# MODULE 1

## INTRODUCTION TO SENSOR-BASED MEASUREMENT SYSTEMS

**STRUCTURE**:

➢ General concepts and terminology

➢ sensor classification, primary sensors

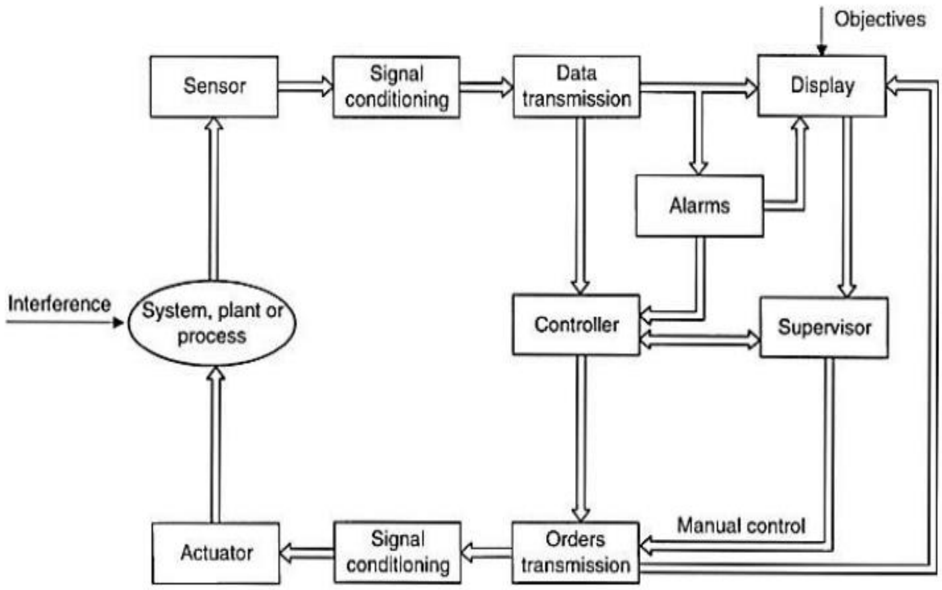
➢ material for sensors

➢ microsensor technology

**Question 1**

**Define the concept of a measurement system, elucidating its core function and providing real-world examples of measurement objectives across various domains.**

- Sensors play a crucial role in measurement systems by generating electric signals containing information about the measured quantity.
- These signals are processed by electronic circuits to extract relevant information, making sensors the foundation of measurement systems.
- A system is composed of various elements, subsystems, and parts required to perform specific functions.
- The primary function of a measurement system is to objectively and empirically assign numerical values to describe properties or qualities of objects or events.
- Measurement objectives can range from process monitoring, where parameters like ambient temperature or gas volume are tracked, to process control, such as regulating temperature or level in a tank.
- Measurement systems are also utilized in experimental engineering, like studying temperature distribution in irregularly shaped objects or analyzing force distribution in car crash simulations.
- Figure 1.1 illustrates the functions and dataflow within a measurement and control system, highlighting the role of sensors and actuators as transducers between electronic systems and processes/experiments.
- Modern measurement systems are organized based on digital bus connectivity rather than traditional dataflow models, emphasizing the importance of information transmission and integration across subsystems.




**Question 2**

**Explain the classification of sensors based on power supply requirement, output signals, and operating mode. Provide examples illustrating each classification.**

Sensor Classification:

| Criterion | Classes | Examples |
|---|---|---|
| Power supply | Modulating | Thermistor |
| | Self-generating | Thermocouple |
| Output signal | Analog | Potentiometer |
| | Digital | Position encoder |
| Operation mode | Deflection | Deflection accelerometer |
| | Null | Servo-accelerometer |

Sensors are classified based on three primary criteria:

Power supply requirement: Modulating (active) sensors vs. self-generating (passive) sensors.

Modulating sensors derive most of their output power from an auxiliary power source, while self-generating sensors generate output power from the input.

Modulating sensors typically require more wires for power supply and may pose a higher risk of explosion in explosive atmospheres.

Modulating sensors offer the advantage of modifying sensitivity with the power supply voltage.

Output signals: Analog sensors vs. digital sensors.

Analog sensors exhibit continuous output changes, often based on amplitude or time domain variations.

Digital sensors produce discrete steps or states in their output, facilitating easier transmission without the need for Analog to Digital Conversion (ADC).

Digital sensors tend to offer more repeatability, reliability, and accuracy compared to analog sensors, although they may not measure all physical quantities.

Operating mode: Deflection sensors vs. null mode sensors.

Deflection sensors produce a physical effect in response to the measured quantity, generating a related opposing effect in some part of the instrument.

Null-type sensors aim to maintain balance by applying a known effect opposing the measured quantity's effect, typically using an imbalance detector and means to restore balance.

**Question 3**

**Discuss the role of primary sensors in measurement systems, focusing on temperature sensors like bimetals. Explain their construction, working principles, and applications in industrial processes.**

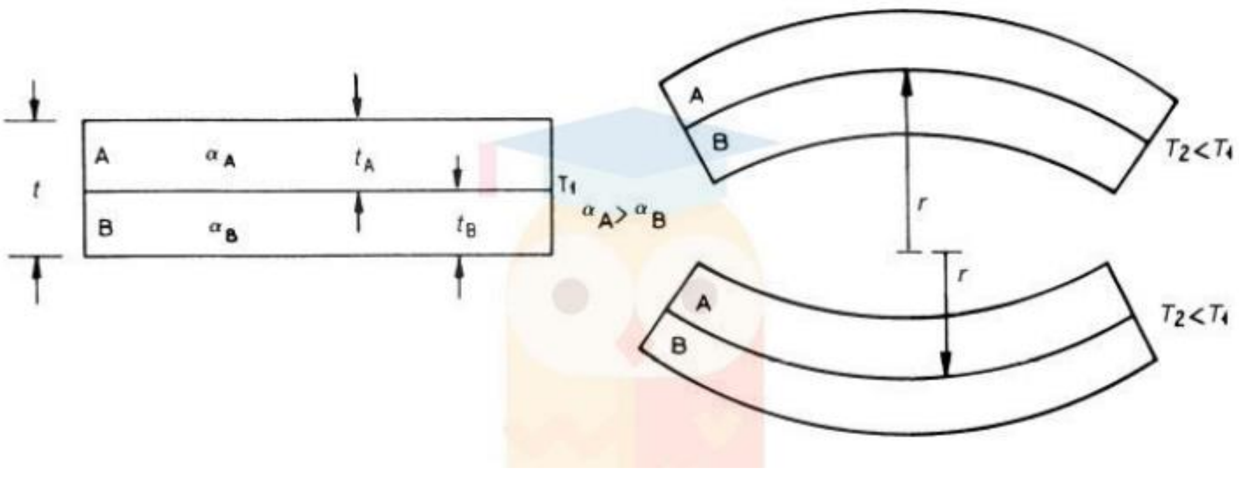
**Primary Sensors:**

Primary sensors are the initial transducers in contact with the pressure pulse, typically displacement transducers converting pressure waves into mechanical displacements. They convert physical quantities into other forms and are categorized based on the measurand.

**Types of Primary Sensors:**

1. **Temperature Sensors:** Bimetals, thermocouples, thermistors.
2. **Pressure Sensors**
3. **Flow Velocity and Flow-rate Sensors**
4. **Level Sensors**
5. **Force and Torque Sensors**
6. **Acceleration and Inclination Sensors**
7. **Velocity Sensors**

**Temperature Sensors - Bimetals:**



- Bimetallic strips act as thermal switches in controlling temperature in manufacturing processes.
- They consist of two metal strips bonded together, each with different coefficients of expansion.
- Upon heating, the strips bend into curved shapes, with the metal having the higher coefficient of expansion on the outside of the curve.
- A typical arrangement includes a setting-up magnet where, as the strips bend, the soft iron comes closer to a small magnet, completing an electric circuit and generating an alarm to prevent overheating.
- Bimetallic strips prevent applications from heating above preset temperatures.
- The radius of curvature of bimetal strips changes with temperature, inversely proportional to the temperature difference if the metals have similar moduli of elasticity and thicknesses.
- Bimetal strips are used as actuators to open/close contacts (e.g., thermostats, on-off controls, starters for fluorescent lamps) and for overcurrent protection in electric circuits.
- When current flows through the bimetal, it heats up due to the Joule effect, reaching a temperature where it exerts mechanical force on a trigger device, opening the circuit and interrupting the current.

$$r \cong \frac{2t}{3(\alpha_A - \alpha_B)(T_2 - T_1)}$$

**Question 4:**

**Discuss the significance of pressure sensors in various applications, highlighting their role as transducers and the different types of pressure measurements they enable. Provide examples of common uses and explain the principles behind measuring pressure differentials**.

**Pressure Sensors:**

- Pressure sensors are devices used for measuring the pressure of gases or liquids.
- Pressure is defined as the force required to stop a fluid from expanding, usually expressed as force per unit area.
- Pressure sensors act as transducers, generating signals based on the pressure applied.
- They find applications in various control and monitoring tasks across numerous everyday scenarios.
- Pressure sensors can indirectly measure other variables like fluid/gas flow, speed, water level, and altitude.

- Alternately referred to as pressure transducers, pressure transmitters, pressure senders, pressure indicators, piezometers, and manometers.
- Blood pressure measurement is a common application in patient diagnosis and monitoring.
- Differential pressure denotes the difference in pressure between two measurement points.
- Gage pressure is measured relative to ambient pressure, while absolute pressure is measured relative to a perfect vacuum.
- Pressure measurement is achieved by comparing it with a known force or by measuring its effect on an elastic element.

**TABLE 1.7 Some Common Methods to Measure Fluid Pressure in Its Normal Range**

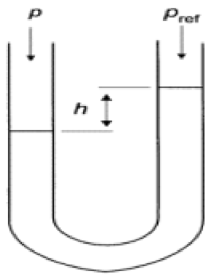
| | |
|---|---|
| 1. Liquid column + level detection | |
| 2. Elastic element | |
| 2.1. Bourdon tube + displacement measurement: | Potentiometer |
| | LVDT |
| | Inductive sensor |
| | Digital encoder |
| 2.2. Diaphragm + deformation measurement | |
| 2.2.1. Central deformation[a]: | Potentiometer |
| | LVDT |
| | Inductive sensor |
| | Unbonded strain gages |
| | Cantilever and strain gages |
| | Vibrating wire |
| 2.2.2. Global deformation: | Variable reluctance |
| | Capacitive sensor |
| | Optical sensor |
| | Piezoelectric sensor |
| 2.2.3. Local deformation: strain gages: | Bonded foil |
| | Bonded semiconductor |
| | Deposited |
| | Sputtered (thin film) |
| | Diffused/implanted semiconductor |

- **Liquid-column U-tube Manometer:**
    - Simplest form of manometer with U-shaped glass tube containing liquid.
    - Measures gauge pressure and used for calibration in workshops.
    - Principle: Pressure applied to one side of the tube causes movement of liquid.
    - Liquid level drops in the leg where pressure is applied and rises in the other leg.
    - Scale between tubes measures displacement.

- Pressure exerted by liquid column balances applied pressure when liquid stops moving.
- Pressure calculation based on length of liquid column (H), density of filling liquid, and acceleration of gravity.
- Comparison with reference pressure yields difference in liquid level (h).
- Level sensor (photoelectric, float, etc.) generates electric output signal.

- **Filling Liquids for Manometers:**

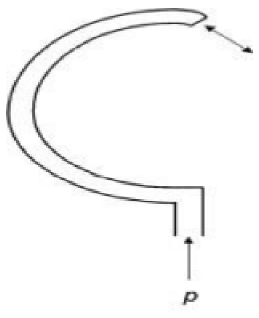
1. Water ($\rho = 1000$ kg/m³)
2. Oil ($\rho$ varies between 800 and 950 kg/m³)
3. Mercury ($\rho = 13560$ kg/m³)




(a)

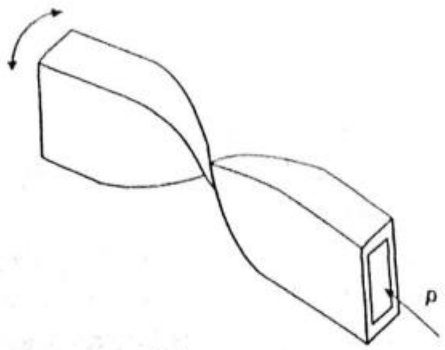
- **C-shaped Bourdon Tube:**
    - Radially formed tubes with oval cross-section used for pressure measurement.
    - Measuring medium pressure acts on inside of tube, causing motion in non-clamped end.
    - Motion indicates pressure level.
    - Consists of C-shaped hollow tube with one fixed end connected to pressure tapping and other end free.
    - Elliptical cross-section of tube.
    - When pressure applied, tube tries to straighten, causing free end to move up based on pressure magnitude.
    - Deflecting and indicating mechanism attached to free end rotates pointer to indicate pressure reading.
    - Materials commonly used: Phosphor Bronze, Brass, Beryllium Copper.
    - Useful travel of free end for 2" overall diameter C-tube is approximately 1/8".
    - Other tube shapes include helical, twisted, or spiral.

- Wide operating range depending on tube material.
- Suitable for positive or negative pressure ranges, though accuracy is reduced in vacuum.



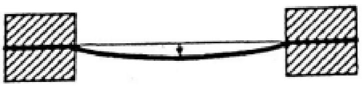

(b)

- **Twisted Bourdon Tube:**




(c)

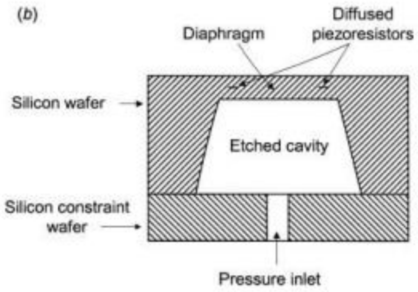
  - Bourdon tube wound in helical form.
  - Tip movement converted to circular motion.
  - Central shaft installed inside helix, connected to tip to create circular motion.
- **Diaphragm Pressure Gauges:**
  - Used for measuring gases and liquids, covering spans from 10 mbar to 40 bar.
  - Measuring element: Circular diaphragm clamped between flanges.
  - Positive or negative pressure deforms diaphragm, proportional to pressure being measured.
  - Deformation coupled to pointer mechanism.
  - Diaphragm: Flexible circular plate, strains under pressure difference.



(d)

- Materials: Beryllium-copper, stainless steel, nickel-copper alloys.

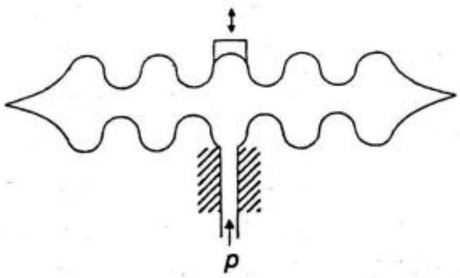
- **Micromachined diaphragm:**
  - Etched silicon wafer with gages sensing strain.
  - Used in cars and hospitals.
  - Diaphragm and elements must withstand medium and required temperature.
  - Stainless steel diaphragms can protect sensing diaphragms from corrosive media, but fluid interposition increases compliance and thermal sensitivity.
  - Center deflection (z) for thin plate with thickness (t) and radius (R) experiencing pressure difference ($\Delta p$) is $z < t/3$, where E is Young's modulus and $\nu$ is Poisson's ratio for the plate material.




(e)

$$z \cong \frac{3(1-\nu^2)R^4}{16Et^3}\Delta p$$

**Pressure Sensing Capsules:**




Adapts diaphragm sensing principle for measuring low pressures.

Consists of two diaphragms welded at the edge, allowing pressure media to act on both simultaneously.

Provides twice the displacement compared to a single-diaphragm structure.

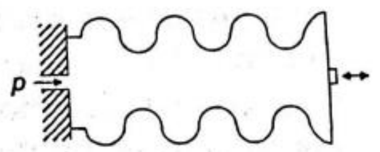
Can be used as single capsule or stacked for pressure sensing.

Some capsules feature profiling (e.g., corrugations) for linearity and mechanical strength optimization.

Advantages: Stability, simplicity, small size, ability to measure lower pressures compared to similar-sized diaphragm sensors.

Disadvantage: Not suitable for measuring pressure in liquid media due to lack of self-draining.

**Bellows Sensing Elements:**




(g)

Container that expands in response to pressure medium force.

Typically made from metals like phosphor bronze, brass, beryllium copper, or stainless steel.

Machined from solid stock, rolled from tube, or fabricated with welded annular rings.

Internally or externally mounted spring enhances response to pressure changes.

Deflection characteristics influenced by mechanical properties of bellows and spring.

Mechanical movement converts bellows expansion/contraction into proportional pointer deflection.

Alternatively, movement can be connected to potentiometer for electrical analog of pressure.

Advantages: Simplicity, low cost, ability to connect directly to pointer, high resolution.

Disadvantages: Must operate within elastic limit, risk of fatigue over time, drainage challenges with liquid media.

Can be filled with inert liquid and sealed with diaphragm for liquid pressure monitoring.

**Flow Velocity and Flow-Rate Sensors:**

- Electronic devices measuring or regulating flow rate of liquids and gases in pipes and tubes.
- Differences in pressure (vortices) generated measured to determine flow rate.

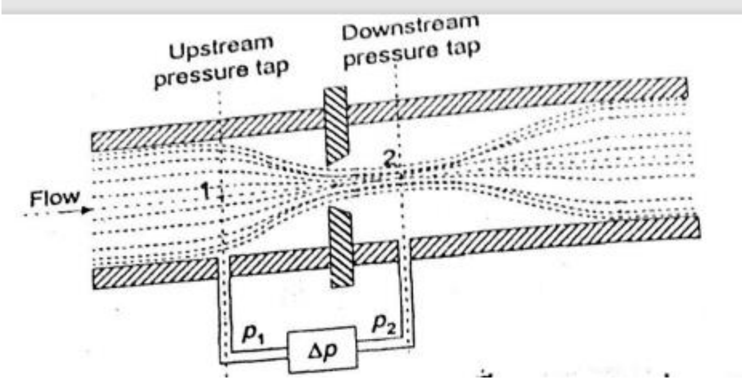
- Liquid flow measured using Bernoulli's principle through constriction, with fluid flow volume proportional to square root of pressure difference.
- Various flow measurement devices include Orifice plate, Turbine meter, etc.

**TABLE 1.8 Measurement Principles Used in Flowmeters**

| Input Quantity | Measurement Principle | Output Signal |
|---|---|---|
| Fluid velocity: local | Pitot probe | Differential pressure |
| | Thermal (hot wire anemometry) | Temperature |
| | Laser anemometry | Frequency shift |
| Fluid velocity: average | Electromagnetic | Voltage |
| | Ultrasound: transit time | Time |
| | Ultrasound: Doppler | Frequency |
| Volume flow rate[a] | Orifice plate | Differential pressure |
| | Venturi tube | Differential pressure |
| | Pitot probe | Differential pressure |
| | Flow nozzle and tube | Differential pressure |
| | Elbow | Differential pressure |
| | Laminar flow element | Differential pressure |
| | Impeller (paddlewheel) | Cycles, revolutions |
| | Positive displacement | Cycles, revolutions |
| | Target (drag force) | Force |
| | Turbine | Cycles, revolutions |
| | Variable area (rotameter) | Float displacement |
| | Variable area (weir, flume) | Level |
| | Vortex shedding | Frequency shift |
| Mass flow rate | Coriolis effect | Force |
| | Thermal transport | Temperature |

[a] Volume flow rate can also be calculated by multiplying the average fluid velocity by the pipe cross section.

- **Orifice Plate:**




- Consists of disc with hole at center for fluid flow.
- Pressure difference measured between upstream and downstream points.
- Simple construction with no moving parts, but exhibits nonlinear behavior and not suitable for slurries.
- Accuracy: ±1.5%.

At the same time, from (1.45) we have

$$p_1 + \rho g h_1 + \frac{\rho v_1^2}{2} = p_2 + \rho g h_2 + \frac{\rho v_2^2}{2}$$

If $h_1 = h_2$, these two equations yield

$$v_2 = \sqrt{\frac{2(p_1 - p_2)}{\rho\left[1 - \left(\frac{A_1}{A_2}\right)^2\right]}}$$

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- **Flow Nozzle:**

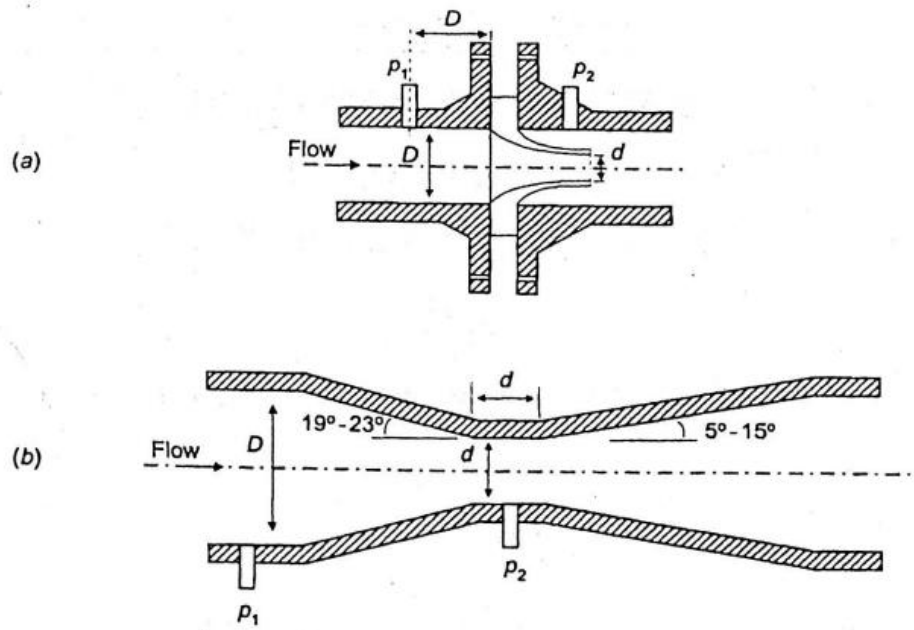
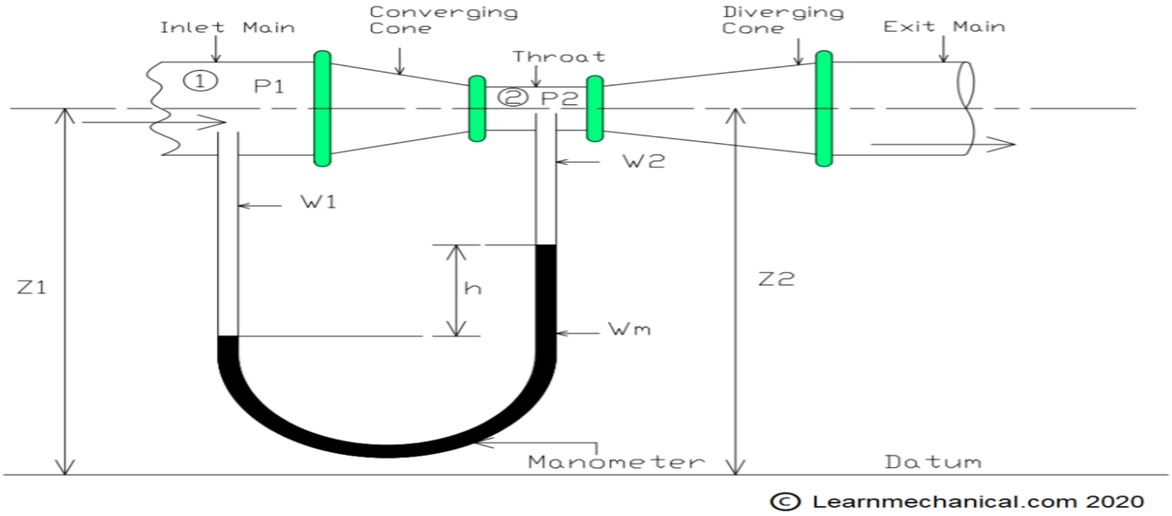



**Figure 1.16** Flow nozzles (*a*) and Venturi tubes (*b*) inserted in pipes yield a lower drop in pressure than orifice plates, hence saving energy.

- Causes pressure drop in pipe, varying with flow rate.
- Pressure drop measured using differential pressure sensor.
- Components: Flow nozzle, differential pressure sensor (e.g., u-tube manometer).
- Used for measuring flow rates of liquid discharged into atmosphere, in situations with settling suspended solids, and for high pressure and temperature steam flows.

- **Venturi Flow Meter**




- Contains throat smaller than pipeline diameter.
- Fluid flow leads to lower pressure at throat compared to upstream pressure.
- Flow rate proportional to pressure difference (P1 - P2), with coefficient dependent on pipeline and throat diameter, density, and discharge coefficient.
- Accuracy: about 0.5%, suitable for turbulent flow, HVAC applications, and liquids with particles and slurries.
- **Venturi Effect:**
- Reduction in fluid pressure when flowing through constricted pipe section.
- Fluid velocity increases, static pressure decreases.
- Change in pressure used to determine flow rate in various flow measurement devices.
- **Rotameter:**

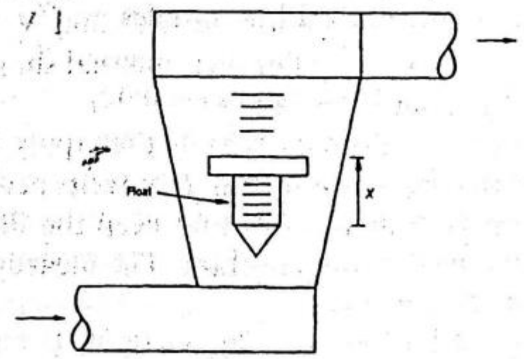



**Figure 1.17** A rotameter is a variable area flowmeter in which the position of a float indicates the flow rate.

- Variable area flowmeter with float indicating flow rate.
- Float position determined by fluid flow, maintaining constant pressure difference.
- Float displacement indicates flow rate, detected magnetically or photoelectrically.
- Suitable for low-pressure, high flow rates.
- **Pitot Tube:**

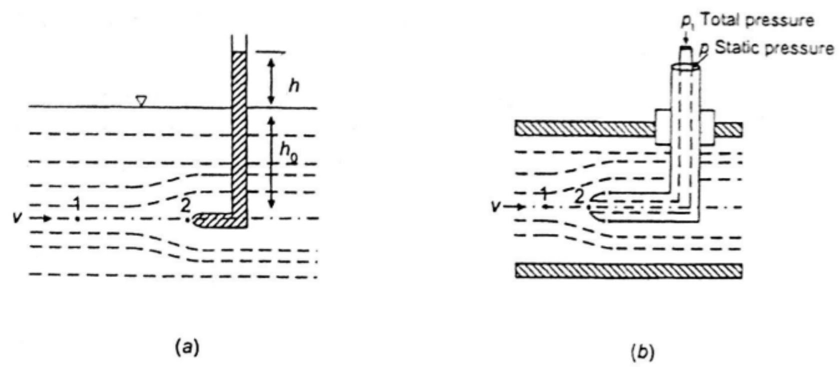



**Figure 1.18** Pitot tube for point velocity flow measurement. (*a*) In an open conduit the velocity is indicated by the emerging fluid height. (*b*) In a closed conduit the velocity is calculated from the difference between total pressure and static pressure.

- Measures point velocity flow in open or closed conduits.
- Velocity calculated from difference between total pressure and static pressure.
- Used in various flow measurement applications.

$$\frac{v^2}{2g} + \frac{p_1}{\rho g} = \frac{p_2}{\rho g} = h_0 + h$$

Also the static pressure in an open conduit comes from the weight of the fluid column, $p_1 = \rho g h_0$. Therefore

$$v = \sqrt{2gh} \tag{1.50}$$

We can thus infer the fluid velocity at the measurement point from the height of the column emerging above the surface.

If the Pitot tube is placed in a pressurized pipe, from (1.45) we obtain

$$v = \sqrt{\frac{2(p_t - p)}{\rho}} \tag{1.51}$$

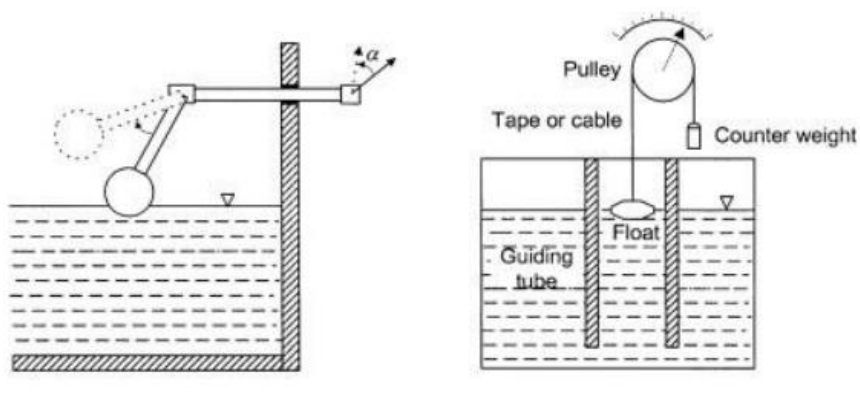
Laminar flowmeters, also called laminar resistance flowmeters, rely on the Poiseuille's law. Jean M. Poiseuille—a physician—established in 1840 that for laminar flow in a tube much longer than wide, the volumetric flow rate is a linear function of the pressure drop according to

$$\Delta p = Q\frac{8\eta L}{\pi r^4} \tag{1.52}$$

where $\eta$ is the fluid viscosity, $L$ is the tube length, and $r$ is its radius. Laminar flowmeters consist of a bundle or a matrix of capillary tubes, or one or more fine mesh screens and two pressure connections. They are used for leak testing, for calibration work, and in respiratory pneumotachometers.

# Level Sensors:

- **Dipsticks:**
    - Simple level sensors but don't provide electric signal easily.
- **Floats:**
    - Based on Archimedes' buoyancy principle.
    - Convert liquid level to force or displacement.
    - Used for continuous level sensing.
    - Magnetic float rises and falls with liquid levels.
    - Movement of float creates magnetic field, actuating a sealed reed switch.
    - Float position detected magnetically in sealed or high-pressure containers.
    - Build-up and deposits on float surface limit performance.




(a) (b)

- **Principle of Operation:**
    - Works on buoyancy principle.

- Float immersed in liquid buoyed upwards by equal force to weight of displaced liquid.
- Float partially submerges, covering same distance as liquid level moves.

- **Working:**
  - Float-type liquid level switch used.
  - Float activates switch when level moves upwards.
  - Float may contain magnet to vary switch state.
  - Advantages: Simple, accurate, suitable for various products.

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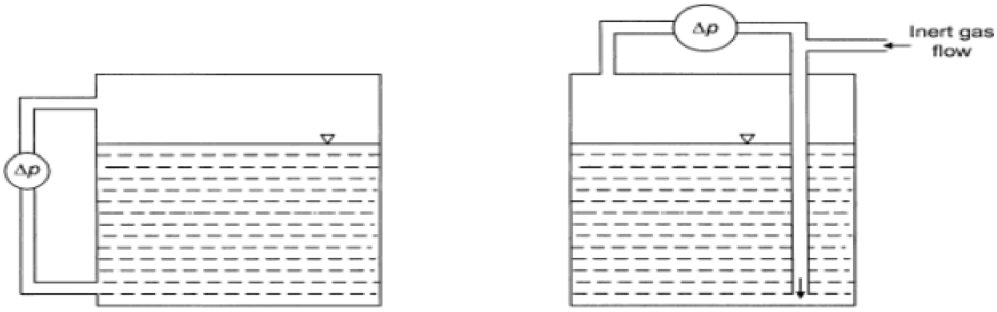



(c) (d)

- **Pressure Calculation:**

pressure of liquid or solid is proportional to level according to

$$h = \frac{\Delta p}{\rho g} \qquad (1.56).$$

where ρ is density and g is the acceleration of gravity. This method is suitable for both pressurized and open containers. Temperature interferes because it varies density

  - Pressure of liquid or solid proportional to level.
  - Formula: Pressure = ρ * g * h (where ρ is density, g is acceleration due to gravity, h is height).
  - Suitable for both pressurized and open containers.
  - Temperature variation affects density.

- **Bubble Tube:**
  - Overcomes need for pressure port near container bottom.
  - Dip tube with open end close to bottom of tank.
  - Inert gas flows through dip tube.

- Gas bubbles escape from open end, equalizing gas pressure with hydraulic pressure from liquid.
- Level calculated from pressure.

**Force and Torque Sensors:**

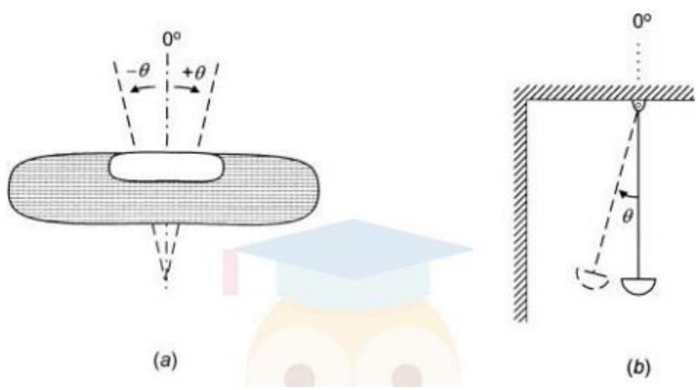
| Element | Deflection | Maximal Stress |
|---|---|---|
| Cantilever | $x = \dfrac{4Fl^3}{Ewt^3} = \dfrac{2\sigma l^2}{3Et}$ | $s_M = \dfrac{6Fl}{wt^2} = \dfrac{3Etx}{2l^2}$ |
| Helical spring | $x = \dfrac{8FnD^3}{Gd^4} = \dfrac{\pi n D^2 \tau}{Gdk_1}$ | $\tau_M = \dfrac{8k_1 DF}{\pi d^3} = \dfrac{Gdxk_1}{\pi n D^2}$ |
| Torsion bar | $\theta = \dfrac{32FDl}{\pi d^4 G} = \dfrac{2\tau l}{dG}$ | $\tau_M = \dfrac{16FD}{\pi d^3} = \dfrac{dG\theta}{2l}$ |

- **Measurement Methods:**
    - Comparison with a known force (e.g., scales).
    - Effect of force on an elastic element (load cell).
- **Load Cells:**
    - Electric load cells: Measure deformation or displacement.
    - Hydraulic and pneumatic load cells: Measure increase in pressure of liquid or gas.
    - Manufacturers and types listed in Measurements & Control annually.
- **Principle of Operation:**
    - Mechanical force applied to fixed elastic element.
    - Strains until strain-generated stresses balance those from applied force.
    - Change in dimensions of element proportional to applied force if shape is appropriate.
- **Arrangements:**
    - Figure illustrates three suitable arrangements for force and torque sensors

**Acceleration Sensors:**

- **Application:**
    - Used to determine speed and position of vehicles like planes, ships, cars, robots, etc.

- **Classification:**
    - Direct measurement of force (e.g., piezoelectric sensor).
    - Indirect measurement through displacement or deformation of sensing element.
- **Measurement Principle:**
    - Inertial force measured through strain or deformation of elastic element.
- **Inclinometer Sensors:**
- **Definition:**
    - Also known as tilt sensor, clinometer, or slope sensor.
    - Measures angle of object with respect to gravity force.
- **Applications:**
    - Used in activities like tunnelling, excavation, and de-watering to measure slope gradient.
    - Monitors ground movement supporting structures.
- **Installation:**
    - Installed vertically to monitor cut slope or movement in shoring wall.
    - Installed horizontally to monitor settlement of soil above tunnelling spot.
- **Types and Installation:**
    - Different types of inclinometer sensors for various applications.
    - Installation depends on specific application requirements.



**Velocity Sensor:**

- **Integration or Differentiation:**
    - Linear velocity can be measured by integrating acceleration or differentiating displacement.
- **Conversion to Rotational Velocity:**
    - Linear velocity can be converted to rotational velocity by coupling a rack to the moving object and connecting it to a pinion gear.

**Seismic Sensors for Linear Velocity:**

- **Principle:**
    - Seismic sensors can sense linear velocity without a direct link between the moving object and the reference frame.
- **Method:**
    - Integrating mass displacement proportional to input acceleration yields input velocity.
    - Integrates mass displacement to measure input velocity.
    - Output proportional to input speed relative to inertial reference.
    - $\frac{\dot{X}_o(s)}{\dot{X}_i(s)} = \frac{sX_o(s)}{sX_i(s)} = \frac{s^2X_o(s)}{s^2X_i(s)} = \frac{M}{K}\frac{s^2(K/M)}{s^2 + s(B/M) + K/M}$
- **Output Signal:**
    - At frequencies above the natural frequency of the system, the output of the velocity sensor is proportional to the input speed relative to an inertial reference.

**Angular Velocity Measurement with Gyroscopes:**

- **Classic Single-Axis Mechanical Gyro:**
    - Motor-driven spinning mass supported within a gimbal, with bearings attached to a case.
- **Two-Axis Gyro:**
    - Bearings supporting inner gimbal attached to an outer gimbal capable of rotating with respect to the case.
- **Rate Gyro:**
    - Single-axis gyro with elastic restraint of the spin axis about the output axis.
    - Rotation around perpendicular axis develops angular momentum sensed by torque or force sensors.
- **Micromachined Gyros:**

- Have no rotating parts or bearings.
- Sense rotation from Coriolis effect on vibrating mechanical elements.

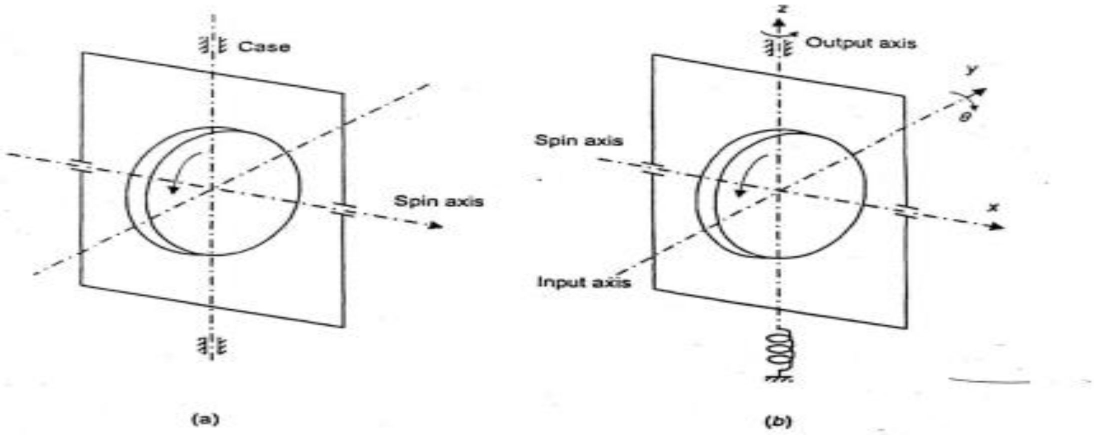



**Figure 1.25** Single-axis mechanical gyroscope. (*a*) A spinning wheel defines the *x*-axis. (*b*) A rotation around the *y*-axis, perpendicular to the *x*-axis, yields a torque around the *z*-axis, perpendicular to both *x*- and *y*-axes.

The Coriolis effect is an apparent acceleration that arises in a moving element in a rotating body. Consider a traveling particle with velocity $\mathbf{v}$ (Figure 1.26) and an observer placed on the *x*-axis watching the particle. If the coordinate system (including the observer) rotates around the *z*-axis with angular velocity $\Omega$, the observer thinks that the particle is moving toward the *x*-axis with acceleration

$$a_{\mathrm{Cor}} = 2\Omega \times \mathbf{v} \tag{1.58}$$

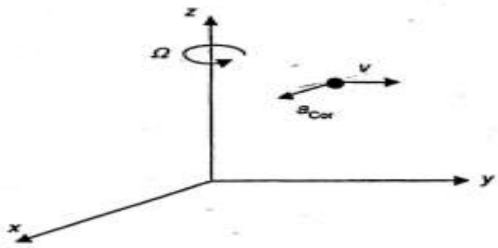
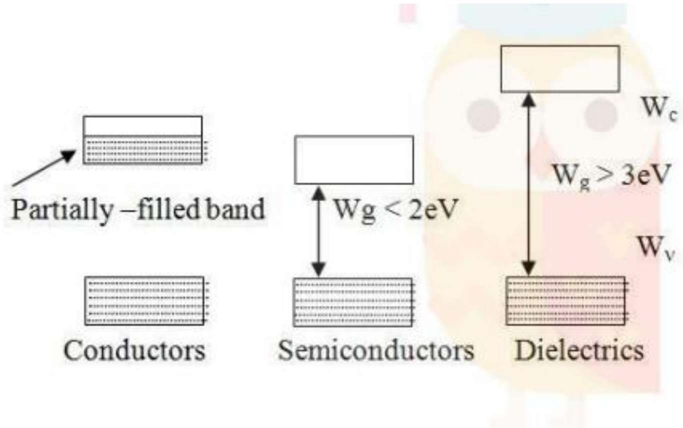



**Figure 1.26** The Coriolis acceleration appears on a traveling particle when the coordinate system rotates with angular velocity $\mathbf{\Omega}$.

**Question 5:** Explain the materials used in sensors and their properties.

**Answer:**

1. **Materials for Sensors:**
   - Sensors rely on physical or chemical phenomena and materials with high sensitivity, repeatability, and specificity.
   - Phenomena may concern the material itself or its geometry.
   - Major changes in sensors come from new materials or fabrication techniques.
2. **Conductors, Semiconductors, and Dielectrics:**




   - Atoms consist of a positive nucleus and electrons orbiting around it in shells.
   - Bond types include ionic, metallic, covalent, and van der Waals.
   - Conductors have partially filled energy bands, allowing conductivity.
   - Semiconductors and dielectrics have empty bands above filled bands.
3. **Conductors:**
   - Include substances with partially filled bands like alkali metals.
   - Used for carrying electrical current, e.g., Copper and Aluminum.
4. **Semiconductors:**
   - Include substances like Silicon and Germanium with empty bands above filled ones.
   - Used in electronic devices like diodes and transistors.
   - Extrinsic semiconductors are doped to make n-type and p-type semiconductors.
5. **Dielectrics:**
   - Include substances with a forbidden energy gap separating bands.

- Used where no conductivity is permitted, e.g., insulating supports for conductors.

6. **Applications:**
    - Conductors like Copper and Aluminum carry electrical current.
    - Semiconductors are used in electronic devices.
    - Dielectrics and insulators prevent conductivity.
    - Room-temperature superconductors are yet to be discovered.

**Magnetic materials:**

Magnetic materials are materials studied and used mainly for their magnetic properties. The magnetic response of a materials is largely determined by the magnetic dipole moment associated with the intrinsic angular momentum, or spin, of its electrons. A material's response to an applied magnetic field can be characterized as diamagnetic, paramagnetic, ferromagnetic or antiferromagnetic.

The magnetic ¯ux in vacuum is proportional to the applied magnetic ®eld

$$B = \mu_0 H \tag{1.64}$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the permeability of vacuum. All materials modify the magnetic flux to some extent, so that

$$B = \mu_0(H + M) = \mu_0 \mu_r H \tag{1.65}$$

where $M$ is the magnetic dipole moment per unit volume, or *magnetization*, and $\mu_r$ is the *relative permeability*.

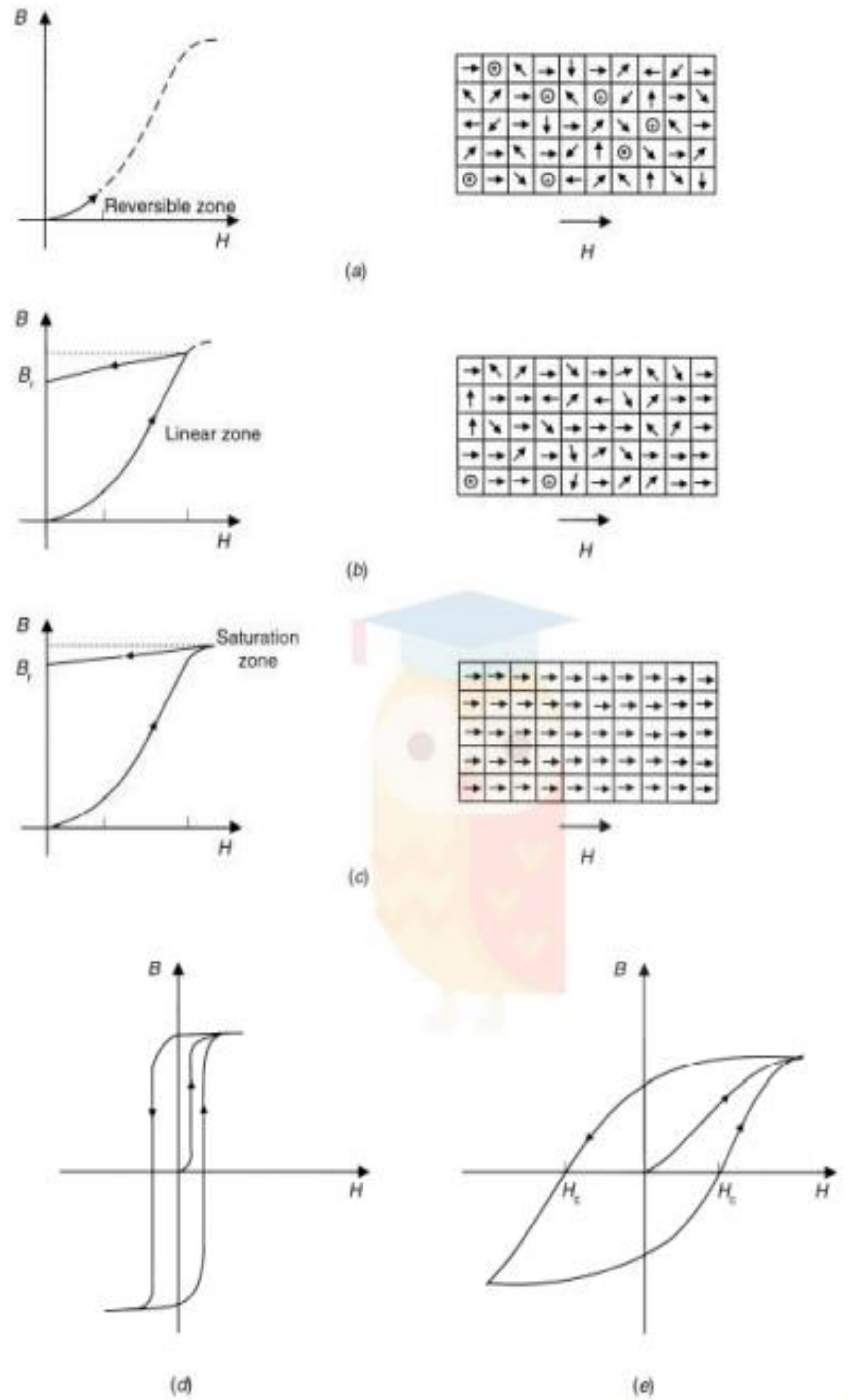



**Figure 1.29** The magnetization of ferromagnetic materials results from domain displacement and orientation. (*a*) The magnetization under weak magnetic force is reversible. (*b*) The magnetization for stronger magnetic force is almost proportional to it, but the remanence is smaller than the induction under the applied field. (*c*) An intense external field saturates the material. (*d*) Soft magnetic materials have a narrow hysteresis cycle. (*e*) Hard magnetic materials have a wide hysteresis cycle.

**Question 6:** Explain the technologies used in microsensor fabrication and their characteristics.

**Answer:**

1. **Microsensor Technology:**
    - Microsensor materials are tailored to the sensing principle and application.
    - Integrated circuit (IC) technology and micromachining are increasingly used for small, reliable, and low-cost sensors.
2. **Thick-Film Technology:**
    - Popular since the 1970s, chip resistors (SMD) are widely used due to their low cost.
    - A special paste comprising a binder, carrier, and metal oxides is printed onto a substrate at 850°C.
    - Resistor pastes often include oxides of ruthenium, iridium, and rhenium, forming a cermet.
    - The resistive layer becomes glasslike after firing, providing protection against moisture.
    - Thickness is around 100 micrometers, and the process is additive, allowing sequential addition of resistive layers.
3. **Thin Film Technology:**
    - Resistive layer is sputtered onto a ceramic base, creating a uniform metallic film about 0.1 micrometer thick.
    - Often uses Nickel-Chromium alloy (Nichrome) and allows for different layer thicknesses to achieve various resistance values.
    - Suitable for precision applications due to high tolerances, low temperature coefficients, and low noise.
    - Can be trimmed for resistance calibration using subtractive processes like photo etching or laser trimming.
    - Base materials include alumina ceramic, silicon, or glass, with applications ranging from medical equipment to audio installations and precision controls.
    - Better performance in high-frequency applications compared to thick film, with lower inductance and capacitance.
4. **Comparison:**
    - Thick film: Lower cost, suitable for general applications.
    - Thin film: Higher cost, precision performance, and better for high-frequency applications.