Bangabandhu Sheikh Mujibur Rahman Digital University

IRE 215 : SENSOR TECHNOLOGY

LECTURE-1: SENSOR FUNDAMENTALS

Sadia Enam

Lecturer
Department of IRE, BDU

LECTURE CONTENTS

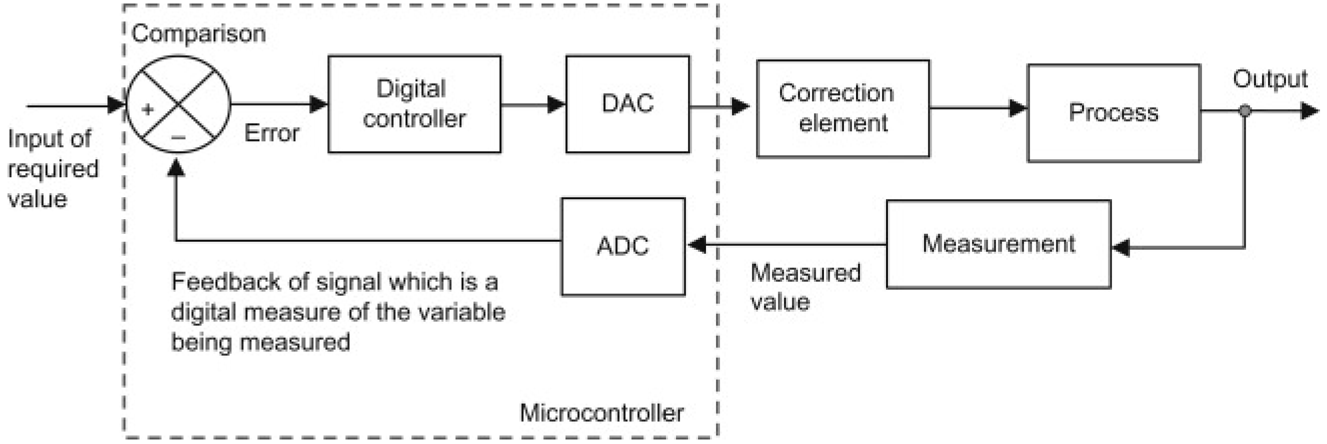
- Definition of sensor, transducer, and actuator
- Historical evolution of sensors
- Classification of sensors

SENSORS AND ACTUATORS IN A CLOSED LOOP CONTROL SYSTEM

- **Correction element:** Produces change in the process to change or correct the controlled condition.

- Correction element that provide power to carry out the control action is known as **actuator**. Example: A motor that rotates the drum of an automatic washing machine.

- **Measurement element/ Sensor:** Produces a signal related to the variable condition of the process and provides feedback to the controller.



A microcontroller based closed-loop control system (Saha, 2013)

Saha, S. S. (2013). Basic principles of control systems in textile manufacturing. In Process Control in Textile Manufacturing (pp. 14-40). Woodhead Publishing.

SENSORS AND ACTUATORS IN A CLOSED LOOP CONTROL SYSTEM

In a closed-loop control system, sensors and actuators play crucial roles in maintaining desired system behavior by providing feedback and executing control actions.

- **Closed-Loop Control System**

A closed-loop control system, also known as a feedback control system, continually monitors its output and adjusts its input to achieve the desired outcome. The system includes the following key components:

1. **Reference Input (Setpoint):** The desired value that the system aims to maintain.
2. **Controller:** Compares the sensor's feedback with the reference input and computes the control action needed to minimize the error.
3. **Actuator:** Executes the control action by adjusting the system's input.
4. **Process/System:** The part of the system being controlled.
5. **Sensor:** Measures the output of the process and provides feedback to the controller.

SENSORS AND ACTUATORS IN A CLOSED LOOP CONTROL SYSTEM

- **Sensors in Closed-Loop Control Systems**
- Sensors are critical for providing accurate and real-time feedback about the system's state. Types of sensors commonly used include:

1. **Temperature Sensors:**
   - **Thermocouples, RTDs (Resistance Temperature Detectors), Thermistors:** Used in HVAC systems, industrial processes, and automotive systems.
2. **Position Sensors:**
   - **Encoders, Potentiometers, LVDTs:** Used in robotics, CNC machines, and servo mechanisms.
3. **Pressure Sensors:**
   - **Piezoelectric, Capacitive, Piezoresistive Sensors:** Used in hydraulic systems, pneumatic systems, and fluid dynamics.
4. **Flow Sensors:**
   - **Turbine Flow Meters, Ultrasonic Flow Meters:** Used in water treatment plants, chemical processing, and fuel systems.
5. **Speed Sensors:**
   - **Tachometers, Hall Effect Sensors:** Used in automotive systems, motor controls, and conveyor systems.

SENSORS AND ACTUATORS IN A CLOSED LOOP CONTROL SYSTEM

- **Actuators in Closed-Loop Control Systems**
- Actuators are responsible for implementing the control actions determined by the controller. Types of actuators commonly used include:

1. **Electric Actuators:**
   - **DC/AC Motors, Stepper Motors, Solenoids:** Used in robotic arms, conveyor belts, and automated manufacturing systems.
2. **Hydraulic Actuators:**
   - **Hydraulic Cylinders, Hydraulic Motors:** Used in heavy machinery, construction equipment, and aircraft systems.
3. **Pneumatic Actuators:**
   - **Pneumatic Cylinders, Pneumatic Motors:** Used in automated systems, assembly lines, and material handling systems.
4. **Thermal Actuators:**
   - **Thermostatic Valves:** Used in heating and cooling systems, and process control.

SENSORS AND ACTUATORS IN A CLOSED LOOP CONTROL SYSTEM

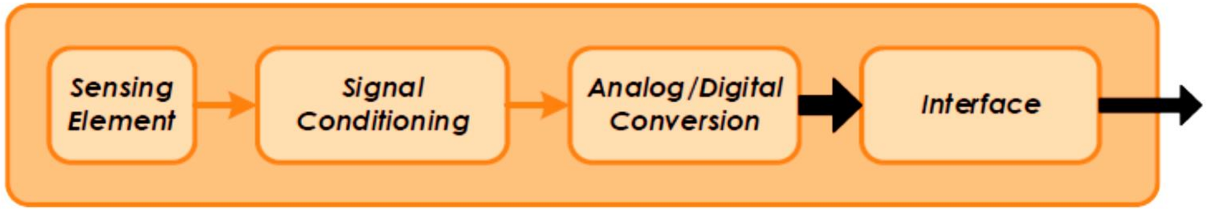
Example of a Closed-Loop Control System

- **Temperature Control System:**

1. **Reference Input (Setpoint):** Desired temperature (e.g., 25°C).
2. **Sensor:** A thermistor or thermocouple measures the current temperature.
3. **Controller:** A PID controller compares the current temperature with the setpoint and calculates the required heating or cooling.
4. **Actuator:** An electric heater or a cooling fan adjusts the temperature accordingly.
5. **Process/System:** The environment or space being temperature-controlled.
6. **Feedback Loop:** The sensor continuously monitors the temperature and provides feedback to the controller to adjust the actuator as needed.

SENSORS AND TRANSDUCERS

- A **transducer** transforms energy from one form to another.
- **Example of a transducer:** Electric motor that converts electrical energy to mechanical.
- A **sensor** produces a signal relating to the quantity being measured.
- It can be analog or digital.
- **Example of a sensor:** Electrical resistance temperature element where quantity being measured is temperature and sensor transforms temperature input into change in resistance.
- A sensor may need one or more transducers for signal conversion.
- **Signal conditioning** such as A/D conversion, filtering, amplification, etc. are required for sensors.
- In an **integrated sensor**, signal conditioning elements are embedded.

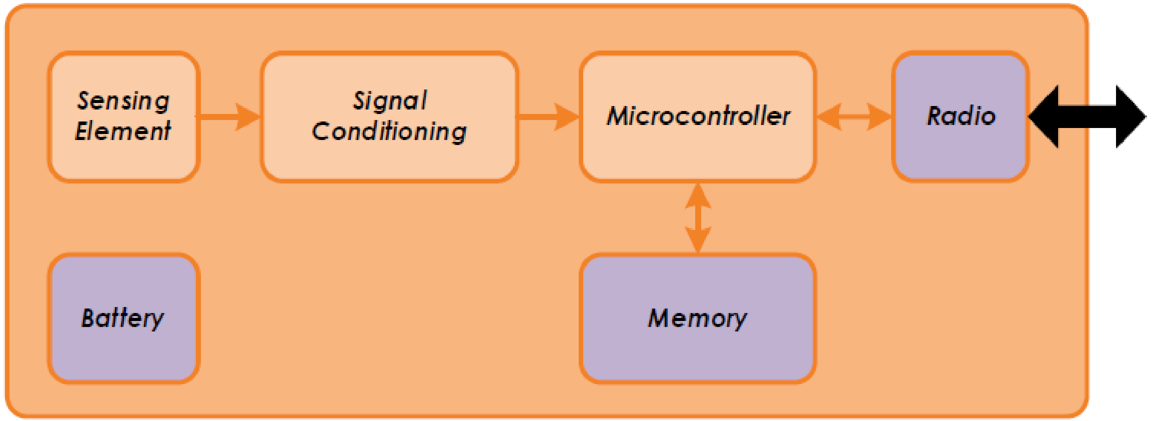


Architecture of an Integrated Sensor (Corrêa Alegria, 2021)

Corrêa Alegria, F.A. Sensors and Actuators. World Scientific Pub Co Inc

SMART/ INTELLIGENT SENSORS

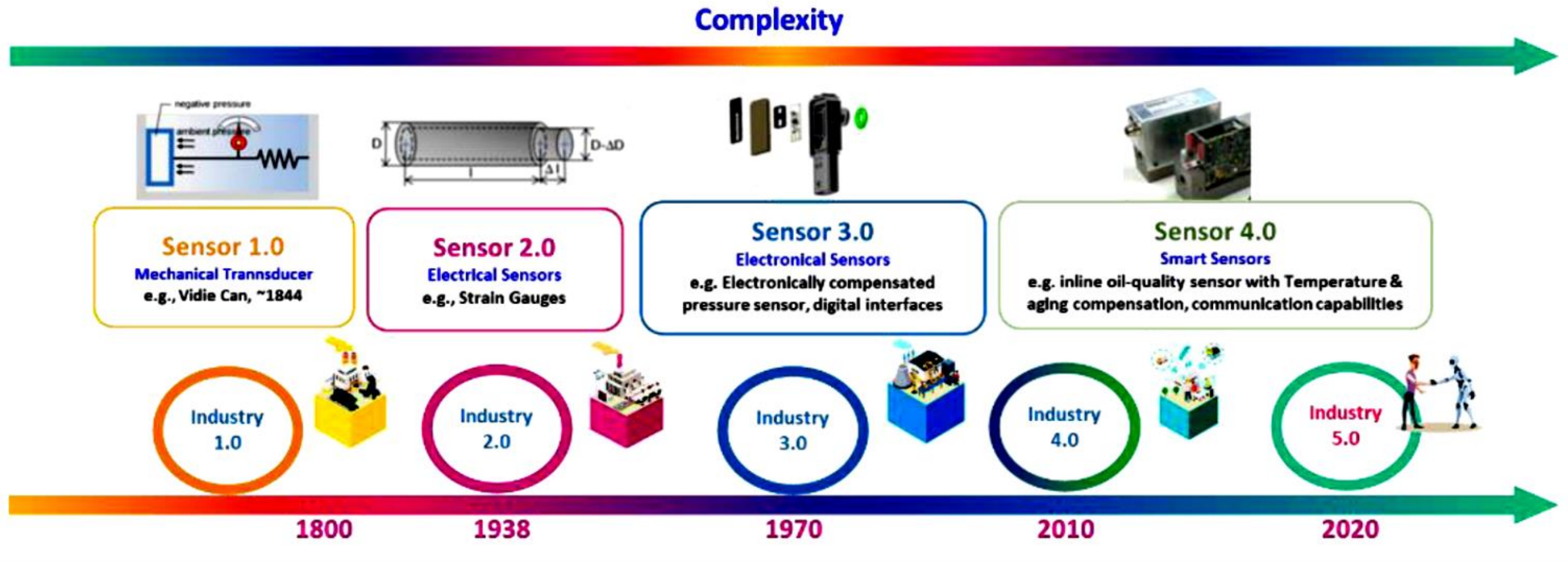
- Smart sensors can be integrated into a sensor network.
- Ability to be addressed, to store information, to compress, and to encrypt the data to be transmitted, among others.
- Capable of performing validation of the acquired data.



Typical composition of a smart sensor capable of being integrated into a wireless network. (Corrêa Alegria, 2021)

Corrêa Alegria, F.A. Sensors and Actuators. World Scientific Pub Co Inc

HISTORICAL EVOLUTION OF SENSORS



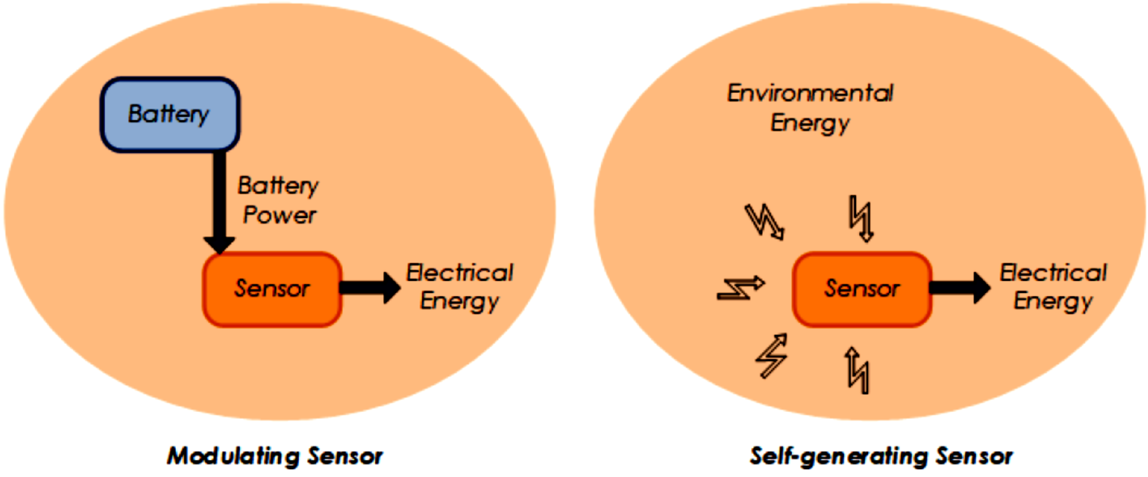
Mourtzis, D., Angelopoulos, J., & Panopoulos, N. (2022). Operator 5.0: A survey on enabling technologies and a framework for digital manufacturing based on extended reality. *Journal of Machine Engineering*, 22.

CLASSIFICATION OF SENSORS AND ACTUATORS

- **<u>Regarding the energy source</u>:**

i. **Modulating/ parametric sensors:** Work by changing a given parameter of an electrical circuit, such as resistance, capacitance, or inductance. The circuit receives power from a battery or a signal generator. Example: strain gauge that changes resistance with deformation. A Wheatstone bridge needs to be connected with the strain gauge that is powered by a constant voltage source.

ii. **Self generating sensors:** Produces an electrical signal without the need to be connected to a power supply. Example: a thermocouple that extracts thermal energy and produces a voltage signal.



Different types of sensors according to their power source (Corrêa Alegria, 2021)

Corrêa Alegria, F.A. Sensors and Actuators. World Scientific Pub Co Inc

CLASSIFICATION OF SENSORS AND ACTUATORS

- **Regarding the signal conditioning:**

i. **Passive sensors:** Self-generator but output signals are typically weak and often require amplification. Examples: electrodynamic microphones, thermocouples, photodiodes, and piezoelectric sensors.

ii. **Active sensors:** Modulating and allow signal gain from input to output. Example: Linear Variable Differential Transformer (LVDT) sensor, strain gauges, and temperature sensors.

CLASSIFICATION OF SENSORS AND ACTUATORS

- **Regarding the reference value:**

i. **Absolute sensors:** responsive to a quantity relative to an absolute scale which is independent of the measurement conditions. Example: thermistor is an example of an absolute sensor since the absolute value of its electrical resistance depends directly on the Kelvin temperature scale.

ii. **Relative sensors:** produces a signal which is proportional to the difference between the value of the measured quantity and a reference value used for that quantity. A thermocouple is an example of a relative temperature sensor since the value of the output voltage depends on the temperature difference between two points.

CLASSIFICATION OF SENSORS AND ACTUATORS

- **Regarding complexity:**

i. **Simple sensors:** Use a single energy transformation. Example: thermistor.

ii. **Complex sensors:** Uses more than one transformation of energy. Example: optical fiber based displacement sensor where electrical energy is converted to photon by a LED and the light is focused to the object through optical fiber. The light reflected by the object enters a second optical fiber that directs it to a photodiode which in turn produces an electrical current proportional to the displacement. therefore, conversion of electrical energy into photons (by the LED) and photons into electrical energy (by the photodiode).

STRAIN GAUGE

- It is a resistor used to measure the strain or deformation of an object.
- When an external force is applied on an object, a deformation occurs on the shape of the object.
- The deformation of the shape can be both compressive or tensile.
- When the object deform within the range of its elasticity, either it becomes narrower and longer or it becomes shorter and broader. As result of it there is a change in resistance end to end.
- By measuring the change of resistance of that object, the amount of induced stress can be measure.

STRAIN GAUGE

Strain: Strain is a dimensionless unit, defined as a change in length per unit length.

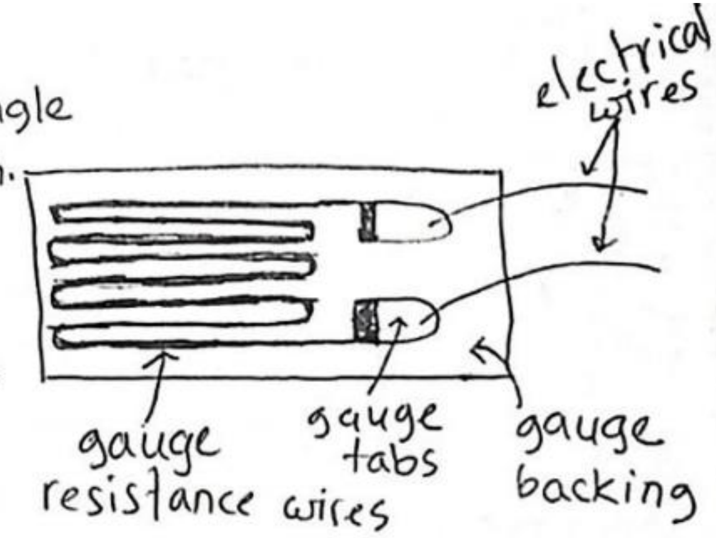
Strain gauge:

- If a metal conductor is stretched or compressed, its resistance changes on account of the fact that both length and diameter of conductor change. This property of the conductor is called piezoresistive effect and strain gauge transducer is designed on the basis of this properties.
- A strain gauge is a thin wafer-like device that can be attached (bounded) to a variety of materials to measure applied strain.

STRAIN GAUGE

Construction

- A strain gauge is connected from a single wire that is wound back and forth.
- The gauge is attached to the surface of an object with wire in the direction where the strain is to be measured.



- The electrical resistance in the wires change when they are elongated.
- Thus, the voltage change in the wires can be collaborated to the change in strain.
- Most strain gauge measurement devices automatically collaborate the voltage change to the strain, so the device output is the actual strain.

STRAIN GAUGE

Theory of strain gauge

For a wire of cross sectional area A, resistivity ρ and length L, the resistance is given by,

$$R = \frac{\rho L}{A}$$

When the wire is stretched, the cross sectional area A is reduced, which causes the total wire resistance to increase. In addition, since the lattice structure is altered by the strain, the resistivity may also change, and this, in general, causes the resistance to increase further.

The sensitivity of a strain gauge is described in terms of a characteristic called the gauge factor define as the unit change in resistance per unit change in length.

$$\text{Gauge Factor, } G = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\epsilon_a}$$

STRAIN GAUGE

$\frac{\Delta R}{R}$ = Fractional change in resistance

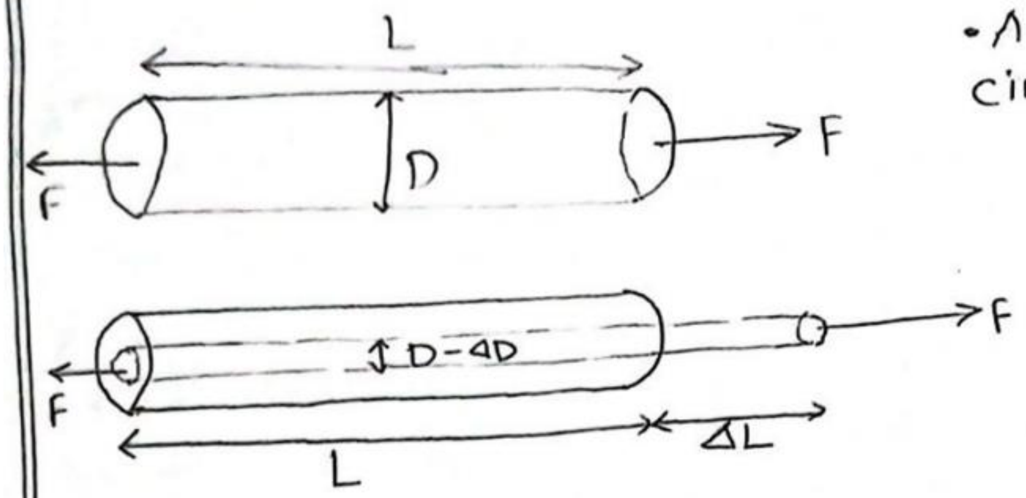
$\frac{\Delta L}{L}$ = Fractional change in length.

The change in the resistance is proportional to the applied strain and is measured with a specific adapted Wheatstone bridge.

Higher gauge factor are generally more desireable.

The higher the gauge factor, ∴ the higher the resolution of the strain gauge.

STRAIN GAUGE



The resistance of unstrained gauge as,

$$R = \frac{\rho L}{A}$$

let,

- A strain gauge is made of circular wire.

L = length

A = area

D = diameter before strain

ρ = resistivity of the wire

S = stress applied to the wire

ΔL = change in length after stress

ΔA = change in area after stress

ΔR = change in resistance after stress.

STRAIN GAUGE

After differentiating with respect to S,

$$\frac{dR}{dS} = \frac{\rho}{A}\frac{\partial L}{\partial S} - \frac{\rho L}{A^2}\frac{\partial A}{\partial S} + \frac{L}{A}\frac{\partial \rho}{\partial S}$$

After dividing by $R = \frac{\rho L}{A}$,

$$\frac{1}{R}\frac{dR}{dS} = \frac{1}{L}\frac{\partial L}{\partial S} - \frac{1}{A}\frac{\partial A}{\partial S} + \frac{1}{\rho}\frac{\partial \rho}{\partial S}$$

or, $\frac{1}{R}\frac{dR}{dS} = \frac{1}{L}\frac{\partial L}{\partial S} - \frac{2}{D}\frac{\partial D}{\partial S} + \frac{1}{\rho}\frac{\partial \rho}{\partial S}$

or, $\frac{1}{R}\frac{dR}{dS} = \frac{1}{L}\frac{\partial L}{\partial S} + \nu\frac{2}{L}\frac{\partial L}{\partial S} + \frac{1}{\rho}\frac{\partial \rho}{\partial S}$

$$A = \frac{\pi}{4}D^2$$

$\therefore \frac{\partial A}{\partial S} = 2\cdot\frac{\pi}{4}D\,\frac{\partial D}{\partial S}$

or, $\frac{1}{A}\frac{\partial A}{\partial S} = \frac{\frac{2\pi}{4}D}{\frac{\pi}{4}D^2}\cdot\frac{\partial D}{\partial S} = \frac{2}{D}\frac{\partial D}{\partial S}$

STRAIN GAUGE

$$\text{or, } \frac{\Delta R}{R} = \frac{\Delta L}{L} + 2\nu \frac{\Delta L}{L} + \frac{\Delta \rho}{\rho}$$

$$\text{or, } \frac{\Delta R}{R} = \epsilon + 2\nu\epsilon + \frac{\Delta \rho}{\rho}$$

$$= \epsilon\left(1 + 2\nu + \frac{\Delta\rho/\rho}{\epsilon}\right)$$

poisson's ratio,

$$\nu = -\frac{\text{lateral strain}}{\text{longitudinal strain}}$$

$$= -\frac{\partial D/D}{\partial L/L}$$

$$\therefore \frac{\partial D}{D} = -\nu \frac{\partial L}{L}$$

$$\text{or. } \frac{\Delta R/R}{\epsilon} = 1 + 2\nu + \frac{\Delta\rho/\rho}{\epsilon}$$

$$\therefore G = 1 + 2\nu + \frac{\Delta\rho/\rho}{\epsilon}$$

$$= 1 + 2\nu$$

if the change of the resistivity of material is small when strained then $\frac{\Delta\rho/\rho}{\epsilon}$ can be neglected.