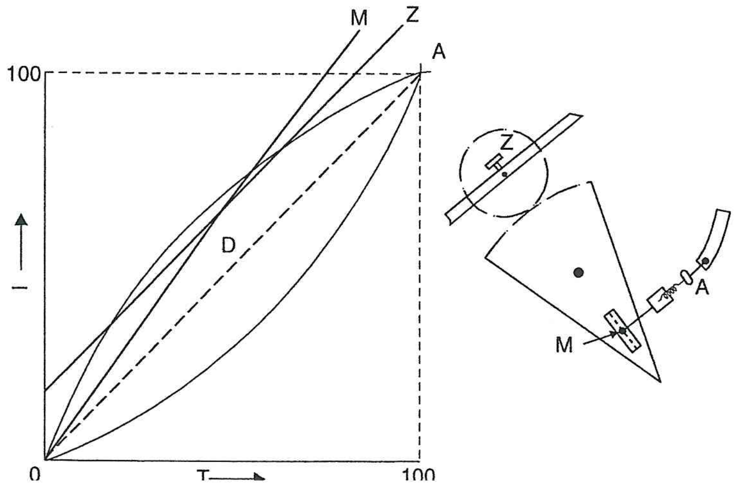
Instrument Calibration: Testing and Adjustment

This is generally a specialist subject. Pneumatic instruments would be tested by master gauge, standard manometer or deadweight testers. Electrical instruments are tested by standard resistors, potentiometers, capacitors, etc.

Using a Bourdon pressure gauge as example:

1. Zero (error) adjustment changes base point without changing the slope or shape of the calibration curve. It is usually achieved by rotating the indicator pointer relative to the movement, linkage and element.
2. Multiplication (magnification) adjustment alters the slope without changing base point or shape. This is effected by altering the drive linkage length ratios between primary element and indicator pointer.
3. Angularity adjustment changes the curve shape without altering base point and alters scale calibration at the ends. This error is minimised by ensuring that link arms are perpendicular with the pointer at mid-scale.

Figure 5.19 shows the calibration curves and adjustment for the Bourdon link-type instrument mechanism.



Instrument readings (I), true values (T), desired result (D). Zero error and adjustment (Z), multiplication error and adjustment (M), angularity error and adjustment (A) – error curves or lines for actual values.

Over the design range, pointer movement bears a linear relationship to pressure, and the scale is calibrated accordingly.

Hysteresis is a vibration phenomena. It is best eliminated by correctly meshed gearing and fitted pivots to reduce backlash, etc.

Test Examples

1. Explain the principle of operation of a carbon dioxide recorder for monitoring the uptake of gases.
   State what normal maintenance it requires.
   State what action is taken if the carbon dioxide content is unacceptably low.
   If this action does not alter the carbon dioxide reading, explain how the accuracy of the recorder is checked and adjusted.
2. Explain the term 'photo-electric effect' and describe equipment suitable for crankcase monitoring and fire detection in which this phenomenon is utilised.
3. Describe, with the aid of sketches, a torsionmeter.
4. Explain the principle of operation and briefly describe the construction of the shaft and indicator units.
5. Describe an application for an encoder.
6. Discuss the errors liable to be exhibited by link-type instruments. Describe how such an instrument could be calibrated and adjusted to reduce these errors to a minimum.

6

TELEMETERING

The objective of this chapter (and Chapter 7) is to link instrumentation (described in preceding chapters) and measuring devices with control elements (as described in subsequent chapters). Some repetition may inevitably result in the presentation.

There are a wide range of variables to be measured. Detection and measurement devices are mainly electrical and electronic although a significant number are displacement-operated mechanical types. Chemical devices are also used.

Transducers can generally be simplified into three basic reversible types:

Mechanical displacement	↔	Pneumatic
Mechanical displacement	↔	Electrical
Pneumatic	↔	Electrical

Pneumatic principles are invariably flapper nozzle, orifice, diaphragm. Electrical principles include resistance change, variable inductance, variable capacitance, current or voltage, with frequency and phase used to a limited extent. Conversion of electrical signal is also used, that is, resistance-current, voltage-current, etc. and such modern transducers often incorporate electronic oscillators and amplifiers.

Telemetering may be defined as signal transmission over a considerable distance. The device at the measure point, usually a transducer, is then often called a transmitter with the receiver located at the recording or control centre.

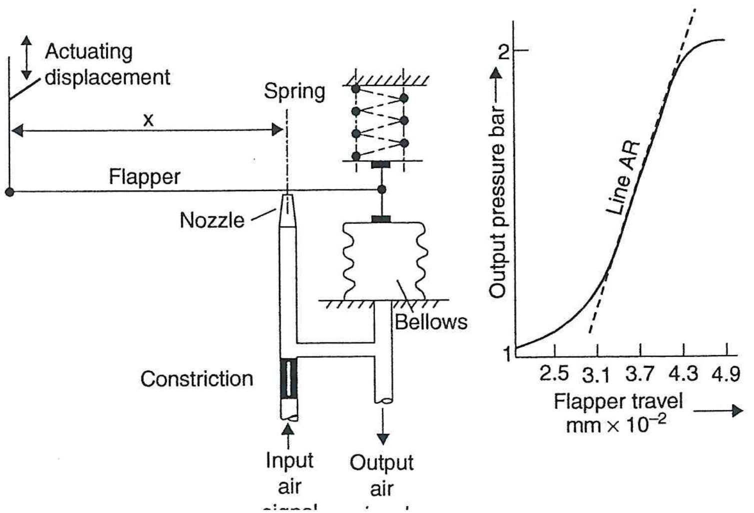
The discussion in this chapter will be divided into three sections: pneumatic transmitters, electrical transmitters, receivers.

Pneumatic Transmitters

Position-balance transducer (pneumatic)

Displacement of a mechanical linkage gives variation in pneumatic signal output pressure. The flapper-nozzle is the basis of many pneumatic mechanisms and the position (motion) balance is essentially a *balance* of positions (see Figure 6.1).

Ideally equal increments of flapper movement should produce equal increments of pressure output, that is, linear proportionality. In practice this is only achieved when there is limited flapper travel. To ensure increased sensitivity and linearity negative feedback is used via a bellows. Linear output over the pressure range is obtained for an effective flapper travel range near the nozzle of about 0.015 mm. Output signal pressure is proportional to actuating link travel and the device is adjustable by varying the mechanical advantage of the flapper lever, that is altering the *x* dimension to the right or the left. A typical output pressure-flapper travel characteristic is included in Figure 6.1. The device is obviously a displacement'air pressure transducer, displacement variation from flow, level, etc. variables. A pneumatic relay can be fitted on the air input.

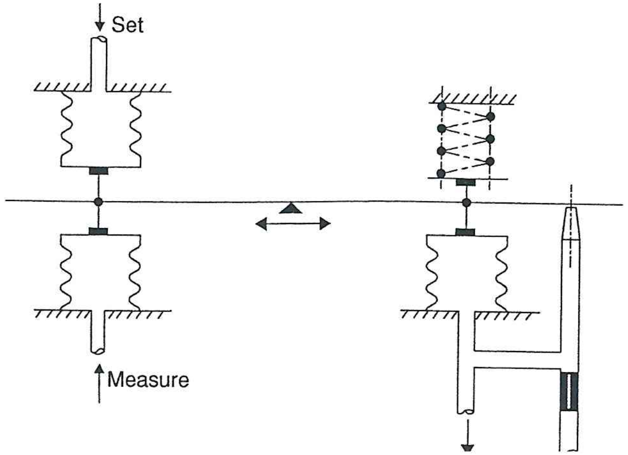


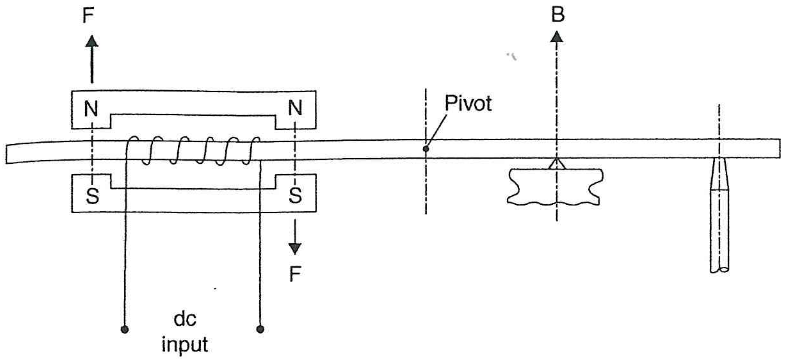
Force-balance transducer (pneumatic)

This is essentially a *null* method, that is, equal and opposite forces (torques) which eliminates inherent errors of the position-balance device. Consider Figure 6.2, the flapper is a constrained bar pivoted about a fulcrum (adjustment of which varies mechanical advantage and thus changes proportion of input to output change). Bellows have equal effective area. With the device in equilibrium assume an increase in measured signal pressure which will produce a net up force and clockwise torque on the bar. The flapper movement towards the nozzle will continue until the increased output pressure in the feedback bellows produces an anti-clockwise torque, to balance the actuating torque, and at this point equilibrium is restored. Again a displacement variable to air pressure transducer. A relay may be fitted.

Electro-pneumatic transducer

The unit shown in Figure 6.3 is based on the force balance principle with input variable of current (4–20 mA dc is usual). Electrical current signal variation causes a torque motor to produce a variable force (*F*) which is balanced by the feedback pneumatic bellows force (*B*) at equilibrium. The bar is circular and between the poles of the permanent magnet acts as an armature when excited by a dc current. Consider an increase in armature current; the strength of the armature poles will increase accordingly. The S pole will move up as unlike poles attract and produce a clockwise moment about the pivot whilst the N pole will move down producing an anti-clockwise moment. The moment arm of the S pole force is greater so there is a net clockwise moment. This action closes in on the nozzle giving a higher output pressure and increasing the feedback bellows force until equilibrium is achieved, that is, a direct acting transducer. An alternative torque motor design utilises a suspended coil within the magnetic field of a permanent magnet. Figure 6.3 is an input electrical (current) to output pneumatic pressure transducer (I/PP).





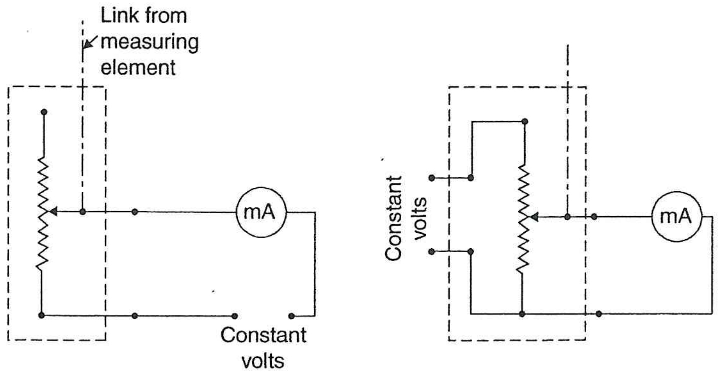
▲ **Figure 6.3** *Electro-pneumatic transducer*

Electrical Transmitters

Consider the first three examples of position (motion) balance converters: variable resistance, inductance and capacitance.

Variable resistance transducer

In this simple and early form of transducer the mechanical movement of the measuring element connection varies the electrical circuit resistance. The device is restricted in use due to contact problems, variations in wire connection resistance and the need for a constant stabilised voltage supply. Two types are shown in Figure 6.4, that is, mV measurement and mA measurement locally or remote; the latter is a potentiometer technique.



▲ **Figure 6.4** *Variable contact resistance transducer*

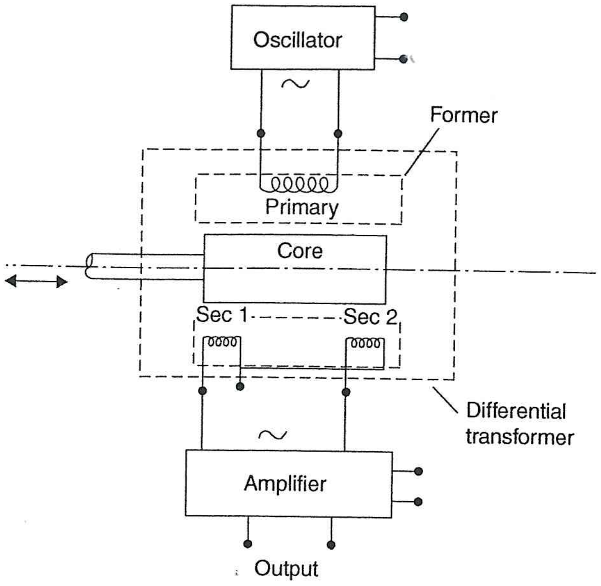
voltage variations. One coil is directly energised from supply (current proportional to voltage) and a cross-coil is deflected by measurement current so that deflection of the meter within the permanent magnet is proportional only to resistance of the transmitter. This is a two-coil ratiometer.

Other resistance systems

The Wheatstone bridge principle is used in many cases, both dc and ac, with direct or null balance techniques. The bridge together with electrical resistance sensors for resistance thermometers (Chapter 1) and strain gauges (Chapter 2) have been described in detail already. Another electrical resistance transmitter has also been discussed previously in Chapter 3 namely the type utilising electrical resistors in mercury for measurement of level.

Variable inductance transducer

The unit shown in Figure 6.5 is a differential transformer with three coils fully wound on a cylindrical former (only half the winding is shown on the sketch for simplicity). The core, which is moved laterally by displacement of a sensor element, provides the magnetic linking flux path between coils. The primary ac voltage induces secondary voltages and as the two secondary windings are in series opposition the two outputs are opposite in magnitude and phase with the core laterally in the middle of the former.



▲ **Figure 6.5** *Variable inductance transducer*

with zero volts at mid-travel. Input displacement, from Bourdon tube or diaphragm is converted to an electrical signal for telemetering to indicators, recorders, data processing or electronic controllers.

Many electrical transducers are combined in the transmitting unit with oscillators and amplifiers of solid state modular assemblies. The oscillator supply in Figure 6.5 from a power supply unit is commonly at 12 V dc and incorporates a chopper unit, ac amplifier and output-feedback stage. A stabilised current to the primary winding of about 5 mA is often used from say a 1.6 kHz oscillator. The amplifier itself, 12 V dc supply, accepts ac input from the differential transformer via ac bridge circuits at up to 2 mA and gives output via demodulator-filter circuits at about 50 mA maximum, dc. It is effectively a dc input dc output system. Components mentioned above are considered in more detail in the next chapter.

This *inductance ratio* system can employ any type of receiver. For a simple system direct ac supply, without oscillator and amplifier, can be used and ac output passed across a bridge rectifier for each coil to a two-coil ratiometer with pointer indicator.

In an *inductance balance* system the receiver is identical to the transmitter with secondary windings interconnected. Unbalanced emfs due to displacement and inductance change at the transmitter result in corresponding displacement at the

Variable capacitance transducer

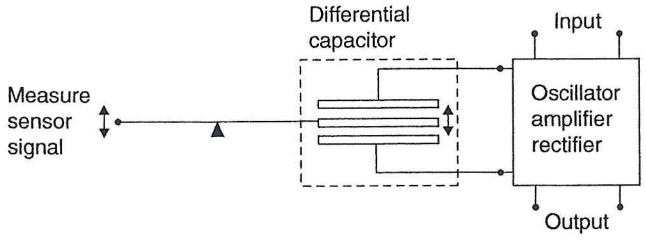
The capacitance of a parallel plate capacitor is given by

$$C = \frac{A\varepsilon}{d}$$

A is plate area, ε absolute permittivity and d plate separation. Change of capacitance utilisation in conjunction with an ac bridge circuit has been considered previously with reference to level probes (Chapter 3). For displacement measurement a parallel RL resonant circuit can be utilised. Alternatively a differential capacitor principle can be used for displacement-current conversion, and is now described.

Consider Figure 6.6. The central plate of the differential capacitor is moved vertically by the displacement of a sensor device. The outer plates are connected to a combined oscillator, amplifier, rectifier unit.

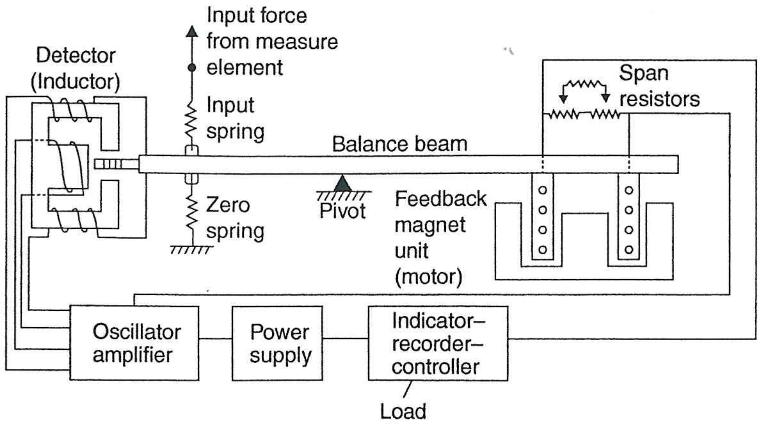
Movement of the centre plate towards one fixed plate and away from the other gives a change in capacitance to the oscillator-amplifier. A change in output current to receiver results.



▲ **Figure 6.6** *Differential capacitor transducer*

Electronic Force-Balance System

An electro-pneumatic converter has already been described and an alternative pneumatic (pressure force displacement etc.) electric converter can now be considered

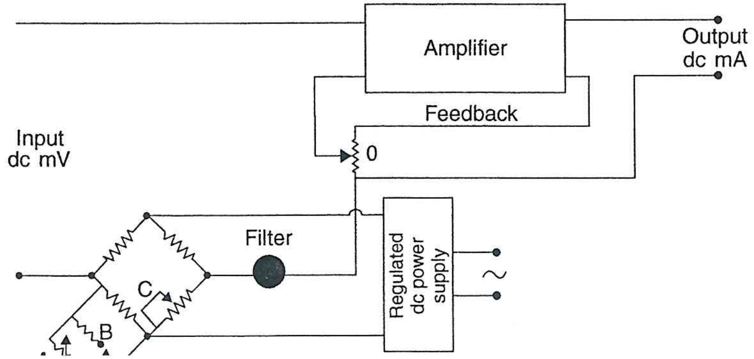


▲ **Figure 6.7** *Electronic force balance system*

When movement varies the inductance, coupled to the oscillator amplifier, let us assume amplifier output current increases. This will continue until the feedback current on the force motor produces equilibrium. Effective full-scale beam travel is only about 25 µm. Input may be from the Bourdon tube or diaphragm. The device is referred to as a PP/I transducer.

Voltage-Current Transducer

It is often necessary to use a mV/I converter when dealing with thermocouple or resistance thermometer inputs. Such a device is shown in Figure 6.8.



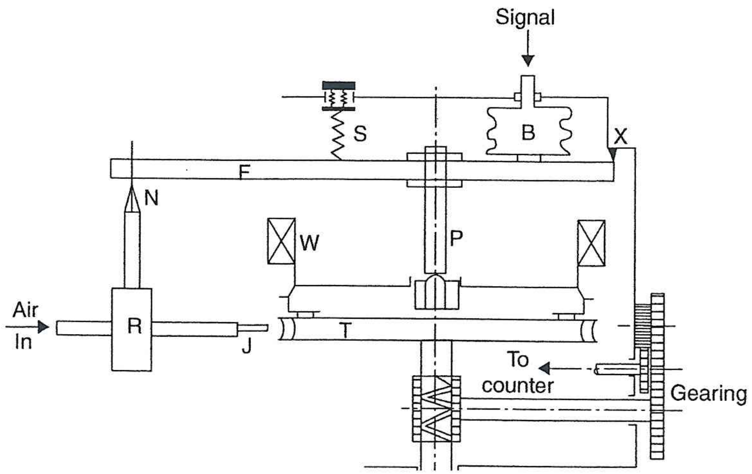
Deviation between input mV and a standardised zero suppression voltage, from a zener diode power pack and bridge, is algebraically added and passed through a filter network (to avoid stray ac pick-up). This signal is algebraically added to the feedback stabilising loop of the amplifier and passed through the amplifier to output. Adjustable resistors A, C, D allow temperature correction, zero adjustment and span control of feedback; B measured value. A dc amplifier can be used. If an ac amplifier is preferred a chopper input and synchro-rectifier output is needed, output and feedback isolated by a transformer.

Receivers

Receiver types are many and range from direct measuring meters, recorders, display units, to controllers and analysing units. In many cases if a transducer is used it is merely a form of converter device as already described in this chapter. Frequently it is not possible to sensibly separate transmitter and receiver because they are inherently linked in operating principle. With these provisos in mind a selection of units not previously, or subsequently, described are now presented.

Receiver integrator

Refer to Figure 6.9. This receiver is for flow recording. Down force on bellows (B) from increased (above datum) input signal (proportional to square of flow measurement) and about fulcrum (X) closes force bar (F) into nozzle (N). Increased pressure from relay (R) acts on a 60 'tooth' turbine wheel (T) to cause rotation and equilibrium is obtained when up force due to centrifugal force (proportional to square of turbine wheel speed) through thrust pin (P) on bar balances down force. Adjustment is via spring (S) causing movement of weights (W) (up increases feedback force and reduces counts per unit input pressure).



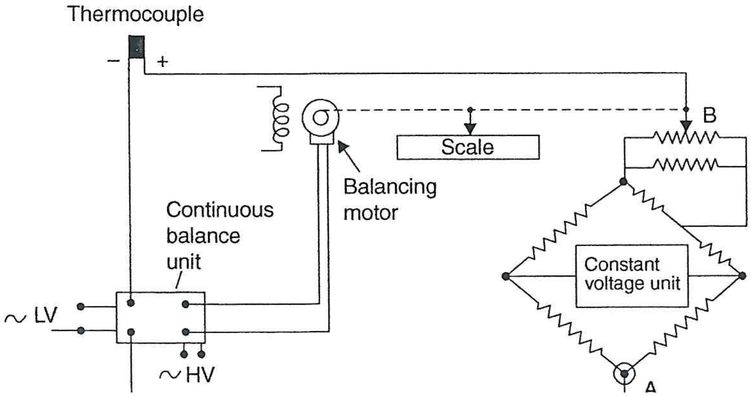
Turbine wheel speed is directly proportional to flow, and by gear reduction to the counter, indication is of total flow

Potentiometric Pen Recorder

The potentiometer is used a great deal in instrument systems and also control systems (position control, Chapter 14). For recording of small dc voltage it is usual to convert to a suitable frequency ac and amplify although dc amplification can be used. Conversion to ac is achieved in a dc chopper amplifier with output direct to servo-amplifier pen drive motor.

Figure 6.10 is a simplified sketch of a continuous balance system.

Input dc voltage, from say a thermocouple, is measured against slidewire voltage at B with a constant voltage bridge source. Difference between A and B is amplified at the continuous balance unit so energising the balancing motor to move pen arm and B until the voltage difference is zero. Similar arrangements utilise conductivity, ratio, bridge, etc. circuits. The balancing motor is two phase with a reference winding



and a control winding from the balance unit. Input to the balance unit incorporates a converter and centre tap of an input transformer. The vibrating reed converter, in moving between two contacts, allows current to pass alternately through each half of the transformer. Secondary ac voltage is amplified and fed to the control winding of the balancing motor, so timed with ac supply to give the correct restoring action. The chart is driven by a constant speed geared motor. A damping feedback tachogenerator driven from the balance motor is often fitted.

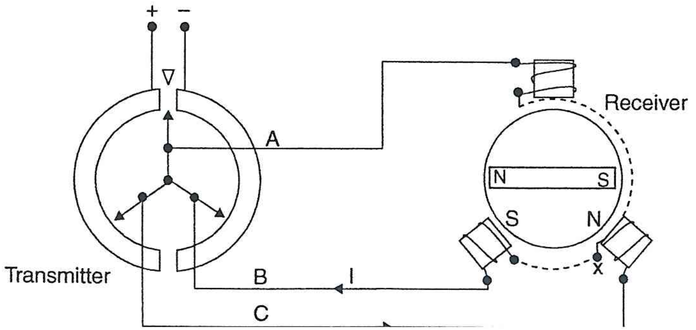
XY Recorder

Used to measure a quantity *Y*, varying with *X*, where *X* is not a function of time. Two servo systems, perpendicularly connected, cause the pen to move to any area position on the chart. Inputs cause perpendicular travel related to *X* and *Y*.

Position Motors (dc)

One technique is to feed current into a toroid resistor transmitter with three tappings connecting to a three-phase star winding enclosing a two-pole rotor receiver. This is sometimes referred to as a Desynn transmission link. A similar principle is used in the position indicator (electric telegraph).

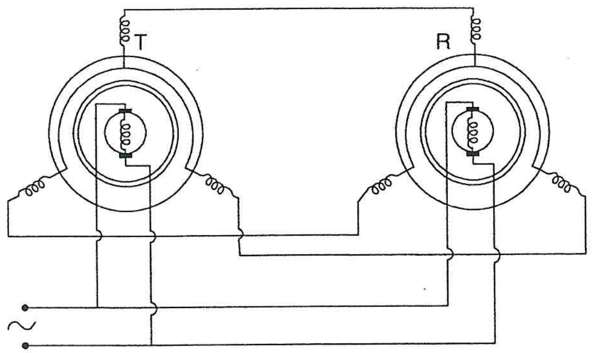
Figure 6.11 shows the arrangement in equilibrium with equal currents (I) in line B and C and zero current in line A. The receiver rotor is locked by equal and opposite torques from the attractions on unlike pole faces. Assume the transmitter to be moved 30° clockwise. Current flows to receiver from line C subdivides at point X and equal currents return through lines A and B of magnitude I/2. This creates a strong N pole at fixed magnet X and two weak S poles at the other two fixed magnets. The receiver indicator will therefore turn to the corresponding equilibrium position, that is, 30° clockwise.



Position Motors (ac)

These devices are usually known by trade names such as synchro, resolver, magslip and for larger powers, selsyn. Figure 6.12 shows a transmitter and receiver of a synchro system.

Both rotors are supplied from the same ac source and stators are linked in star. With rotors in the same angular position, emfs from transmitter and receiver stators balance and there is no circulatory current. If the transmitter rotor is moved, induced emfs are unequal and current circulates so producing a torque to bring the receiver rotor into line and restore equilibrium. Zero receiver torque exists at alignment and maximum occurs at 90° out of alignment. The resolver system is similar but utilises two phase and is used for both fine control and data processing systems. An intermediate synchro (follow through, hunter differential, etc.) can be arranged, with three-phase rotor and stator connections, so that summing or differential control outputs are possible.



▲ **Figure 6.12** *Synchro system*