SENSORS AND TRANSDUCERS

2.0 Basic definitions:

The sensing element is the first element in the measurement system; it is in contact with, and draws energy from, the process or system being measured. American National Standards Institute (ANSI) definition is A device which provides a usable output in response to a specified measurement. The input to this element is the true value of the measured variable; the output of the element depends on this value. The elements are classified according to whether the output signal is:

- Electromagnetic: - photo sensors
  - Current, voltage,
- Mechanical: - physical like pressure, force,
  - accelerometer
  - sound
  - Heat.
- chemical: - smell
  - taste
  - pH
- Biological: DNA, T cell count.
- Nuclear

Elements with an electrical output are further divided into passive and active. Passive devices such as resistive, capacitive and inductive elements require an external power supply in order to give a voltage or current output signal; active devices, e.g. electromagnetic and thermoelectric elements, need no external power supply. In this part the main physical principles used in measurement sensors, and then it goes on to discuss the range of sensors and instruments that are available for measuring various physical quantities.

2.1 Specifications of Sensor:

- **Accuracy:** error between the result of a measurement and the true value being measured.
- **Resolution:** the smallest increment of measure that a device can make.
- **Sensitivity**: the ratio between the changes in the output signal to a small change in input physical signal. Slope of the input-output fit line.
- **Repeatability/Precision**: the ability of the sensor to output the same value for the same input over a number of trials
- **Dynamic Range**: the ratio of maximum recordable input amplitude to minimum input amplitude, i.e. **Linearity**: the deviation of the output from a best-fit straight line for a given range of the sensor
- **Transfer Function** (Frequency Response): The relationship between physical input signal and electrical output signal, which may constitute a complete description of the sensor characteristics.
- **Bandwidth**: the frequency range between the lower and upper cutoff frequencies, within which the sensor transfer function is constant gain or linear.
- **Noise**: random fluctuation in the value of input that causes random fluctuation in the output value.

2.2 Attributes of Sensors:

- **Operating Principle**: Embedded technologies that make sensors function, such as electro-optics, electromagnetic, piezoelectricity, active and passive ultraviolet.
- **Dimension of Variables**: The number of dimensions of physical variables.
- **Size**: The physical volume of sensors.
- **Data Format**: The measuring feature of data in time; continuous or discrete/analog or digital.
- **Intelligence**: Capabilities of on-board data processing and decision-making.
- **Active versus Passive Sensors**: Capability of generating vs. just receiving signals.
- **Physical Contact**: The way sensors observe the disturbance in environment.
- **Environmental durability**: will the sensor robust enough for its operation conditions.

2.3 Physical Principles:

- **Ampere's Law**: A current carrying conductor in a magnetic field experiences a force (e.g. galvanometer)
- **Curie-Weiss Law**: There is a transition temperature at which ferromagnetic materials exhibit paramagnetic behavior
- **Faraday's Law of Induction** :A coil resist a change in magnetic field by generating an opposing voltage/current (e.g. transformer)
- **Photoconductive Effect**: When light strikes certain semiconductor materials, the resistance of the material decreases (e.g. photo resistor)

2.4 Types:

2.4.1 Resistive sensing elements:

Resistive sensors rely on the variation of the resistance of a material when the measured variable is applied to it. This principle is most commonly applied in temperature measurement, and in displacement measurement. In addition, some moisture meters work on the resistance-variation principle. The types are:

i. Potentiometers for linear and angular displacement measurement.

Figure 2.1 shows potentiometers for the measurement of (a) linear (rectilinear) and (b) angular (rotary) displacement. They consist of a former with a cylindrical cross-section which is either a straight cylinder or an arc of a circle. Resistive material is then placed on the former so that the resistance per unit length is constant (the usual case). This means that resistance is proportional to the distance *d* travelled by the wiper between A and B.

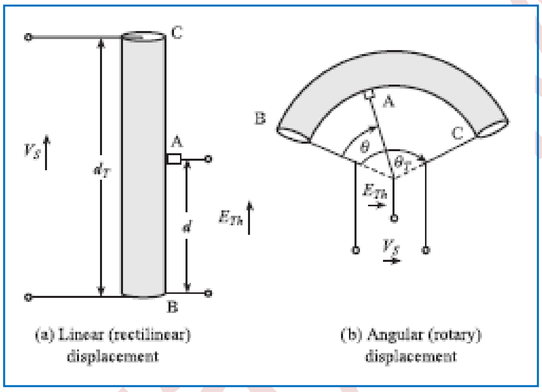
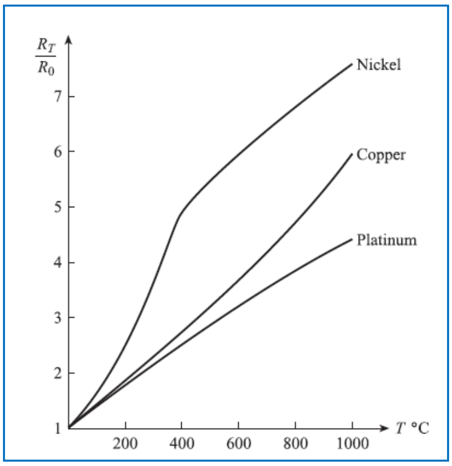


Figure2.1 linear and angular displacements.

ii. Resistive metal and semiconductor sensors for temperature measurement.

This principle is most commonly applied in temperature measurement using resistance thermometers or thermistors.

Figure 2.2 Metal resistive temperature sensors, Resistance/ temperature characteristics of commonly used metals.



iii. Metal and semiconductor resistive strain gauges.

Before discussing strain gauges we must first briefly explain the concepts of stress, strain, elastic modulus and Poisson's ratio.

Stress is defined by force/area, so that in Figure 2.3(a) the stress experienced by the body is $+F/A$, the positive sign indicating a tensile stress which tends to increase the length of the body. In Figure 2.3(b) the stress is $-F/A$, the negative sign indicating a compressive stress which tends to reduce the length of the body. The effect of the applied stress is to produce a strain in the body which is defined by (change in length)/(original unstressed length). Thus in Figure 2.3(a) the strain is $e = +\Delta l / l$ (tensile), and in 2.3(b) the strain is $e = -\Delta l / l$ (compressive); in both cases the strain is longitudinal, i.e. along the direction of the applied stress. The relationship between strain and stress is linear for a given body over a certain range of values; the slope of the straight line is termed the elastic modulus of the body:

$$Elastic\ modulus = \frac{stress}{strain}$$

For linear tensile or compressive stress the elastic modulus is called **Young's modulus** *E*; for shear stress the relevant elastic modulus is **shear modulus** *S*. Returning to Figure 2.3(a) we note that the increase in length of the body is accompanied by a decrease in cross-sectional area, i.e. a reduction in width and thickness. Thus in Figure 2.3(a) the longitudinal tensile strain is accompanied by a transverse compressive strain, and in Figure 2.3(b) the longitudinal compressive strain is accompanied by a transverse tensile strain. The relation between longitudinal strain e_L and accompanying transverse strain e_T is:

$$e_T = -ve_L$$

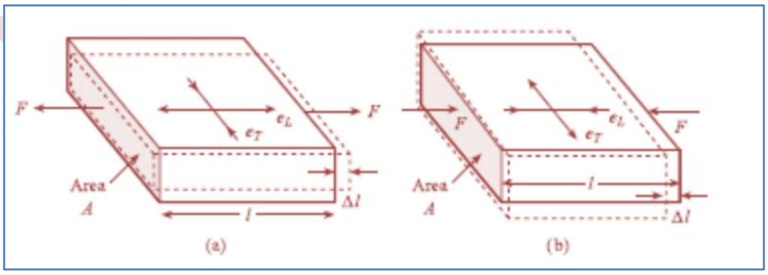


Figure 2.3 Stress and strain**: (a)** Effect of tensile stress **(b)** Effect of compressive stress**.**

Strain gauges are devices that experience a change in resistance when they are stretched or strained. They are able to detect very small displacements, usually in the range 0–50 μm, and are typically used as part of other transducers, for example diaphragm pressure sensors that convert pressure changes into small displacements of the diaphragm. Measurement inaccuracies as low as 0.15% of full-scale reading is

achievable and the quoted life expectancy is usually three million reversals. Strain gauges are manufactured to various nominal values of resistance, of which 120Ω, 350Ω and 1000Ω are very common. The typical maximum change of resistance in a 120Ω device would be 5Ω at maximum deflection. The traditional type of strain gauge consists of a length of metal resistance wire formed into a zigzag pattern and mounted onto a flexible backing sheet, as shown in Figure 2.4(a). The wire is nominally of circular cross-section. As strain is applied to the gauge, the shape of the cross-section of the resistance wire distorts, changing the cross-sectional area. As the resistance of the wire per unit length is inversely proportional to the cross-sectional area, there is a consequential change in resistance. The input–output relationship of a strain gauge is expressed by the *gauge factor*, which is defined as the change in resistance (R) for a given value of strain (S), i.e.

In use, strain gauges are bonded to the object whose displacement is to be measured. The process of bonding presents a certain amount of difficulty, particularly for semiconductor types. The resistance of the gauge is usually measured by a d.c. bridge circuit and the displacement is inferred from the bridge output measured. The maximum current that can be allowed to flow in a strain gauge is in the region of 5 to 50 mA depending on the type. Thus, the maximum voltage that can be applied is limited and consequently, as the resistance change in a strain gauge is typically small, the bridge output voltage is also small and amplification has to be carried out. This adds to the cost of using strain gauges.

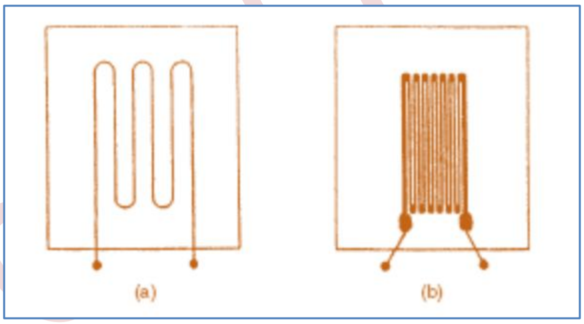


Figure 2.4 Strain gauges**: (a)** wire type**; (b)** foil type**.**

iv. Semiconductor resistive gas sensors.

Metal oxide sensors have semiconducting properties which are affected by the presence of gases. The resistance of chromium titanium oxide is affected by reducing gases such as carbon monoxide (CO) and hydrocarbons. Here oxygen atoms near the surface react with reducing gas molecules; this reaction takes up conduction electrons so that fewer are available for conduction. This causes a decrease in electrical conductivity and a corresponding increase in resistance. The resistance of tungsten oxide is affected by oxidizing gases such as oxides of nitrogen (NO_x) and ozone.

Figure 2.5 shows a typical construction of a metal oxide sensor using thick film technology. This consists of an alumina substrate with a film of oxide printed on one side and a platinum heater grid on

the other. A typical NO_X sensor has an ambient temperature range of −20 °C to +60 °C and operating power of 650 mW. The resistance is typically 6 kΩ in air, 39 kΩ in 1.5 ppm NO2 and 68 kΩ in 5.0 ppm NO_2.

A typical CO sensor has an ambient temperature range of −20 °C to +60 °C and an operating power of 650 mW. The resistance is typically 53 kΩ in air, 85 kΩ in 100 ppm CO and 120 kΩ in 400 ppm CO.

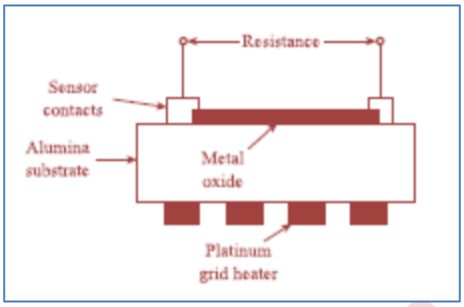


Figure 2.5 Typical construction of metal oxide gas sensor.

2.4.2 Capacitive sensing elements:

Capacitive devices are often used as displacement sensors, in which motion of a moveable capacitive plate relative to a fixed one changes the capacitance. Often, the measured displacement is part of instruments measuring pressure, sound or acceleration. Alternatively, fixed plate capacitors can also be used as sensors, in which the capacitance value is changed by causing the measured variable to change the dielectric constant of the material between the plates in some way. This principle is used in devices to measure moisture content, humidity values and liquid level.

The simplest capacitor consists of two parallel metal plates separated by a dielectric or insulating material (Figure 2.6).

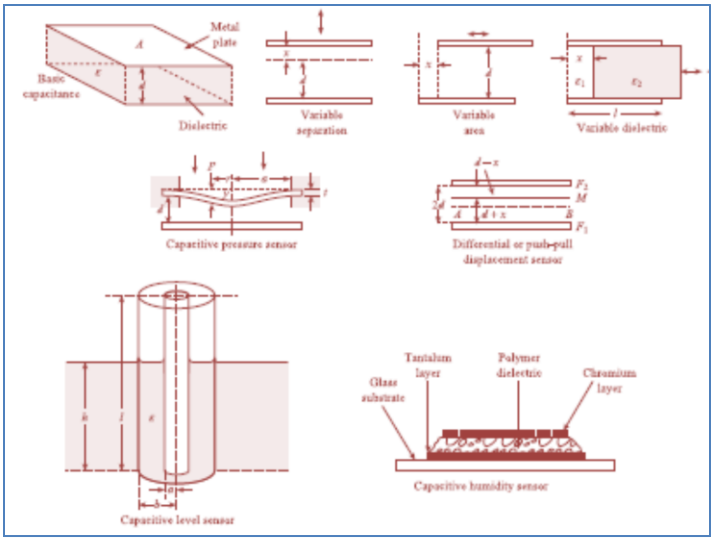


Figure2.6 Capacitive sensing elements.

2.4.3 Inductive sensing elements:

i. Variable inductance (variable reluctance) displacement sensors.

In order to discuss the principles of these elements we must first introduce the concept of a magnetic circuit. In an electrical circuit an electromotive force (e.m.f.) drives a current through an electrical resistance and the magnitude of the current is given by

$$\text{e.m.f.} = \text{current} \times \text{resistance}$$

A simple magnetic circuit is shown in Figure 2.7(a): it consists of a loop or core of ferromagnetic material on which is wound a coil of *n* turns carrying a current *i*. By analogy we can regard the coil as a source of magneto motive force (m.m.f.) which drives a flux through the magnetic circuit.

Figure 2.7(b) shows the core separated into two parts by an air gap of variable width. The total reluctance of the circuit is now the reluctance of both parts of the core together with the reluctance of the air gap. Since the relative permeability of air is close to unity and that of the core material many thousands, the presence of the air gap causes a large increase in circuit reluctance and a corresponding decrease in flux and inductance. Thus a small variation in air gap causes a measurable change in inductance so that we have the basis of an **inductive displacement sensor**.

Figure 2.7(c) shows a typical variable reluctance displacement sensor, consisting of three elements: a ferromagnetic core in the shape of a semi toroid (semicircular ring), a variable air gap and a ferromagnetic plate or armature.

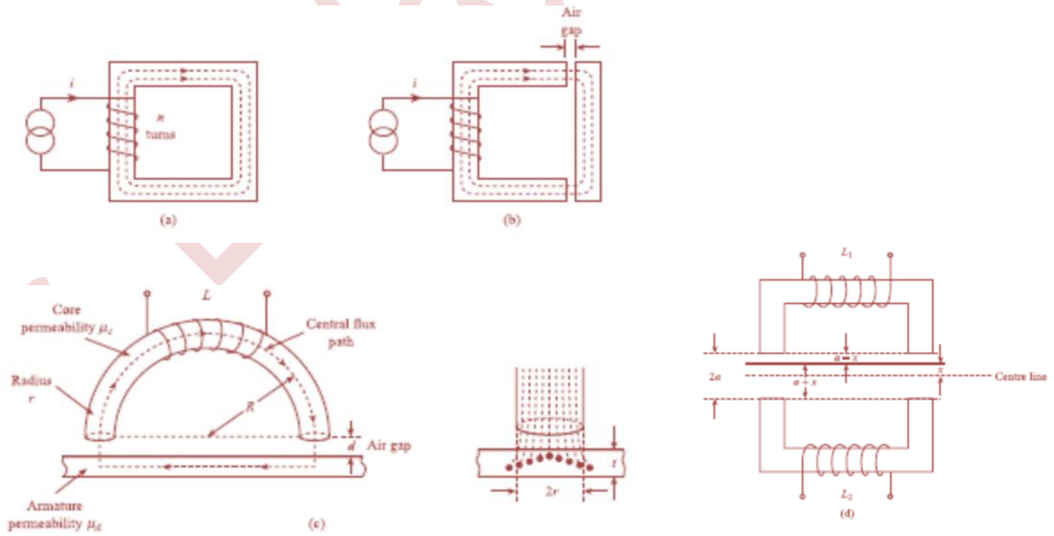


Figure 2.7 Variable reluctance elements: (a)(b) Basic principle of reluctance sensing elements (c) Reluctance calculation for typical element (d) Differential or push/pull reluctance displacement sensor.

ii. Linear Variable Differential Transformer (LVDT) displacement sensor.

This sensor is a transformer with a single primary winding and two identical secondary windings wound on a tubular ferromagnetic former (Figure 2.8). The primary winding is energized by an a.c. voltage of amplitude V_P and frequency f Hz; the two secondaries are connected in series opposition so that the output voltage V_{OUT} $\sin(2\pi\ f\ t + \varphi)$ is the difference ($V_1 - V_2$) of the voltages induced in the secondaries. A ferromagnetic core or plunger moves inside the former; this alters the mutual inductance between the primary and secondaries. With the core removed the secondary voltages are ideally equal so that $V_{OUT} = 0$. With the core in the former, V_1 and V_2 change with core position x, causing amplitude V_{OUT} and phase φ to change.

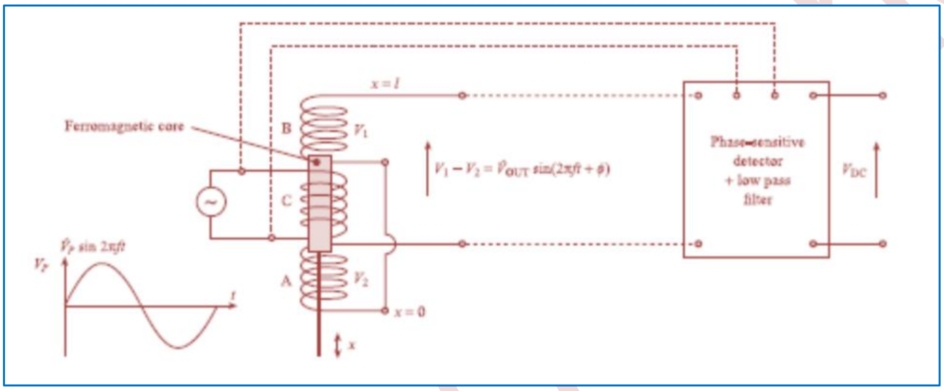


Figure 2.8 LVDT and connections to phase-sensitive detector.

2.4.4 Electromagnetic sensing elements.

These elements are used for the measurement of linear and angular velocity an based on Faraday's law of electromagnetic induction. This states that if the flux linked by a conductor is changing with time, then a back e.m.f. is induced in the conductor with magnitude equal to the rate of change of flux.

In an electromagnetic element the change in flux is produced by the motion being investigated; this means that the induced e.m.f. depends on the linear or angular velocity of the motion. A common example of an electromagnetic sensor is the variable reluctance tachogenerator for measuring angular velocity (Figure 2.9).

It consists of a toothed wheel of ferromagnetic material (attached to the rotating shaft) and a coil wound onto a permanent magnet, extended by a soft iron pole piece. The wheel moves in close proximity to the pole piece, causing the flux linked by the coil to change with time, thereby inducing an e.m.f. in the coil.

The magnitude of the e.m.f. can be calculated by considering the magnetic circuit formed by the permanent magnet, air gap and wheel. The e.m.f. is constant with time and depends on the field strength of the permanent magnet. The reluctance of the circuit will depend on the width of the air gap between the wheel and pole piece. When a tooth is close to the pole piece the reluctance is minimum but will increase as the tooth

moves away. The reluctance is maximum when a 'gap' is adjacent to the pole piece but falls again as the next tooth approaches the pole piece.

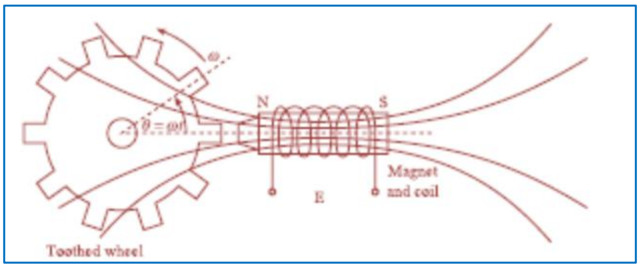


Figure2.9 Variable reluctance tachogenerator, angular variations in reluctance and flux.

2.4.5 Thermoelectric sensing elements.

Thermoelectric or thermocouple sensing elements are commonly used for measuring temperature. If two different metals *A* and *B* are joined together, there is a difference in electrical potential across the junction called the junction potential. This junction potential depends on the metals *A* and *B* and the temperature *T* °C of the junction.

A thermocouple is a closed circuit consisting of two junctions (Figure 2.10), at different temperatures T_1 and T_2 °C. If a high-impedance voltmeter is introduced into the circuit, so that current flow is negligible, then the measured e.m.f. is, to a close approximation, the difference of the junction potentials, i.e.

Thus the measured e.m.f. depends on the temperatures T_1, T_2 of both junctions. In the following discussion T_1 will be the temperature to be measured, i.e. the temperature of the measurement junction, and T_2 will be the temperature of the reference junction. In order to accurately infer T_1 from the measured e.m.f., the reference junction temperature T_2 must be known.

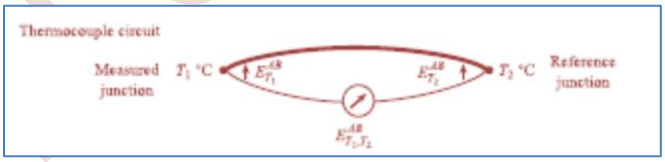


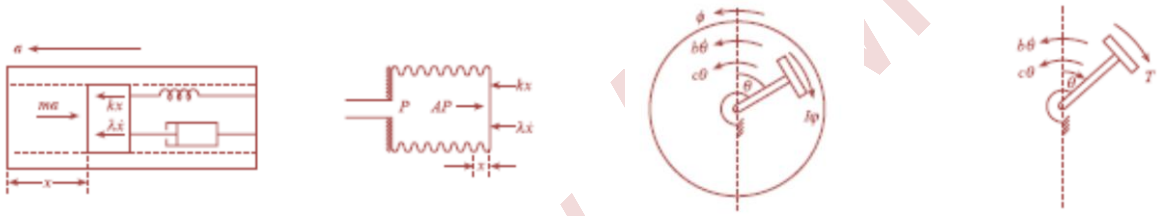
Figure 2.10 thermocouple principles.

2.4.6 Elastic sensing elements.

If a force is applied to a spring, then the amount of extension or compression of the spring is approximately proportional to the applied force. This is the principle of elastic sensing elements which convert an input force into an output displacement. Elastic elements are also commonly used for measuring torque, pressure and acceleration.

In a measurement system an elastic element will be followed by a suitable secondary displacement sensor, e.g. potentiometer, strain gauge or LVDT, which converts displacement into an electrical signal. The displacement may be translational or rotational.

Elastic sensing elements have associated mass (interance) and damping (resistance) as well as spring characteristics. Figure 2.11 shows dynamic models of elastic elements for measuring linear acceleration, torque, pressure and angular acceleration.



a b c d

Figure 2.11 Dynamic models of elastic elements:

(a) Linear accelerometer (b) Pressure sensor (c) Angular accelerometer (d) Torque sensor.

2.4.7 Piezoelectric sensing elements.

If a force is applied to any crystal, then the crystal atoms are displaced slightly from their normal positions in the lattice. This displacement is proportional to the applied force: i.e., in the steady state, the dynamic relation between *and can* be represented by the second-order transfer function.

Piezoelectric elements are commonly used for the measurement of acceleration and vibration. The following are same types of the piezoelectric sensing materials.

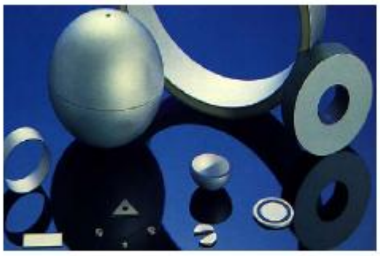
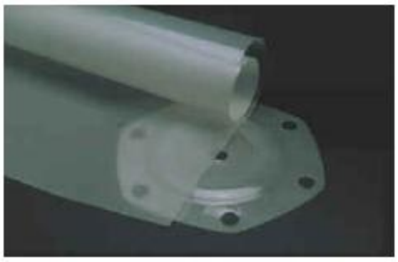




Figure 2.12 Single crystals (Quarts) Polycrystalline ceramics (PTZ) Polymer (PVDF)

2.4.8 Piezoresistive sensing elements.

The piezoresistive effect was defined as the change in resistivity of a material with applied mechanical strain; silicon doped with small amounts of *n*- or *p*-type material exhibits a large piezoresistive effect and is used to manufacture strain gauges with high gauge factors as shown in figure 2.13.

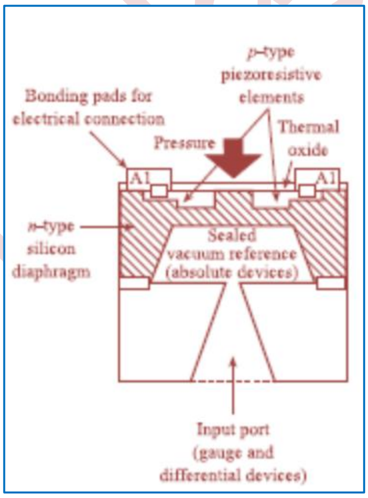


Figure 2.13 Piezoresistive sensors

2.4.9 Electrochemical sensing elements:

i. **Ion selective electrodes.**

Ion selective electrodes (ISEs) are sensors which directly measure the activity or concentration of ions in solution. They could, for example, be used to measure the concentration of lead, sodium or nitrate ions in drinking water. When an ISE is immersed in a solution, a reaction takes place between the charged species in the solution and those on the sensor surface. Equilibrium is then established between these species: there is a corresponding equilibrium potential difference between the sensor and solution, which depends mainly, but not entirely, on the activity of a single ion. This output signal depends also, to some extent, on the activity of other ions present in the solution; the electrodes are therefore *selective* rather than *specific*. Figure 2.14 show the basic system for ion concentration.

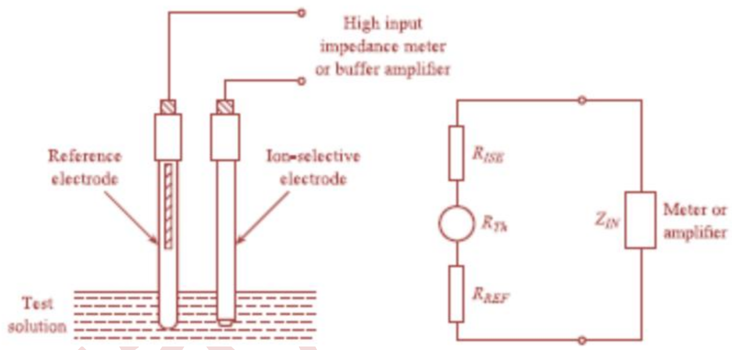


Figure2.14 Basic system for ion concentration measure and equivalent circuit

ii. **Electrochemical gas sensors.**

Some solid-state materials give an electrochemical response to certain gases. An example is zirconia, which is sensitive to oxygen. Zirconia is based on zirconium oxide (ZrO2) with small amounts of other metal oxides present. These atoms replace Zr atoms at lattice sites and enable the material to conduct both electrons and oxygen O2− ions. Opposite surfaces of a slab of zirconia are coated with a thin layer of platinum, which is porous to oxygen molecules, to give two electrodes. If a surface is exposed to a gas containing oxygen, then oxygen molecules diffuse into the zirconia.

A practical sensor consists of a small hollow cone of zirconia, coated on both the inside and outside with a layer of porous platinum and held at a constant temperature of 640 °C.

iii. Chemically sensitive field effect transistors (CHEMFET).

It is a chip of silicon crystal with impurities added to create areas of *n*-type and *p*-type material. The device has four terminals. The source S and drain D are regions of enriched *n*-type material, the body or substrate (B) is *p*-type material and the gate G is metal or polysilicon material. The body is often connected to the source to give a three-terminal device. The gate is insulated from the substrate by a thin layer of silicon dioxide so that negligible current is drawn through the gate terminal. Figure 2.15 shows the construction of chemically sensitive field effect transistors. This type is used to analyze the liquids and the gases.

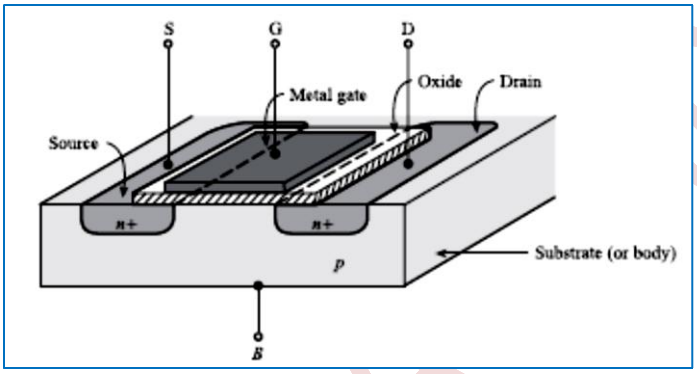


Figure 2.15 The construction of chemically sensitive field effect transistors.

2.4.10 Hall effect sensors.

An important application of Hall devices is to measure magnetic field. It consists of a conductor carrying a current that is aligned orthogonally with the magnetic field, as shown in Figure 2.16. This produces a transverse voltage difference across the device that is directly proportional to the magnetic field strength.

For an excitation current I and magnetic field strength B, the output voltage is given by V = KIB, where K is known as the Hall constant.

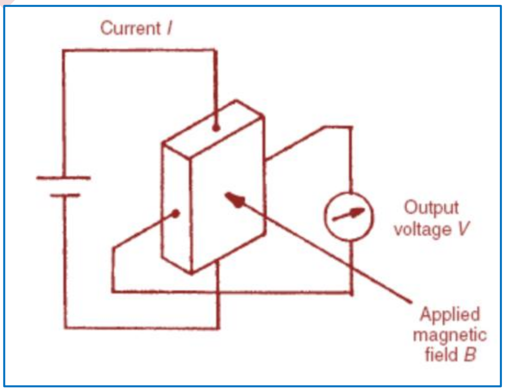


Figure 2.16 principles of Hall-effect sensor.

The conductor in Hall-effect sensors is usually made from a semiconductor material as opposed to a metal, because a larger voltage output is produced for a magnetic field of a given size. In one common use of the device as a proximity sensor, the magnetic field is provided by a permanent magnet that is built into the device. The magnitude of this field changes when the device becomes close to any ferrous metal object or boundary. The Hall-effect is also commonly used in keyboard pushbuttons, in which a magnet is attached underneath the button. When the button is depressed, the magnet moves past a Hall-effect sensor. The induced voltage is then converted by a trigger circuit into a digital output. Such pushbutton switches can operate at high frequencies without contact bounce.

2.4.11 Optical sensors

Optical sensors are based on the modulation of light travelling between a light source and a light detector, as shown in Figure 2.17. The transmitted light can travel along either an air path or a fibre-optic cable. Either form of transmission gives immunity to electromagnetically induced noise, and also provides greater safety than electrical sensors when used in hazardous environments. Light sources suitable for transmission across an air path include tungsten-filament lamps, laser diodes and light-emitting diodes (LEDs). However, as the light from tungsten lamps is usually in the visible part of the light frequency spectrum, it is prone to interference from the sun and other sources. Hence, infrared LEDs or infrared laser diodes are usually preferred. These emit light in a narrow frequency band in the infrared region and are not affected by sunlight.

The main forms of light detector used with optical systems are photocells (cadmium sulphide or cadmium selenide being the most common type of photocell), phototransistors and photodiodes. These are all photoconductive devices, whose resistance is reduced according to the intensity of light to which they are exposed. Photocells and phototransistors are particularly sensitive in the infrared region, and so are ideal partners for infrared LED and laser diode sources.

Air-path optical sensors are commonly used to measure proximity, translational motion, rotational motion and gas concentration.

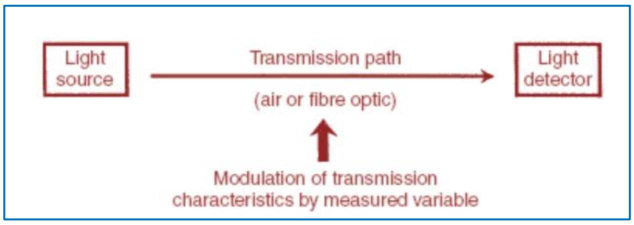


Figure 2.17 principles of optical sensors.

optical sensors can use fibreoptic cable instead to transmit light between a source and a detector. In such sensors, the variable being measured causes some measurable change in the characteristics of the light transmitted by the cable.

2.4.12 Nuclear sensors.

Nuclear sensors are uncommon measurement devices, partly because of the strict safety regulations that govern their use, and partly because they are usually expensive. Some very low-level radiation sources are now available that largely overcome the safety problems, but measurements are then prone to contamination by background radiation.

The principle of operation of nuclear sensors is very similar to optical sensors in that radiation is transmitted between a source and a detector through some medium in which the magnitude of transmission is attenuated according to the value of the measured variable. Caesium-137 is commonly used as a gamma-ray source and a sodium iodide device is commonly used as a gamma-ray detector. One current use of nuclear sensors is in a non-invasive technique for measuring the level of liquid in storage tanks, They are also used in mass flow rate measurement and in medical scanning applications.

2.4.13 Micro sensors.

Microsensors are millimeter-sized two- and three-dimensional micromachined structures that have smaller size, improved performance, better reliability and lower production costs than many alternative forms of sensor. Currently, devices to measure temperature, pressure, force, acceleration, humidity, magnetic fields, radiation and chemical parameters are either in production or at advanced stages of research.

Microsensors are usually constructed from a silicon semiconductor material, but are sometimes fabricated from other materials such as metals, plastics, polymers, glasses and ceramics that are deposited on a silicon base. Silicon is an ideal material for sensor construction because of its excellent mechanical properties. Its tensile strength and Young's modulus is comparable to that of steel, whilst its density is less than that of aluminum. Sensors made from a single crystal of silicon remain elastic almost to the breaking point, and mechanical hysteresis is very small. In addition, silicon has a very low coefficient of thermal expansion and can be exposed to extremes of temperature and most gases, solvents and acids without deterioration.

2.5 Transducers:

A transducer is defined as a device that receives energy from one system and transmits it to another, often in a different form (electrical, mechanical or acoustical).

2.6 Specification of transducers:

Same for sensors.

2.7 Classification of transducers:

1. Based on principle of transduction
2. Active & passive
3. Analog & digital
4. Inverse transducer

There are mainly **two types** of transducers:

1) Electrical

2) Mechanical

The electrical output of a transducer depends on the basic principle involved in the design.

The output may be analog, digital, or frequency modulated.

2.7.1 Electrical Transducer

Electrical transducers can be classified into two major categories:

Active transducers

Generates an electrical signal directly in response to the physical parameter (does not require external power to operate). Example: piezo-electric sensor and photo cells.

Passive transducers

Requires external power to operate. Example: Strain gauges and thermistors.

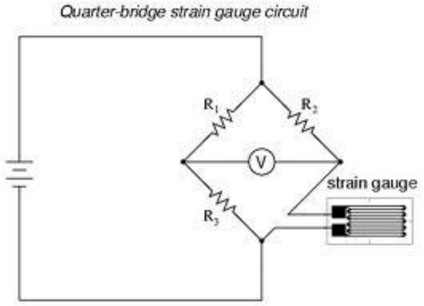
2.7.2 Resistive Position Transducer:

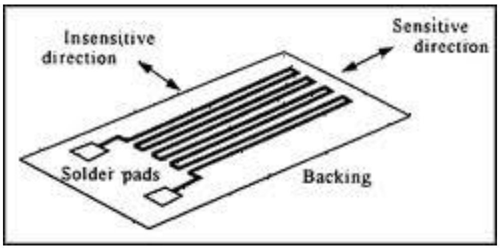
Operates under a principle of **resistance change** by the physical movement under measurement.

, The shaft and wiper can be moved to the left or right causes a change in the circuit resistance.

Strain Gauges

The **strain gauge** is an example of a passive transducer that senses the strain produced by a force on the wires. When a gauge is subjected to a **positive stress**, its length increases while its area of cross-section decreases thus **increases** its resistance. The main strain gauge is wire strain gauges, A fine wire element is cemented to a thin sheet of paper, Bakelite or Teflon. The measurement of the sensitivity of a material to strain is called the gauge factor.

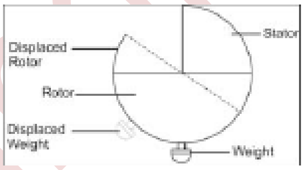




2.7.3 Capacitive Transducer

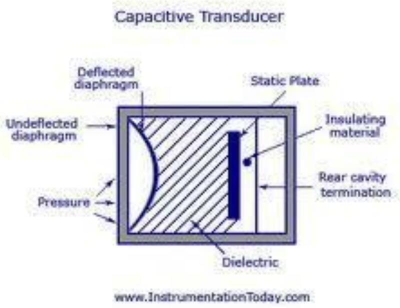
Capacitive transducer operates by a **linear change** in capacitance.

A variable plate area transducer is shown in the figure below.



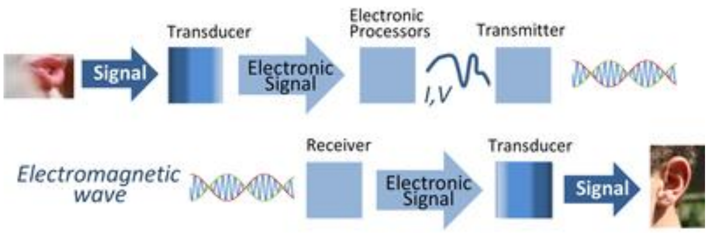
It is made of a fixed plate called **Stator** and a movable plate called the **Rotor**. The capacitance of the transducer is changing as the rotor changes its position relative to the stator. This transducer can be used to detect the amount of roll in an aircraft.

Another example of capacitive transducer is the capacitive pressure transducer as shown in the figure. This sensor is designed to measure pressure (in vacuum). A metallic diaphragm will move to the right when pressure is applied to the chamber and to the left when vacuum is applied. This diaphragm is used as one plate of a variable capacitor. The capacitive transducer is simple to construct, inexpensive, and effective for HF variations.



2.7.4 Inductive Transducer

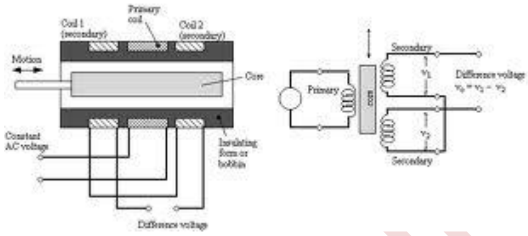
Inductive transducers may be either of the self-generating or the passive type. The **self-generating type** utilizes the basic electrical generator principle. a motion between a conductor and magnetic field induces a voltage in the conductor. A **tachometer** is an example of the self-generating transducer which directly converts speed or velocity into an electrical signal. An inductive **electromechanical transducer** converts physical motion into a change in inductance.



For the measurement of displacement of linear and angular movement respectively. Works on the principle of the variation of **permeability** causing a change in self-inductance. the variable reluctance transducer.

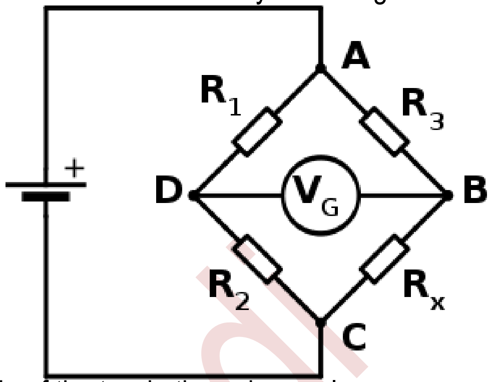
2.7.5 LVDT is Linear Variable Differential Transformer.

An movable soft iron slides within the hollow part of the transformer thus affects the magnetic coupling between the primary and the secondary windings. The frequency of the ac voltage applied to the primary winding ranges from 50 Hz to 20 kHz.



2.8 Wheatstone bridge

A **Wheatstone bridge** is an electrical circuit used to measure an unknown electrical resistance by balancing two legs of a bridge circuit, one leg of which includes the unknown component. Its operation is similar to the original potentiometer. It was invented by Samuel Hunter Christie in 1833 and improved and popularized by Sir Charles Wheatstone in 1843. One of the Wheatstone bridge's initial uses was for the purpose of soils analysis and comparison.



2.8.1 Operation

In the figure, $R_x$is the unknown resistance to be measured; R_1, $R_2$and R_3 are resistors of known resistance and the resistance of $R_2$is adjustable. If the ratio of the two resistances in the known leg $(R_2/R_1)$is equal to the ratio of the two in the unknown leg (R_x/R_3), then the voltage between the two midpoints (**B** and **D**) will be zero and no current will flow through the galvanometer V_g. If the bridge is unbalanced, the direction of the current indicates whether $R_2$is too high or too low. $R_2$is varied until there is no current through the galvanometer, which then reads zero.

Detecting zero current with a galvanometer can be done to extremely high accuracy. Therefore, if R_1, $R_2$and $R_3$are known to high precision, then $R_x$can be measured to high precision. Very small changes in $R_x$disrupt the balance and are readily detected.

At the point of balance, the ratio of

$$\frac{R_2}{R_1} = \frac{R_x}{R_3}$$
$$\Rightarrow R_x = \frac{R_2}{R_1} \cdot R_3$$

Alternatively, if R_1, R_2, and $R_3$are known, but $R_2$is not adjustable, the voltage difference across or current flow through the meter can be used to calculate the value of R_x, using Kirchhoff's circuit laws (also known as Kirchhoff's rules). This setup is frequently used in strain gauge and resistance thermometer measurements, as it is usually faster to read a voltage level off a meter than to adjust a resistance to zero the voltage.

2.8.2 Derivation

First, Kirchhoff's first rule is used to find the currents in junctions **B** and **D**:

$$I_3 - I_x + I_G = 0$$
$$I_1 - I_2 - I_G = 0$$

Then, Kirchhoff's second rule is used for finding the voltage in the loops **ABD** and **BCD**:

$$(I_3 \cdot R_3) - (I_G \cdot R_G) - (I_1 \cdot R_1) = 0$$
$$(I_x \cdot R_x) - (I_2 \cdot R_2) + (I_G \cdot R_G) = 0$$

The bridge is balanced and $I_G = 0$, so the second set of equations can be rewritten as:

$$I_3 \cdot R_3 = I_1 \cdot R_1$$
$$I_x \cdot R_x = I_2 \cdot R_2$$

Then, the equations are divided and rearranged, giving:

$$R_x = \frac{R_2 \cdot I_2 \cdot I_3 \cdot R_3}{R_1 \cdot I_1 \cdot I_x}$$

From the first rule, $I_3 = I_x$ and $I_1 = I_2$. The desired value of R_x is now known to be given as:

$$R_x = \frac{R_3 \cdot R_2}{R_1}$$

If all four resistor values and the supply voltage (V_S) are known, and the resistance of the galvanometer is high enough that I_G is negligible, the voltage across the bridge (V_G) can be found by working out the voltage from each potential divider and subtracting one from the other. The equation for this is:

$$V_G = \left(\frac{R_x}{R_3 + R_x} - \frac{R_2}{R_1 + R_2}\right) V_s$$

Where V_G is the voltage of node B relative to node D.

2.8.3 Modifications of the fundamental bridge

The Wheatstone bridge is the fundamental bridge, but there are other modifications that can be made to measure various kinds of resistances when the fundamental Wheatstone bridge is not suitable. Some of the modifications are:

1-D.C. bridge measurements

The simplest form of a D.C. four-arm resistance bridge is the Wheatstone bridge. This is suitable for the measurement of resistance typically in the range from 1 Ω to 10 Ω and is shown in Figure above. The detector which may be either a galvanometer or an electronic detector is used to detect a null potential between the points D and B of the bridge, or Strain gauges and platinum resistance thermometers may be situated at a considerable distance from the bridge and the long leads connecting the active element to the bridge will have a resistance which will vary with temperature.

2-A.C. bridge measurements:

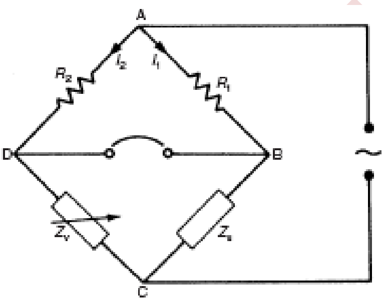
i. *Null-type impedance bridge*

A typical null-type impedance bridge is shown in Figure below. The null point can be conveniently detected by monitoring the output with a pair of headphones connected via an operational amplifier across the points BD. This is a much cheaper method of null detection than the application of an expensive galvanometer that is required for a D.C. Wheatstone bridge.

$I_1R_1 = I_2R_2$ $I_1Z_u = I_2Z_v$

Thus:

$Z_u = Z_vR_1/R_2$

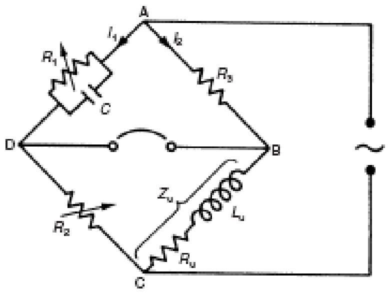


Z_u is capacitive,

Notice that the expression for Z_u as an inductive impedance has a resistive term in it because it is impossible to realize a pure inductor.

ii. *Maxwell bridge*

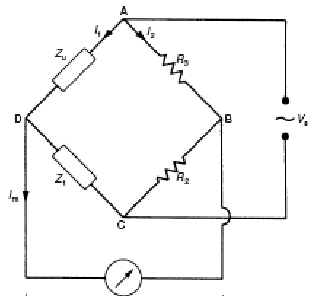
The requirement for a variable inductance box is avoided by introducing instead a second variable resistance. The circuit requires one standard fixed-value capacitor, two variable-resistance boxes and one standard fixed-value resistor, all of which are components that are readily available and inexpensive.

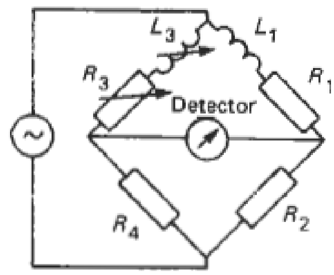
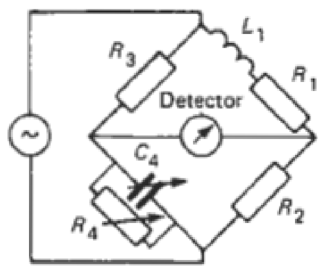
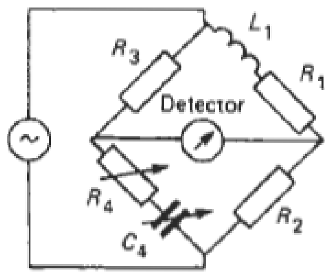
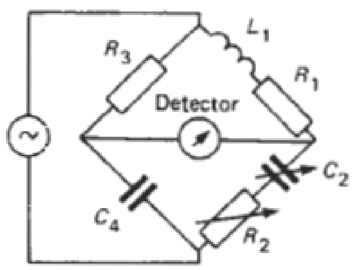
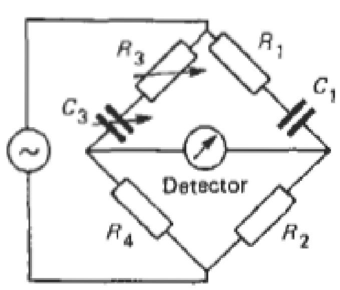


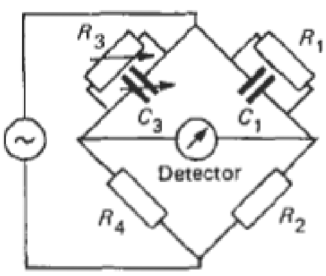
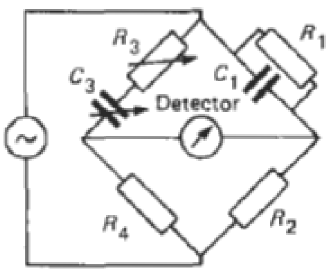
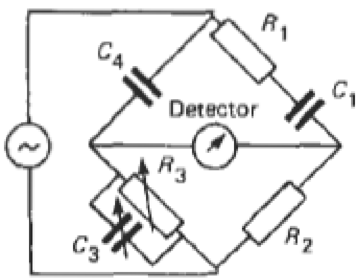
$I_1Z_{AD} = I_2Z_{AB}$ $I_1Z_{DC} = I_2Z_{BC}$

thus: $Z_{BC}/Z_{AB} = Z_{DC}/Z_{AD}$ or $Z_{BC}=(Z_{DC} * Z_{AB})/Z_{AD}$

iii. *Deflection-type A.C. bridge*



A.C. bridges for the measurement of ***capacitance*** and ***inductance***			
Bridge	***Circuit***	***Balance conditions***	***Notes***
Maxwell		$L_1=(R_2/R_4)L_3$	used to measure the parallel components **of** an unknown inductance
Maxwell-Wien1		$L_1=R_2 R_3C_4$ $R_1=R_2R_3/R_4$ $Q_1=\omega C_4R_4$	used for the measurement of inductance; if ***C4*** and ***R4*** are variable bridge measures ***L1*** and ***R1;*** if ***R4*** and ***R2*** or ***R3*** are variable bridge measures ***L1*** and **Q1**
Hay		$L_1=\frac{R_2R_3C_4}{1+\omega^2C_4^2R_4^2}$ $R_1=\frac{R_2R_3\omega^2C_4^2R_4^2}{(1+\omega^2C_4^2R_4^2)}$ $Q_1=\frac{1}{\omega C_4R_4}$	measurement of A.C inductance in the presence of D.C. bias current; used for the measurement *of* inductances with high ***L*** and ***Q***
Owen		$L_1= C_4R_3.\ R_2$ $G_1=1/R_1=(1/C_4R_3)C_2$	measurement of the series inductance and conductance of an unknown inductor; used as a high-precision bridge
Series capacitance Component bridge		$C_1=\frac{R_4}{R_2}.\ C_3$ $R_1=\frac{R_2}{R_4}.\ R_3$ $D_1=\omega C_3R_3$	used for the measurement of capacitance; if ***C3*** and ***R3*** are variable bridge measures C1 and ***R1;*** if ***R3*** and ***R4*** are variable bridge measures **C1** and ***D1***

Bridge	***Circuit***	***Balance conditions***	***Notes***
Parallel capacitance component bridge		$C_1=\frac{R_4}{R_2}.C_3$ $R_1=\frac{R_4}{R_2}.R_3$ $D_1=\frac{1}{\omega C_3R_3}$	measurement of the parallel capacitance and resistance of an unknown capacitor; used particularly for high *D* capacitor measurement
Maxwell-Wien2		$C_1=\frac{R_4}{R_2}.\frac{C_3}{1+\omega^2C_3^2R_3^2}$ $R_1=\frac{R_2}{R_4}.\frac{1+\omega^2C_3^2R_3^2}{\omega^2C_3^2R_3}$ $D_1=\omega C_3R_3$	measurement of the parallel capacitance and resistance of an unknown capacitor; used as a frequency-dependent circuit in oscillators
Schering		$C_1=\frac{C_4}{R_2}.R_3$ $R_1=\frac{R_2}{C_4}.C_3$ $D_1=\omega C_3R_3$	measurement of the parallel capacitance and resistance of an unknown capacitor: used for measuring dielectric losses at high voltage and r.f. measurements