Chapter 2

TRANSDUCERS–II

2.1. ELEMENTS OF INSTRUMENTATION SYSTEM

As we know, instruments are eyes of any processing plant. Process operators visualize the status of the process through instruments only. Similarly, instrumentation and control systems are the heart of any processing plant. No operation can be made possible without proper instrumentation systems.

In earlier days, control of processes were basically manual through suitably installed and manually operated regulating valves. But nowadays majority of the process controls are automatic. Very few process controls work through manual control. Whatever may be the form of controls, automatic or manual, the final control actions are to be performed through pneumatically operated control valves only. Thus, control valve or the final control element is the basic and the all important element in any instrumentation system.

In any instrumentation system, a few or all of the following components or elements shall be present, in general:

(*i*) Transmitter,
(*ii*) Receiver instrument,
(*iii*) Controller,
(*iv*) Final control element, and
(*v*) Instrument accessories.

Figure 2.1 shows the complete system in a block diagram form.

(*i*) *Transmitter*

This is the very first element, which consists of primary sensor and the transducer. This is installed before the final control element. This will measure the process variable and will transform the same into suitable form, i.e. 0.2 to 1.0 kg/cm^2 in case of pneumatic signal system or 4 to 20 mAmps. D.C. in case of electrical signal system. In general, transmitters are available in three different varieties:

(*a*) Pneumatic type, (*b*) Electrical/Electronic type and (*c*) Smart type.

Wherein the basic primary sensing system remains the same, it is the secondary transducer part of the system that decides the different varieties. When the operation of the transducer is fully pneumatic, the transmitter shall same receiver instrument can be used for any measurement variable by only changing the scale, since the initiating signal from all form of measurement variable is same.

Types of receiver instrument is again based on types of transmitter to which these are connected for obtaining initiating measurement signal. Thus, receiver instrument can be of two types only, i.e. pneumatic type and electrical/ electronic type.

Receiver instrument can be in the form of indicating as well as recording. The indicating form shall give the instantaneous value of the measurement variable only whereas the recording form shall present record for a period to be specified as required. Recording is carried out by means of a pen filled with slow drying ink placed lightly on a chart paper (strip, circular or fanfold). The chart paper is moved at a constant speed of 1/3 revolution per hour, usually. The curve traced in this way shows the actual variation in the value of the measurement variable for a definite period of time.

(*iii*) *Controller*

In the instrumentation systems, control actions are generated by the element, commonly known as controller. The control action generated depends upon the change in measurement variable with respect to its set value. The set value is decided by the process designer as per the process requirement. The change in measurement variable, on the other hand, is dependent upon the following factors:

(*i*) Supply side disturbances in the process,
(*ii*) Load side variations, and
(*iii*) Environmental changes.

The changes in measurement variable can be of the following type:

(*i*) Sudden changes,
(*ii*) Constant rate of changes with respect to time,
(*iii*) Changes proportional to square of the time, and
(*iv*) Impulsive changes.

Accordingly the requirement of control actions/modes to be generated by the controller element can be of the following types:

(*i*) On-off control,
(*ii*) Proportional control,
(*iii*) Integral control, and
(*iv*) Derivative control.

In addition to single mode implementation, a combination of two or three modes are also implemented depending upon the types of disturbances to be controlled. A good controller with proper combination of modes provides following results to meet the evaluation criteria of the control performance:

(*i*) Minimum deviation following a disturbance,
(*ii*) Minimum time interval before return to set value and
(*iii*) Minimum offset due to changes in operating conditions.

The best response of a controlled variable, provided by a perfect controller is ¼ amplitude decay following a disturbance as shown in Figure 2.2.

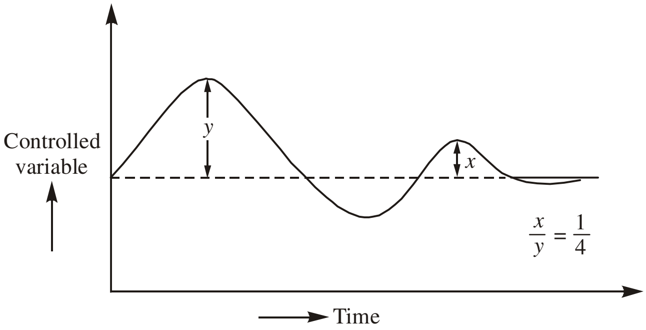


Fig. 2.2: ¼ amplitude decay response

While basic control actions remaining same, classification of controller depends upon how the actions are generated and what is the medium of operation. Based on this concept, the controllers can be of the following types:

(*i*) Pneumatic controller,
(*ii*) Hydraulic controller,
(*iii*) Analog electronic controller, and
(*iv*) Digital electronic controller.

In pneumatic controller, actions are generated pneumatically wherein the well-known flapper-nozzle system combined with feedback action is employed. Here the basic input and output signals are in the form of 0.2 to 1.0 kg/cm^2 itself, the standard pneumatic supply system being instrument air at 1.4 kg/cm^2.

In hydraulic controller, on the other hand, the system is operated upon by non-compressible and non-reactive petroleum fluid. Pressure of the standard supply system, however, in this case is 6 kg/cm^2 since it has to operate higher capacity equipment which require more power for their operations. The output of the controller varies from 1 kg/cm^2 to 4.5 kg/cm^2 for this.

In analog electronic controller, the actions are generated by means of combination of passive circuit elements along with operational amplifier. Here the input as well as output are in the form of 4 to 20 mAmps. D.C. The standard supply system is 110 volt A.C. In addition to this, the controller can provide a 24 volt D.C. supply system to the field mounted transmitters as well.

In digital electronic controller, on the other hand, the actions are performed in binary form. A digital controller incorporates all the elements of a digital computer e.g. microprocessor system, memory system, input/output system, etc. All the indications pertaining to digital controller are in decimal form. The best part of a digital controller is its diagnoistic feature in addition to its many other important factors.

(*iv*) *Final control elements*

The job of a final control element in an instrumentation system is to bring back the process variable to stable condition following a system disturbance. This is placed on the line after the transmitter as shown in Figure 2.1. It obstructs the flow of process fluid if the flow crosses the set point limit. It allows more fluid to pass through, if the flow tends to go below the set limit.

Depending upon the type of flow to be controlled, the final control elements can be of three types:

(*i*) Pneumatically actuated control valve,
(*ii*) Pneumatic cylinder actuated dampers, and
(*iii*) Hydraulic cylinder actuated dampers.

Based on the volume of mass flow to be controlled, the final control element can be **valves** or **dampers.** Whereas valves are invariably pneumatic actuator operated, dampers are pneumatic as well as hydraulic cylinder operated. Selection of type of final control elements (valves or dampers) depends upon the type of control action required by the process. For sophisticated process control applications, control valves are selected and for coarse regulating applications and also for large flow at lower pressure, dampers are the obvious choice. For finer control, the control valve internals (called trim or seat and plug) should have specific contour. These contours define the type of valves e.g. linear valve, equal percentage valve or quick opening valve. The detailed characteristic curves of these three types of valves have been shown in Figure 2.3.

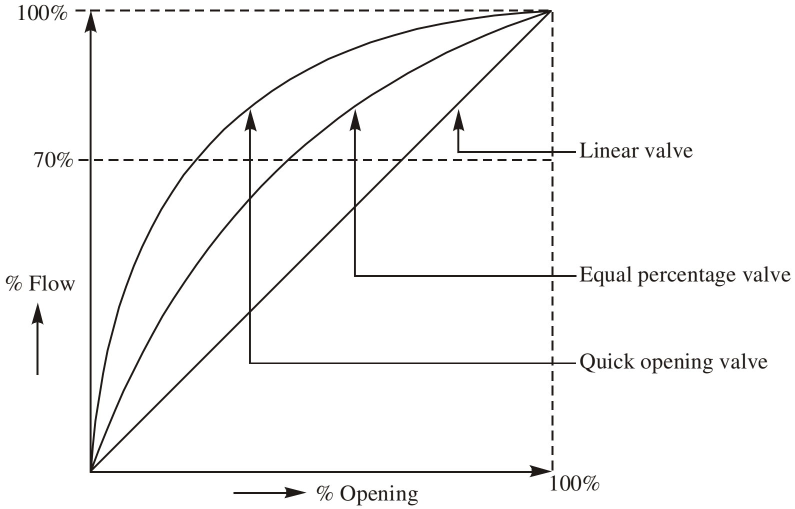


Fig. 2.3: Control valve characteristics

(*v*) *Instrument accessories*

In addition to above four basic elements, there are other elements called accessories, but have the same importance requirementwise. These are:

(*i*) Auto/manual loading station
(*ii*) Bypass unit
(*iii*) Lock-up relay
(*iv*) Current to pneumatic converter
(*v*) Air set
(*vi*) Valve positioner.

(*a*) *Auto-manual loading station*

In normal operating conditions, a controller may fail to operate on automatic mode. In such circumstances, an arrangement for operation of system on manual becomes the obvious requirement. Such an arrangement is known as auto/manual loading station. Normally this unit is an integral part of a controller, but sometimes it is an independent unit. When a signal controller is connected to a number of final control elements it may be required to put some of the final control elements on manual control whereas others remaining on automatic mode. This action cannot be performed from controller. Hence, an additional auto/manual station is required to be incorporated in between the controller and the final control element. This arrangement allows independent operation of the final control element wherever required. The arrangement has been shown in Figure 2.4.

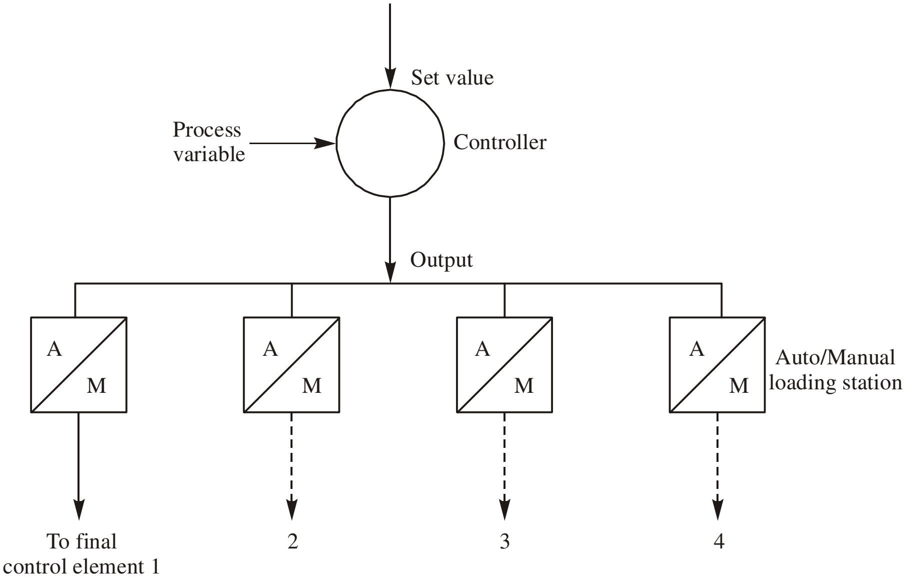


Fig. 2.4: Four auto-manual loading station connected together to operate four independent final control elements

(*b*) *Bypass unit*

Sometimes main control unit, which is in operation, may become faulty and need immediate maintenance. In such circumstances, for continuance of uninterrupted operation, a similar control unit as standby is made available in the design stage itself. For changing over from main control unit to standby unit, a changeover mechanism is required at the control panel. This unit is called a bypass unit.

(*c*) *Air set*

An air set is employed for providing air supply to the pneumatically operated instruments, i.e. transmitters, control valves and dampers. The air is called instrument air. The instrument air has to be filtered first before applying to the instrument. Then it has to be regulated/adjusted at the specified pressure, i.e. 1.4 kg/cm^2 for transmitter and/or 4.5 kg/cm^2 for control valves and dampers. The air set is a combination of air filter and regulator. A small drain cock is provided for flushing the dust and other particles settled at the bottom of the air set. An indicating pressure gage is also installed in the output line for visualizing the correct regulated pressure. The outlet pressure required is regulated by means of a circular knob located on the top of the air set. The system has been shown in Figure 2.5.

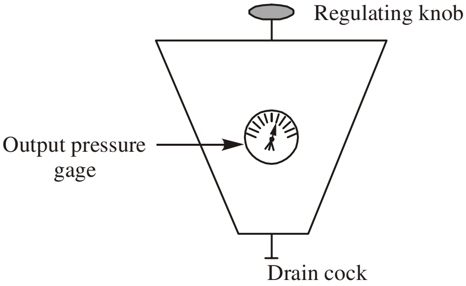


Fig. 2.5 Air set (air filter/regulator)

(d) Valve positioner

The job of a valve positioner is to position the control valve accurately with respect to the control signal obtained from the controller element. The positioning of control valve may not be accurate due to hysteresis which is caused by friction and non-linear characteristics of the actuator. Sometimes the force generated by the actuator may not be sufficient to overcome the opposition created by the fluid flow. These limitations can be minimized by using a valve positioner. It provides sufficient power to the actuator for proper positioning.

A valve positioner constitutes a closed loop system. It provides additional force through a feedback linkage which is essential for a closed loop system implementation.

Table 2.1

	Kp/cm^2 Kgf/cm^2 at	Kp/m^2	N/m^2	Bar	Atm.	PSIg.
Kp/cm^2 Kgf/cm^2 at	1	10^4	98066.5	0.9807	0.96784	14.2233
Kp/m^2	10^{-4}	1	9.80665	0.9807×10^{-4}	0.96784×10^{-4}	0.1422×10^{-2}
N/m^2	1.0197×10^{-5}	0.101972	1	10^{-5}	0.987×10^{-5}	0.145×10^{-3}
Bar	1.01972	10197.2	10^5	1	0.98692	14.5038
atm	1.03323	10332	1.0133×10^5	1.01325	1	14.696
PSIG	0.07031	70307	6894.76	0.06895	0.6805	1

Unit Transfer Look-up Table 2.1

Kp/cm^2 = kg-weight/cm^2
Kgf/cm^2 = kg-force/cm^2
at = Technical atmosphere
atm = Physical atmosphere
N/m^2 = Newton/m^2
Bar = kg/cm^2

When we use atmospheric pressure as the reference, the pressure above that of the atmosphere is referred as gage pressure (psig) or positive (+ve) pressure. Pressures below atmosphere are referred as vacuum or negative (–ve) pressure. A vacuum should be understood as going down from atmospheric pressure.

The gage pressure is a measure of stress within a vessel and the tendency of the fluids to leak out. It is really a special case of differential pressure. The advantage of making absolute pressure measurement rather than gage pressure is that it eliminates errors introduced by barometric variations.

2.2.2 Classification of Pressure Measurement System

Broadly, the pressure measurement system can be classified into three categories:

(*i*) Manometers
(*ii*) Direct pressure-measurement devices and
(*iii*) Indirect pressure-measurement devices.

(*i*) *Manometers*

Manometers are supposed to be the basic pressure measurement devices and therefore, these are used as standard instrument. These can be called gravity-balance pressure measurement devices as well since they measure the pressures height was same on both the legs. The difference in the manometer-liquid-height h has come due to application of pressure P_1 only. Thus, the net pressure on the manometer shall be $(P_1 - P_2)$, which will be given by:

$$(P_1 - P_2) = \rho h \qquad ...(2.2)$$

Advantages

(*i*) Simple construction,
(*ii*) High accuracy,
(*iii*) Good repeatability,
(*iv*) Wide range of manometer liquids are available,
(*v*) Used as primary standard instrument.

Disadvantages

(*i*) Lack of portability,
(*ii*) Need of levelling,
(*iii*) Becomes hazardous when mercury is used as manometer liquid,
(*iv*) Exposed to atmosphere,
(*v*) If diameter of the U-tube used is small, then the reading error shall be observed due to meniscus.

Range of application is from 0 to 150 inches (3750 mm.) when the manometer liquid used is water and upto 400 psig operating pressure. The range of application can be increased by use of mercury as manometer liquid.

(*ii*) *Well-type manometer*

The well-type manometer has been shown in Figure 2.7. Basic principle of the well-type manometer is same as U-type manometer, but the construction is completely different. A direct measurement scale graduated in terms of height or pressure $(P_1 - P_2)$ is sometimes fixed on the right leg for ease of taking reading. The pressure is applied on well side. All other discussions applicable to U-tube manometer are applied with well-type manometer as well.

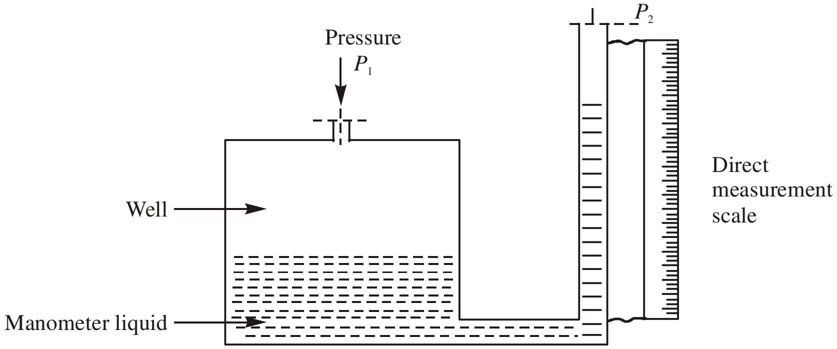


Fig. 2.7 Well-type manometer

(*iii*) *Inclined manometer*

The inclined manometer has been shown on Figure 2.8. In this manometer the leg which is open to atmosphere for comparison in not vertical, but inclined at an angle θ with respect to horizontal axis. The vertical displacement h of the fluid due to effective differential pressure ($P_1 - P_2$) is given by:

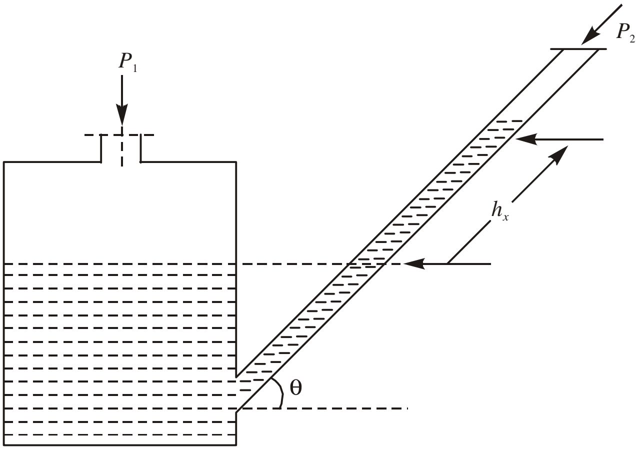


Fig. 2.8 Inclined manometer

$$h = h_x \sin\theta \qquad ...(2.3)$$

where h_x is the distance travelled by the fluid up the tube. By the help of inclined manometer, measurement of low pressures can be accomplished more accurately and easily.

Measurement of pressure with manometer is always referenced to atmospheric pressure. If the pressure leg (P_2) is evacuated, then it is possible to measure absolute pressure as well. A barometer is special type of manometer with a vacuum in one leg and atmospheric pressure on the other leg.

(ii) Direct pressure-measurement devices

Under this category, measurement of gage pressure ranging from zero millimetre of water column (0 mm WC) to 1300 kg/cm^2 (practical figure) is possible by employing direct mounted pressure gages. The range of measurement can be divided into three subcategories:

(*a*) Pressure gage,
(*b*) Receiver gage, and
(*c*) Millimetre gage.

Under subcategory (*a*), different ranges of pressure gages are designed and fabricated which are as follows:

0 to 2.5 kg/cm^2; 0 to 6 kg/cm^2; 0 to 10 kg/cm^2;
0 to 16 kg/cm^2; 0 to 25 kg/cm^2; 0 to 60 kg/cm^2;

0 to 160 kg/cm^2; 0 to 250 kg/cm^2; 0 to 400 kg/cm^2; and higher ranges upto 1300 kg/cm^2.

Under subcategory (*b*), only one range is designed and that is 0.2 to 1.0 kg/cm^2. This is used for measurement of transmitter as well as controller output signals in pneumatic form.

Under subcategory (*c*), very low range gages are designed and fabricated. These gages are used as calibration gages and also used for measurement of positive draft in steam generating boiler system.

Generally, receiver gages as well as pressure gages of upto 400 kg/cm^2 ranges are generally made of C-type bourdon tube element. Receiver gages are made of bellows element also. The Figure 2.9 along with Figure 2.10 shows external and internal view of such pressure gages where a C-type bourdon element has been used.

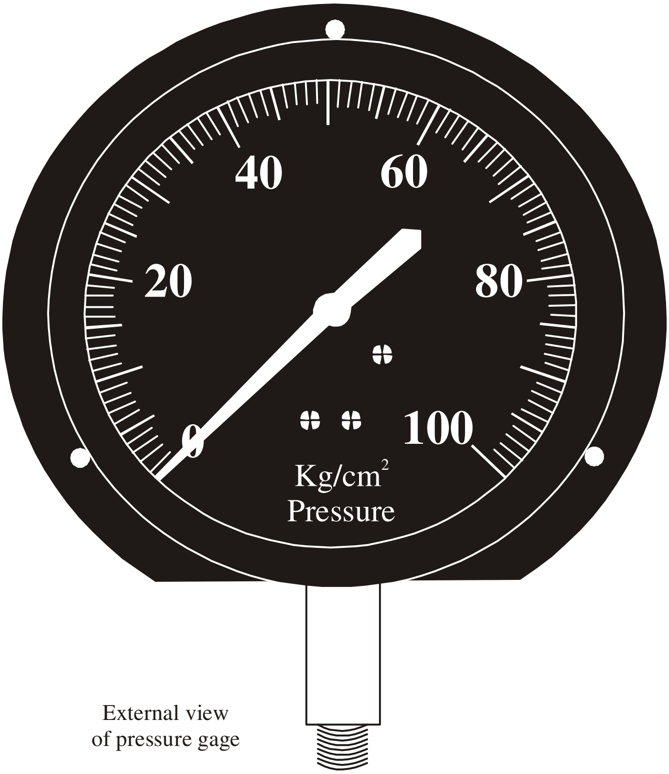


Fig. 2.9

The process pressure is applied at the open end of the bourdon tube. The system works on motion balance principle. The effect of motion balance on application of pressure is seen at the closed end, i.e. free end of the bourdon tube in terms of angular displacement. The angular displacement is the result of uncoiling of bourdon tube due to application of process pressure. This angular

(*c*) *Backlash*

Due to repeated operation of gear-system, the teeth may get eroded (normal wear and tear) thereby producing play in gear teeth. This phenomena is called backlash. The solution to this problem is overhauling, replacement of gear and recalibration of the instrument.

(*d*) *Lost motion*

The error encountered due to lost motion is related to friction in the spindle bearings. The solution to this problem is again overhauling, refixing and recalibration.

Millimeter Gages

These are low range gages. These are made of spiral type, bourdon tube, capsule or bellows elements. These low range gages are generally used for measurement of draft loss starting from Induced Draft Fan discharge to combustion chamber of the boiler. The usual ranges include 0 to 4000 mm (positive) of water column with respect to atmosphere and also from 220 mm (negative) of water column to zero.

Another very sensitive element used for manufacture of millimeter gages is slack diaphragm. Slack diaphragm uses a calibrated spring to balance the action of process pressure to be measured as shown in Figure 2.11.

As we observe the primary elements used for manufacture of low range gages are delicate in nature and sensitive in response because these are to be operated upon by extremely low pressure.

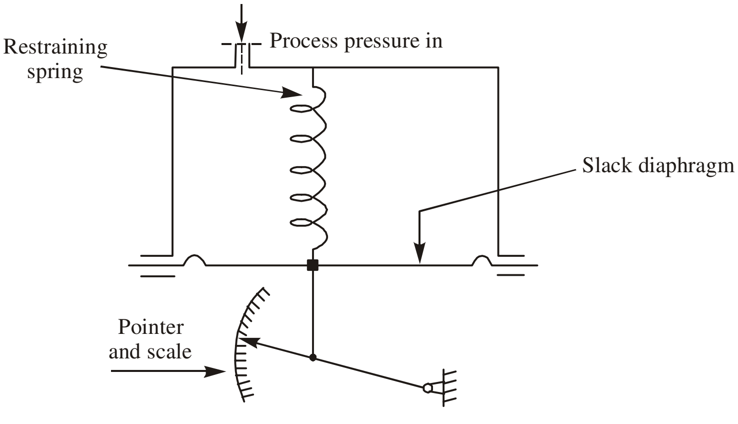


Fig. 2.11

Absolute Pressure Gage

The observed pressure with reference to vacuum is absolute pressure. In normal calculation, the absolute pressure is calculated by adding the atmospheric (*ii*) Fluid under measurement is strongly corrosive in nature and the material available to fight the corrosion is too expensive to be selected.

(*iii*) When the fluid freezes due to sharp change in ambient condition.

To meet the above conditions chemical seals are utilized in the gage. The most effective chemical seal is made of a thin flexible diaphragm which acts as separating member between fluid and the element. The space above the diaphragm is completely filled with properly selected, temperature stable non-compressible liquid. These liquids can be glycerene, oil or silicone fluid free from air droplets. Such a diaphragm gage has been shown on Figure 2.14.

Volumetric Seal Gages

This is a special version of a diaphragm gage. The diaphragm seal and the gage element are separated by means of a metallic capillary tubing. The capillary tubing as well as the entire gage element are all filled with sealing fluid. The volumetric seal design allows installation point to be separated from the measurement point, which presents vibration free atmosphere for the gage components.

Installation connection for the diaphragm element in case of diaphragm gages or volumetric seal gages can be of flange type or socket weld type as shown in Figures 2.14 and 2.15. In case of volumetric seal gages, three small holed thin metallic strips are provided as shown for fixing the gage in a wall or on a fixing stand.

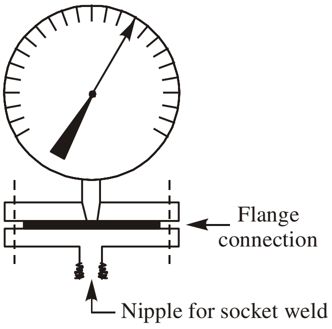


Fig. 2.14: Diaphragm gage

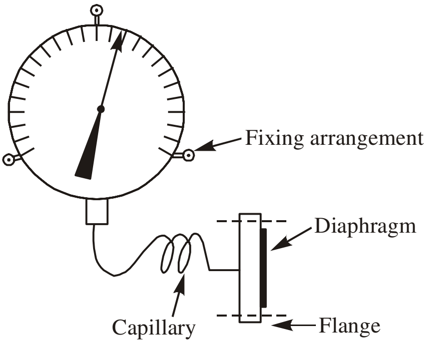


Fig. 2.15: Volumetric seal gage

(*iii*) *Indirect measurement devices*

All types of pressure transmitting systems fall under this category. The category is called indirect because the pressure in this is measured by inferential techniques and is indicated in terms of standard output signal. This standard output analog signal being 0.2 to 1.0 kg/cm^2 (pneumatic type when the medium used is instrument air) or 4 to 20 mAmps. D.C. (electronic type) are obtained by employing different transducer element along with required supply system. Following types of transmitters shall be discussed here:

(*a*) Pneumatic pressure transmitter,
(*b*) Electrical strain gage transmitter,
(*c*) Capacitance pressure transmitter,
(*d*) Variable inductance pressure transmitter,
(*e*) Resonant frequency pressure transmitter,
(*f*) Digital transmitter,
(*g*) Smart transmitter.

(a) Pneumatic pressure transmitter

Flapper-nozzle system combined with pneumatic feedback system as described earlier is the heart of pneumatic transmitter. The overall functioning of this transmitter has been shown in Figure 2.16. The process pressure applied on the diaphragm capsule positions the flapper connected to the force bar to the nozzle. The resulting back pressure is amplified by the pneumatic relay and appear as output (0.2 to 1.0 kg/cm^2 pneumatic) as a measurement signal for

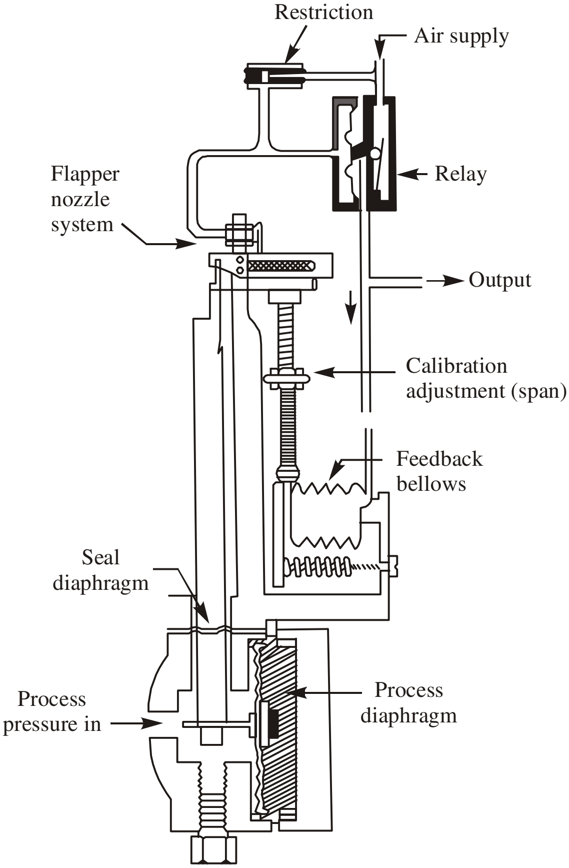


Fig. 2.16

the output pressure, which is applied to the valve surface area. The output pressure goes on increasing until this pressure on valve is enough to create a force equal to that of the nozzle pressure acting on the diaphragm. The force on both sides of the diaphragm are equal which results in equilibrium of the diaphragm, valve and seat. This has been shown in Figure 2.17.

When flapper moves away from the nozzle, decreasing the backpressure, the ball is on to right decreasing restriction between supply and output ports. This results in decrease in output pressure. This output goes on decreasing until force due to output pressure balances the nozzle pressure.

The gain of pneumatic amplifier ranges from 1.2 to 20. Since the feedback force is in opposition to the applied pressure, it is said to be negative feedback. Zero adjustment in the measurement signal is done by reference adjustment screw whereas a span adjustment is done by the range wheel. Accuracy of 1% of calibrated span is obtainable which includes linearity, hysteresis and repeatability.

(b) Electrical strain gage transmitter

The measuring systems of this type of open loop electronic transmitter utilizes the basic system of change in resistance. The basic transducer element for this transmitter is the bonded strain gage element. The change in resistance with respect to process pressure to be measured shall be very small but precise, making the measurement operation completely linear. The change in resistance is measured by a D.C. Wheatstone's bridge circuit. Figure 2.18 shows a typical measurement circuit for a pressure measuring transmitter. Each arm of the bridge contains a strain-sensitive element (a few of these may be dummy as well). If it is considered to be balanced initially, a change in pressure shall result in unbalance of the bridge. The unbalance voltage Delta V shall be given by:

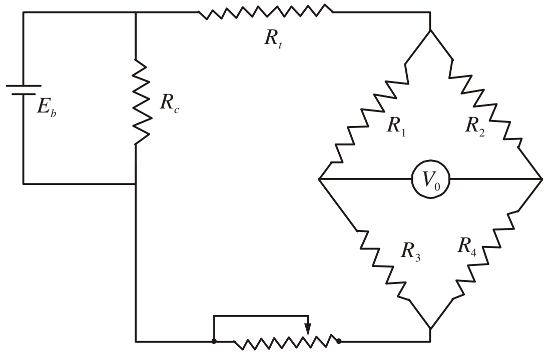


Fig. 2.18: Calibration adjustment

$$\text{Delta } V = \frac{E_b}{R_o}\left[(\Delta R_1 + \Delta R_3) - (\Delta R_2 + \Delta R_4)\right] \tag{2.4}$$

where R_o is the initial resistance of each element (being same for all); R_t is the resistance for temperature compensation; R_c is the resistance for terminal resistance compensation.

A simplified diagram of such strain gage transmitter has been shown on Figure 2.19. An increase in pressure applied on high-pressure port develops a force, which changes the strain on the sensing element (strain gage force unit along with connecting wire). The resulting voltage output which shall be proportional to applied pressure is sensed by input amplifier that drives the output current regulator. The span adjustment sets the closed loop gain of input amplifier. This in turn sets the measurement span of the instrument. The zero adjustment establishes the zero reference current to 4 mAmps. D.C. at the required lower range limit.

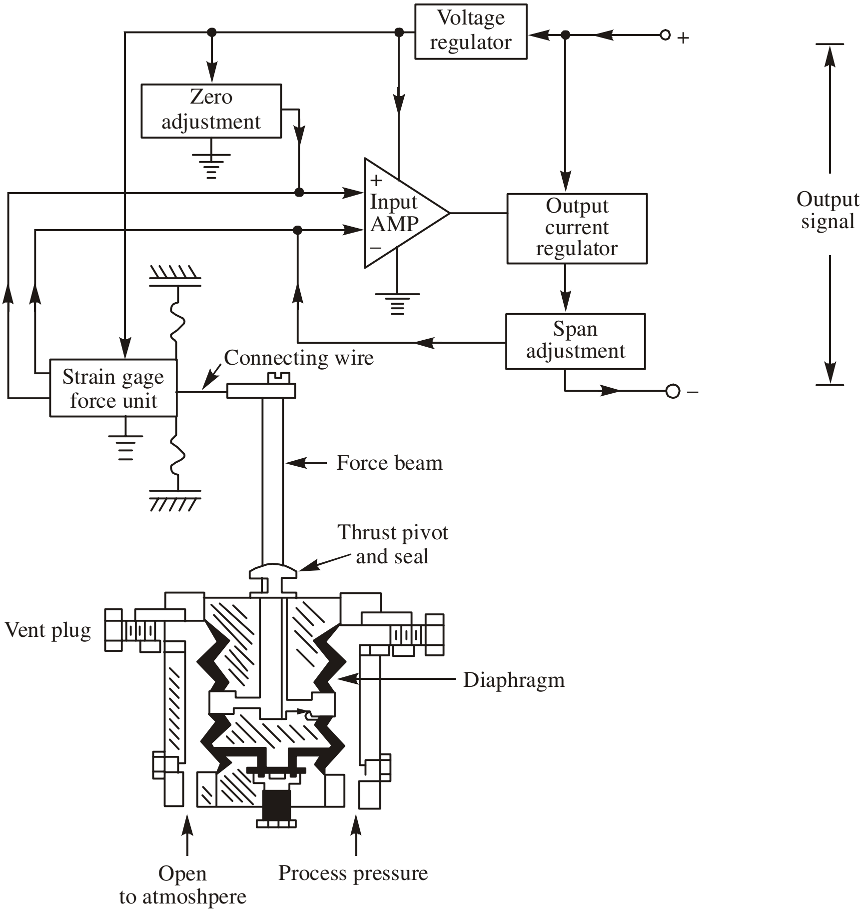


Fig. 2.19

Problems encountered with strain gage transducers

(*i*) Pressure-strain characteristic as well as strain-resistance characteristic, in general, have poor linearity. These characteristics become completely unsatisfactory especially in the region of low differential pressure for measurement of low flow.

(*ii*) Temperature compensation is required to deal with the non-linear variation in resistance value due to change in temperature, which becomes complicated as well as expensive.

These problems have been removed by designing capacitance type transmitter.

(c) Capacitance pressure transmitter

The capacitance type transmitter belongs to structural type of design whereas strain gage type transmitter is from physical property type. The basic operating principle for capacitance pressure transmitter lies in the measurement of change in capacitance of capacitive transducer resulting from the movement of a pressure element due to applied pressure. In such a measurement system, two capacitor plates are arranged with a gap between them, an oscillator circuit is placed to energise the sensing element and a capacitance detecting circuit is used to detect the change in capacitance value. Sensing element has been shown in Figure 2.20 and the oscillator circuit along with capacitance detecting circuit has been shown in Figure 2.21. During construction of sensing element, specific amount of initial tension is required to be put to the sensing diaphragm

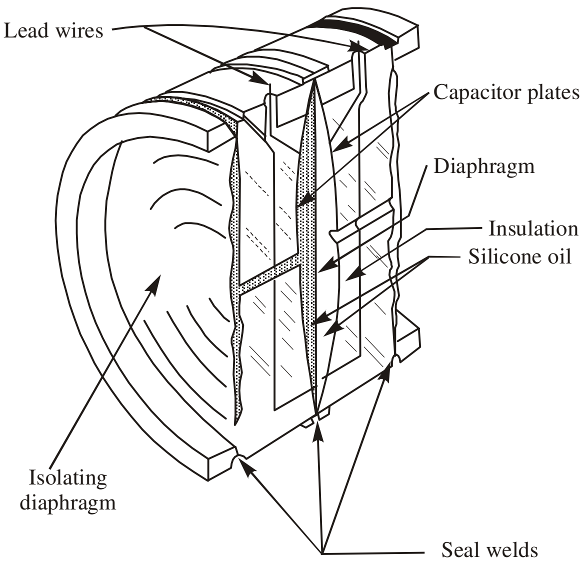


Fig. 2.20

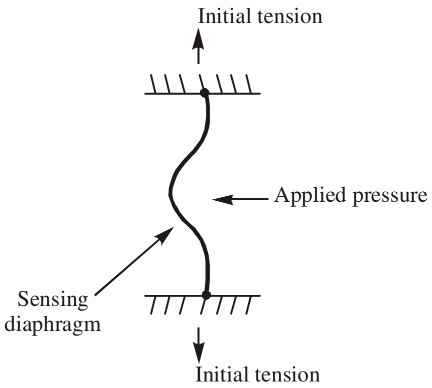


Fig. 2.22

The sensing element which is essentially the variable capacitor detects the position of the sensing diaphragm. The process pressure positions the sensing diaphragm accordingly to vary the capacitance of the sensing element. The initial capacitance of the sensing element is usually 80 picofarad. Oscillator at normally 80 kHz and 70 volts (peak-to-peak) drives the sensing element. The output from the sensing element is rectified by a demodulator which consists of a full-wave bridge rectifier circuit. The voltage regulator provides constant voltage supply of 6.4 volts D.C. for reference and 7 volts D.C. to oscillator.

The current controlled amplifier drives the control to a level such that the detector feeds back a current equal to sensor current. The current limiting circuit prevents the output from exceeding 35 mADC in an over range condition.

An advantage of this type of capacitance pressure transmitter is its inherent high over range capability. This type of instruments have a proven track record with very good specification. They are available in a number of ranges and operate over a variety of ambient conditions with an accuracy of ±0.5% of calibrated span.

(d) Variable inductance pressure transmitter

As is known, the relative motion of a core with respect to a coil wound around shall result in a change in the inductance of the coil. Such arrangement constitutes basic design feature for the variable inductance transmitter. The coil is part of an A.C. oscillator circuit located inside the electronic unit as shown in Figure 2.23. A small amount of movement of the position detector core with respect to the force coil results in a shift of frequency output of the oscillator. This shift in frequency generates a proportional output signal.

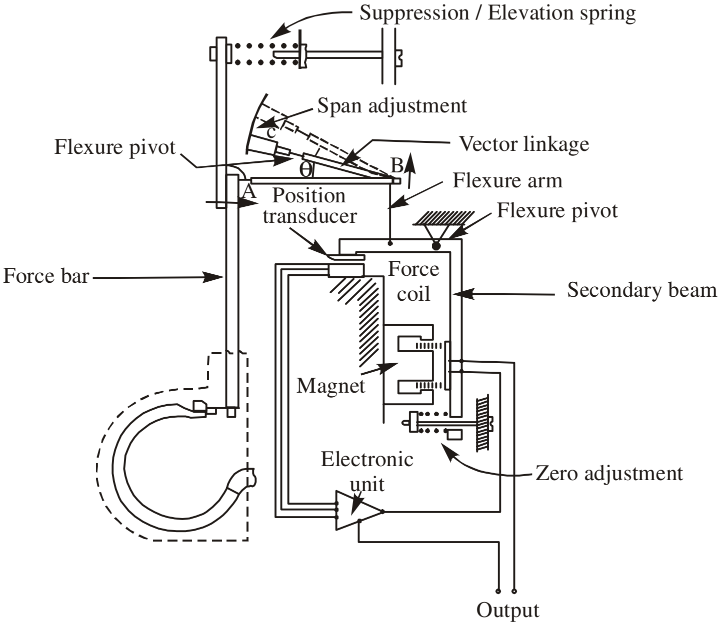


Fig. 2.23

This output signal is detected by a discriminator circuit which is incorporated in the electronic unit. This is in fact proportional to change in pressure input of the bourdon element. The pressure input produces motion in the position detector core of the inductor assembly through vector linkage and '*T*' flexure link. The generated output which is in the form of 4 to 20 mAmps. D.C. is also fed to the feedback system, which consists of a magnetic coil placed on the secondary beam. This arrangement produces an equal and opposite force on the beam to balance the force created by the change in bourdon element due to measurement input pressure. This negative feedback provides stabilization.

(e) Resonant frequency transmitter

The resonant frequency type transmitter works on the principle of natural frequency of a mechanical object under tension. For instance, a plane wire of considerable cross-section is allowed to resonate at its natural frequency under tension, the resulting changes in the wire change its resonant frequency. This wire being an integral part of an oscillator circuit causes the oscillator to change the frequency which shall be ultimately proportional to the process input pressure. Resonant frequency f_r of the wire under tension is proportional to the tension created in the wire by the applied process input pressure. Thus, by performing exact electronic operation on the resonant frequency signal, an output signal can be developed which shall be proportional to applied fluid pressure.

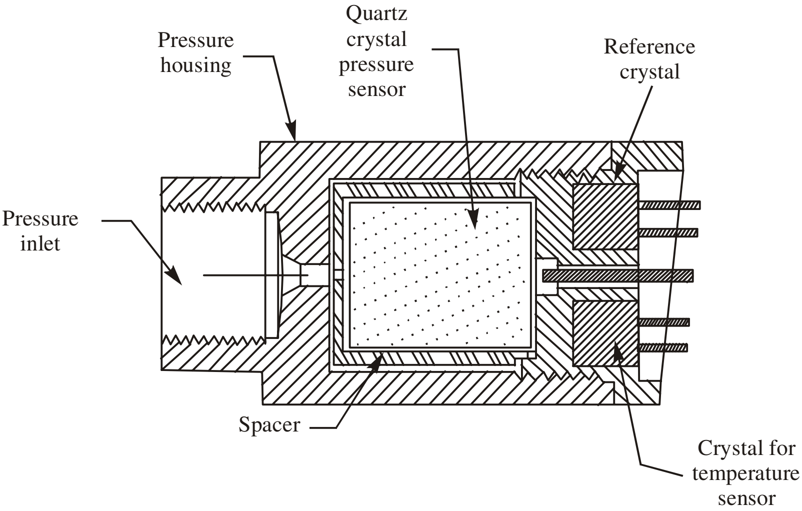


Fig. 2.25

(f) Digital pressure transmitter

The basic design criteria for digital pressure transmitter remains same as that of the analog transmitter described earlier, e.g. strain gage transmitter, capacitance or variable inductance transmitter or even pneumatic transmitter. The only difference lies in the electronic part wherein an additional circuit called analog to digital converter (A/D) is added. The function of A/D converter is to convert the analog signal of 4 to 20 mAmps DC to binary digital form. The binary converted signal so obtained is fed to a digital indicator and/or further processed. The pneumatic transmitter output however is first converted to electrical signal, i.e. 4 to 20 mAmps. D.C. by means of a pneumatic to electrical converter. The pneumatic to electrical converter together with analog to digital converter is also sometimes called signal-conditioning unit. The selected components contained in the signal-conditioning unit depend upon the requirement of a particular system of conversion.

(g) Smart transmitter

The analog process transmitter works basically on analog sensor technology and provides standard output signal for remote transmission employing electronic signal conditioning unit. These transmitters have been working successfully for a long period of time but are limited in terms of high degree of versatility, reliability, accuracy and precision which are the requirements of a modern instrumentation system. Errors due to drift in sensor-component behaviour, non-linear characteristics of sensing element, environmental changes, static pressure and temperature effects of the process are some of the factors that are so complicated that it is very difficult to compensate for.

These, errors however, have completely been eliminated by designing a smart transmitter. A smart transmitter provides linear output signal free from all the above-mentioned errors. The use of microprocessor technology does the actual job. In addition, this transmitter provides facility for two-way communication as well. This means, in addition to obtaining the output signal at the receiving end, calibration data or any other changes can be performed on the transmitter from the receiving end itself.

In process industries, two types of basic design for such transmitters are in use. In the first design type, the same basic principle of analog system is applied and the resulting analog system is converted to digital form. This digital output signal is fed to a microprocessor circuit for performing all the smart functions. Obviously the accuracy of this design shall be limited by the accuracy standard of the analog to digital conversion techniques. Accuracy obtainable by this technique has always been less than ± 0.25% of calibrated span.

Figure 2.26 shows this type of smart transmitter using capacitance sensing element, alongwith temperature compensating sensor. The analog to digital converter provides equivalent digital signal to be processed by microprocessor. During characterization of the sensing element at the manufacturing site, all the sensing elements are allowed to run through different temperature and pressure cycles. Data from these tests are stored in a PROM (known as self-characterization PROM of the transmitter) to carry out signal correction functions during actual operation. The EEPROM stores the characterization data. The data which are changed by the transmitter-software from time-to-time, are also stored in the EEPROM. When sensing element, i.e. primary transducer is replaced by a new one, these data are removed. The RAM is used by the microprocessor for temporary calculations and is never addressable by the user. Transmitter-configuration data as well as sensing element linearization data stored in EEPROM are retained on power failure.

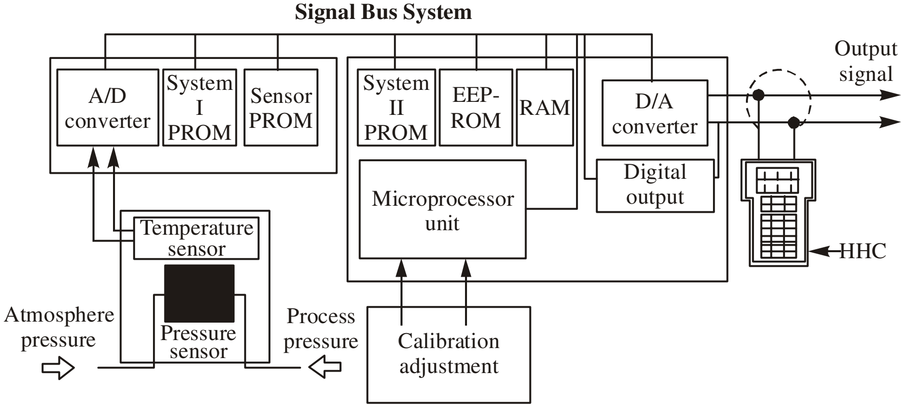


Fig. 2.26

The output of the transmitter is compatible with HART protocol (to be described later). Communication between the Instrument Engineer and the transmitter is done by a remote terminal called HHC (described later).

Improvement in accuracy obtainable by a smart transmitter has always been important for the designers. If measurement accuracy is improved, tighter control around the set value of the control system can be achieved. This will result in improvement in product quality, optimization in use of raw material and increase in profit.

In the other design consideration of smart transmitter, the process variable is sensed in digital form directly and thus there is no need of an analog to digital converter as such. By employing this technique, an accuracy from 0.075% to 0.1% of calibrated span is obtainable.

Several techniques for direct digital conversion of process variable are available, but two of them are more popular:

(*i*) Resonant silicon sensing element, and
(*ii*) Dual inductive sensing element.

(*i*) *Resonant silicon sensing element*

The resonant silicon sensing element is fabricated from a single crystal silicon using a special electronic technique. This technique is called 3-D semiconductor micro-matching technique. By this fabrication method silicon acquires improved characteristic features which ultimately provides good stability and repeatability to the transmitter with almost no hysteresis.

In the construction of the transmitter there are two H-shaped resonators, which resonate at their natural frequency of 90 KHz as shown in Figure 2.27. The applied process pressure forces the central resonator into tension and the outer resonator into compression. As a result, their resonating frequencies change (one in increasing order F_a and the other one in decreasing order F_b as shown

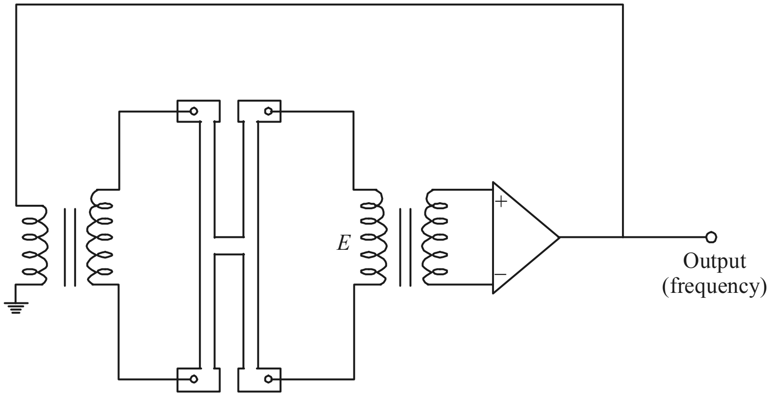


Fig. 2.27

mental measurements are taken. The microprocessor compares this data with respect to characterized data and the correction is done. The accuracy obtained by this transmitter is ± 0.1% of calibrated span.

Communication Interface

Since we have already discussed that the smart transmitter has the especiality of two-way communication, special interface is required to be used for carrying out the same. The option of 4 to 20 mAmps. D.C. signal transmission is available from the field, hence smart transmitter can respond to a request for specific digital data from the control room. These requests are related to diagnostics, process data status and even transmitter specification details. These data help in remote checking, re-ranging if need be, troubleshooting in the event of any failure or even for process documentation.

Communication is done by means of HHC (Hand-held Communicator), which can be connected at any point in the loop. These HHCs are normally of two types: universal and/or dedicated. While universal type communicator shall communicate with all types of smart transmitters irrespective of make and type, the dedicated one is designed for a particular make and type of transmitter and cannot respond to other transmitters.

As far as communication protocols are concerned many protocols are available to communicate with the transmitter. Out of these the Bell 202 FSK (Frequency Shift Keying) protocol is popular and is in general use. This standard imposes a high frequency signal onto the 4 to 20 mAmps. D.C. signal. The 1's and 0's are represented on different frequencies. This format helps in digital communication along with 4 to 20 m Amps. D.C. signaling uninterrupted. The communication is in parallel with the smart transmitter and can be initiated from any point in the instrumentation loop.

Outstanding Features of Smart Transmitters

(*i*) The smart transmitters are remote configurable as indicated below:
  - Output is selectable in either 4 to 20 mAmps. D.C. or digital form.
  - Span in percentage or in Engineering units.
  - Range selection in lower and upper values.
  - Transmitter details, e.g. serial number, linear or square root output, tag number etc.
  - Calibration details, e.g. last calibration data, next calibration due, range of calibration.
  - Alarm details, e.g. Low, High, etc.

(*ii*) Self-diagnostic features.

(*iii*) Two-way communication available.

(*iv*) Increased accuracy upto ± 0.1% and 0.075% of calibrated span. Accuracy includes hysteresis, linearity, repeatability and drift.

(*v*) Over ranging effect from usual span range to maximum pressure rating is normal.

(*vi*) No error due to vibration, humidity, mounting position, temperature effects, environemental effects or static effect.

(*vii*) Reduced power consumption and reduced maintenance cost.

Installation of Pressure Measuring Instruments

Installation of instrument is an important part of measurement system. Reliable operation and accurate reading of any measurement system also depend upon correct installation practices. The installation practices are laid down according to the characteristics of process fluids under measurement. We know that the pressure measuring elements or any measuring element come into physical contact with the process fluid. Due to this, there is every possibility of damage or other adverse effects to the element. These effects can be due to pulsating nature of the fluid, excessive temperature fluctuation or viscosity effect of the process fluid and many others. While design refinements are possible in the element itself to minimize these effects, modification in installation practices can also remove these problems. Pulsating dampeners (Figure 2.29) temperature equalizing columns (Figure 2.30) are some of the acceptable auxiliaries employed in the industrial installation almost invariably for combating above-mentioned problems. The capillary piping popularly known as pigtail in the industries, are normally of ½ inch size shown on Figure 2.29. For measurement of pressure by using pressure gages or transmitters, this is the universal pulsating dampener. This capillary piping is sometimes called syphon also and is used for the measurement of steam pressure at elevated temperature. The syphoning helps in condensing the steam and thereby keeping the pressure measuring element away from the high temperature steam.

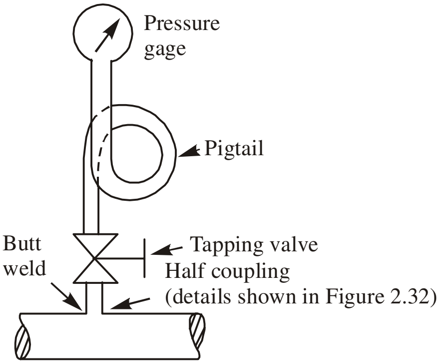


Fig. 2.29

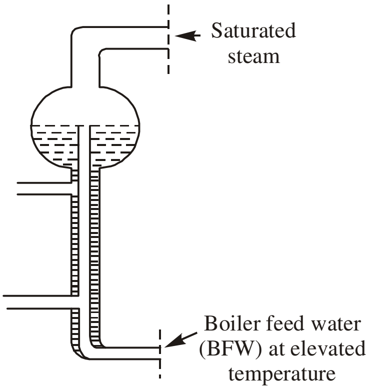
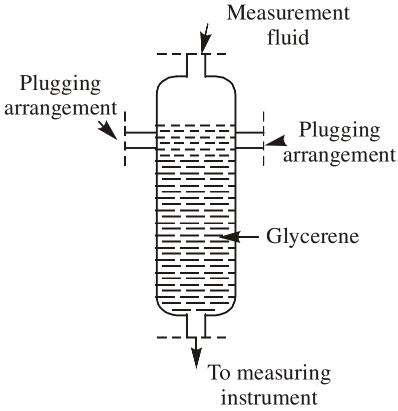
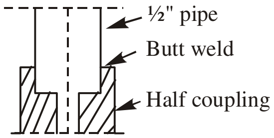


Fig. 2.30



Seal Pot

Fig. 2.31



Details of half coupling

Fig. 2.32

The use of temperature equalizing column helps in bringing the temperature of process fluid to equal level before measurement takes place and hence the temperature fluctuations vanish. Temperature equalizing column also brings the fluids at the same phase.

Seal pots are used to keep the process fluid away from the measuring element. Seal pots do not allow the measuring elements to come into contact of the process fluid. In fact, it is the sealing liquid, which is in physical contact of the measurement fluid. In industries usually glycerene is the liquid, which is used as sealing fluid for measurement of viscous fluid.

Impulse Lines

The impulse line connects the process fluid to the main body of the instrument through proper isolation and draining system. Figure 2.33 shows a typical installation details for measurement of process pressure. The two isolation valves at the tapping point are selected for obtaining 100% redundancy. One end of the Tee joint-1 has been plugged. This is opened periodically for removal of entrapped air bubble and/or for pouring in the sealing fluid if required. The drain valve is opened when it is required for flushing out the impulse line for cleaning. The instrument is clamped with respect to mounting stand and is connected to the impulse piping through union joint and an isolation valve. This isolation valve assists in removal of instrument for repair and recalibration or overhauling. This is a general installation arrangement, however, slight variations may be observed depending upon the characteristics of the process fluid under measurement.

Zero Suppression/Elevation

Sometimes the measurement system for a particular process fluid is installed in such a way that an appreciable amount of static head acts on the instrument.

(*i*) Variable resistance type
(*ii*) Variable inductance type
(*iii*) Variable capacitance type.

(i) Variable resistance transducer

Variable resistance arrangement in the form of linear or angular potentiometer have been employed for construction of this type of transducer. The movable contact wiper makes contacts with the potentiometer element against its own spring action. The motion of the contact point can be linear or angular depending upon the type of motion and hence the shape of the potentiometer.

The resistance element, i.e. potentiometer element is a very important part in this transducer arrangement shown in Figure 2.34. The resistivity and the temperature coefficient are two very critical properties of the resistance element to be considered for selecting a material for this scheme. Mostly alloys of copper-nickel, nickel-chromium or silver-palladium are in use. Resistivity of these materials lies between 0.4 micro ohmmeter and 1.3 micro ohmmeter and temperature coefficient lies between 0.002% per degree centigrade and 0.01% per degree centigrade. The element is precision drawn and properly enameled wire having diameter upto 50 microns. The wiper which runs on the potentiometer is made of spring material e.g. phosphor bronze (properly tempered) or beryllium copper. Sometimes leaf springs are also used to minimize the effect of vibration.

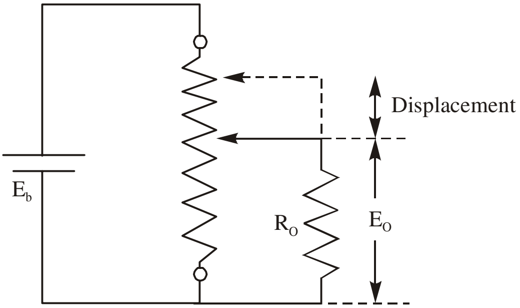


Fig. 2.34

In this type of transducer arrangement, error due to noise is considerable. Noise error is developed due to contact resistance of movable wiper and thermoelectric effect. These are, however, minimized by adjusting the contact pressure and modifying the wiper structure.

Advantages

(*i*) Measurement circuit is simple.
(*ii*) High precision measurement is possible for very small displacement as well.

Disadvantages

(*i*) It is very much susceptible to vibration as well as shock.
(*ii*) It has poor dynamic response.
(*iii*) Noise error in this case is prominent.

(*ii*) *Variable inductance transmitter*

The most popular and widely used displacement transducer working on this principle is known as LVDT (Linear Variable Differential Transformer). The LVDT consists of a primary A.C. voltage source coil and two identical (mechanically as well as electrically) secondary coils for obtaining output. A movable magnetic core connected with an arm is placed centrally and allowed to move axially. The movement or displacement of movable core enduces proportional voltage and is measured as output. The system has been shown in Figure 2.35.

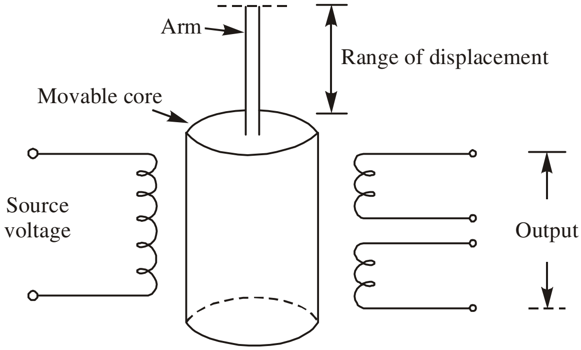


Fig. 2.35

The secondary coils are placed symmetric to each other and with respect to primary coil. When the core is at the centre, the two secondary coils shall

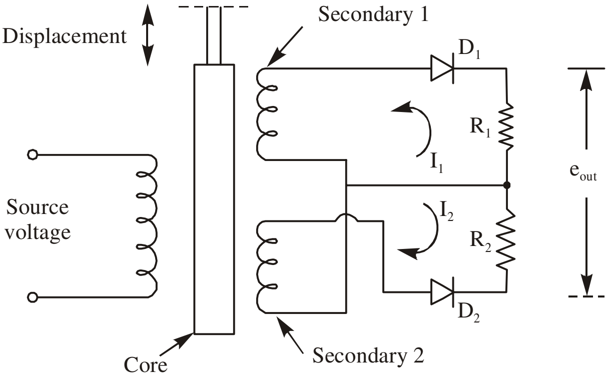


Fig. 2.36

have the current flow as shown in Figure 2.36 in the event of positive half cycle of the input. For negative half cycle, these currents are blocked altogether and output becomes zero. The two resistances are equal and both the secondary coils are electrically similar the currents through these are equal but since their polarity is different, net output equals zero.

When the core is near to secondary 1, voltage in secondary 1 is increased and IR_1 becomes greater than IR_2, e_{out} becomes positive. Similarly, when the core is near to secondary 2, e_{out} becomes negative.

The magnitude of e_{out} shall be proportional to position of core with respect to central position. The greater the displacement, the greater shall be the output. Polarity of e_{out} indicates the direction of displacement. D.C. output can be obtained by rectification and filtering. A.C. waveform can be obtained directly by connecting the two secondary coils in series opposition arrangement as shown in Figure 2.37. Use of phase detector shall be essential.

Proper design of secondary coils gives linear output for specified measurement range of displacement.

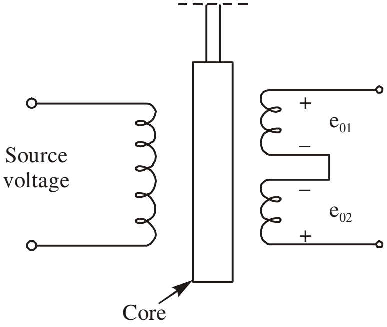


Fig. 2.37

The coils made of enamelled copper wire are wound on strong former (made of ceramic or phenolic). The entire unit is enclosed in a suitable case for providing magnetic and electrostatic shielding. The normal range of measurement is from ± 10 microns to ± 10 mm.

Advantages of the System

(*i*) Design as well as fabrication are simple.
(*ii*) Resolution obtained is very high.
(*iii*) Constructional feature is rugged.
(*iv*) Output is linear.
(*v*) High sensitivity is obtainable.
(*vi*) Stability of the instrument is higher.

The only disadvantage is that it is expensive instrument. But practically the higher cost can be met easily by the advantages obtained.

On similar pattern as LVDT, measurement of angular displacement can also be carried out by employing an arrangement called RVDT (Rotary Variable Differential Transformer). The basic principle of operation remains same as that of LVDT. The main difference in the construction however lies in the core which has to be designed just like a cam. The cam is made of magnetic material as is the requirement. The primary as well as secondary coils are designed like the shape of an arc. The shape of the cam is selected in such a way that its angular movement in the air gap produces linear output. The arrangement has been shown in Figure 2.38.

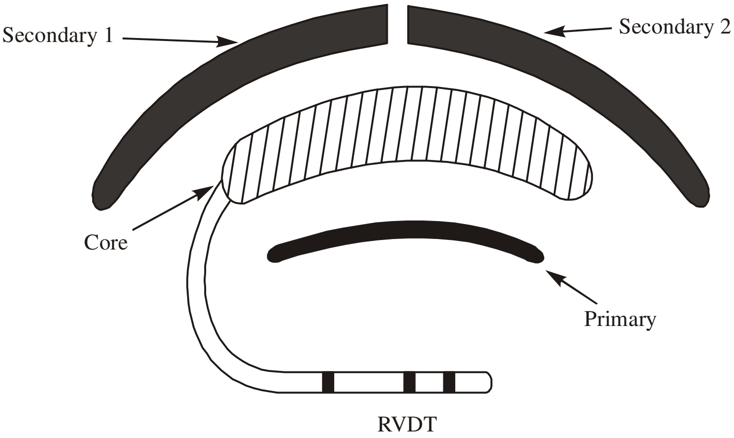


Fig. 2.38

(iii) Variable capacitance transducer

The most commonly designed variable capacitance type displacement transducer is based on the basic principle of change of capacitance C_p between two parallel plates capacitor according to the relation:

$$C_p = \frac{\rho A}{d_o} \qquad \text{...(2.5)}$$

where ρ is dielectric constant for the medium; A is the cross-sectional area of the capacitor plate and d_0 is the spacing between the capacitor plates.

As the above relation indicates, the change in the capacitance in such an arrangement can be brought about by three ways: (*a*) by changing d_0; (*b*) by changing A or (*c*) by changing ρ. The resultant variation in capacitance value can be converted to a 4 to 20 mAmps. D.C. electrical signal by designing suitable electronic circuit. One of the circuits has been shown in Figure 2.39.

$$e_o = -\frac{C_p}{C}\, e_i \qquad \text{...(2.6)}$$

(a) Relative Velocity Measurement Transducers

Measurement of relative velocity, in direct sense, however, can be implemented by two basic methods:

(*i*) Moving magnet method and
(*ii*) Moving coil method.

In this method, the basic principle of induction is utilized which states that if a conductor is rotated or moved in a static magnetic field, an emf is induced which shall be proportional to the movement. In this way, if we can arrange to move the magnet and keep the coil or conductor standstill, the method is called **Moving Magnet Method**. On the other hand, when the coil or conductor is allowed to move keeping the magnetic system steady, the method is called **Moving Coil Method**. These two methods are based on the fundamental mathematical equation:

$$E = Blv \sin\theta \text{ volt} \qquad ...(2.8)$$

Where E is induced emf; B flux density in Wb/m^2; l the effective length of the conductor or the coil in metre; v the relative velocity of the coil/magnet in metre/sec and θ being the angle of coil movement with respect to the direction of field.

A basic **moving magnet type** of arrangement used for designing a velocity transducer has been shown in Figure 2.40. The sensing element is essentially a rod (attached to the magnet), which is coupled rigidly to the main equipment whose velocity has to be measured. This sensing element moves inside the air gap/space of the coil and thereby induces emf in the stationary coil. The emf so induced shall be proportional to the velocity of the magnet attachment.

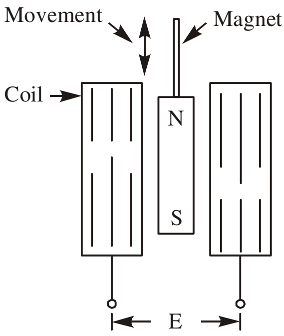


Fig. 2.40

In the same way, a **moving coil** type of arrangement has been shown in Figure 2.41. With this arrangement the movement of coil itself is conceptualized inside the magnetic field to the contrary. Therefore, the sensing element, which is the coil here is to be connected to the main equipment of which the velocity is to be measured. The induced emf output shall be proportional to the velocity of the coil in this case.

Advantages of moving magnet system lie in its simple construction, requires minimum maintenance (more or less maintenance free), induced emf being linear with respect to velocity change and last but not the least it is inexpensive. Disadvantages being disturbances in performance due to stray field, limited frequency response and inaccessible for vibration measurement.

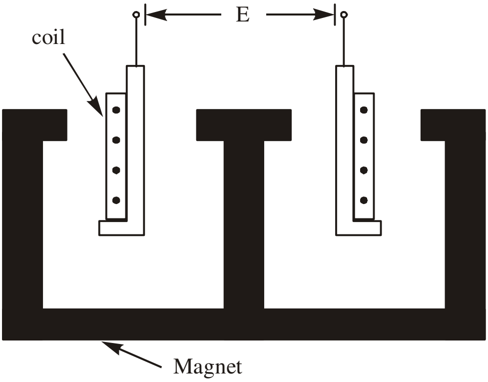


Fig. 2.41

In the same way, the advantage of moving coil system is that the arrangement can be encased easily in an anti-magnetic enclosure to protect it from stray field.

The only disadvantage with this arrangement is that the maintenance becomes difficult.

(b) Absolute Velocity Measurement Transducer

As indicated earlier, the absolute velocity measurement can be carried out by means of seismic transducer. The basic absolute arrangement has been shown in Figure 2.42. This arrangement is popularly known as single degree-of-freedom seismic spring-mass system. Degree-of-freedom of a system is essentially related to a number of characteristic variables that define the position of the system completely at any particular instant. For instance, the latitude, longitude and altitude define the position of a moving object completely. However, position of a railway train shall be defined by longitude only, the position of a boat freely running on water surface, on the other hand, shall be defined by longitude as well as latitude. Similarly, for defining the position of an aeroplane flying in air we shall require all the three characteristics, i.e. longitude, latitude and altitude. Consequently we conclude that the degree-of-freedom of above-mentioned objects are one, two and three respectively.

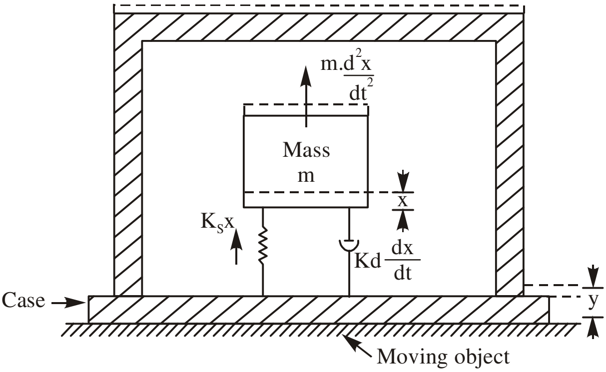


Fig. 2.42

The system indicated in Figure 2.42 consists of a mass *m*, a spring of constant k_s and a damping arrangement (dash-pot) having constant k_d. The arrangement is installed on a support. The mass *m* is free to move only in one axis that is normal to the support. The equation of motion of such a system can be described by:

$$\frac{d^2x}{dt^2} + 2GW_n\frac{dx}{dt} + W_n^2 x \;=\; \frac{d^2y}{dt^2} \qquad ...(2.9)$$

where *x* and *y* are the displacement of mass and the support respectively, $\frac{d^2x}{dt^2}$ and $\frac{d^2y}{dt^2}$ are the acceleration of the mass and the support respectively, *G* which is equal to $\frac{k_d}{2\sqrt{k_s m}}$ is the damping ratio and W_n that equals $\sqrt{\frac{k_s}{m}}$ is the undamped natural frequency.

In this arrangement, the damping unit, which is in fact a dashpot filled with viscous fluid of fine quality, increases the range of frequency over which the system can operate. This arrangement transforms the absolute movement *y* of the support into the movement *x* of the mass relative to the support. In actual measurement therefore, the movement of the mass *m* is measured relative to the support. For this a relative velocity measuring transducer using resistance potentiometer or other alternative arrangement is connected in between the mass *m* and the support.

(c) Angular Velocity Measurement Transducer

For measurement of angular velocity, the arrangement used has to be physically attached to the rotating shaft of the main equipment and a voltage proportional to speed may be obtained by employing suitable system. Based upon the voltage output obtained (D.C. or A.C.), two types of tachometers can be designed:

(*i*) D.C. Generator Tachometer,
(*ii*) A.C. Generator Tachometer.

(*i*) In case of D.C. generator tachometer, the usual principle of D.C. generator working is employed. The armature proper is coupled mechanically with the main machine whose speed is to be measured. The rotation of armature in presence of permanent magnet field generates emf directly proportional to the product of flux and speed as shown on Figure 2.43. Since the flux due to permanent magnet is constant, the emf induced will be proportional to speed only. This emf being a D.C. one, can be measured by a PMMC (Permanent Magnet Moving Coil) voltmeter having the scale calibration is terms of speed directly.

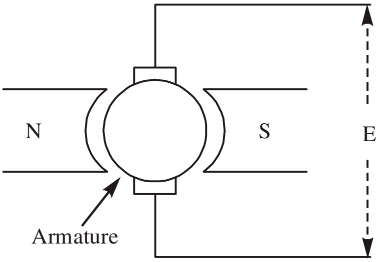


Fig. 2.43

Advantages of this arrangement lie in its simple construction and operation and hence widely used. The output voltage is in milivolt being 10 mv/rpm and hence is measured by PMMC easily. The direction of rotation of the main equipment can also be found out by checking the polarity of the output voltage.

The disadvantages are usually similar to that of a D.C. machine. Commutator and brushes need periodic maintenance. Error is introduced by increase in armature current, which distorts the field.

(*ii*) A.C. generator type tachometer is in fact a small alternator. The necessary field for excitation is produced either by permanent magnet or electric magnet mounted on the rotor of the tachometer and this rotor is coupled mechanically to the shaft of the main machine. The coil on the other hand is wound on the stator. The rotation of the rotor induces an A.C. voltage in the stater coil, amplitude and frequency of which is proportional to the speed. This A.C. voltage can be rectified before sending it to a PMMC indicator which is calibrated in terms of speed. Figure 2.44 shows this arrangement.

One advantage of this arrangement is that the maintenance problem created due to commutator and brushes are completely removed.

The disadvantage is that at very low rotational speed, the output voltage becomes very low and so ripples are not smoothened out by the *RC*-filter. This causes error in measurement on low speed. To minimize this effect however, larger number of poles can be designed on the rotor so the frequency of the output is increased even at low speed.

This system has been installed on turbine-driven centrifugal compressor for nitrogen compression in Sindri Fertilizer Plant and has worked uninterruptively for a period of 26 years with minor maintenance works during annual overhauling.

When the speed is exceptionally high (11000 RPM or more upto 15000), as is the case with synthesis mixture (consisting of 3 parts of hydrogen and 1 part of nitrogen) compressor in the same plant, another arrangement has been applied very successfully. A pole wheel with fixed number of gear teeth is connected mechanically to the main shaft. The gear ratio, which is the ratio of number of teeth on pole wheel to the number of teeth on the main shaft becomes the multiplying factor of the RPM indicator.

When the pole wheel rotates in front of the ferrostate transmitter (speed transducer), the output of the supplementary circuit shall supply an A.C. voltage. Each cycle of this A.C. voltage shall correspond to the passing of one pole of the pole wheel before the transducer pick-up.

The magnitude of the transmitted voltage depends on the distance d_o; pole wheel size, ambient temperature and circuit constant. Thus, the magnitude of transmitted voltage V_g, which is proportional to the gap distance d_o shall be given by:

$$V_g = Kd_o$$

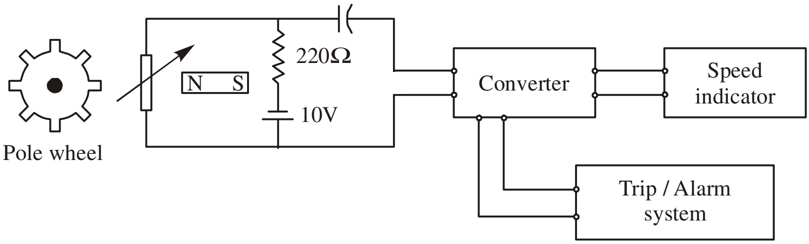


Fig. 2.46: High-speed measurement system

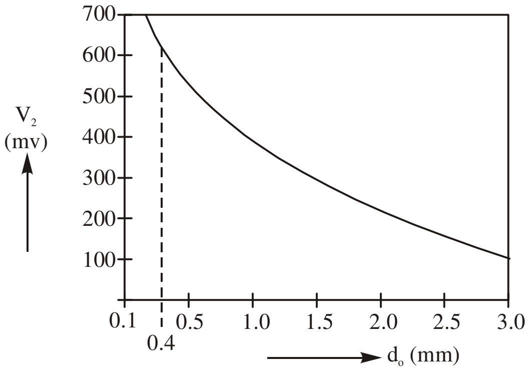


Fig. 2.47: Usual value of d_o is 0.4 millimetre initially

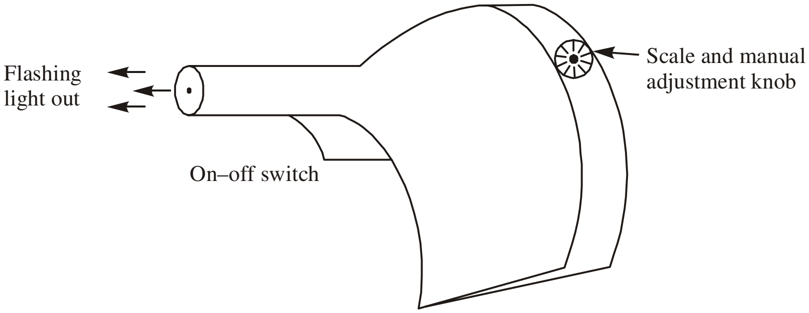


Fig. 2.48

Disadvantages are imposed due to inherent limitation of variable frequency oscillator, which cannot always deliver fixed frequency.

2.3.3 Acceleration

As is known to us, the displacement, velocity or acceleration are all different conditions of a system under the influence of mechanical vibration. A steady state condition in a particular direction at a particular instant of time is displacement. A variation in the displacement with respect to time in straight line is linear velocity. An angular displacement with respect to time or revolution with respect to time is angular velocity or speed. Similarly variable velocity with respect to time is acceleration. All three can be derived from the measurement of vibration, therefore, a vibration-sensing device can determine all the three variables.

These three variables are so related to one-another with respect to time that the displacement can be differentiated successfully to obtain velocity as well as acceleration. Similarly, acceleration can be integrated to obtain velocity as well as displacement.

For measurement of acceleration, the most popular system is the seismic accelerometer. We have already discussed the seismic spring-mass arrangement in the velocity measurement system. The basic principle as well as the relation for damping ratio and undamped natural frequency shall apply here also. Based on this basic theory, we shall discuss four different arrangements for measurement of acceleration:

(*i*) Potentiometric accelerometer,
(*ii*) Bonded strain gage accelerometer,
(*iii*) LVDT accelerometer, and
(*iv*) Piezoelectric accelerometer.

(i) Potentiometric accelerometer

In this system a seismic mass, which is connected to a potentiometer is equipped with a wiper. The motion of the seismic mass relative to the support of the transducer is sensed by the potentiometer and a proportional voltage output is obtained from the potentiometer as shown in Figure 2.49.

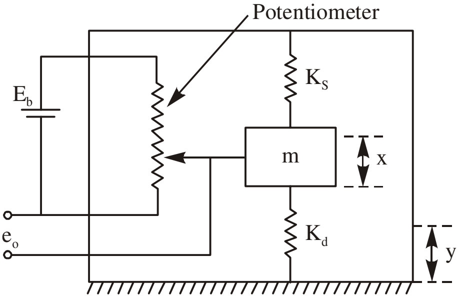


Fig. 2.49

Advantage of such a system is only one and that is the simplicity in construction.

The disadvantages being very low natural frequency (less than 100 Hz) and also very low resolution.

(ii) Bonded strain gage accelerometer

This is also a very simple device as shown in Figure 2.50. Strain developed by the vibration of the mass and cantilever combination is proportional to acceleration and is measured by the strain gage output. The displacement *x* of the mass *m* can be expressed as:

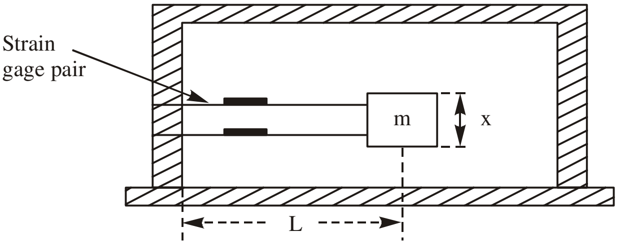


Fig. 2.50

$$x = \frac{F_d L^3}{3EI} \qquad \text{...(2.11)}$$

where F_d is the deflecting force on the mass, L is the length of the cantilever, E is the Young's modulus of elasticity and I is moment of inertia of the cantilever structure.

Now spring constant K_s of the system is given by:

$$K_s = \frac{F_d}{x} = \frac{3EI}{L^3} \qquad \text{...(2.12)}$$

through vibration reed and rod combination as shown in Figure 2.52. The combination of reed and the rod provide spring action as well. The output signal e_0 is proportional to the amplitude of the vibration.

Advantage of this system is that a very high natural frequency is obtainable by this. Also the resolution is better.

(iv) Piezoelectric accelerometer

In piezoelectric accelerometer a force-sensitive piezoelectric crystal is employed and therefore, it becomes an active transducer system that does not require auxiliary power supply. The transducer converts the force proportional to acceleration acting on the mass into electrical signal. The force F_a first of all generates an electrical charge q_e, which is given by the relation:

$$q_e = K_c \times F_a \qquad ...(2.15)$$

where K_c is charge sensitivity constant of the crystal.

The voltage output e_o is given by:

$$e_o = \frac{q_e}{C_p} \qquad ...(2.16)$$

where C_p is the capacitance offered by the crystal. When the value of q_e is put in the above relation, the expression for e_o becomes:

$$e_o = \frac{K_c \times F_a}{C_p} = \frac{K_c m \dfrac{d^2 y}{dt^2}}{C_p} \qquad ...(2.17)$$

where $$F_a = m\frac{d^2 y}{dt^2}$$

As shown in Figure 2.53, the piezoelectric crystal is positioned under the seismic mass against a heavy spring. Under the influence of acceleration, the seismic mass stresses the crystal and as a result voltage output e_o is obtained. Advantages of the system are small size and also higher natural frequency (100 KHz). Disadvantage is that it cannot be employed for low frequency application.

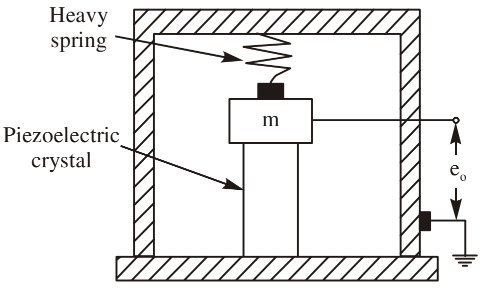


Fig. 2.53

2.3.4 Torque

Torque is the rotational effect of a force when applied tangentially. The rotation of a household door with respect to its hinge is an example of creation of torque. Thus, the torque can be defined as torsional twisting moment that twists or tends to twist a rigid body. The resultant motion, which is in terms of angular displacement, can be employed for measurement of torque.

Many methods have been devised for measurement of torque, which fall under.

(*a*) Stress type torque meter,
(*b*) Electrical torque meter, and
(*c*) Dynamometer torque meter.

(a) Stress type torque meter

Rotating machine while in action experiences torsional stress on the rotating shaft. This creates tensile as well as compressive strain on the shaft at an angle of ± 45°. These two principal strains (tensile and compressive) are of equal magnitude but of opposite polarity. These strains are proportional to torque T_g producing the strains. The approximate relation between T_g and strain $\in$ is given by:

$$T_g = \frac{0.196\, E \in d_o^{\,2}}{1+v} \qquad \ldots(2.18)$$

where E is Young's modulus of elasticity, d_o is the diameter of rotating shaft.

These can be measured accurately by four numbers of highly sensitive bonded strain gage placed at an angle of 45° with respect to the rotating shaft axis as shown in Figure 2.54. This combination of four numbers of bonded strain gages are connected to a Wheatstone bridge network for measurement. The strain gages 1,2 are for sensing tensile strain and that of 3, 4 are for

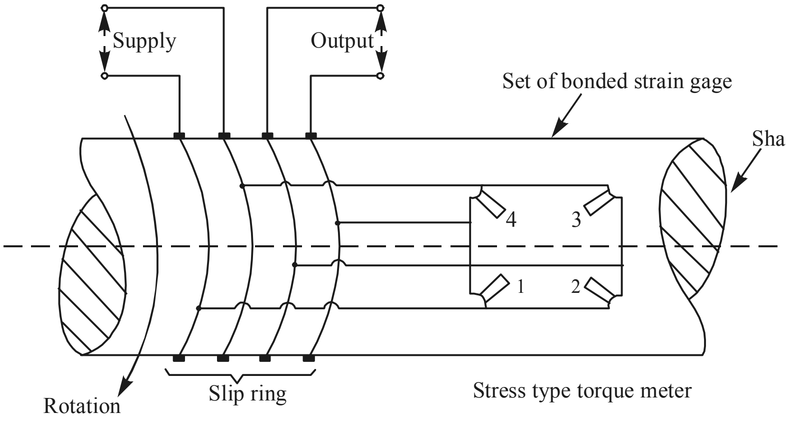


Fig. 2.54

sensing compressive strain. Use of this instrument is limited in between 2000 and 6000 RPM due to obvious limitation created by slip ring and brush combination.

Another stress type torque meter can be designed using rotating transformer and oscillator, which is completely contactless and can be used for higher speed rotating machines.

(b) Electrical torque meter

Under this category we shall discuss three different design variations based upon the type of detector used. These are:

(*i*) Use of A.C. generator as detector,
(*ii*) Use of proximity sensor as detector, and
(*iii*) Use of optical sensor as detector.

(i) Using A.C. generator as detector

Two gears separated by a gap of sufficient length are arranged on a rotating shaft. Two A.C. generators are coupled separately to these gear systems. These A.C. generators supply power to the primary windings of a transformer-set connected in phase opposition. The voltages thus are normally cancelled but due to torsion effect of the shaft, incomplete cancellation results. This difference induces a voltage in secondary of the transformers. Since this induced voltage is a result of torsional effect, this is proportional to torque. The entire system has been shown in Figure 2.55.

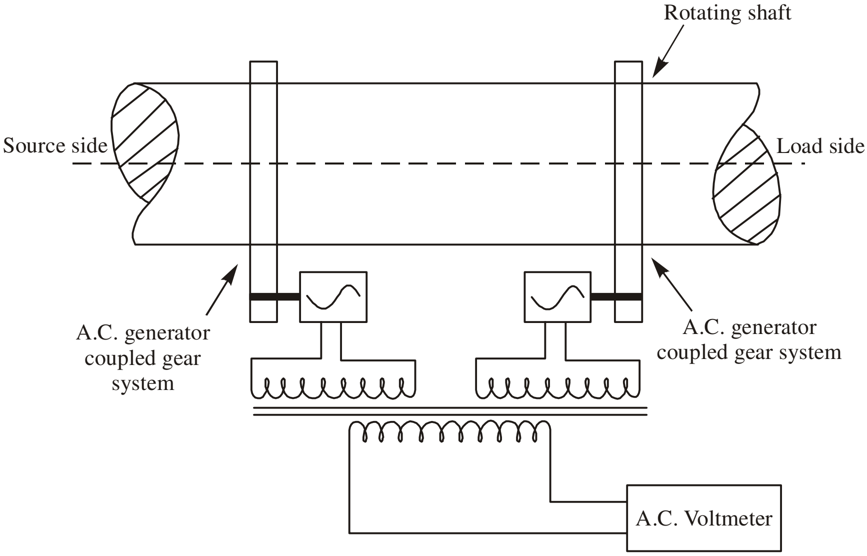


Fig. 2.55

Advantages obtainable from this arrangement depend upon the mechanical characteristics of the shaft material, e.g. elasticity which should be sufficient to create large phase difference in the generated voltage of the order of 10 to 15 degrees.

Disadvantages are that this is not a much accurate method of measurement and also static calibration is not possible.

(ii) Using proximity sensor as detector

In another scheme under electrical method, proximity sensor can be employed in place of A.C. generator as shown in Figure 2.56.

Proximity sensors are essentially magnetic pick-ups, which generate series of electrical pulses with respect to rotation of the gear system. Phase difference created due to load on rotating shaft is sensed by the phase detector, which is proportional to torque. This is comparatively more accurate method.

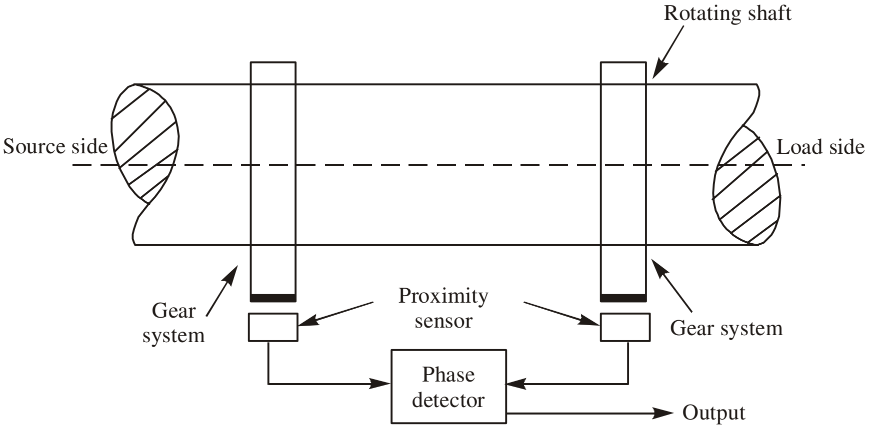


Fig. 2.56

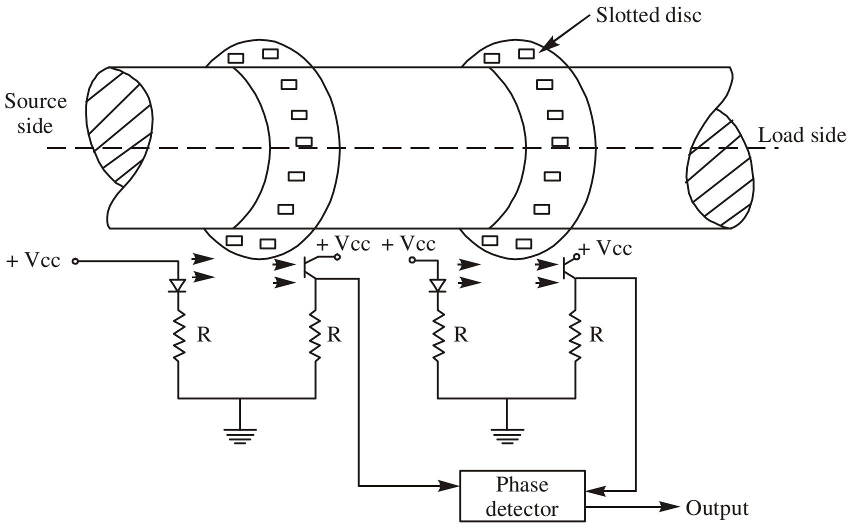


Fig. 2.57

(iii) Using optical sensor as detector

In this scheme, the pulses are generated by LED-photo transistor combination as shown Figure 2.57. A slight difference in light propagation created by the load on the shaft between two slotted discs fixed on the periphery of the rotating shaft is sensed by the photo detector. The sensor output is proportional to the torque. This is also a very accurate method of measurement.

(c) Dynamometer torque meter

This method employs belt transmission system. In belt transmission system, difference in belt tension can be balanced effectively by a suitably placed mass. Such an arrangement has been shown in Figure 2.58.

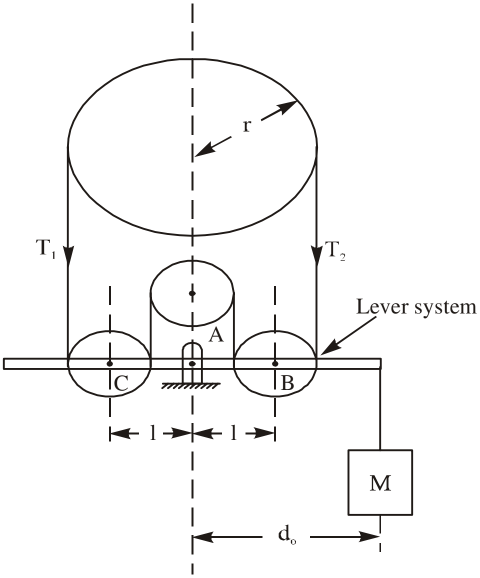


Fig. 2.58

The resultant tension due to T_1 and T_2 is acting on the lever system pivoted at *A* is being counter-balanced by the mass *M*. The resultant torque due to tension T_l and T_2 is given by $(T_2 - T_1) \times 2l$, where l is the length *AB* as shown in the diagram. Similarly the balancing torque created by the mass *M* is given by $Mg\ d_0$ where g is the acceleration due to gravity and d_0 is the distance between the mass and the pivot.

At equilibrium condition,

$$(T_2 - T_1) \times 2l = Mg\ d_0 \qquad \ldots(2.19)$$

Output torque can be found out by the relation,

$$(T_2 - T_l) \times r = \frac{Mgd_o}{2l} \times r \qquad \ldots(2.20)$$

Example 2.4

A pressure of 40 *psi* is applied to a mercury manometer. The specific gravity of mercury is 13.6. Find the displacement of mercury inside the manometer.

Solution

We know that 0.036 *psi* is the pressure created by the displacement of 1 inch of water column, therefore, the pressure (P_s) in *psi* created by displacement of x inch of liquid of specific gravity ρ shall be given by:

$$P_s = x \times 0.036 \times \rho\ .$$

$$\therefore \qquad \text{Displacement } x = \frac{40\,psi}{0.036\dfrac{psi}{\text{inch}}\times 13.6}$$

$$= 81.7 \text{ inches.}$$

Example 2.5

One leg of a 'U-tube manometer water filled type' is connected to a vacuum pump and the air is completely evacuated. The other leg is open to atmosphere. The displacement in water observed is 34 feet, calculate the atmospheric pressure.

Solution

As we know, 1 ft $WC \approx 0.433$ *psi*,

Hence, 34 ft $WC \approx 34 \times 0.433$

$= 14.722$ *psi*.

Thus, atmospheric pressure = 14.722 *psi*.

Example 2.6

A mercury manometer reads pressure in *psi*. If specific gravity of mercury is 13.6, find the linear scale length representing 1 *psi*.

Solution

We know, 1 *psi* = 27.7 inches

The scale shall be;

$$\frac{27.7}{13.6} = 2.036 \text{ inches.}$$

Hence, 2.036 inches shall represent 1 *psi*.

Example 2.7

A pressure-measuring transmitter has been mounted 40 feet below the level of a steam drum in a boiler house. Find the zero suppression required to compensate for the error introduced by the hydrostatic head of 40 feet.

Solution

1 *ft* of *WC* ≈ 0.433 *psi.*

The pressure created by 40 feet *WC* = 0.433 × 40

= 17.32 *psi.*

The pressure 17.32 must be deducted from the indicated reading or may be adjusted by means of zero suppression adjustment spring if installed in the transmitter.

Example 2.8

The output of a LVDT is connected to a 10 volt voltmeter through an amplifier of gain 300. The voltmeter has a scale of 100 divisions and the readability of the scale is upto 1/5 of a division. An output of 2 mV appears across the terminals of the LVDT, when the core is displaced through a distance of 0.5 mm. Find out the:

(*i*) Sensitivity of LVDT and also of entire set-up, and
(*ii*) Resolution of the instrument.

Solution

Here LVDT output V_o = 2 mV and the displacement d = 0.5 mm.

(*i*) Hence, sensitivity of LVDT $= \dfrac{V_0}{d} = \dfrac{2\text{ mV}}{0.5\text{ mm}}$

$= 4\text{ mV/mm}$

Also sensitivity of entire set-up,

= Amplification factor × Sensitivity of the LVDT.

= 300 × 4 mV/mm = 1200 mV/mm.

(*ii*) 1 scale division $= \dfrac{10}{100} = 100\text{ mV}$

Minimum voltage read on the voltmeter $= \dfrac{1}{5} \times 100\text{ mV} = 20\text{ mV}.$

$$\text{Resolution} = \frac{20\text{ mV}}{1200\text{ mV}/\text{mm}} = 0.0167\text{ mm}.$$

Example 2.9

A seismic mass accelerometer of seismic mass of 0.07 kg and spring constant of 2.8×10^3 N/m has maximum displacement of ± 0.029 metre. Find the maximum acceleration and natural frequency.

Hence, diagonal strain $\in \; = \dfrac{\Delta L}{L} = \dfrac{\alpha/\sqrt{2}}{\sqrt{2}} = \dfrac{\alpha}{2}$

But $\dfrac{\Delta R}{R} = G\in \; = 2 \times \dfrac{\alpha}{2} = \alpha$

$\therefore \quad \alpha = \dfrac{\Delta R}{R} = \dfrac{0.24}{120} = 2 \times 10^{-3}$ radians.

Torque $T = \dfrac{G_s \pi r^3}{2} \times \alpha$

where G_s is the shear modulus of steel.

$$= \frac{80 \times \pi \times 15^3}{2} \times 2 \times 10^{-3}$$

$$= 847.8 \text{ Nm.}$$

Example 2.11

A disc mounted on the shaft of a machine has 12 marked points. The number of flashes projected on to the disc by a stroboscope is 6000 in one minute. Find the speed of the machine if the disc appears stationary and has single image of 12 points. If the disc appears to move forward in the direction of rotation at 10 rpm, find the speed of the disc.

Solution

Here the speed of the machine N is given by, $N = \dfrac{F}{n}$ where F is number of flashes in one minute and n is number of marked point.

$\therefore \quad N = \dfrac{6000}{12} = 500$ rpm.

When the disc appears to move in the direction of rotation, the speed of the machine becomes,

$$500 + 10 = 510 \text{ rpm.}$$

Example 2.12

An A.C. operated LVDT is supplied by an input voltage of 10 volt. If the variation in output ranges from – 7.1 to + 7.1 for the core displacement between – 10 mm and + 10 mm, find:

(*a*) Output voltage V_s. Core displacement varies from – 6 mm to + 8 mm?
(*b*) Output voltage when the core is at – 5 mm from the zero position?