Sources of Error :

The major sources of error that may contaminate the result are :

i. The measurer, and

ii. The instrument itself.

Sometimes, the measurer may suffer from temporary factors like fatigue, boredom, anxiety or other distractions. Such factors limit the ability of the measurer to take the measurements accurately and fully. Hunger, impatience, or general variation in mood can also affect the readings.

Any condition that creates strain on the user during the measurement session can have serious effect on data collection.

A defective instrument can also cause error in measurement.

The error also occurs due to noise, response time, design limitations, effect of friction in the instrument movement, resolving power, transmission, errors of observation and interpretation.

... that may arise

The generalized classification of the measurement errors is given below :

A. Gross Errors :

1. Gross errors are caused by mistake in using instruments or meters, calculating measurement and recording data results.
2. The best example of these errors is a person or operator reading pressure gage 1.01 N/m^2 as 1.10 N/m^2.

B. Measurement Errors :

1. The measurement error is the result of the variation of a measurement of the true value.
2. Usually, measurement error consists of a systematic error and random error.

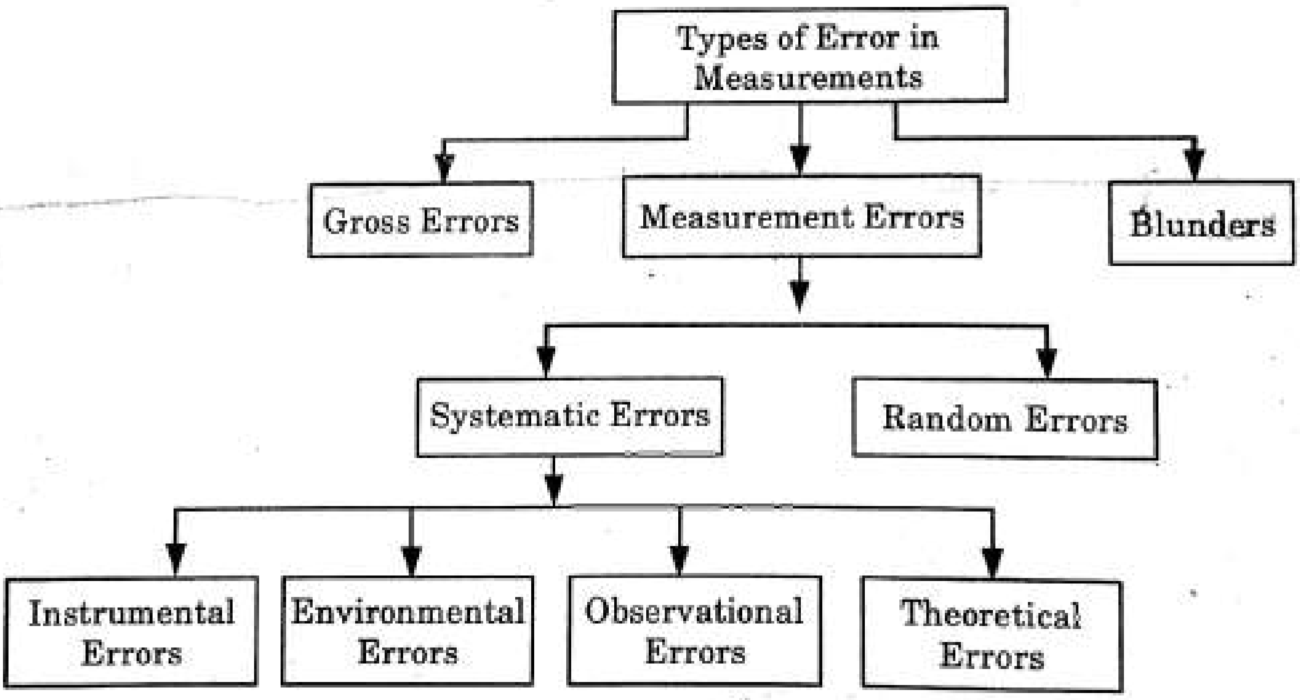

Fig. 1.17.1.

a. Systematic Errors :

1. The errors that occur due to fault in the measuring device are known as systematic errors. Usually they are called as zero error a positive or negative error.
2. These errors can be detached by correcting the measurement device.

i. Instrumental Errors :

1. Instrumental errors occur due to wrong construction of the measuring instruments.
2. These errors may occur due to hysteresis or friction.

ii. **Environmental Errors :**

1. The environmental errors occur due to some external conditions of the instrument. External conditions mainly include pressure, temperature, humidity etc.
2. In order to reduce the environmental errors, try to maintain the humidity and temperature constant in the laboratory by making some arrangements.

iii. **Observational Errors :**

1. These types of errors occur due to wrong observations or reading in the instruments which may be due to parallax.
2. In order to reduce the parallax error highly accurate meters are needed e.g., meters provided with mirror scales.

iv. **Theoretical Errors :**

1. Theoretical errors are caused by simplification of the model system.
2. For example, a theory states that the temperature of the system surrounding will not change the readings taken when it actually does, then this factor will begin a source of error in measurement.

b. **Random Errors :**

1. Random errors are caused by the sudden change in experimental conditions and noise and tiredness in the working persons. These errors are either positive or negative.
2. Examples : Changes in humidity, unexpected change in temperature and fluctuation in voltage.
3. These errors may be reduced by taking the average of a large number of readings.
4. Some of the prominent random errors are :
   i. Frictional errors.
   ii. Mechanical vibrations.
   iii. Backlash in the movement.
   iv. Hysteresis of the elastic members.
   v. Finite scale divisions.

C. **Blunders :**

1. Blunders are final source of errors and these errors are caused by faulty recording or due to a wrong value while recording a measurement, or misreading a scale or forgetting a digit while reading a scale.
2. These blunders should stick out like sore thumbs if one person checks the work of another person. It should not be comprised in the analysis of data.

This cannot be more than unity, because the pickup cannot generate information but can only receive and process it. Obviously, as high a transfer efficiency as possible is desirable.

Sensitivity may be expressed as

$$\eta = \frac{d\,I_{out}}{d\,I_{in}} \tag{1c}$$

Very often sensitivity approximates a constant; that is, the output is the linear function of the input.

2 LOADING OF THE SIGNAL SOURCE

Energy will always be taken from the signal source by the measuring system, which means that the information source will always be changed by the act of measurement. This is an axiom of measurement. This effect is referred to as *loading*. The smaller the load placed on the signal source by the measuring system, the better.

Of course, the problem of loading occurs not only in the first stage, but throughout the entire chain of elements. While the first-stage detector-transducer loads the input source, the second stage loads the first stage, and finally the third stage loads the second stage. In fact, the loading problem may be carried right down to the basic elements themselves.

In measuring systems made up primarily of electrical elements, the loading of the signal source is almost exclusively a function of the detector. Intermediate modifying devices and output indicators or recorders receive most of the energy necessary for their functioning from sources *other* than the signal source. A measure of the quality of the first stage, therefore, is its ability to provide a usable output without draining an undue amount of energy from the signal.

3 THE SECONDARY TRANSDUCER

As an example of a system of mechanical elements only, consider the Bourdon-tube pressure gage, shown in Fig. 1. The primary detecting-transducing element consists of a circular tube of approximately elliptical cross section. When pressure is introduced, the section of the flattened tube tends toward a more circular form. This in turn causes the free end A to move outward and the resulting motion is transmitted by link B to sector gear C and hence to pinion D, thereby causing the indicator hand to move over the scale.

In this example, the tube serves as the primary detector-transducer, changing pressure into near linear displacement. The linkage-gear arrangement acts as a secondary transducer (linear to rotary motion) and as an amplifier, yielding a magnified output.

A modification of this basic arrangement is to replace the linkage-gear arrangement with either a differential transformer (Section 11) or a voltage-dividing potentiometer (Section 6). In either case the electrical device serves as a secondary transducer, transforming displacement to voltage.

As another example, let us analyze a simplified compression-type force-measuring *load cell* consisting of a short column or strut, with electrical resistance-type strain gages (see Section 7) attached (Fig. 2). When an applied force deflects or strains the block, the force effect is transduced to deflection (we are interested in the unit deflection in this case). The load is transduced to strain. In turn, the strain is transformed into an electrical resistance change, with the strain gages serving as secondary transducers.

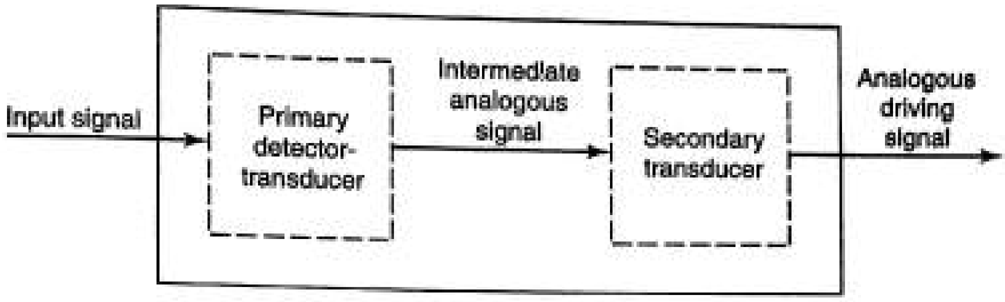

FIGURE 3: Block diagram of a first-stage device with primary and secondary transducers.

4 CLASSIFICATION OF FIRST-STAGE DEVICES

It appears, therefore, that the stage-one instrumentation may be of varying basic complexity, depending on the number of operations performed. This leads to a classification of first-stage devices as follows:

Class I. First-stage element used as detector only

Class II. First-stage elements used as detector and single transducer

Class III. First-stage elements used as detector with two transducer stages

A generalized first stage may therefore be shown schematically, as in Fig. 3.

Stage-one instrumentation may be very simple, consisting of no more than a mechanical spindle or contacting member used to transmit the quantity to be measured to a secondary transducer. Or it may consist of a much more complex assembly of elements. In any event the primary detector-transducer is an *integral* assembly whose function is (1) to sense selectively the quantity of interest, and (2) to process the sensed information into a form acceptable to stage-two operations. It does not present an output in immediately usable form.

More often than not the initial operation performed by the first-stage device is to transduce the input quantity into an analogous displacement. Without attempting to formulate a completely comprehensive list, let us consider Table 1 as representing the general area of the primary detector-transducer in mechanical,measurements.

We make no attempt now to discuss all the many combinations of elements listed in Table 1. In most cases we have referred in the table to sections where thorough discussions can be found. The general nature of many of the elements is self-evident. A few are of minimal importance, included merely to round out the list. However, we can make several pertinent observations at this point.

Close scrutiny of Table 1 reveals that, whereas many of the mechanical sensors transduce the input to displacement, many of the electrical sensors change displacement to an electrical output. This is quite fortunate, for it yields practical combinations in which the mechanical sensor serves as the primary transducer and the electrical sensor as the secondary. The two most commonly used electrical means are variable resistance and variable inductance, although others, such as photoelectric and piezoelectric effects, are also of considerable importance.

11 THE DIFFERENTIAL TRANSFORMER

Undoubtedly the most broadly used of the variable-inductance transducers is the differential transformer (Fig. 10), which provides an ac voltage output proportional to the displacement of a core passing through the windings. It is a mutual-inductance device making use of three coils generally arranged as shown.

The center coil is energized from an ac power source, and the two end coils, connected in phase opposition, are used as pickup coils. This device is often called a *linear variable differential transformer* or LVDT.

12 VARIABLE-RELUCTANCE TRANSDUCERS

In transducer practice, the term *variable reluctance* implies some form of inductance device incorporating a *permanent magnet*. In most cases these devices are limited to dynamic application, either periodic or transient, where the flux lines supplied by the magnet are cut by the turns of the coil. Some means of providing relative motion is incorporated into the device.

In its simplest form, the variable-reluctance device consists of a coil wound on a permanent magnet core (Fig. 11). Any variation of the reluctance of the magnetic flux path causes a change in the flux. As the flux field varies, a voltage is induced in the coil according to Faraday's law:

$$V = -n \frac{d}{dt} \Phi \tag{5}$$

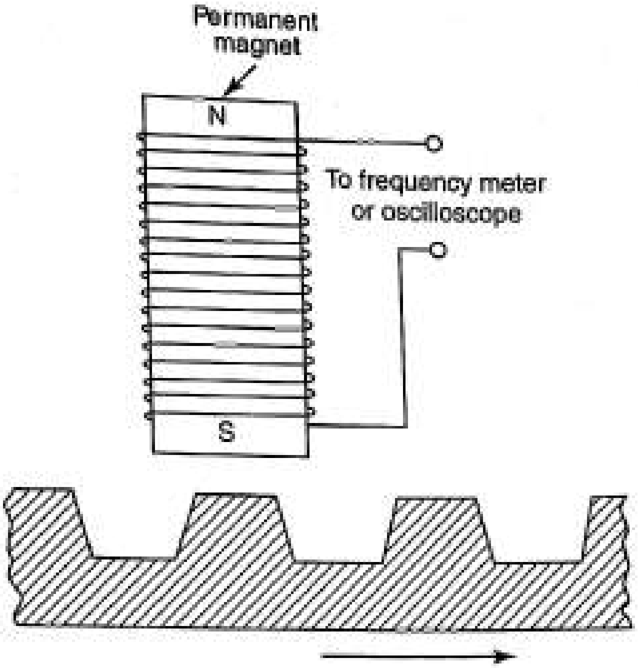

FIGURE 11: A simple variable-reluctance pickup.

where

V = induced voltage (V)
n = number of turns in coil
Φ = magnetic flux through coil (Wb)

Since the rate of change of the flux depends directly on the speed at which the teeth move past the magnet in Fig. 11, the variable-reluctance transducer is sensitive to velocity, rather than displacement.

Whereas the preceding arrangement depends upon changes of the reluctance of the magnetic flux path, other devices separate the magnet from the coil and depend upon relative movement between the coil and the flux field.

13 CAPACITIVE TRANSDUCERS

When a capacitor is formed from a pair of parallel flat plates, its capacitance is given by the following equation:

$$C = \frac{\varepsilon_0 KA}{d} \tag{6a}$$

where

C = capacitance (pF),
ε_0 = permittivity of free space, 8.8542 pF/m,
K = dielectric constant of medium between plates (= 1 for air),
A = area of one side of one plate (m^2),
d = separation of plate surfaces (m)

Greater sensitivity can be obtained by using several capacitors in parallel. This may be accomplished with a stack of n equally spaced plates in which alternate plates are connected to one another. For example, if five plates were stacked, plates 1, 3, and 5 would be connected to one voltage, while plates 2 and 4 would be connected to another. The capacitance of such a stack is

$$C = \frac{\varepsilon_0 KA(n-1)}{d} \tag{6b}$$

All the terms represented in Eqs. (6), except possibly the number of plates, have been used in transducer applications [7,8]. The following are examples of each.

Changing Dielectric Constant

Figure 12 shows a device developed for the measurement of level in a container of liquid hydrogen [11]. The capacitance between the central rod and the surrounding tube varies with changing dielectric constant brought about by changing liquid level. The device readily detects liquid level even though the difference in dielectric constant between the liquid and vapor states may be as low as 0.05.

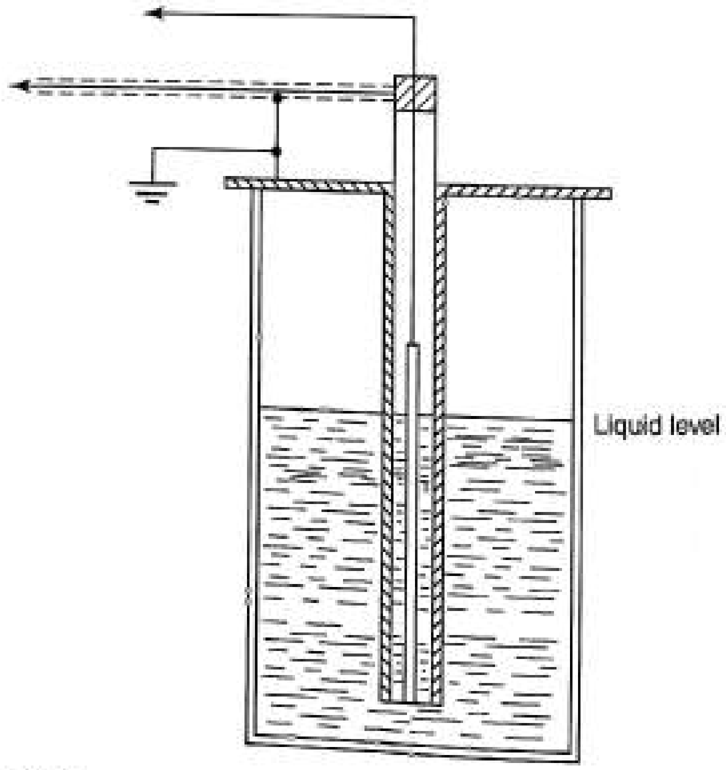

FIGURE 12: Capacitance pickup for determining level of liquid hydrogen.

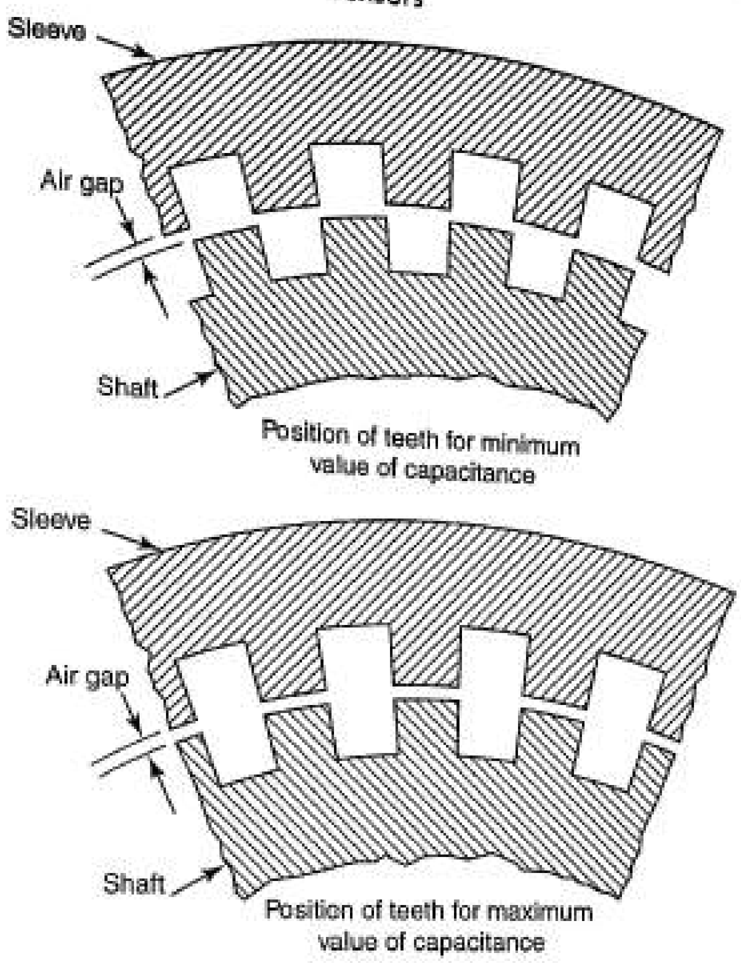

FIGURE 13: Section showing relative arrangement of teeth in capacitance-type torque meter.

Changing Area

Capacitance change depending on changing effective area has been used for the secondary transducing element of a torque meter [12]. The device uses a sleeve with teeth or serrations cut axially, and a matching internal member or shaft with similar axially cut teeth. Figure 13 illustrates the arrangement. A clearance is provided between the tips of the teeth, as shown. Torque carried by an elastic member causes a shift in the relative positions of the teeth, thereby changing the effective area. The resulting capacitance change is calibrated in terms of torque.

Changing Distance

Varying the distance between the plates of a capacitor is undoubtedly the most common method for using capacitance in a pickup.

Figure 14 illustrates a capacitive-type pressure transducer, wherein the capacitance between the diaphragm to which the pressure is applied and the electrode foot is used as a measure of the diaphragm's relative position [13–15]. Flexing of the diaphragm under pressure alters the distance between it and the electrode.

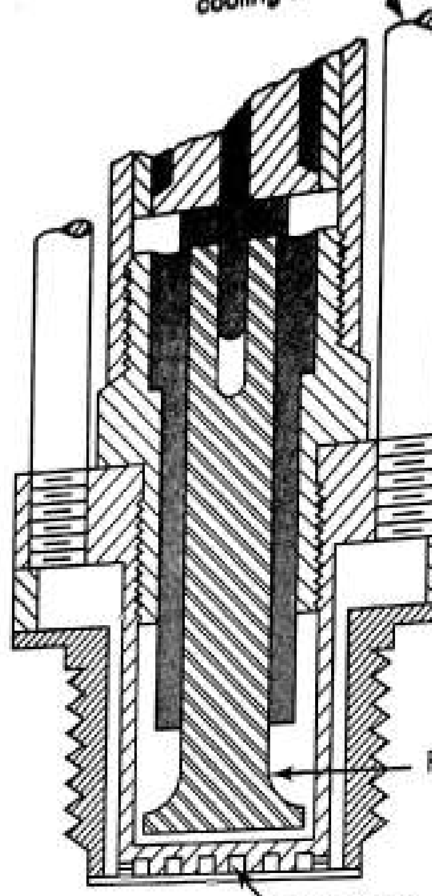

FIGURE 14: Section through capacitance-type pressure pickup.

14 PIEZOELECTRIC SENSORS

Certain materials can generate an electrical charge when subjected to mechanical strain or, conversely, can change dimensions when subjected to voltage [Fig. 15(a)]. This is known as the *piezoelectric*[3] *effect.* Pierre and Jacques Curie are credited with its discovery in 1880. Notable among these materials are quartz, Rochelle salt (potassium sodium tartarate), properly polarized barium titanate, ammonium dihydrogen phosphate, certain organic polymers, and even ordinary sugar.

Of all the materials that exhibit the effect, none possesses all the desirable properties, such as stability, high output, insensitivity to temperature extremes and humidity, and the ability to be formed into any desired shape. Rochelle salt provides a very high output, but it requires protection from moisture in the air and cannot be used above about 45°C (115°F). Quartz is undoubtedly the most stable, but its output is low. Because of its stability, quartz is commonly used for regulating electronic oscillators. Often the quartz is shaped into a thin disk with each face silvered for the attachment of electrodes. The thickness of the plate is ground to the dimension that provides a mechanical resonance frequency corresponding to the desired electrical frequency. This crystal may then be incorporated in an appropriate electronic circuit whose frequency it controls.

[3] The prefix *piezo* is derived from the Greek *piezein*, meaning "to press" or "to squeeze."

15 SEMICONDUCTOR SENSORS

The semiconductor revolution has profoundly influenced measurement technology. In addition to digital voltmeters, computer data-acquisition systems, and other readout and data-processing systems, semiconductor technology has produced compact and inexpensive sensors. A principal strength of semiconductor sensors is that they take advantage of microelectronic fabrication techniques. Thus, the sensors can be quite small, mechanical structures (such as diaphragms and beams) can be etched into the device, and other electronic components (resistors, transistors, etc.) can be directly implanted with the sensor to form a transducer having onboard signal conditioning.

15.1 Electrical Behavior of Semiconductors

Semiconducting materials include elements, such as silicon and germanium, and compounds, such as gallium arsenide and cadmium sulphide. Semiconductors differ from metals in that relatively few free electrons are available to carry current. Instead, when a bound electron is separated from a particular atom in the material, a positively charged *hole*

16 LIGHT-DETECTING TRANSDUCERS

Light-sensitive transducers, or photosensors, are used to detect light of all types: thermal radiation from warm objects, laser light, light emitted by diodes, or even sunshine. These transducers may be categorized as either *thermal detectors* or *photon detectors*. The thermal detectors use a temperature-sensitive element which is heated by incident light. The photon detectors respond directly to absorbed photons, either by emitting an electron from a surface (the *photoelectric effect*) or by creating additional electron-hole pairs in a semiconductor (as discussed in Section 15.3).

Among the issues to be considered in selecting a photodetector are the wavelength to be sensed, the speed of response needed, and the sensitivity required. In general, thermal detectors are much slower than photon detectors but respond to a broader range of wavelengths. For any detector, the speed of response will also depend upon the supporting circuitry. For visible and near-infrared light, semiconductor detectors are commonly used. Photoemissive detectors can be sensitive well into the ultraviolet range. To detect long-wave infrared light, which is the heat emitted by objects near room temperature, either thermal detectors or cryogenically cooled semiconductors may be used.

16.1 Thermal Detectors

changes in the detecting element when light heats