People's Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

UNIVERSITY MUSTAPHA STAMBOULI OF MASCARA

FACULTY OF SCIENCE AND TECHNOLOGY

Sensors and Instrumentation

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This course is intended for students of the third year electronic license

Algeria

2024

Contents

Preface

This document on sensors and instrumentation complies with the official national program for the 3rd year of the LMD system in higher education and scientific research, specializing in electronics. It includes lectures and solved exercises on sensors and instrumentation intended for third-year undergraduate students majoring in electronics, specifically for the fundamental teaching unit.

The objective of this handout is to present the broadest possible range of fundamental knowledge on sensors and instrumentation. To achieve this, the handout is dedicated to describing the components of a measurement chain and electronic circuits: constituent elements of a chain, overall structure of a complete measurement chain (acquisition, processing, restitution), sensors: types, characteristics, different types of sensors (passive, active), physical phenomena used in sensors (electromagnetic induction law, Hall effect, thermoelectric effect, magnetoresistive effect, photoelectric effect, piezoelectric effect, Doppler effect, etc.), metrological characteristics (sensitivity, linearity, calibration curve, resolution, speed, response time and bandwidth, usage limits, calibration, measurement range, nominal range of use, non-deterioration zone), criteria for choosing a sensor, sensor conditioning (potentiometric mounting, push-pull mounting, bridge mounting).

This description will be followed by a presentation of analog linearization and conditioning circuits and amplification of the measured signal (differential amplifier, instrumentation amplifier, common-mode rejection ratio, isolation amplifier), sensor classification, and finally, a few examples of sensors and their manufacturing, outlining the advantages and disadvantages of each.

This document consists of five chapters, and at the end of each chapter, there is a series of solved exercises to reinforce the understanding of the course. The exercises often focus on different aspects of the sensor-related issues (physics, electronics, statistics, etc.).

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Chapter 1

Sensors and Acquisition Chain

1.1 Introduction

This chapter explores the fundamentals of sensors and the acquisition chain, providing a comprehensive understanding of the key components and processes involved. The topics covered include various types of sensors, their characteristics, and the sequential stages of the acquisition chain.

1.2 Acquisition Chain:

The acquisition chain, known as the signal acquisition chain, refers to the sequence of processes involved in capturing, converting, and processing signals from sensors. This chain is a critical component in various technological applications, facilitating the transformation of physical phenomena into usable data. The acquisition chain typically consists of several interconnected stages, each playing a distinct role in the overall process (see the figure 1.1):

1. **Signal Acquisition**
    - *Definition:* The initial stage where sensors capture physical signals or phenomena.
    - *Examples:* Capturing temperature changes, measuring light intensity, or recording pressure variations.
2. **Signal Conditioning:**
    - *Purpose:* Raw signals from sensors often need adjustments for accuracy and compatibility..

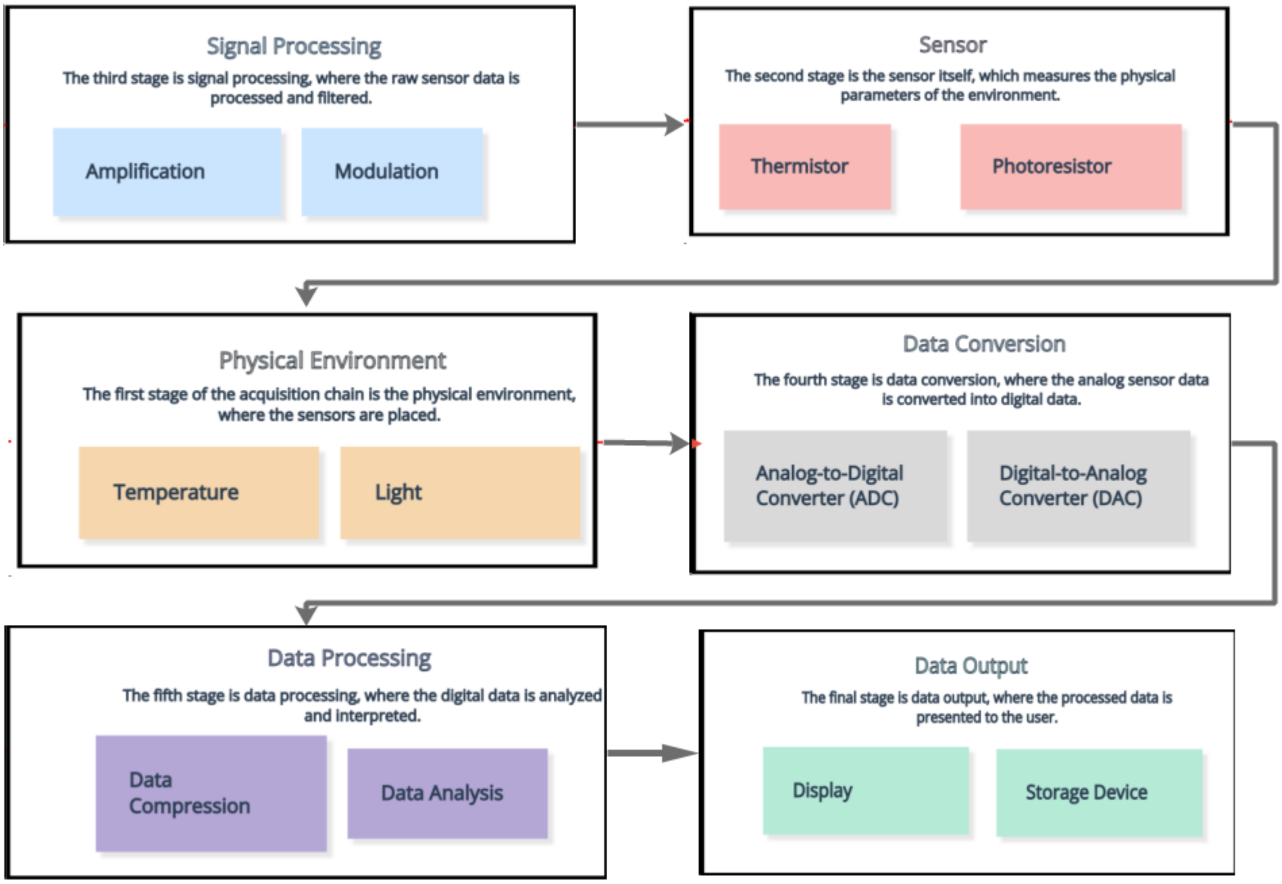


Figure 1.1: Acquisition Chain

- *Processes:* Amplification, filtering, and modulation to enhance or modify the signals.

3. **Analog-to-Digital Converter (ADC):**

    - *Transformation:* Analog signals from sensors are converted into digital form.
    - *Importance:* Digital signals are easier to process, store, and transmit.

4. **Digital Signal Processing (DSP):** The digital signal is then processed using DSP techniques such as filtering, averaging, and Fourier analysis.

5. **Microcontroller:** The final component in the acquisition chain is a microcontroller. It is responsible for controlling the acquisition chain and communicating with other devices.

Understanding the acquisition chain is crucial for engineers, scientists, and technicians involved in designing and implementing systems reliant on sensor data.

It ensures the reliability and accuracy of the information gathered, contributing to the success of applications in fields such as industrial automation, environmental monitoring, healthcare, and more.

1.3 Definitions and Generalities on Sensors

Mesurand:

This is the general term for a non-electrical physical quantity that one intends to measure. The measurand can be any physical quantity, such as length, temperature, pressure, voltage, or any other measurable property. In summary, it is what you are trying to quantify or determine through the process of measurement.
Types of Physical Quantities (Measurands): Physical quantities can be classified into six families, with each sensor associating itself with one of these six families:

- **Mechanical:** Displacement, force, mass, flow, etc.
- **Thermal:** Temperature, thermal capacity, thermal flux, etc.
- **Electrical:** Current, voltage, charge, impedance, dielectric, etc.
- **Magnetic:** Magnetic field, permeability, magnetic moment, etc.
- **Radiative:**Visible light, X-rays, etc.
- **(Bio) Chemical:** Humidity, gases, etc.

Sensor:

A sensor is a device that transforms an input physical quantity, known as the measurand (m), into an electrical quantity (typically), referred to as the response.
A sensor is a device or transducer that detects and measures physical properties or changes in the environment and converts them into electrical signals or other forms suitable for interpretation, display, or further processing. Sensors play a crucial role in various applications, providing valuable data for monitoring, control, and automation in fields such as electronics, engineering, environmental science, healthcare, and more. They come in diverse types, each designed to

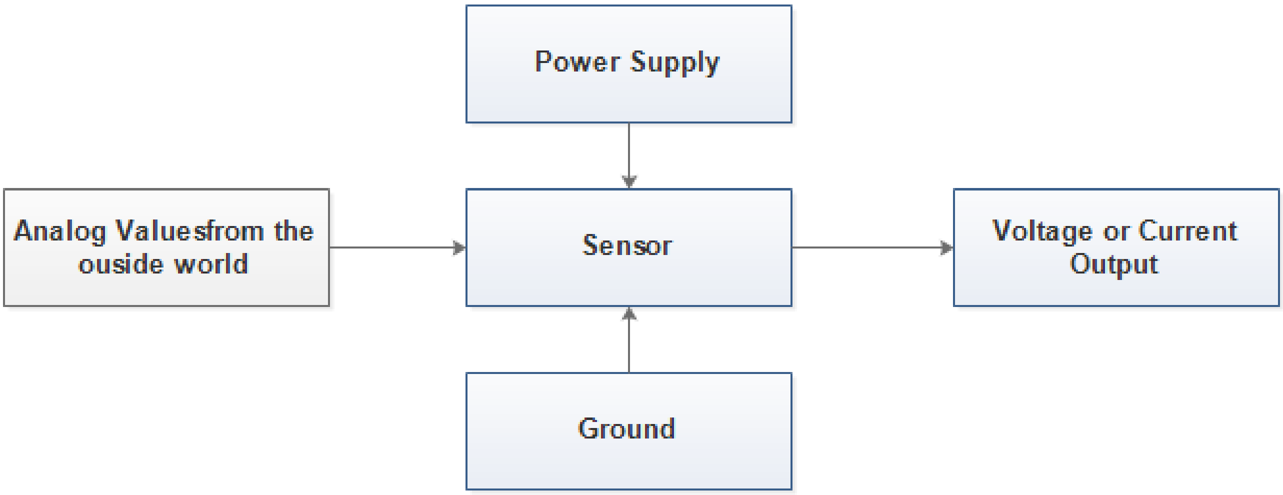


Figure 1.2: Structure of a Sensor.

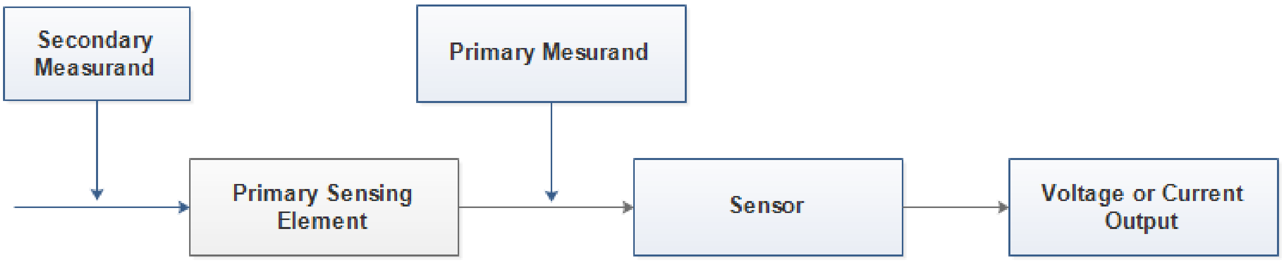


Figure 1.3: Primary Sensing Element

sense specific physical quantities such as temperature, pressure, light, motion, or chemical substances.

Primary Sensing Element:

Primary Sensing Element refers to the core or main component within a sensor responsible for directly interacting with the physical phenomenon being measured. It is the part of the sensor that directly senses or responds to changes in the external environment, and its characteristics influence the accuracy and reliability of the sensor. The primary sensing element typically undergoes a physical change in response to variations in the measured quantity, and this change is then converted into an electrical signal or another measurable output by the sensor's internal mechanisms.

Simple example: Measurement of a mechanical force. An elastic element is used as the Primary sensing element , The force measured is transformed into a displacement measured quantity. The force sensor thus uses displacement sensor technologies.

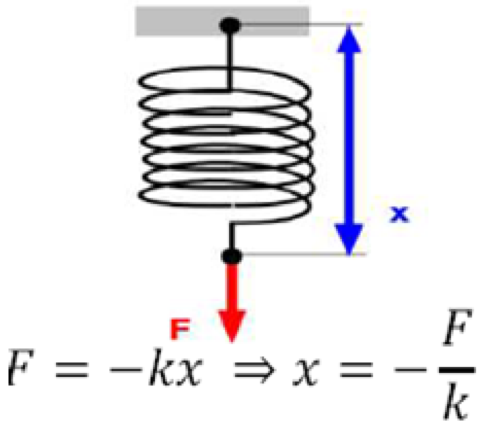


Figure 1.4: Primary sensing element exemple

1.4 The Different Types of Sensors

Passive sensors

Passive sensors are devices that do not require an external power supply to operate and provide an electrical output signal. These sensors typically use the physical property of the sensing element to generate an electrical signal proportional to the measured quantity. Passive sensors are simpler and less expensive than active sensors, but generally have lower sensitivity and accuracy. Examples of passive sensors include temperature sensors based on resistance, capacitive sensors for humidity measurement, and magnetoresistive sensors for position detection. Passive sensors are commonly used in applications where low power consumption, simplicity, and cost-effectiveness are important, such as in home appliances, automotive systems, and environmental monitoring. This concerns impedances (R, L, or C) whose one of the determining parameters is sensitive to the measured quantity.
The sensor is passive when the exploitable electrical quantity is an impedance with a dominant capacitive, inductive, or resistive component.

- The measured quantity is evaluated through the measurement of resistance.
- Passive sensors do not require an excitation source to provide an electrical measuring signal.

Passive sensors are often used in applications where minimal disturbance to the environment is desired, and where the natural occurrence of the observed phe-

Measurable	Sensitive electrical characteristic	Types of materials used.
Temperature.	Resistivity	Metals: platinum, nickel, copper, semiconductors
Optical radiation flux	Resistivity	Semiconductors.
Deformation	Resistivity	Nickel alloys, doped silicon.

Table 1.1: Passive sensors: physical principles and materials

nomena provides sufficient information for measurement. They are commonly found in areas such as environmental monitoring, surveillance, and some types of biomedical sensors.

Active sensors

Active sensor is generally based on a physical effect that ensures the conversion into electrical energy of the form of energy specific to the measured quantity (thermal, mechanical, or radiation energy). The most significant of these effects are grouped in Table 1.2

Active sensors are devices that require an external power supply to operate and

Measured variable	Effect used	Output quantity.
Temperature	Thermoelectricity	Voltage.
Force, Pressure Acceleration	Piezoelectricity	Charge.
Position (magnet).	Hall Effect	Voltage

Table 1.2: Active sensors: basic physical principles

provide an electrical output signal. Active sensors typically have a higher sensitivity and accuracy compared to passive sensors due to the active control and processing of the electrical signal. Examples of active sensors include piezoelectric sensors, strain gauges, and thermocouples. Active sensors are commonly used in industrial, medical, and scientific applications where high precision and reliability are required.

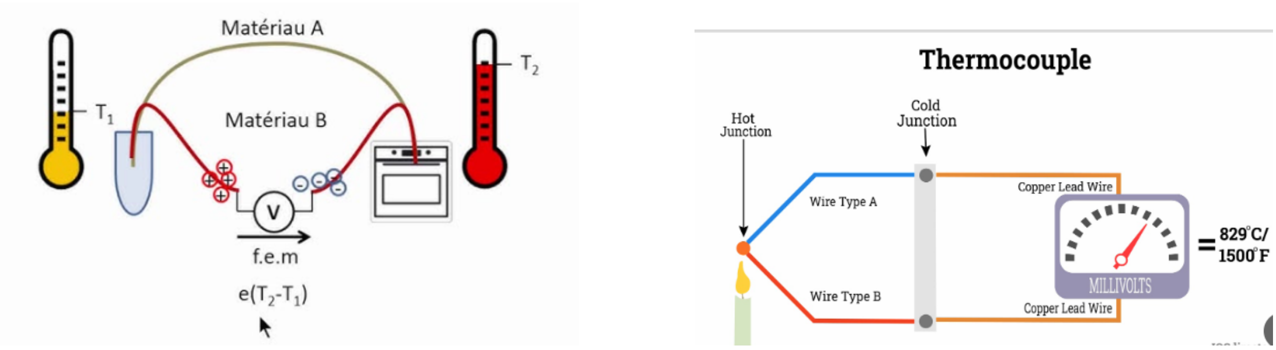
Active sensors are commonly employed in various fields such as robotics, autonomous vehicles, surveillance, and industrial automation, where precise and controlled measurements are essential for accurate decision-making and control systems.

1.5 Physical phenomena used in sensors

Thermoelectricity

The principle of a thermocouple is based on the Seebeck effect 1821, which states that when two dissimilar metals are joined together at two different temperatures, a voltage is produced that is proportional to the temperature difference.

In a thermocouple, two different metal wires are connected at two junctions, and when one junction is exposed to a higher temperature than the other, a voltage is generated across the two wires due to the Seebeck effect. This voltage can be measured and is proportional to the temperature difference between the two junctions. By calibrating the thermocouple with known temperatures, it can be used to accurately measure the temperature of a system.



(a) (b)

Figure 1.5: Seebeck effect 1821

Photoelectricity

The photoelectric effect is a phenomenon where electrons are emitted from a material when it is exposed to electromagnetic radiation, such as visible light or ultraviolet light. The principle of the photoelectric effect is based on the fact that when a photon of light is absorbed by an atom, it can transfer enough energy to an electron to allow it to overcome the binding energy of the atom and become free. The electron is then ejected from the material and can be detected as a current or voltage. The photoelectric effect is important in the development of electronic devices, such as photovoltaic cells . In a photovoltaic cell, the photoelectric effect is used to convert light energy into electrical energy.

When photons of light are absorbed by a material, they can cause electrons to be ejected from the material and flow as a current.

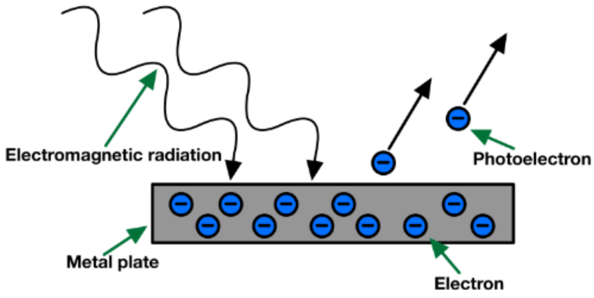


Figure 1.6: The photoelectric effect

Electromagnetic induction

Electromagnetic induction is a physical phenomenon that occurs when the magnetic field passing through a loop of wire changes.
This causes an electromotive force (EMF) that produces an electric current in the loop. This phenomenon is used in current sensors and electromechanical meters.

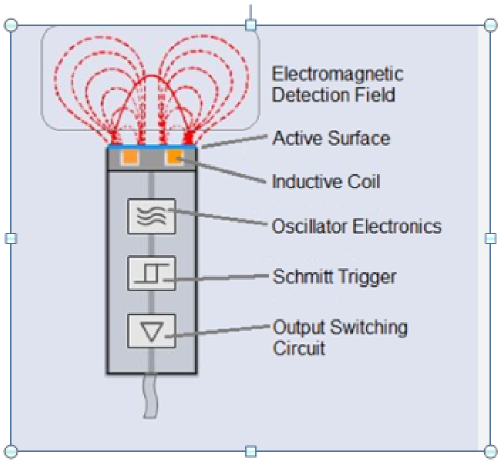


Figure 1.7: Proximity Sensor, Inductive, M18, 3 Wire, 120V photoelectric effect

The Hall effect

The Hall effect is the production of a voltage difference (the Hall voltage) across an electrical conductor when a magnetic field is applied in a direction perpendicular to the electric current. This phenomenon is named after Edwin Hall, who discovered it in 1879. The KY-024 Hall effect linear magnetic sensor re-

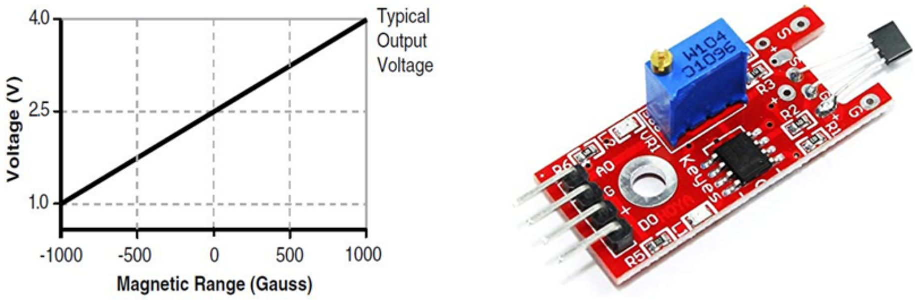


Figure 1.8: KY-024 Hall effect linear magnetic sensor

acts in the presence of a magnetic field. It is equipped with a potentiometer to adjust the sensitivity of the sensor and provides two analog and digital outputs.

Piezoelectricity

Piezoelectricity is a physical phenomenon observed in certain materials where they generate an electric charge when subjected to mechanical stress such as pressure, tension.

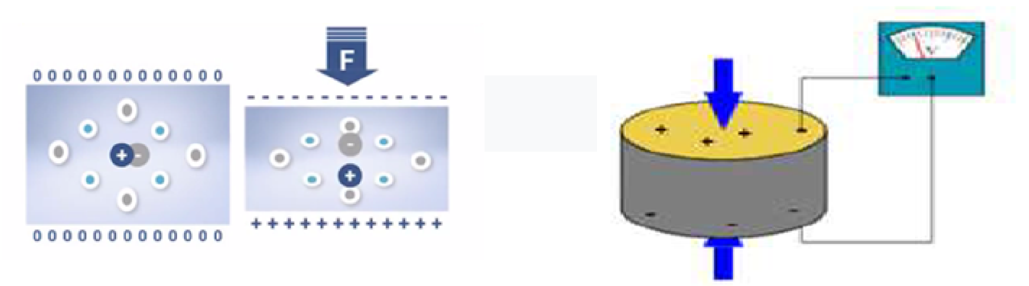


Figure 1.9: Piezoelectricity

$$E = K.h.P \tag{1.1}$$

Where $k : cte, h : height, p : pressure$

Piezoelectricity is useful in a wide range of applications, such as in the construction of sensors, transducers, and actuators. It is also used in the production of electricity in devices such as piezoelectric generators, which can convert mechanical energy into electrical energy. Additionally, piezoelectric materials are used in medical imaging devices, such as ultrasound machines, and in various consumer electronics, such as microphones and speakers.

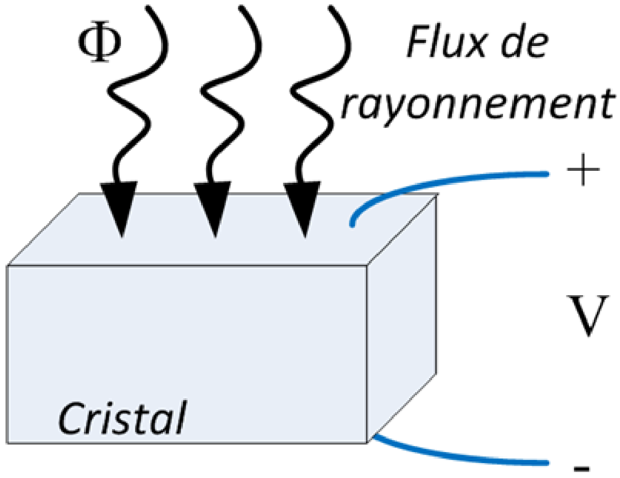


Figure 1.10: Pyroelectricity

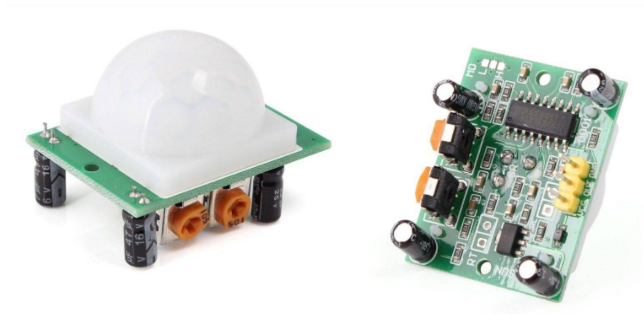


Figure 1.11: Arduino Pyroelectricity Sonsor

Pyroelectricity:

Pyroelectricity is a physical phenomenon observed in certain materials where they generate an electric charge in response to a temperature change.
Specifically, when the temperature of a pyroelectric material changes, its positive and negative electrical charges are separated, creating an electrical polarization.
Pyroelectricity is often observed in crystals such as tourmaline, quartz, topaz, and some polymers. Pyroelectric materials are used in a variety of applications, including temperature sensors, thermal imaging cameras, motion sensors, and microphones.

1.6 Conclusion

The first chapter provides a general overview of sensors and the acquisition process, presenting various types of sensors that express their physical phenomena used in sensors.

Exercises

Exercise 1: Hall Effect

Hall Effect When a material, typically a semiconductor in the form of a wafer, is traversed by a current I and subjected to an induction B at an angle θ to the current I, a voltage V_h perpendicular to the current and the induction appears. This is given by the following equation: $V_h = K_h * I * B * sin(\theta)$ where K_h is a constant.
For values of θ close to 0, $(tg\theta = \theta)$, the errors made are 2% on I, 1% on B, and 3% on θ.
Calculate the possible error on V_h.

Exercise 2: Thermoelectric Generator Calculation

You are designing a thermoelectric generator to convert waste heat from an industrial process into electrical power.
The generator uses a bismuth-antimony (Bi-Sb) alloy as the thermoelectric material, and the hot side of the generator is at 300°C, while the cold side is at 100°C. The Seebeck coefficient for the Bi-Sb alloy is $200\,\mu$V/°C.

1. Calculate the temperature difference (ΔT) between the hot and cold sides of the generator.
2. Determine the Seebeck voltage (V_{Seebeck}) generated by the thermoelectric effect.
3. If the generator has 10 thermocouple pairs in series, calculate the total Seebeck voltage (V_{Total}).
4. Assuming a load resistance (R_{load}) of $5\,\Omega$, calculate the generated power ($P_{\text{generated}}$).
5. Discuss how you could improve the power output of the thermoelectric generator.

Exercise 3: Designing a Piezoelectric Sensor

You are tasked with designing a piezoelectric sensor for measuring mechanical vibrations in an industrial setting.

The sensor will utilize the piezoelectric effect to generate electrical signals in response to mechanical stress.
Specifications:

1. The sensor should have a sensitivity of at least 1 mV/g (millivolts per gravity unit).

2. It needs to operate in a frequency range of 10 Hz to 1 kHz.

3. The sensor output should be compatible with standard data acquisition systems, providing an output voltage in the range of 0 to 10 V for the specified frequency range.

Given:

1. Piezoelectric material with a known piezoelectric coefficient.

2. The mechanical structure with known mass.

Tasks:

1. **Select an Appropriate Piezoelectric Material:** Choose a piezoelectric material suitable for vibration sensing applications. Consider factors such as the piezoelectric coefficient, mechanical stability, and temperature sensitivity.

2. **Calculate Required Sensitivity:** Calculate the required sensitivity (S) in mV/g using the formula $S = \frac{\text{Output Voltage}}{\text{Acceleration}}$. Determine the minimum required output voltage for a known acceleration, ensuring it meets the specified sensitivity.

3. **Determine Sensor Configuration:** Select a suitable piezoelectric sensor configuration. Consider whether a thin-film configuration or a bulk configuration is more appropriate for your application.

4. **Sketch Circuit Diagram:** Sketch a basic circuit diagram that includes the piezoelectric sensor, signal conditioning components (if needed), and an output interface suitable for standard data acquisition systems.

5. **Calculate Expected Output Voltage:** Use the piezoelectric coefficient of the selected material and the known acceleration to calculate the expected output voltage for different frequencies within the specified range.

Solutions

Exercise 1 Solutions

To calculate the possible error on V_H, we can use the formula for error propagation. The general formula for the relative error propagation is given by:

$$\frac{\Delta f}{f} = \sqrt{\left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta B}{B}\right)^2 + \left(\frac{\Delta C}{C}\right)^2 + \ldots}$$

Where f is the function for which you want to calculate the relative error, and ΔA, ΔB, ΔC, etc. are the independent variables with their respective relative errors.

In your case, the voltage V_H is given by the formula:

$$V_H = K_H \times I \times B \times \sin(\theta)$$

The relative errors on I, B, and θ are $2\%, 1\%, and 3\%$, respectively.

So, the relative error on V_H ($\frac{\Delta V_H}{V_H}$) is given by:

$$\frac{\Delta V_H}{V_H} = \sqrt{\left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta B}{B}\right)^2 + \left(\frac{\Delta \theta}{\theta}\right)^2}$$

Plug in the values:

$$\frac{\Delta V_H}{V_H} = \sqrt{\left(\frac{2}{100}\right)^2 + \left(\frac{1}{100}\right)^2 + \left(\frac{3}{100}\right)^2}$$

Calculate this to obtain the relative error on V_H

Exercise 2 Solutions

1. $\Delta T = T_{\text{hot}} - T_{\text{cold}} = 300°\text{C} - 100°\text{C} = 200°\text{C}$
2. $V_{\text{Seebeck}} = S \times \Delta T = 200\,\mu\text{V}/°\text{C} \times 200°\text{C} = 40\,\text{mV}$
3. $V_{\text{Total}} = N \times V_{\text{Seebeck}} = 10 \times 40\,\text{mV} = 400\,\text{mV}$
4. $P_{\text{generated}} = \frac{V_{\text{Total}}^2}{4 \times R_{\text{load}}} = \frac{(400\,\text{mV})^2}{4 \times 5\,\Omega} = 40\,\text{mW}$
5. To improve power output, consider:

- Increasing the number of thermocouple pairs (N).
- Using thermoelectric materials with higher Seebeck coefficients.
- Enhancing heat transfer efficiency between the hot and cold sides.

Exercise 3 Solutions

1. **Selecting Piezoelectric Material:**
   Let's assume a lead zirconate titanate (PZT) ceramic as the piezoelectric material due to its high piezoelectric coefficient and stability.

2. **Calculating Required Sensitivity:**
   If the sensitivity (S) is 1 mV/g and the acceleration is 10 g, then the required output voltage (V_{required}) is $S \times \text{Acceleration} = 1\,\text{mV/g} \times 10\,\text{g} = 10\,\text{mV}$.

3. **Determining Sensor Configuration:**
   Choose a disk-shaped PZT sensor for simplicity, providing a uniform response to mechanical stress.

4. **Sketching Circuit Diagram:**
   Create a circuit with the piezoelectric sensor connected to signal conditioning components, such as an amplifier. Ensure the output voltage is within the 0 to 10 V range.

5. **Calculating Expected Output Voltage:**
   Use the piezoelectric coefficient of the PZT material and the known acceleration to calculate the expected output voltage for different frequencies within the specified range.

Chapter 2

Metrological characteristics of a sensor

2.1 Introduction

Metrological characteristics of a sensor refers to the properties or features of a sensor related to metrology, which is the scientific study of measurement. These characteristics include factors such as accuracy, precision, sensitivity, resolution, repeatability, and linearity. In the context of sensors, metrological characteristics help assess and describe how well a sensor performs in terms of measuring and reporting physical quantities.

2.2 Metrological characteristics

Measuring range

The measuring range of a sensor refers to the range of values within which the sensor can accurately measure a physical quantity. It defines the minimum and maximum values of the parameter that the sensor is designed to detect or measure.

For example, if you have a temperature sensor with a measuring range of -20°C to 100°C, it means the sensor is designed to accurately measure temperatures within that specific range. If the temperature falls below -20°C or goes above 100°C, the sensor's readings may become less accurate or may not be reliable at all. Therefore, understanding the measuring range is crucial for using sensors in specific applications where accurate measurements within a certain range are essential.

The sensitivity

The sensitivity of a sensor, for a given value of the measurand, is equal to the ratio of the change in the electrical signal to the change in the physical signal. The sensitivity (SM) of a sensor can be expressed mathematically as:

$$SM = \frac{\Delta \text{Electrical Signal}}{\Delta \text{Physical Signal}} \tag{2.1}$$

- SM represents sensitivity.
- ΔElectrical Signal is the change in the electrical output or signal of the sensor.
- ΔPhysical Signal is the change in the physical quantity being measured (measurand).

This ratio quantifies how much the sensor's electrical output changes in response to a change in the physical quantity it is designed to measure. The sensitivity is a key parameter in understanding how responsive and accurate the sensor is in translating physical changes into electrical signals.
The sensitivity can be determined graphically from the calibration curve. The sensitivity is the slope of the curve at point M_0. When the physical law $S = f(M)$ is known, the sensitivity σ is derived by differentiation (figure2.1:

$$\sigma = \frac{dS}{dM}$$

This equation represents the rate at which the physical quantity S changes concerning the variable M, providing the sensitivity of the system. The specific form of the equation may depend on the nature of the physical law $S = f(M)$ and how it is mathematically expressed.
Example: For a thermistor with a resistance R_0 at the absolute temperature T_0, the state equation is:

$$R(T) = R_0 \cdot \exp\left(B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right)$$

The sensitivity of this sensor is:

$$\frac{d}{dx}\left(\frac{A}{B}\right) = \frac{B\frac{dA}{dx} - A\frac{dB}{dx}}{B^2}$$

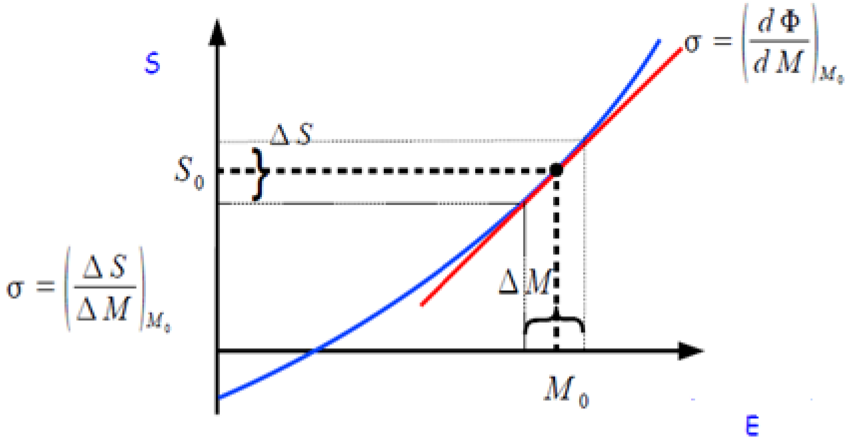


Figure 2.1: Sensitivity of sensor

$$\frac{d}{dx}(e^u) = e^u \cdot \frac{du}{dx}$$

$$\sigma(T) = \frac{dR}{dT} = -B \cdot \frac{1}{T^2} \cdot R_0 \cdot \exp\left(B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right)$$

Note that in the provided expressions, B is a constant associated with the thermistor.

Calibration

The calibration of a sensor involves the process of adjusting and verifying its measurements to ensure accuracy and reliability.
During calibration, the sensor's output is compared to known standards or reference values, and adjustments are made to correct any discrepancies.
This ensures that the sensor provides accurate and consistent measurements within its specified range. Calibration is essential for maintaining the reliability of sensors in various applications, such as scientific research, industrial processes, and environmental monitoring (see figure 2.2).

This type of calibration process typically involves the following steps:

1. Determine the reference standard
2. Compare the sensor output to the reference standard
3. Make adjustments to the sensor
4. Verify the calibration

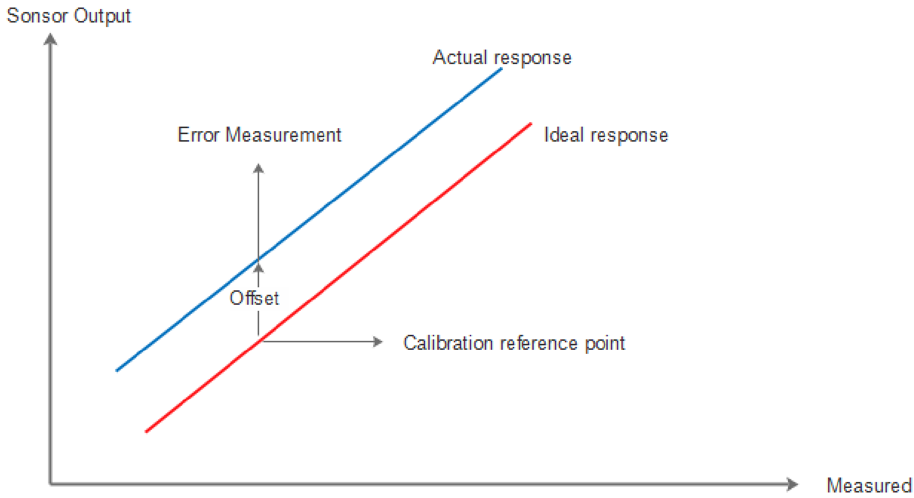


Figure 2.2: Calibration of a sensor

Accuracy

Sensor Accuracy refers to the closeness of the measurements made by a sensor to the actual or true values of the quantity being measured. It is a measure of how well a sensor can provide reliable and correct readings. The accuracy of a sensor is often expressed as a percentage or in terms of the deviation from the true value. High accuracy implies that the sensor readings closely match the actual values, while lower accuracy indicates a greater potential for measurement errors.
The accuracy (A) of a sensor is often quantified as a percentage of the full-scale range or as a specific deviation from the true value. The equation for accuracy is:

$$A = \left| \frac{\text{Measured Value} - \text{True Value}}{\text{True Value}} \right| \times 100\%$$

In this equation:

- Measured Value is the value recorded by the sensor.
- True Value is the actual or reference value.

The absolute difference between the measured value and the true value is divided by the true value, and the result is multiplied by 100 to express accuracy as a percentage.

For example, if a sensor measures a quantity as 98 units, but the actual or true value is 100 units, the accuracy would be calculated as:

$$A = \left| \frac{98 - 100}{100} \right| \times 100\% = 2\%$$

This means the sensor has an accuracy of 98% compared to the true value.

Precision

The "Precision of a sensor" refers to the degree of repeatability or consistency in the sensor's measurements when the same quantity is measured repeatedly under the same conditions. Precision is a measure of how closely individual measurements agree with each other.
It is often characterized by the standard deviation.
The precision (σ) of a sensor is often quantified using statistical measures such as the standard deviation. The standard deviation is a measure of the dispersion or spread of a set of values and can be calculated using the following equation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N}}$$

Here:

- N is the number of measurements.
- x_i represents each individual measurement.
- $\bar{x}$ is the mean (average) of the measurements.

The variance (σ^2) is the square of the standard deviation and is sometimes used as a measure of precision:

$$\sigma^2 = \frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N}$$

A lower standard deviation or variance indicates higher precision, as it implies that the measurements are closely clustered around the mean.

Exemple: calibration

Modern sensors and transmitters are electronic devices, and the reference voltage, or signal, may drift over time due to temperature, pressure, or change in

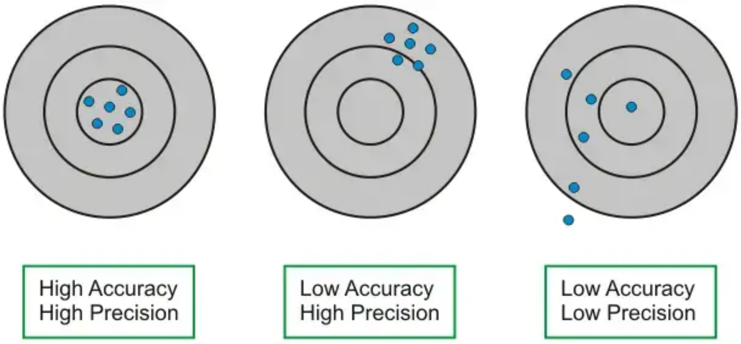


Figure 2.3: Accuracy and precision

ambient conditions.(Error due to Shift in Sensor's Range,Error due to Improper Zero Reference and Error due to Mechanical Wear or Damage).
Most modern process plants have sensor calibration programs, which require instruments to be calibrated periodically.

Figure 2.4: Errors in Sensor Measurement

1. Step 1: Perfom an "As-Found" or "Five-Point" Check
2. Step 2: Calculate the Deviations (Errors) of a Sensor.
3. Step 3: If the deviation is greater than the maximum allowed, then a full calibration is performed.If the deviation is less than the maximum allowed, then a sensor calibration is not required.
4. Step 4: Perform a Sensor Calibration

Hysteresis

Hysteresis: It is the difference in output when input is varied in two ways- increasing and decreasing

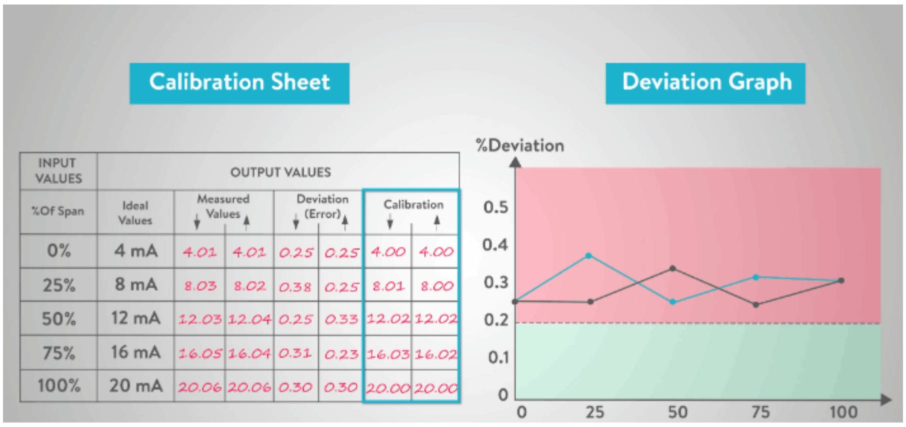


Figure 2.5: Calibration sheet

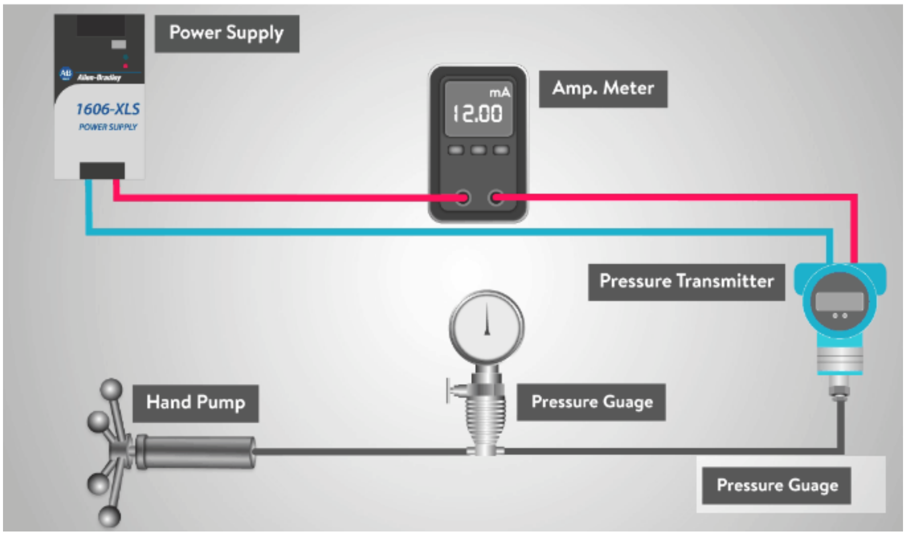


Figure 2.6: Sensor Calibration

Linearity

Linearity is the maximum deviation between the measured values of a sensor from ideal curve.

Resolution

Resolution: It is the minimum change in input that can be sensed by the sensor.

Example: Suppose we have a digital temperature sensor with a full-scale range of 100 degrees Celsius. The sensor output is represented using 10 bits ($n = 10$). We can use the resolution equation to calculate the smallest detectable

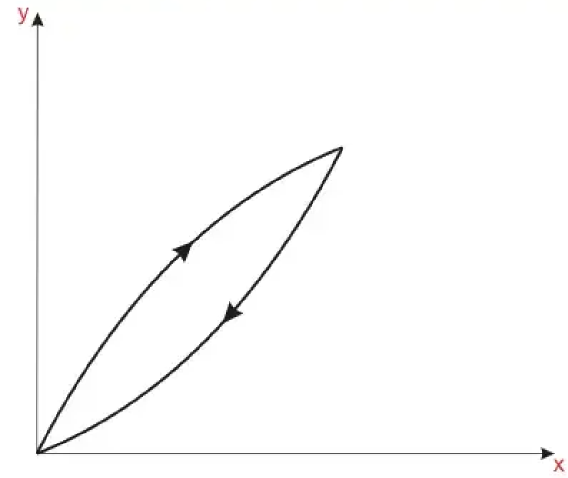


Figure 2.7: Hysteresis

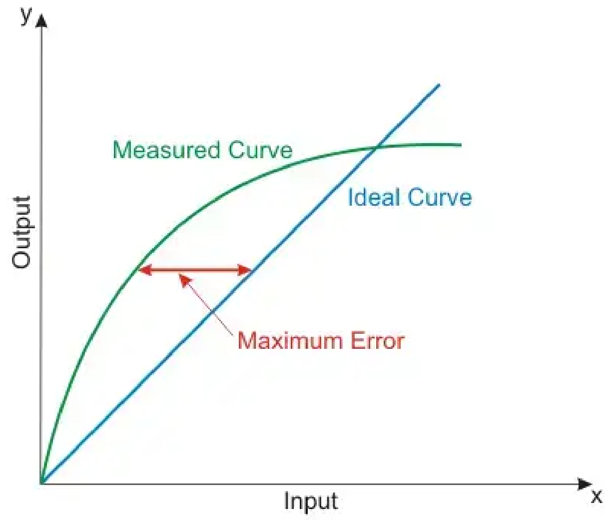


Figure 2.8: Linearity

change in temperature:

$$R = \frac{\text{Full Scale Range}}{2^n}$$

Substituting the given values:

$$R = \frac{100}{2^{10}} = \frac{100}{1024} \approx 0.0977$$

So, the resolution of this temperature sensor is approximately 0.0977 degrees Celsius. This means the sensor can detect changes in temperature as small as 0.0977 degrees due to its 10-bit digital representation.

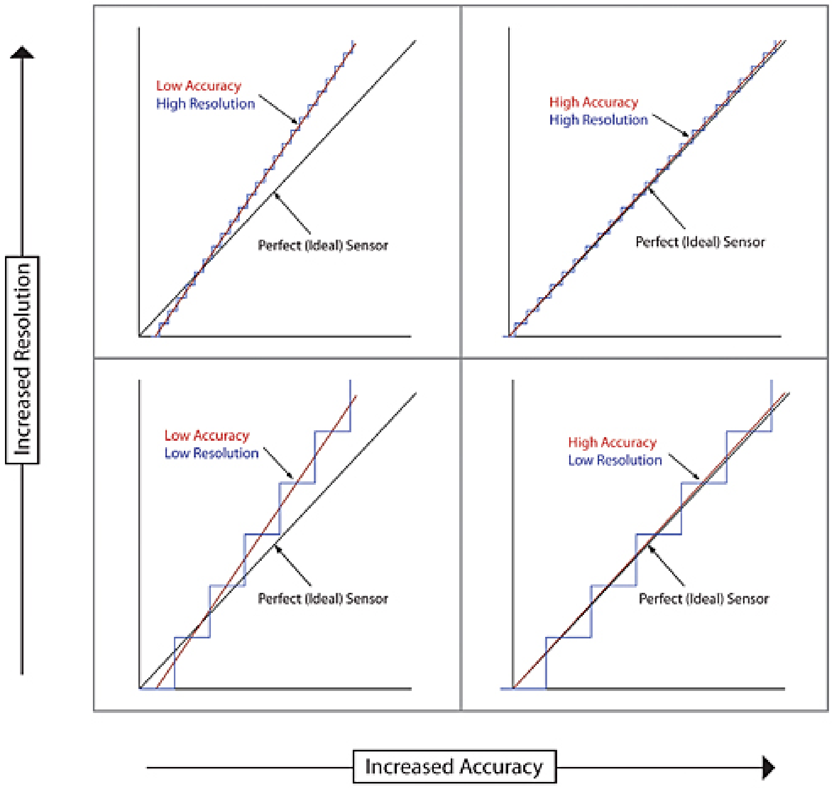


Figure 2.9: Resolution

Exercises

Exercise 1:

The resistance of a thermistor at a temperature T is given by the following relationship:

$$R = R_0.e^{\beta\cdot\left(\frac{1}{T}-\frac{1}{T_0}\right)}$$

Where:

- R_0: The resistance value at temperature T_0 [K], $R_0 = 5000\Omega$ at 23 °C.
- β: A constant in the considered domain.

Calibration is performed to determine the value of the constant β within the study domain.
The experimental results are illustrated in the following table:

T	23	30	35	40	45	50	55	60
$R(T)$ in Ω	5000	3950	365	2890	2500	2150	1860	1630

1. Provide the meaning of calibration and explain how to conduct such an experiment.
2. Using linear regression (least squares method), determine the best estimate of β.

Exercise 2:

A sensor is calibrated in an environment at a temperature of 21°C. The deflection/load characteristics are illustrated in the following table: Deflection/Load Characteristics at 21°C

When it is used at 35°C, its characteristics change as follows:
Deflection/Load Characteristics at 35°C

Load (kg)	0	50	100	150	200
Deflection (mm)	0	1	2	3	4

Table 2.1: Deflection/Load Characteristics at 21°C

Load (kg)	0	50	100	150	200
Deflection (mm)	0.2	2.4	3.5	3.5	4.6

Table 2.2: Deflection/Load Characteristics at 35°C

1. Determine the sensitivity of the sensor at 21°C and 35°C. What do you notice?
2. Calculate the zero offset and sensitivity deviation at 35°C.

Solutions

Exercise 1

1. Meaning of calibration and experimental procedure

Calibration is the process of determining and adjusting the parameters of an instrument or experimental method.
In the case of the thermistor, calibration aims to find the value of the constant β to obtain accurate temperature measurements.

2 Determine the best estimate of β

$$R = R_0.e^{\beta\cdot\left(\frac{1}{T}-\frac{1}{T_0}\right)}$$

the relationship becomes linear: $y = \beta x + b$ With this change of variable, we obtain We obtain: $\beta = 2985.6\,\mathrm{K}$, $b = 8.52$.

T(°C)	R(Ω)	T(K)	X	Y
23	5000	296	0	8.5
30	3950	303	-8E-5	8.3
35	365	308	-1E-4	8.1
40	2890	313	-2E-4	8.0
45	2500	318	-2E-4	7.8
50	2150	323	-3E-4	7.7
55	1860	328	-3E-4	7.5
60	1630	333	-4E-4	7.4

Table 2.3: Temperature and Resistance Data

$$s_{reg} = a\,e + b$$

$$a = \frac{N\sum s_i e_i - \sum s_i . \sum e_i}{N. \sum e_i^2 - (\sum e_i)^2}$$

$$b = \frac{\sum s_i . e_i^2 - \sum s_i . e_i . \sum e_i}{N. \sum e_i^2 - (\sum e_i)^2}$$

Exercise 2

1. **Sensitivity at 21°C and 35°C:**

   At 21°C:

   $$S_{21} = \frac{4.0\,\mathrm{mm} - 0.0\,\mathrm{mm}}{200\,\mathrm{kg} - 0\,\mathrm{kg}}$$

   At 35°C:

   $$S_{35} = \frac{4.6\,\mathrm{mm} - 0.2\,\mathrm{mm}}{200\,\mathrm{kg} - 0\,\mathrm{kg}}$$

   Observation: The sensitivity has changed from 21°C to 35°C, indicating a temperature dependency.

2. **Zero Offset and Sensitivity Deviation at 35°C:**

   $$Z_{35} = 0.2\,\mathrm{mm}$$

   $$SD_{35} = S_{35} - S_{21} = \frac{4.6\,\mathrm{mm} - 0.2\,\mathrm{mm}}{200\,\mathrm{kg} - 0\,\mathrm{kg}} - \frac{4.0\,\mathrm{mm} - 0.0\,\mathrm{mm}}{200\,\mathrm{kg} - 0\,\mathrm{kg}}$$

   Results:

   $$\begin{aligned} S_{21} &= 0.02\,\mathrm{mm/kg} \\ S_{35} &= 0.022\,\mathrm{mm/kg} \\ Z_{35} &= 0.2\,\mathrm{mm} \\ SD_{35} &= 0.002\,\mathrm{mm/kg} \end{aligned}$$

Chapter 3

Conditioners for passive sensors

3.1 Introduction

This chapter will be dedicated to the conditioning of passive sensors; potentiometric circuits, push-pull setups, bridges, and oscillators will be described. The conditioner is the output element of the sensor that converts variations in the primary or secondary measurand into exploitable electrical variations (voltage, current, etc.). The choice of a conditioner is an important step in the realization of a measurement system. The constitution of the conditioner determines a certain number of performances of the measurement system.

3.2 General characteristics of passive sensor conditioners

The response of a passive sensor to the variation in the measurand Δm results in a change in impedance ΔR, ΔL, ΔC.

Figure 3.1: The variation in the measurand

Examples:

1. **Resistance (ΔR):** In a passive temperature sensor like a thermistor, an increase in temperature leads to a decrease in resistance, while a decrease in temperature leads to an increase in resistance.

2. **Inductance (ΔL):**
   In a passive inductive sensor such as a proximity sensor, the presence of a metallic object causes an increase in inductance, while the absence of such an object results in a decrease in inductance.

3. **Capacitance (ΔC):**
   In a passive capacitive sensor like a touch sensor, the proximity of a conductive object causes an increase in capacitance, while the absence of such an object results in a decrease in capacitance.

Main types of conditioners

We can distinguish two main groups of conditioners based on whether they transfer information related to variations in the sensor's impedance.

1. **1st group:** A voltage proportional to the measurand is obtained: $V = e \cdot F(Z_1, Z_2)$. This is the case for potentiometric circuits and bridges.

2. **2nd group:** The frequency of the output signal is modulated by the measurand: $f = G(Z_1, Z_2)$. In this case, they are oscillators.

Qualities of a conditioner

Sensitivity and linearity

When the measurand varies by Δm, it corresponds to a variation ΔZ of the sensor's impedance, which depending on the type of conditioner, results in either a variation in the amplitude of the measuring voltage or its frequency. The overall sensitivity of the combination of the conditioner and the sensor is:
In the first case:

$$S_a = \frac{\Delta V_m}{\Delta m} = \frac{\Delta V_m}{\Delta Z_c} \cdot \frac{\Delta Z_c}{\Delta m}$$

In the second case:

$$S_a = \frac{\Delta f_m}{\Delta m} = \frac{\Delta f_m}{\Delta Z_c} \cdot \frac{\Delta Z_c}{\Delta m}$$

The intrinsic sensitivity of the conditioner is, depending on the case:

$$\frac{\Delta V_m}{\Delta Z_c}, \frac{\Delta f_m}{\Delta Z_c}$$

whereas the sensitivity of the sensor is:

$$\frac{\Delta Z_c}{\Delta m}$$

- The conditioner is linear if its intrinsic sensitivity is independent of ΔZ.
- The combination of a linear conditioner and a linear sensor delivers a measurement signal proportional to variations in the measurand.
- If the conditioner is not linear, it can be linearized by replacing one of the fixed components with a second sensor (operating in push-pull mode).

Compensation of influence quantities

If the sensor is sensitive to an influence quantity, such as temperature or radiation for example, it is important to be able to eliminate its contribution to the measurement signal's variations of ΔZ.
Let's consider the case of a resistive sensor and conditioner

$$V_m = e_s \cdot F(R_c, R_k)$$

The influence quantity, with a value g, may affect both components of the conditioner and the sensor itself.
A variation dg results in a variation dV_m of the measurement voltage:

$$dV_m = \left(\sum_k \frac{\partial V_m}{\partial R_k} \cdot \frac{\partial R_k}{\partial g} + \frac{\partial V_m}{\partial R_c} \cdot \frac{\partial R_c}{\partial g} \right) dg$$

The variations in the influence quantity have no effect on the measurement voltage when the condition is satisfied:

$$\sum_k \frac{\partial V_m}{\partial R_k} \cdot \frac{\partial R_k}{\partial g} + \frac{\partial V_m}{\partial R_c} \cdot \frac{\partial R_c}{\partial g} = 0$$

For example, if only one of the resistances of the conditioner is made sensitive to the influence quantity and is also chosen to be identical to R_c

$$\frac{\partial R_k}{\partial g} = \frac{\partial R_c}{\partial g}$$

and there is compensation for variations in the influence quantity if:

$$\frac{\partial V_m}{\partial R_k} = -\frac{\partial V_m}{\partial R_c}$$

3.3 Potentiometric circuit

Potentiometric circuit is a type of electrical circuit that utilizes a potentiometer, which is a variable resistor, to measure voltage or control the flow of electric current.
In a potentiometric circuit, the potentiometer's resistance can be adjusted manually or automatically to achieve a desired voltage or current level. These circuits are commonly used in applications such as volume control in audio equipment, dimmer switches in lighting systems, and voltage dividers in electronic circuits.

Resistance measurement

The resistance sensor R_c in series with a resistor R_1 is powered by a source with internal resistance R_s and electromotive force e_s, direct or alternating.
The voltage V_m is measured across the sensor by an instrument with resistance R_d; it is established:

$$V_m = e_s \cdot \frac{R_c R_d}{R_c\left(R_s R_1\right) + R_d\left(R_s + R_1 + R_c\right)}$$

Neglecting R_s and assuming that the resistance R_d is very large ($R_c \ll R_d$),

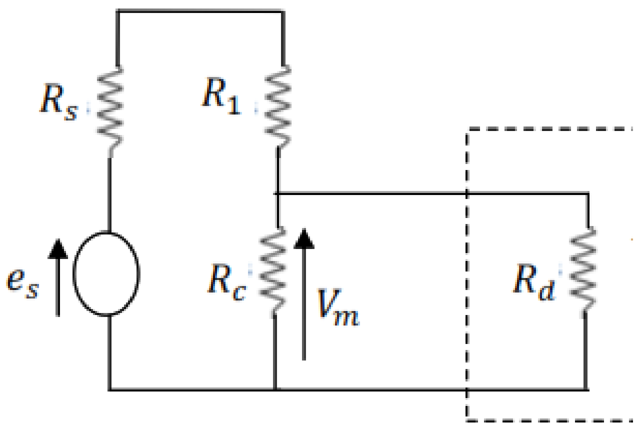


Figure 3.2: Measurement of the voltage across a resistive sensor in a potentiometric circuit

we can obtain the following expression:

$$V_m = e_s \cdot \frac{R_c}{R_c + R_1}$$

The voltage V_m is not a linear function of R_c. Therefore, the sensitivity of the circuit is not constant.

Linearization of measurement

To linearize the sensor response to obtain ΔV_m proportional to ΔR_C, we can use the following two solutions:

Solution N°1 (Small signal operation):

In this case, we consider small variations of the measured quantity: $\Delta R_c \ll R_{c0} + R_1$.

$$R_c \to R_{c0} + \Delta R_c$$

$$V_m \to V_{m0} + \Delta V_m$$

Then we obtain:

$$V_{m0} + \Delta V_m = \frac{R_{c0} + \Delta R_c}{R_{c0} + \Delta R_c + R_1} \cdot e_s$$

$$V_{m0} + \Delta V_m = \frac{R_{c0} + \Delta R_c}{R_{c0} + R_1} \cdot \frac{1}{1 + \frac{\Delta R_c}{R_{c0}+R_1}} \cdot e_s$$

$$V_m = \frac{R_{c0} + \Delta R_c}{R_{c0} + R_1} \cdot e_s$$

$$\Delta V_m = \frac{R_1 \Delta R_c}{(R_{c0} + R_1)^2} \cdot e_s$$

If we choose: $R_{c0} = R_1$:

$$\Delta V_m = \frac{e_s}{4} \cdot \frac{\Delta R_c}{R_{c0}}$$

Solution N°2 (Push-Pull Configuration)

In a push-pull configuration, the fixed resistor R_1 is replaced by a second sensor, identical to the first one but with variations of opposite sign

$$R_1 = R_{c0} - \Delta R_c$$

This arrangement of two sensors operating in opposition is called push-pull.

$$V_{m0} + \Delta V_m = e_s \cdot \frac{R_{c0} + \Delta R_c}{R_s + R_{c0} - \Delta R_c + R_{c0} + \Delta R_c}$$

Let:

$$\Delta V_m = e_s \cdot \frac{\Delta R_c}{R_s + 2R_{c0}}$$

Disadvantages:

The linearity is a significant advantage of potentiometric circuits using passive sensors for small variations in R_c

Elimination of the DC component of the measurement voltage.

With the potentiometric method, the voltage variation ΔV_m carrying the information is superimposed on a generally higher voltage V_{m0}.
This may make the measurement imprecise in the case of static phenomena where ΔR_c is constant or slowly variable.
Example: If $V_{m_0} = 4$ V and $\Delta V_m = 5$ mV, it is very difficult to make a precise reading of ΔV_m on the 6V range of the voltmeter.

Example:

$$V = \frac{R_x}{R_1 + R_x}$$

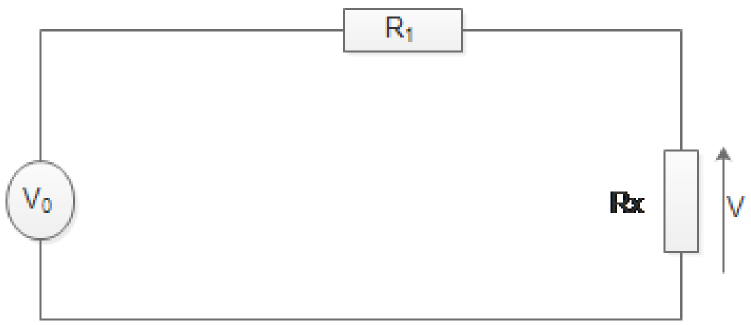


Figure 3.3: Measurement of Rx with voltage divider

Small signal operation: We can write $R_x = R_{x0} + \Delta R_x$, where R_{x0} is the nominal value and ΔR_x expresses the variations of R_x with the measured quantity.
For small variations of R_x, one can obtain a linear voltage V.

$$V = \frac{R_{x0} + \Delta R_x}{R_1 + R_{x0} + \Delta R_x} \Rightarrow V = \frac{R_{x0} + \Delta R_x}{R_1 + R_{x0}}; \Delta R_x \ll R_{x0} + R_1$$

Voltage V of the circuit can be decomposed into two terms:

$$V = \frac{R_{x0}}{R_1 + R_{x0}} + \frac{\Delta R_x}{R_1 + R_{x0}}$$

The first term represents the DC component of the signal
The second term represents the dynamic part of the signal, which carries the information; it is the signal's variation around the DC component.

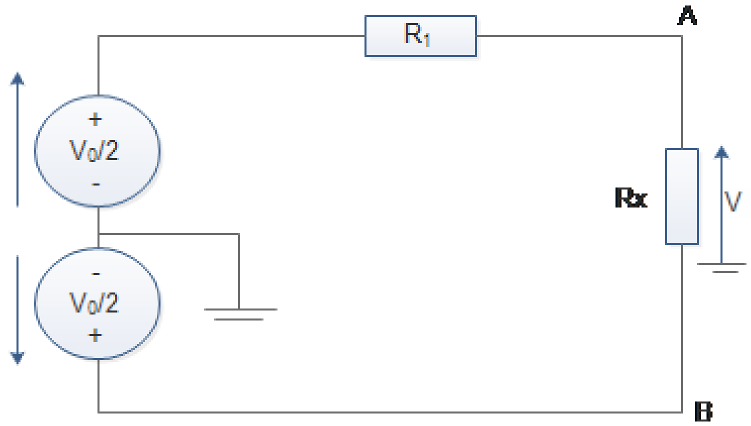


Figure 3.4: Elimination of the static component with two identical voltage sources.

$$V = \frac{V_0}{2} \cdot \left(\frac{R_x - R_1}{R_1 + R_x} \right) \Rightarrow V = \frac{V_0}{2} \cdot \frac{\Delta R_x}{2R_{x0} + \Delta R_x}; R_1 = R_{x0}, R_x = R_{x0} + \Delta R_x$$

- **Advantages:**
  Elimination of the term $R_x \times V_0$. The signal contains only the dynamic component related to R, which allows for amplification with higher gains without risk of signal clipping.

- **Disadvantages:**
  Use of two voltage sources.

Montage Push Pull

- The fixed resistor R1 is replaced by a second resistive sensor R_x^-.

- R_x^- gives variations of the same magnitude as R_x^+, but in the opposite sens.

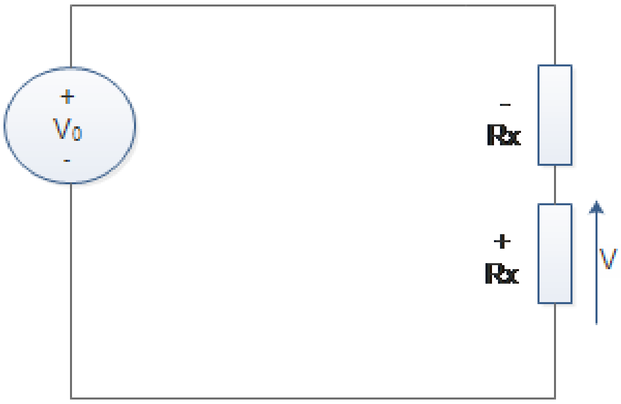


Figure 3.5: Measurement of a resistance Rx using the Push-Pull circuit

$$V = \frac{R_{x0} + \Delta R_x}{R_{x0} - \Delta R_x + R_{x0} + \Delta R_x} V_0$$

$$V = \frac{R_{x0} + \Delta R_x}{2R_{x0}} V_0$$

Advantages: Linear Signal: The main advantage of using a push-pull configuration is that it typically results in a linear signal response.
Disadvantages: Use of Two Sensors: One of the drawbacks of push-pull configurations is the requirement for two sensors or transducers. This can increase the complexity and cost of the system.

Measurement of resistances with a current source

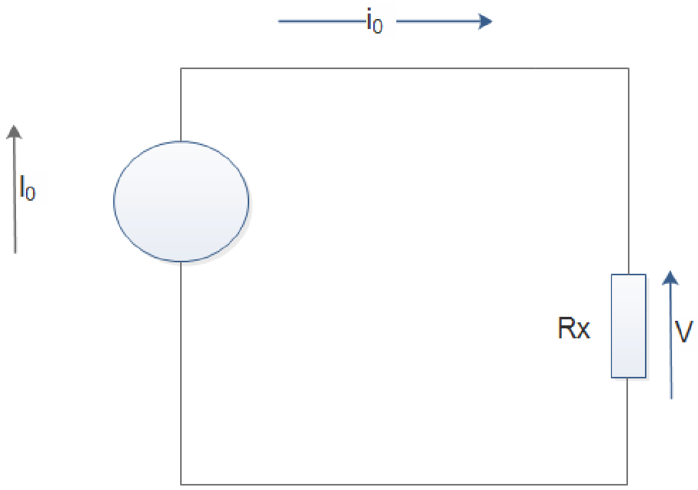


Figure 3.6: Measurement of resistances with a current source

This method involves applying a known voltage across the resistance and measuring the voltage drop across it. By using Ohm's law (V = I * R), where V is the voltage drop, I is the applied current, and R is the resistance, you can calculate the resistance value.

$$V = R_x i_0$$

Advantages: Linear Signal
Disadvantages:
Non-radiometric measurement, dependency on i_0, current source required.

3.4 Bridge circuit

A "bridge circuit" refers to an electrical circuit typically used for measuring resistance changes in sensors, and "passive sensor" indicates a sensor that doesn't require an external power source to operate. So, "bridge circuit for passive sensor" would refer to a circuit configuration designed for use with passive sensors. The use of a potentiometric arrangement has the drawback of having a DC voltage at the output even in the absence of variations in the measured quantity. The use of a Wheatstone bridge arrangement has the advantage of eliminating this DC voltage.
The general structure of the Wheatstone bridge is shown in Figure 3.7

$$InA : V_A = \frac{R_c}{R_c + R_1} \cdot e_s$$

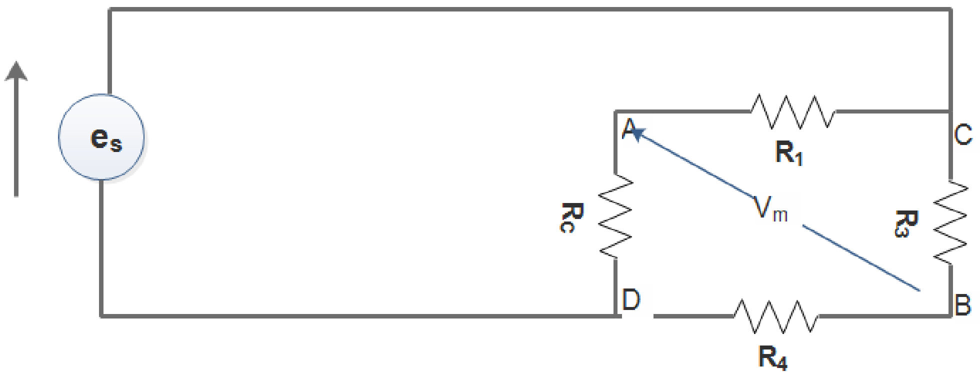


Figure 3.7: Bridge circuit

$$InB : V_B = \frac{R_4}{R_4 + R_3} \cdot e_s$$

One obtains a measurement voltage also called the bridge imbalance voltage:

$$V_m = V_A - V_B = \frac{R_c R_3 - R_1 R_4}{(R_1 + R_c)(R_4 + R_3)} \cdot e_s$$

In the case: $R_c = R_1 = R_2 = R_3 = R_4$:

Wheatstone bridge: linear approximation

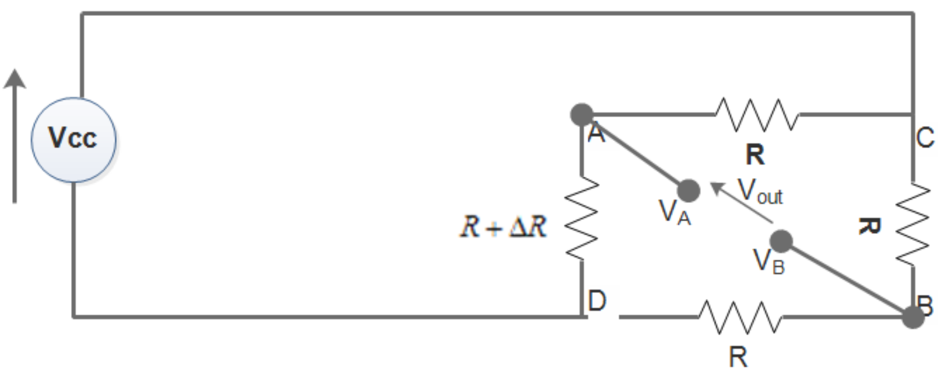


Figure 3.8: Wheatstone bridge: linear approximation

The "linear approximation" refers to the assumption that the relationship between the measured voltage and the unknown resistance in the bridge is linear within a certain range of operation.
This assumption simplifies the analysis and calculations involved in using the

Wheatstone bridge for measurement purposes.
We assume that:

$$R_c = R + \Delta R$$

We obtain then for:

$$V_{out} = V_A - V_B = \left(\frac{\Delta R}{2\left(2R + \Delta R\right)} \right) \cdot V_{cc}$$

And if : $R \gg \Delta R$:

$$V_{out} = \frac{\Delta R}{4R} \cdot V_{cc}$$

Half-bridge push-pull circuit

This phrase refers to a circuit configuration commonly used in electronics, particularly in power amplifiers and motor control circuits. The "push-pull" configuration involves two active devices (transistors, typically) alternately pushing and pulling the current through the load.
The "half-bridge" configuration implies that only one side of the load is driven, as opposed to a full-bridge where both sides are driven.
In this setup, the fixed resistance R_1 is replaced by a second sensor identical to the first but with a variation opposite to the first sensor: $R' = R_{c0} - \Delta R$. We then have 2 fixed resistances R_3 and R_4 and 2 sensors R and R'.

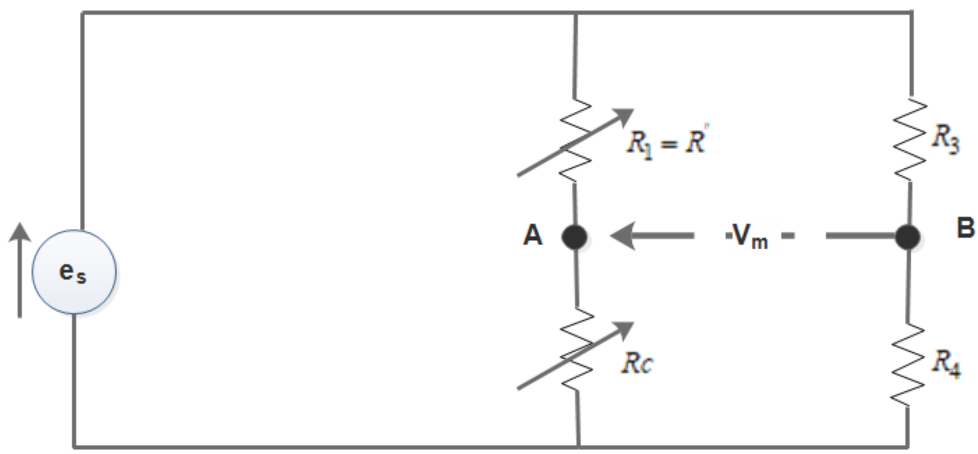


Figure 3.9: Half-bridge push-pull circuit

$$R_c = R = R_{c0} + \Delta R, R_1 = R^{'} = R_{c0} - \Delta R$$

We have as the output signal:

$$V_m = V_A - V_B = \left(\frac{R}{R' + R} - \frac{R_4}{R_3 + R_4} \right) \cdot e_s$$

By setting the values of R_3 and R_4 equal to R_{c0}, we then have and :

$$V_m = V_A - V_B = \left(\frac{R}{R' + R} - \frac{R_{c0}}{R_{c0} + R_{c0}} \right) \cdot e_s$$

Let:

$$V_m = V_A - V_B = \left(\frac{R_{c0} + \Delta R}{2R_{c0}} - \frac{R_{c0}}{R_{c0} + R_{c0}} \right) \cdot e_s$$

We then obtain the expression for Vm:

$$V_m = V_A - V_B = \left(\frac{R_{c0} + \Delta R}{2R_{c0}} - \frac{R_{c0}}{R_{c0} + R_{c0}} \right) \cdot e_s = \left(\frac{1}{2} + \frac{\Delta R}{2R_{c0}} - \frac{1}{2} \right) \cdot e_s$$

$$V_m = \frac{\Delta R}{2R_{c0}} \cdot e_s$$

Advantages of the half-bridge push-pull configuration:

- The DC component of V_m is cancelled out.
- The variation of V_m with ΔR is linear.

Full-bridge circuit

This circuit configuration commonly used in electronics, particularly in applications requiring bidirectional current flow or high power levels.
In a full-bridge circuit, four active components (such as transistors or switches) are arranged in a bridge configuration to control the flow of current through a load.
This configuration allows for more precise control and higher efficiency compared to simpler circuit topologies.
The circuit below delivers the voltage:

$$R_c = R = R_{c0} + \Delta R,$$

$$R_1 = R^{'} = R_{c0} - \Delta R,$$

$$R_3 = R_{c0} + \Delta R$$

$$R_4 = R_{c0} - \Delta R$$

$$V_m = \frac{\Delta R}{R_{c0}} \cdot e_s$$

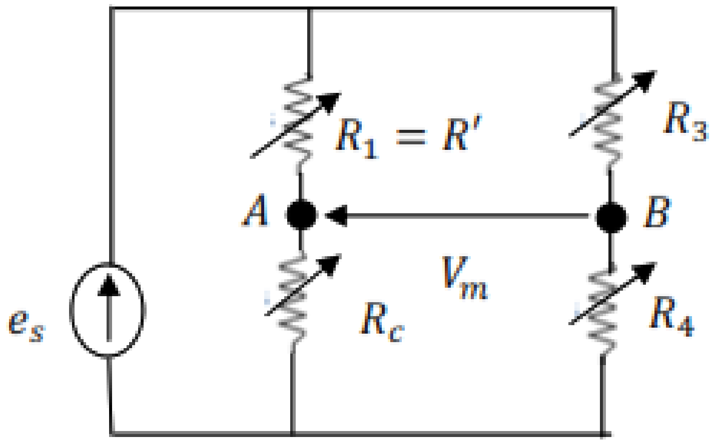


Figure 3.10: Full-bridge circuit

- This circuit, compared to the previous ones, is preferable since it delivers a higher voltage

3.5 Conclusion

The third chapter is dedicated to the conditioning of passive sensors and highlights the four different existing setups. The sensor and its potential conditioner are the source of the electrical signal, which the measurement chain must handle in the most suitable manner for the intended purpose. In the following chapter, we aim to study a number of signal processing devices, known as signal conditioners.

Exercises

Exercise 1:

Consider a potentiometric setup, an electrical resistance R_c in series with R_1 is powered by a voltage source E.
The voltage is measured across R_c by a resistance measuring device R_i.

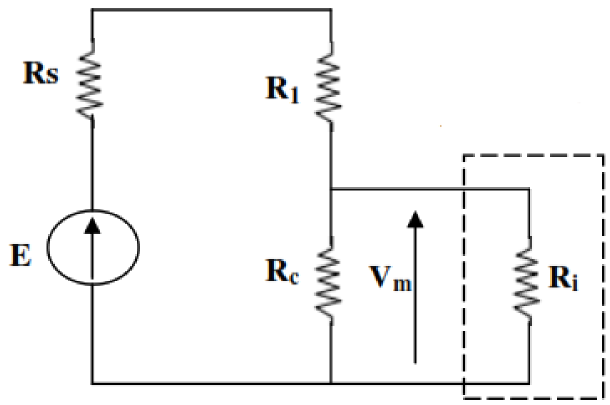


Figure 3.11: potentiometric setup

1. Give the expression of the voltage V_m, knowing that $V_m = V_{m0} + \Delta V_m$, $R_c = R_{c0} + \Delta R_c$, and $R_1 = R_s = R_{c0}$.

2. If the voltage across R_c is independent of the measuring device under the condition that the resistance R_c is much smaller than that of R_i, provide the expression for the measured voltage V_m.

3. Give the new expression of V_m for small variations.

Exercise 2:

We consider the Wheatstone bridge presented in Fig 3.12.

1. Show that the voltage V_{mes} can be obtained by the following expression: $V_{mes} = \left(\frac{R_c}{R_c+R_2} - \frac{R_4}{R_3+R_4}\right) \cdot V_g$

2. At equilibrium, the value of V_{mes} is equal to zero. Deduce a relationship between R_c and the other resistances.

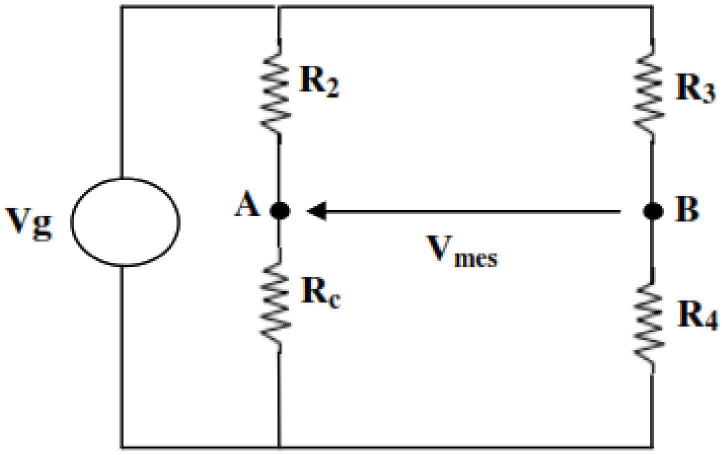


Figure 3.12: The Wheatstone Bridge Circuit

3. We assume that resistors $R3$ and $R4$ are equal, and $R_c = 2 \times R2$. Determine the relative error on V_{mes} knowing that the error on V_g is equal to 1%.

Exercise 3:

A linear displacement sensor is constituted of a linear potentiometer as schematized in Figure 3.13.
Δx represents the value of the displacement of the slider relative to the middle position, which is taken as the origin of the x-axis.

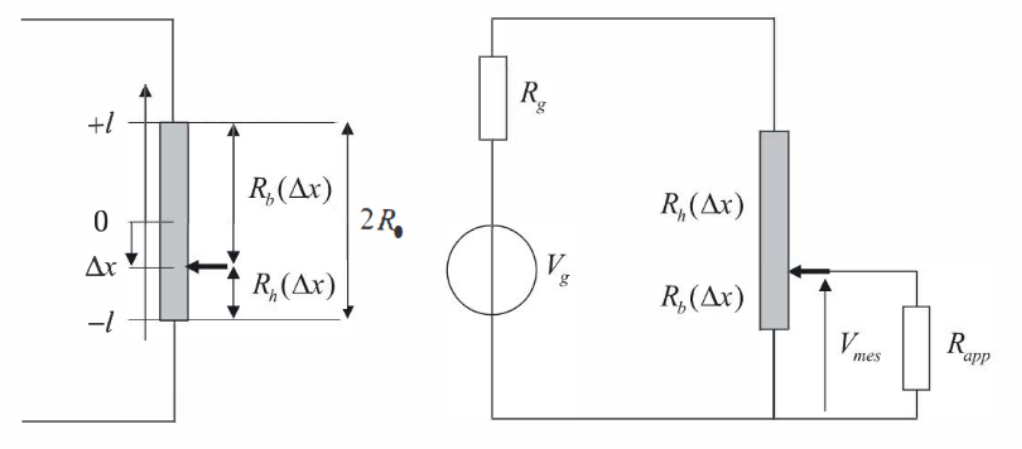


Figure 3.13: A linear potentiometer in a push-pull sensor

1. The useful travel of the potentiometer is $2l = 10$ cm and its total resistance is $2R_0$. Deduce the expression of the resistances $R_b(\Delta x)$ and $R_h(\Delta x)$ of

the potentiometer (see Figure 3.13.) for a displacement Δx of the slider relative to the middle position.

2. The potentiometer is mounted according to the diagram in Figure 1.1. The measurement voltage V_{mes}, representing the position of the slider, is measured by electronics with input impedance R_{app}. Express V_{mes} in terms of $R_b(\Delta x)$, $R_h(\Delta x)$, R_g, R_{app}, and V_g.

3. What does this expression become for $R_{\text{app}} \gg R_0$?

4. Deduce the sensitivity S_{mes} of the measurement.

Exercise 4:

We consider the half-bridge configuration shown in Figure 3.14 where R_1 and R_2 represent the two variable resistances of a rotary potentiometer with a total resistance of $2R_0$ and a total angular travel of Ω (see Figure 3.14).
The resistances R in the other branch of the potentiometer are fixed.

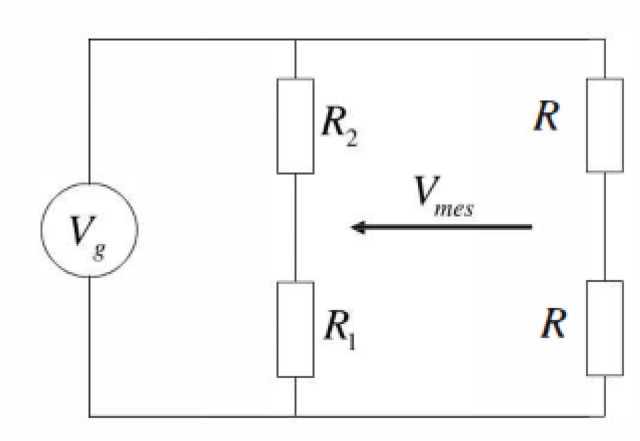
1. Give the expression of the measurement voltage V_{mes} as a function of R_1, R_2, and V_g.

2. The bridge is balanced for a value $alpha_0$ of the angular position. A priori, what value should we choose for α_0? Deduce the values $R_1(\alpha_0)$ and $R_2(\alpha_0)$.

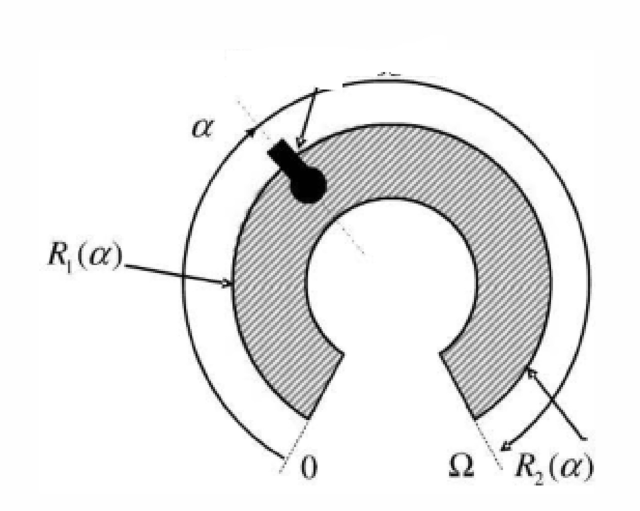
3. The measured quantity changes by $\Delta\alpha$ starting from α_0. Give the expressions for $R_1(\alpha_0 + \Delta\alpha)$ and $\alpha_0 + \Delta\alpha$, then the expressions for ΔR_1 and ΔR_2 as functions of $\Delta\alpha$, Ω and R_0.

4. Give the expression for the variation ΔV_{mes} of the measurement voltage associated with the angle $\alpha_0 + \Delta\alpha$.

5. Calculate the measurement sensitivity. Given $\Omega = 250°$ and $V_g = 1\,\text{V}$.
   The previous measurements were conducted at the reference temperature $T_0 = 0°\text{C}$.
   The temperature now varies and affects the resistivity of the potentiometer track according to $\rho(T) = \rho_0(1 + a_p T)$, where ρ_0 is the resistivity of the metal at 0 °C and the temperature is expressed in °C. Therefore, temperature is presumably an influencing factor in the measurement.



(a) Bridge Conditioning



(b) Rotary Potentiometer

Figure 3.14: Bridge Conditioning and Rotary Potentiometer

6. Why, a priori, do we limit ourselves to such a low supply $V_g = 1\,\mathrm{V}$ that consequently limits the sensitivity of the measurement?

7. At a temperature $T \neq T_0$, give the expressions of $R_1(\alpha_0, T)$ and $R_2(\alpha_0, T)$ as functions of R_0, α_ρ, $\Delta T = T - T_0$ and R_0.

8. Provide the expressions for $R_1(\alpha_0 + \Delta\alpha, T)$ and $R_2(\alpha_0 + \Delta\alpha, T)$ for a change in angle at a temperature $T \neq T_0$.

9. Deduce the new expression for the variation ΔV_{mes} and conclude.

Solutions

Exercise 1

1. $$V_m = E \cdot \frac{R_c R_i}{R_c \left(R_s + R_1\right) + R_i \left(R_s + R_1 + R_c\right)}$$

   and if :

   $$V_m = V_{m0} + \Delta V_m, R_c = R_{c0} + \Delta R_c, R_1 = R_s = R_{c0}.$$

   $$V_{m0} + \Delta V_m = E \cdot \frac{\left(R_{c0} + \Delta R_c\right) R_i}{R_c \left(2R_{c0}\right) + R_i \left(2R_{c0} + \left(R_{c0} + \Delta R_c\right)\right)}$$

2. if

   $$R_i \gg R_c$$

   $$V_m = E \cdot \frac{R_c}{R_s + R_1 + R_c}$$

3. for small variation:

   $$\Delta R_c \ll R_{c0} + R_1 + R_s$$

   $$V_{m0} + \Delta V_m = \frac{R_{c0} + \Delta R_c}{R_{c0} + R_1 + R_s} \cdot \frac{1}{1 + \frac{\Delta R_c}{R_{c0} + R_1}} \cdot E$$

   $$V_{m0} + \Delta V_m = \frac{R_{c0} + \Delta R_c}{R_{c0} + R_1 + R_s} \cdot E$$

   $$V_{m0} + \Delta V_m = \frac{R_{c0} + \Delta R_c}{3R_{c0}} \cdot E$$

Exercise 2

1.
   - In A: $V_A = \frac{R_c}{Rc+R_2} \cdot V_g$
   - In B: $V_B = \frac{R_4}{R4+R_3} \cdot V_g$
   - One obtains a measurement voltage also called bridge imbalance voltage: $V_{mes} = V_A - V_B = \frac{R_c R_3 - R_2 R_4}{(R_2+R_c)(R_4+R_3)} \cdot V_g$

2. $V_{mes} = 0 \Rightarrow \frac{R_c}{Rc+R_2} \cdot V_g = \frac{R_4}{R4+R_3} \cdot V_g \Rightarrow R_c R_3 = R_2 R_4$

3. $V_{mes} = V_g \cdot \left(\frac{2R_2}{3R_2} - \frac{R_4}{2R_4} \right) = \frac{1}{6} V_g \Rightarrow \frac{\partial V_{mes}}{V_{mes}} = \frac{\partial V_g}{V_g} = 1\%$

Exercise 3

1.
   - Directly from Figure: $R_h(\Delta x) = R_0 + \frac{2R_0}{2l} \Delta x = R_0 \left(1 + \frac{\Delta x}{l}\right)$
   - $R_b(\Delta x) = R_0 - \frac{2R_0}{2l} \Delta x = R_0 \left(1 - \frac{\Delta x}{l}\right)$

2. The measurement voltage is given by:
   - $V_{mes} = \frac{R_b(\Delta x) \| R_{app}}{R_g + R_h(\Delta x) + R_b(\Delta x) \| R_{app}} \cdot V_g$
   - $V_{mes} = \frac{R_b(\Delta x) R_{app}}{R_b(\Delta x) R_{app} + (R_b(\Delta x) + R_{app})(R_h(\Delta x) + R_g)} \cdot V_g$

3. For $R_{app} \gg R_0 \Rightarrow R_{app} \gg R_b(\Delta x), R_{app} \gg R_h(\Delta x)$
   - $V_{mes} = \frac{R_b(\Delta x)}{R_g + R_h(\Delta x) + R_b(\Delta x)} \cdot V_g$
   - $V_{mes} = \frac{R_0}{R_g + 2R_0} \left(1 + \frac{\Delta x}{l}\right) V_g$
   - Under this approximation, the measurement is linear.

4. The sensitivity of the measurement is given by:
   - $R_h(\Delta x) = R_b(\Delta x) = R_0$
   - $V_{mes_R 0} = \frac{R_0}{R_g + 2R_0} . V_g$

- $\Delta V_{mes} = \frac{V_{mes}}{V_{mes_R 0}}$

- $S_{mes} = \frac{\Delta V_{mes}}{\Delta x} = \frac{R_0}{} R_g + 2R_0 \cdot \frac{V_g}{l}$

Exercise 4

1. The expression for the measurement voltage V_{mes} is:

$$V_{mes} = \left(\frac{R_1}{R_1 + R_2} - \frac{1}{2}\right) V_g = \frac{R_1 - R_2}{R_1 + R_2} \cdot \frac{V_g}{2}$$

2. The bridge must be balanced for a value α_0 of the angular position that minimizes measurement non-linearities, hence presumably for $\alpha_0 = \frac{\Omega}{2}$. The resistance per unit angle of the resistive track is $\frac{2R_0}{\Omega}$, so we have:

$$R_1(\alpha_0) = \frac{2R_0}{\Omega} \cdot \frac{\Omega}{2} = R_0$$

$$R_2(\alpha_0) = 2R_0 - R_1(\alpha_0) = R_0$$

3. Similarly, we have:

$$R_1(\alpha_0 + \Delta\alpha) = \frac{2R_0}{\Omega} \left(\frac{\Omega}{2} + \Delta\alpha\right) = R_0 \left(1 + 2\frac{\Delta\alpha}{\Omega}\right)$$

$$R_2(\alpha_0 + \Delta\alpha) = 2R_0 - R_1(\alpha_0 + \Delta\alpha) = R_0 \left(1 - 2\frac{\Delta\alpha}{\Omega}\right)$$

The two branches of the potentiometer form two linear sensors in $\Delta\alpha$, operating in push-pull mode.

4.

$$V_{mes} = \frac{R_1 - R_2}{R_1 + R_2} \cdot \frac{V_g}{2} = \frac{R_0 \left(1 + 2\frac{\Delta\alpha}{\Omega}\right) - R_0 \left(1 - 2\frac{\Delta\alpha}{\Omega}\right)}{R_0 \left(1 + 2\frac{\Delta\alpha}{\Omega}\right) + R_0 \left(1 - 2\frac{\Delta\alpha}{\Omega}\right)} \cdot \frac{V_g}{2} = \frac{\Delta\alpha}{\Omega} V_g = \Delta V_{mes}$$

The measurement is linear in $\Delta\alpha$.

5. The sensitivity of the measurement is given by $S_{\text{mes}} = \frac{\Delta V_{\text{mes}}}{\Delta\alpha} = 4\,\text{mV}/^\circ$

6. The resistivity varies with temperature, and consequently, the resistance values also vary with temperature.
   This can potentially cause a drift in the measurement voltage at a fixed angular displacement $\Delta\alpha$, leading to an error in the interpretation of this measurement voltage.
   A too high supply voltage risks causing self-heating due to Joule effect, and therefore, following the principle described above, an error in the interpretation of the measurement voltage.

7. At temperature $T \neq T_0$ and since $T_0 = 0C$, the resistance R_0 now reads $R_0(1+\alpha_\rho T)$

8. Similarly to the previous case, we have:

$$R_1(\alpha_0+\Delta\alpha,T) = R_0\left(1+\alpha_p T\right)\left(1+2\frac{\Delta\alpha}{\Omega}\right)$$
$$R_2(\alpha_0+\Delta\alpha,T) = R_0\left(1+\alpha_p T\right)\left(1-2\frac{\Delta\alpha}{\Omega}\right)$$

9.

$$V_{mes} = \frac{R_0\left(1+\alpha_p T\right)\left(1+2\frac{\Delta\alpha}{\Omega}\right) - R_0\left(1+\alpha_p T\right)\left(1-2\frac{\Delta\alpha}{\Omega}\right)}{R_0\left(1+\alpha_p T\right)\left(1+2\frac{\Delta\alpha}{\Omega}\right) + R_0\left(1+\alpha_p T\right)\left(1-2\frac{\Delta\alpha}{\Omega}\right)}\frac{V_g}{2} = \frac{\Delta\alpha}{\Omega}V_g$$

   This result is strictly identical to result (4). We deduce that while temperature does indeed influence each resistive track taken as a sensor, it has no effect on the measurement due to the push-pull half-bridge conditioning. The argument developed in question 6 is therefore irrelevant, and we can afford to increase the supply voltage to enhance the measurement sensitivity.

Chapter 4

SIGNAL CONDITIONERS

4.1 Introduction

The sensor and its potential conditioner (potentiometer, bridge, oscillator) are the source of the electrical signal, which the measurement chain must process in the most appropriate manner for the intended purpose.
This chapter aims to study a number of processing devices, called signal conditioners, whose function is directly related to the nature of the signal as it results from both the characteristics of the sensor and, if applicable, its conditioner, as well as the practical measurement conditions.
The problems examined include:

- Determining the appropriate interface type between the signal source and the rest of the measurement chain, depending on whether the source is a voltage, current, or charge generator.
- Signal linearization.
- Signal amplification in the presence of common mode voltages.
- Extracting information related to the measured quantity when its variations modulate the electrical signal.

4.2 Adaptation of the signal source to the measurement chain

The sensor, combined with its conditioner, is equivalent to a generator consisting of a source and an internal impedance delivering the signal to the circuit that loads it. In order for the signal to be obtained under the best conditions of sensitivity and stability with respect to possible variations in the internal impedance, the equivalent generator must be loaded with an appropriate impedance.

Impedance matching

When the information corresponding to the measured variable m is delivered in the form of a function of electromotive force f.é.m. $e_c(m)$ in series with a measurement impedance Z_c, from which the information corresponding to the measured variable (m) is collected in front of Z_c in order to minimize the influence of the latter, the device must have a very high input impedance Z_i. This is particularly important when the impedance Z_c, which may be significant and variable, is present.

$$V_m = e_c\,(m) \cdot \frac{Z_i}{Z_i + Z_c}$$

if

$$Z_i \gg Z_c$$

Then

$$V_m = e_c$$

Devices with high input impedance that can be used to achieve impedance

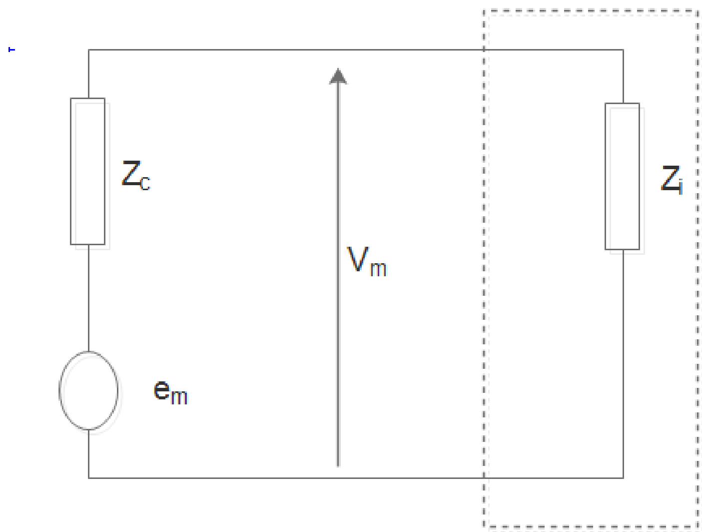


Figure 4.1: Adaptation to the measurement chain of an equivalent electrical voltage source sensor.

matching are based on (Figures: 4.2, 4.3):

- Operational amplifiers in simple follower or follower/amplifier configurations,
- Differential amplifiers, generally in the form of instrumentation amplifiers or isolation amplifiers.

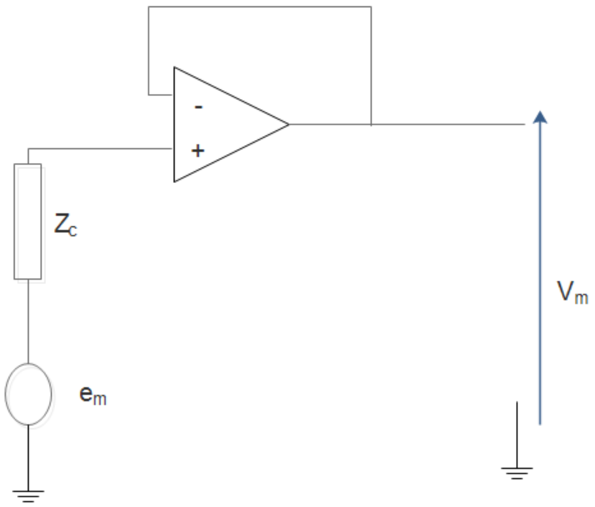


Figure 4.2: Adaptation to the measurement chain of a voltage source sensor:Follower configuration

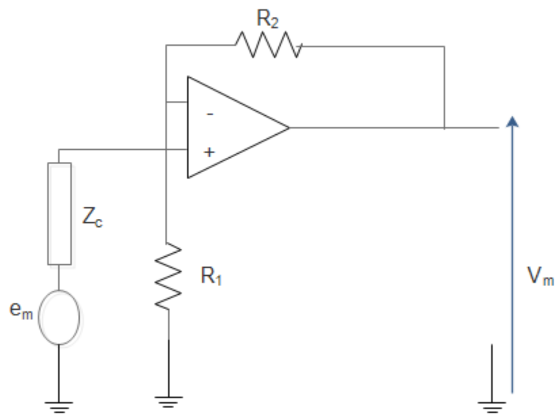


Figure 4.3: Adaptation to the measurement chain of a voltage source sensor:Non-inverting amplifier configuration

Voltage source sensor

The function to be performed by the conditioner is voltage amplification. The source E_c generally has an output impedance Z_c. The conditioner loads this

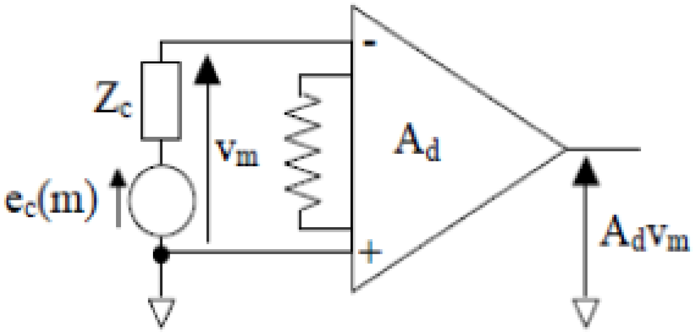


Figure 4.4: Adaptation to the measurement chain of an instrumentation voltage source sensor:

source with its own input impedance. By applying the voltage divider rule, we obtain:

$$V_m = \frac{Z_i}{Z_{in} + Z_c} \cdot E_s$$

The conditioner must have an input impedance much larger than that of the

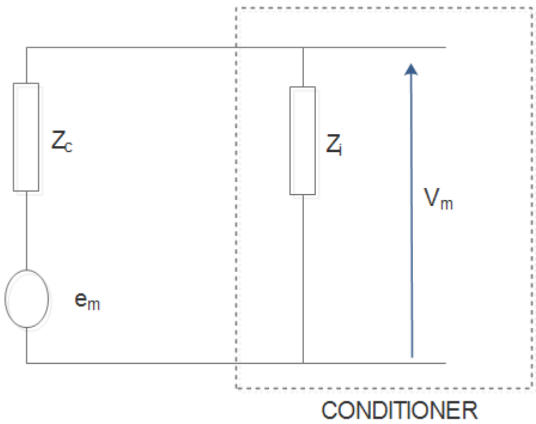


Figure 4.5: Adaptation to the measurement chain of a voltage source sensor: equivalent electrical circuit diagram.

source. The choice depends on the desired accuracy. For a precision of 1/1000, an impedance ratio of the same value is required.
Example: Thermocouple

Current source sensor

Model of the current source sensor

- Conditioning can be limited to a single calibrated resistance $Z_i = R$.
- The measured voltage depends on the measurement resistance and the parallel impedance of the current generator.
- This solution is acceptable for a pure current generator ($Z_c \to \infty$), Figure 4.6

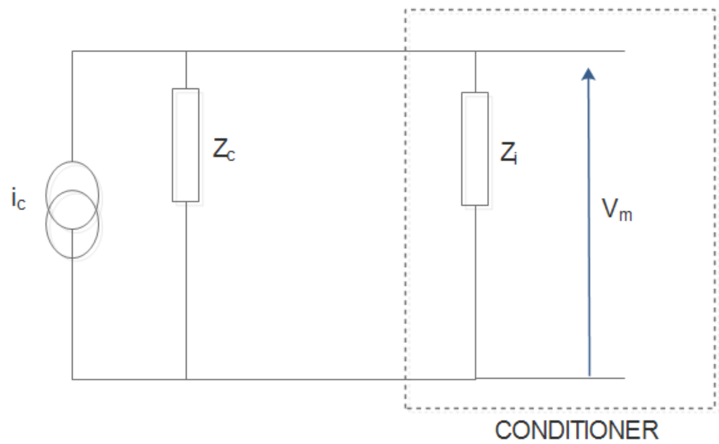


Figure 4.6: Adaptation to the measurement chain of a current source sensor: equivalent electrical circuit diagram

Current/voltage converter

The sensor becomes a current source with zero (and constant) voltage. Its parallel conductance does not affect the measured value. The bandwidth is greatly increased if the sensor has a highly capacitive impedance (Figure 4.7).

$$V_m = R \cdot I_c$$

Example: Phototransistor

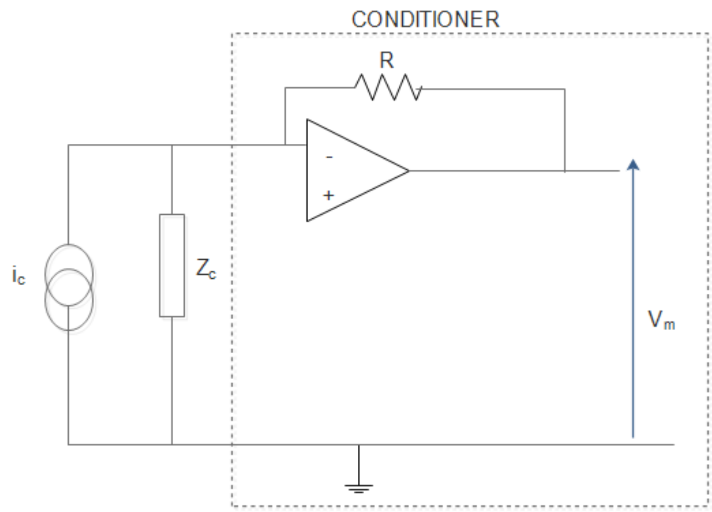


Figure 4.7: Adaptation to the measurement chain of a current source sensor: Current/voltage converter.

Charge source sensor

Model of the charge-generating sensor

$$V_m = \frac{q_c}{C_c + C_i}$$

The input internal resistance R_i introduces discharging of the source (first-order circuit).

- If the discharging is too rapid (low time constant), the measurement is impossible.
- Such a sensor is only suitable for measurements with a zero mean value (e.g., acceleration/vibration).

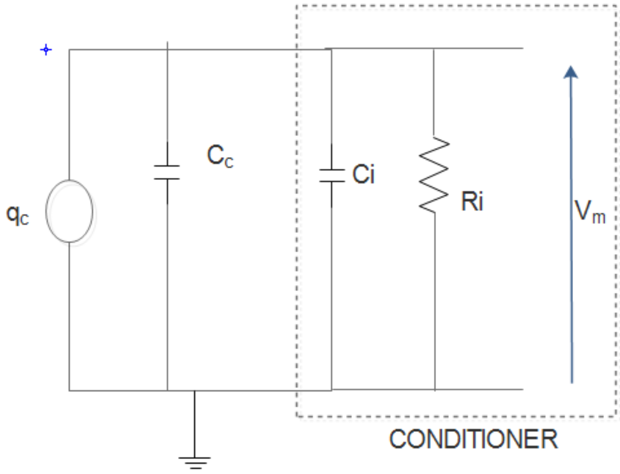


Figure 4.8: Adaptation to the measurement chain of a charge source sensor: equivalent electrical circuit diagram

Charge-to-voltage converter: Charge amplifier

The sensor becomes a charge source with zero (and constant) voltage. Its parallel capacitance does not affect the measured value. The bandwidth is greatly increased if the sensor has a highly capacitive impedance. An auxiliary circuit is necessary to ensure compensation for the drift of the integrator (Figure 4.9).
Example: Piezoelectric sensor

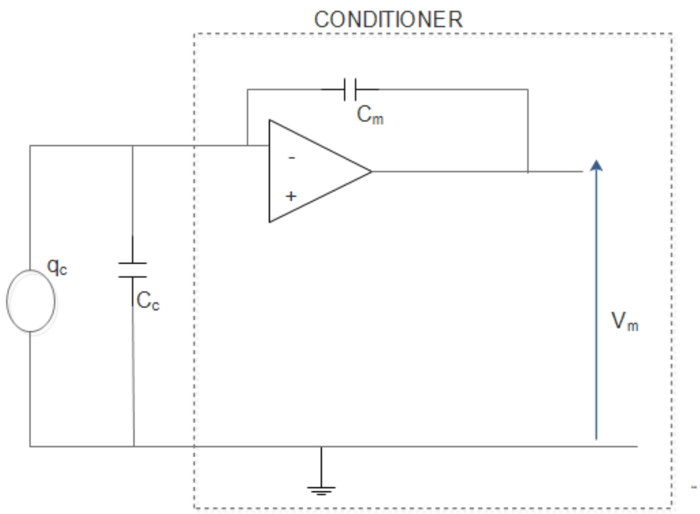


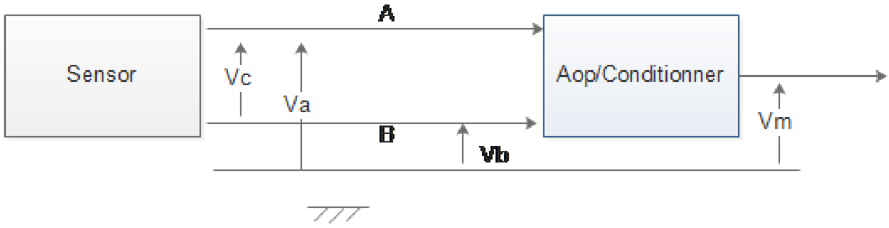
Figure 4.9: Adaptation to the measurement chain of a charge source sensor: Charge amplifier

4.3 Measurement of voltage

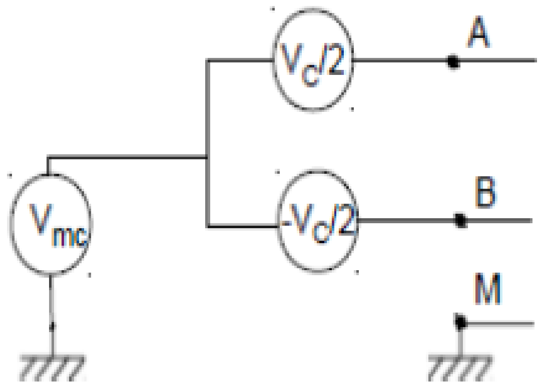
The sensor, together with its conditioner, is equivalent to a generator consisting of a source and an internal impedance delivering the signal to the circuit that loads it. In order for the signal to be obtained under the best conditions of sensitivity and stability with respect to possible variations in the internal impedance, the equivalent generator must be loaded by an appropriate impedance.

Problematic of voltage measurement

Signals from sensors are of low level and need to be amplified. The useful signal is generally a potential difference between two points, whereas common measurement tools (operational amplifiers) evaluate the potential with respect to an imposed reference called ground (Figure 4.10).



(a) Differential



(b) Common-mode voltages.

Figure 4.10: General definition of differential and common-mode voltages

- The measurement voltage V_c from a sensor is the potential difference between the two conductors A and B: $V_c = V_{diff} = V_m = V_A - V_B$.
- The voltage of common mode $V_{mc} = \frac{V_A+V_B}{2}$ thus $V_A = V_{mc} + \frac{V_c}{2}$ and $V_A = V_{mc} - \frac{V_c}{2}$

The common-mode voltage V_{cm} can be much larger than the signal voltage. It can be stable, but most often, it is disturbed by external factors (noise sources, couplings...).

Differential amplifier and common-mode rejection ratio

- The most common method of measuring potentials is the voltmeter. This device allows for evaluating the potential difference between its two measuring points.
- The measurement tool used in instrumentation is the differential amplifier, composed of 2 amplifiers and a subtractor.

The output voltage is:

$$V_s = A_1 V^+ - A_2 V^-$$

On sets:

$$V_{cm} = \frac{V^+ + V^-}{2}, V_{diff} = V^+ - V^-$$

thus

$$V_s = A_1 \left(V_{cm} + \frac{V_{diff}}{2} \right) - A_2 \left(V_{cm} - \frac{V_{diff}}{2} \right)$$

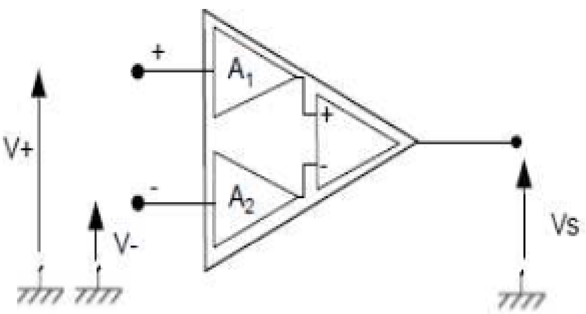


Figure 4.11: The structure of the differential amplifier

We define the common-mode gain and the differential gain:

$$A_{cm} = A_1 - A_2$$

and

$$A_{diff} = \frac{A_1 + A_2}{2}$$

$$V_s = A_{diff} \left(V_{diff} + \frac{1}{\tau} V_{mc} \right)$$

$$\tau = \frac{A_{diff}}{A_{cm}}$$

τ: common-mode rejection ratio

Modeling of the differential amplifier

The differential amplifier is designed like an operational amplifier, with the same inseparable flaws due to technological implementation.

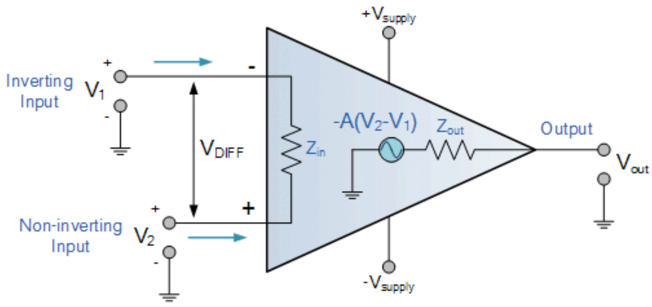


Figure 4.12: Operational Amplifier Basics

Example :
Texas Instruments THS4561 Fully Differential Amplifier: Texas Instruments THS4561 Fully Differential Amplifier (FDA) offers a simple interface from single-ended sources to the differential output required by precision analog-to-digital converters (ADCs).
Characteristics of Texas Instruments THS4561:

- $60MHz$ $(G = 1V/V)$ bandwidth.
- $230V\mu s$ slew rate
- $2.85V$ to $12.6V$ supply operating range
- Rail-to-Rail Output (RRO)

Instrumentation amplifier

The instrumentation amplifier is often considered the ideal differential amplifier.

- Desired characteristics:

- Measurement of the potential difference over a wide common-mode range: $V_s = A_{diff} \cdot (V^+ - V^-)$
- Infinite input impedance to avoid disturbing the circuit being measured.
- Zero output impedance (no signal attenuation due to an output load).
- Infinite common-mode rejection ratio.
- Adjustable differential gain for easy adjustment (choice of resistance, digital connection...).

- The implementation of the instrumentation amplifier is often based on one or more operational amplifiers.

Subtractor operational amplifier circuit (ideal)

he equation for the subtractor operational amplifier circuit (ideal) can be expressed as:

$$V^+ = \frac{R_4}{R_4 + R_3} \cdot V_{e1}$$

$$V^+ = \frac{R_2}{R_2 + R_1} \cdot V_{e2} + \frac{R_1}{R_2 + R_1} \cdot V_s$$

In linear regime: $V^+ = V^-$
Hence:

$$V_s = \frac{R_1}{R_1 + R_2}\left(\frac{R_4}{R_4 + R_3}V_{e1} - \frac{R_2}{R_1 + R_2}V_{e2}\right)$$

To have the same gain on both inputs, we choose:$R_1 = R_3, R_2 = R_4$

$$V_s = \frac{R_2}{R_1}\left(V_{e1} - V_{e2}\right)$$

Input impedances The subtractor circuit has a finite resistance on each of its inputs:

$$R_{in1} = \frac{V_{e1}}{I_1} = R_1 + R_2, V_{e2} = 0$$

$$R_{in2} = \frac{V_{e2}}{I_2} = R_1, V_{e1} = 0$$

The disadvantage (Limitations) :

- If high amplification is desired, R_2 must be large and R_1 small.

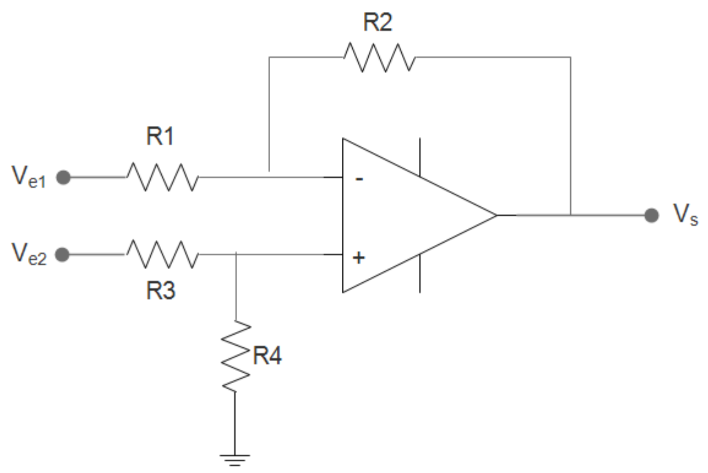
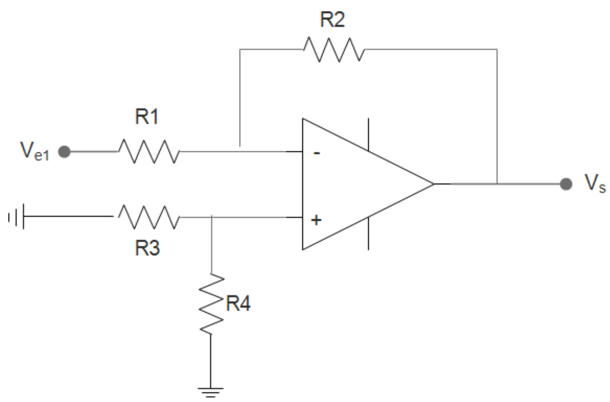


Figure 4.13: Subtractor operational amplifier circuit



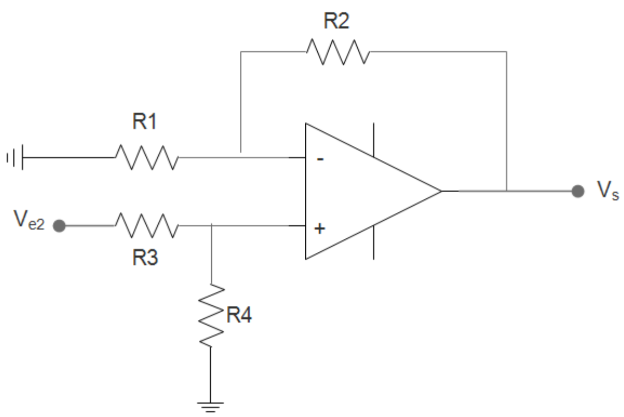


Figure 4.14: Input impedances of a subtractor circuit subtractor circuit

- This configuration is therefore only suitable if V_{e1} and V_{e2} are outputs from other amplifiers.
- The common-mode rejection ratio is directly related to the equality of the resistances.

Solutions

- The "infinite" input impedance of the non-inverting amplifier is utilized: $R_{\text{in}} = R_{\text{in AOP}} \to \infty$.
- The resistors of the subtractor circuit are adjusted by the manufacturer.
- Three-op-amp instrumentation amplifier.

Three-op-amp instrumentation amplifier

The circuit is as follows: The inputs are amplified by buffer stages with a very

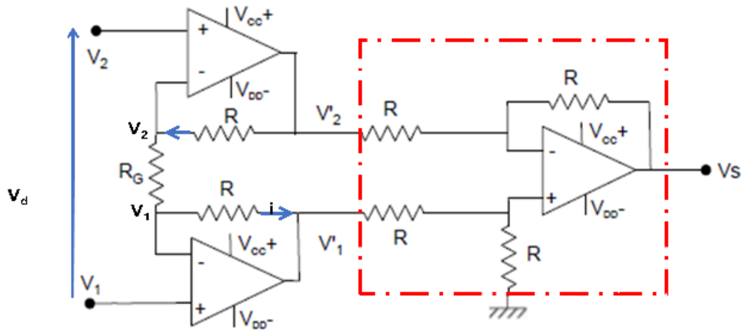


Figure 4.15: Three-op-amp instrumentation amplifier

high dynamic input impedance.

$$V_1 = \left(1 + \frac{R}{R_G}\right) V_1 - \frac{R}{R_G} V_2$$

$$V_1 = \left(1 + \frac{R}{R_G}\right) V_2 - \frac{R}{R_G} V_1$$

Therefore

$$V_s = \left(1 + 2\frac{R}{R_G}\right) (V_1 - V_2)$$

- The gain is set with a single resistor R_G; it is at a minimum of 1.
- The role of the instrumentation amplifier is the same as that of the differential amplifier.

We will choose:

- The differential amplifier if the input source has low impedance;
- The instrumentation amplifier if the input source has high impedance.

Isolation amplifier

A. Functions: An isolation amplifier is an instrumentation amplifier for which the input and output signals are galvanically isolated.
There is no direct path for the passage of current between the input and output. The input and output circuits are electrically isolated; the voltage references (grounds) at the input and output may be at different potentials. **B. Imple-**

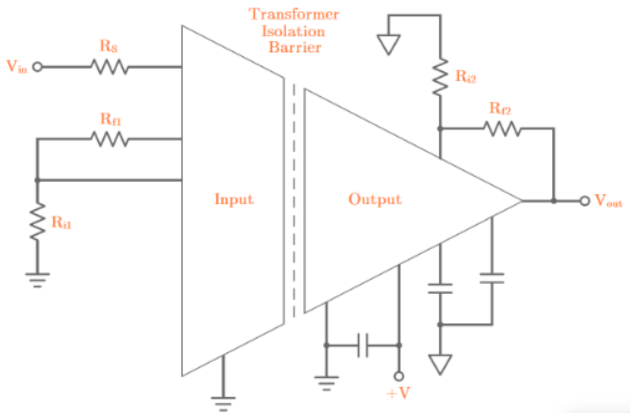


Figure 4.16: Isolation amplifier

mentation Le signal utile est transmis par couplage:

- Capacitif
- Optique
- Magnétique (transformateur) ou galvanique

Dans ce dernier cas, l'alimentation du circuit d'entrée peut également être transmise au circuit de sortie par transformateur.
B. Implementation The useful signal is transmitted by coupling:

- Capacitive
- Optical
- Magnetic (transformer) or galvanic

In the latter case, the power supply of the input circuit can also be transmitted to the output circuit by a transformer.

4.4 Conclusion

This chapter presents the problematics of electrical signal conditioners as well as the linear regime model showing the various types of adaptation used in instrumentation. This description will be followed by a presentation of analog linearization and conditioning circuits and amplification of the measured signal (differential amplifier, instrumentation amplifier, common mode rejection ratio, isolation amplifier).

Exercises

Exercise 1: Effect of the resistance of the connecting wires of a resistive sensor powered by current

Consider a Pt100 thermoresistance with resistance $R_c(T) = R_0(1 + \alpha T)$, where T represents the temperature in °C, $R_0 = 100\,\Omega$ is the resistance at 0°C, and $\alpha = 3.85 \times 10^{-3}\,°\mathrm{C}^{-1}$ is the temperature coefficient. To power this thermoresistance, we have a conditioning card providing a perfectly calibrated current output at $I = 5\,\mathrm{mA}$, the two differential inputs of an instrumentation amplifier, the output terminal of the latter, and a ground terminal. The adjustable resistor R allows varying the gain G of the amplifier, and the input impedances of the latter are considered infinite. The card is schematically depicted in the figure 4.17.

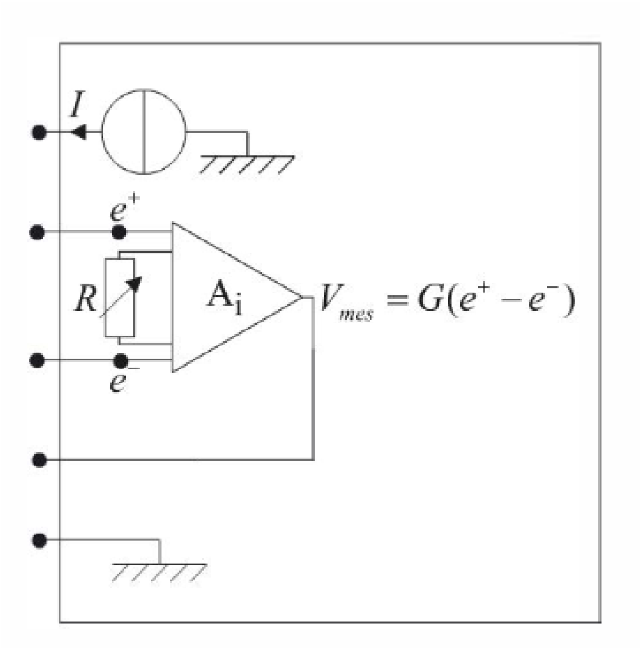


Figure 4.17: Conditioning Card

1. The Pt100 is directly connected between the current source and ground, and its terminals are connected to the instrumentation amplifier (see Figure 4.18).
   The connecting wires have negligible length.

   - Determine the expression of the measurement voltage Vmes and calculate the sensitivity of the measurement $S_{mes} = \frac{\Delta Vmes}{\Delta T}$

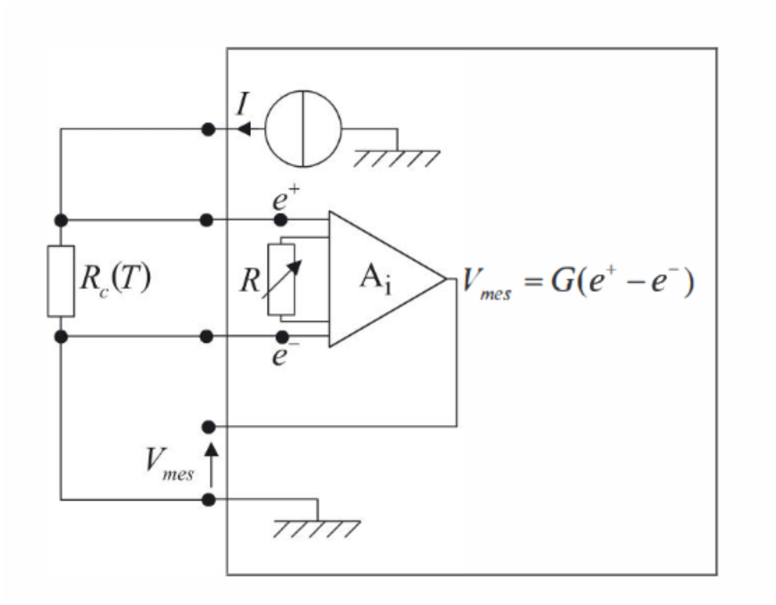


Figure 4.18: Two-wire configuration with negligible resistance

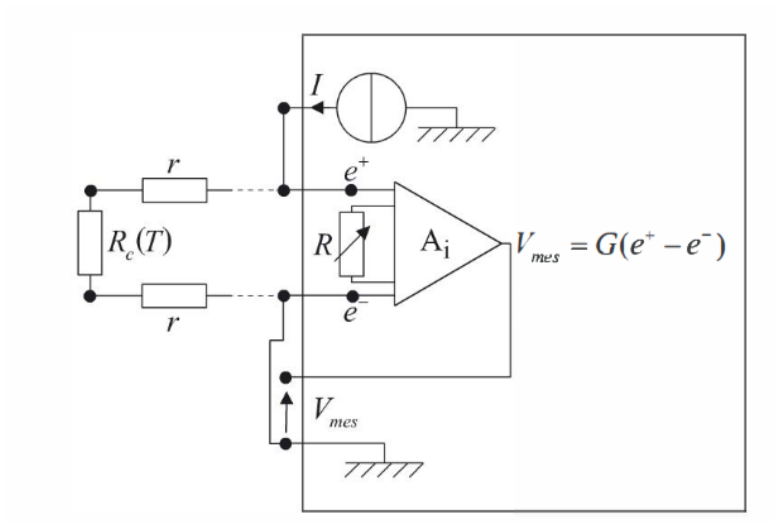


Figure 4.19: 2-wire configuration

- What should be the gain setting of the instrumentation amplifier to achieve a sensitivity $S_{\text{mes}} = 0.1\,\text{V}.^{\circ}C^{-1}$?

2. The Pt100 is now put into service remotely from the card, so the resistance of the connecting wires must be taken into account.
   These connecting wires are copper wires with a resistivity $\rho = 1.72 \times 10^{-8}\,\Omega \cdot \text{m}$, a diameter $d = 0.5\,\text{mm}$, and a length $l = 5\,\text{m}$. Each wire is modeled by its resistance.(Figure 4.19)

   - Determine the new measurement voltage $V_{\text{mes, 2}}$.

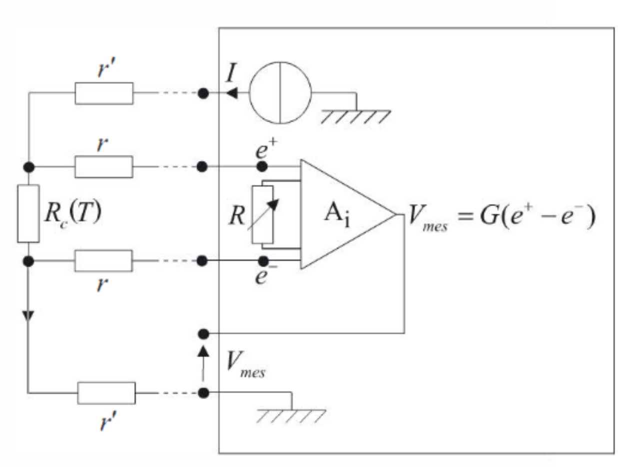


Figure 4.20: 4-wire configuration

- From this, deduce the error $\Delta V_2 = V_{\text{mes},2} - V_{\text{mes}}$ in the measurement voltage introduced by the resistance of the connecting wires.
- What is then the error δT_2 generated in the temperature measurement?

3. To address this error, the setup is modified to obtain a classic configuration known as a four-wire setup: two wires carry the current to the thermoresistance, and two wires are used to measure the voltage across it (see Figure 4.20)

   - Determine the new measurement voltage $V_{\text{mes},4}$ and conclude.

Exercise 2:

The conditioning circuit shown in the figure 4.21 is used to measure a temperature range T from 20 to 100°C. R is a PT100 type temperature sensor with $R_0 = 100$ ohms and $\alpha_0 = 0.000385\,\text{K}^{-1}$.

1. How to choose the value of R_T to ensure a resolution of 0.1°C given that the sensor's self-heating is $\delta = 0.25\,\text{K/mW}$.

2. Propose a value of R_T in order to obtain a sensitivity of $S = 1\,\text{mV/°C}$ where $V_r = 5\,\text{V}$.

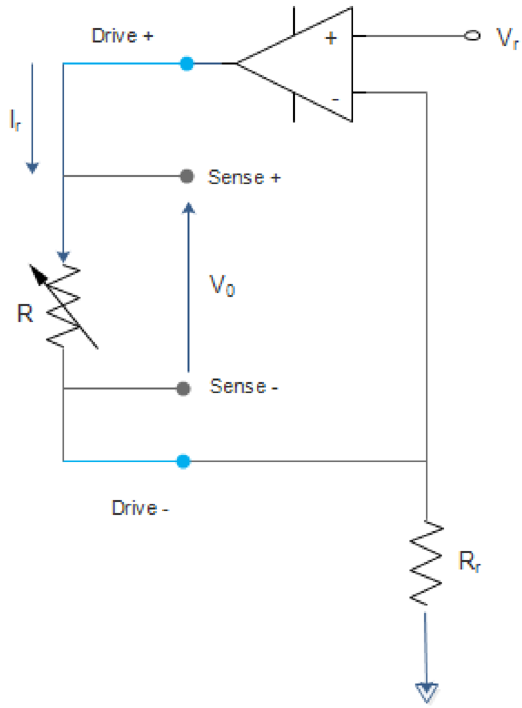


Figure 4.21: Temperature sensor

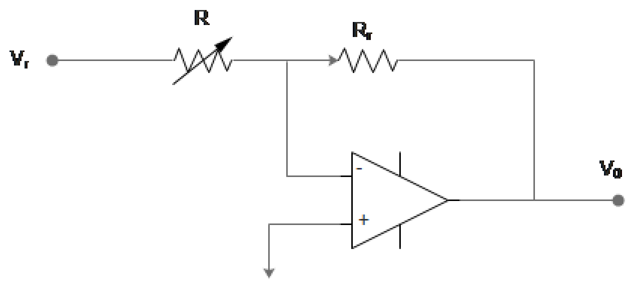


Figure 4.22: PT100 temperature

Exercise 3:

Propose a circuit design for the figure 4.22 that allows for an output V_0 of $0.5V$ to $5V$ in response to a mass applied to the force sensor R, knowing that $R = 200\text{k}\Omega$ at rest and $20\text{k}\Omega$ for a mass of $45kg$.

Exercise 4:

A temperature sensor (platinum ribbon) has a resistance R_0 that varies with temperature θ according to the law: $R_\theta = R_0(1 + a\theta)$ with:

- R_0 (resistance at 0°C) $\rightarrow R_0 = 100\,\Omega$.
- a (temperature coefficient) $\rightarrow a = 3.85 \times 10^{-3}\,°\mathrm{C}^{-1}$.

This sensor is inserted into the conditioning circuit of the figure 4.23

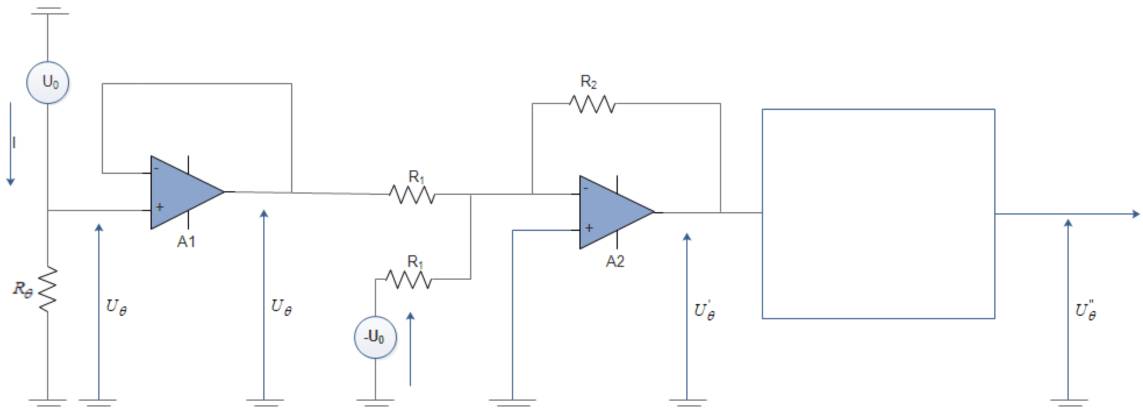


Figure 4.23: Temperature sensor (platinum ribbon)

We are given $I = 10.0\,\mathrm{mA}$.

1. Show that the voltage u_θ across R_θ can be expressed in the form:

$$u_\theta = U_0(1 + a\theta)$$

   . Express U_0 in terms of I and R_0. Calculate U_0.

2. What is the interest of using operational amplifier $A1$ in the circuit?

3. In the circuit built around $A2$, the voltage U_0 is the same as the one defined in question 1.

   - Show that the voltage u'_θ can be expressed in the form: $u'_\theta = -b\theta$.
   - Express b in terms of a, U_0, R_0, and R_1.

4. We want to invert the voltage u'_θ to obtain the voltage u''_θ which is expressed as: $u''_\theta = b\theta$.

   - Represent a circuit with an operational amplifier ensuring this function and completing the conditioner.

Solutions

Exercise 1

1. Part 1:
   Two-wire configuration with negligible resistance

   - The input impedances of the instrumentation amplifier can be considered infinite. According to the setup shown in figure 4.18, the current flowing through the Pt100 is the current I delivered by the source. Therefore, the measurement voltage is simply written as:

     $$V_{\text{mes}} = G(e^+ - e^-) = GR_c(T)I = GR_0(1 + \alpha T)I$$

   - The measurement sensitivity is given by $S_{\text{mes}} = \frac{\Delta Vmes}{\Delta T} = GR_0\alpha$. To achieve $S_{\text{mes}} = 0.1\,\text{V}.^{\circ}C^{-1}$, it suffices to set the gain of the amplifier to $G = 51.95$.

2. Part 2:
   2-wire configuration

   - The measurement voltage is now written as:

     $$V_{\text{mes},2} = G(e^+ - e^-) = G(R_c(T) + 2r)l = Gl\left(R_0(1 + \alpha T) + 2r\right)$$

   - The resistance of the connecting wires introduces an error in the measurement voltage given by $\Delta V_2 = V_{\text{mes},2} - V_{\text{mes}} = Gl \cdot 2r$. The resistance of the wires is given by Ohm's law, so $r = \frac{\rho \cdot l}{S} = 438\,\text{m}\Omega$.

   - The error made on the measurement voltage is therefore $\delta V_2 = 228\,\text{mV}$, which corresponds to an error made on the temperature given by $\Delta T_2 = \frac{\delta V_2}{S_{\text{mes}}} = 2.28\,^{\circ}\text{C}$.

3. Part 3:
   4-wire configuration

   - Given that the input impedances of the amplifier are infinite, we immediately have:

     $$V_{\text{mes},4} = G(e^+ - e^-) = GR_c(T)l = GR_0 l(1 + \alpha T)$$

     We obtain an identical result to V_{mes}. The length of the connecting wires no longer plays a role and therefore no longer disturbs the measurement.

Exercise 2

The dissipation in $P = R \cdot I_r$ and $I_r = \frac{V_r}{R_r}$
- Internal heating in R:$\Delta T = P \cdot \delta$
- The design must ensure that ΔT must always be less - than the desired measurement resolution: $\Delta T < 0.1$ °C
- P is maximal at $T = 100$ °C, so R is replaced by R_{100}:

$$R_{100} \cdot \left(\frac{V_r}{R_r}\right)^2 \cdot \delta < 0.1$$

$$R_r > V_r \cdot \sqrt{\frac{R_{100} \cdot \delta}{0.1}}$$

$$R_{100} = 100[1 + 0.00385\,(100 - 0)] = 138.5\Omega$$

We must choose $R_r > 930\Omega$

$$S = \frac{\Delta V_0}{\Delta T}, V_0 = R \cdot \frac{V_r}{R_r} \Rightarrow \frac{\Delta V_0}{\Delta T} = \frac{Vr}{R_r}\frac{\Delta R}{\Delta T} = 1mV/K$$

$$R_r = \frac{Vr}{1mV/K} \cdot \frac{\Delta R}{\Delta T}, \frac{\Delta R}{\Delta T} = \alpha_0 \cdot R_0$$

We choose $R_r = 1930\Omega$ With a sensitivity of 0.1% , the actual sensitivity will be 0.36% smaller than $1mV/C$, $V_r = 5V$.

Exercise 3

$$V_0 = \frac{R_r}{R} \cdot V_r \Rightarrow R_r \cdot V_r = -R \cdot V_0$$

$$R_r \cdot V_r = -200k\Omega \cdot 0.5V = -20k\Omega \cdot 5V = -100k\Omega.V$$

We can choose $V_r = 5V$ and $R_r = 20k\Omega$

Exercise 4

1.

$$U_\theta = R_\theta I = R_0 I \left(1 + a\theta\right) \Rightarrow$$

$$U_\theta = U_0 \left(1 + a\theta\right), U_0 = R_0 I$$

2. It is a **follower circuit** that allows not to draw current from the temperature sensor while reproducing the same voltage u at the output.

3. The circuit around A_1 is an inverting voltage adder:

$$U'_\theta = -\frac{R_2}{R_1}\left(U_\theta + \left(-U_0\right)\right)$$

So:

$$U'_\theta = -\frac{R_2}{R_1}\left(U_0\left(1 + a\theta\right) + \left(-U_0\right)\right) = -\frac{R_2}{R_1}U_0 a\theta$$

Therefore:

$$U'_\theta = -b\theta$$

With :

$$b = -\frac{R_2}{R_1}U_0 a$$

4. Use an inverting circuit as:

This results in:

$$U''_\theta = -\frac{R}{R}U'_\theta = b\theta$$

Chapter 5

Examples of sensors

5.1 Classification of sensors

Sensors can be classified in various ways based on different criteria such as their working principle, application, or physical properties. Here is a general classification based on working principle:

1- Based on Measurement Property:

- Temperature Sensors: Measure changes in temperature.
- Pressure Sensors: Measure pressure variations.
- Level Sensors: Detect the level of substances such as liquids or solids.
- Flow Sensors: Measure the flow rate of liquids or gases.
- Proximity Sensors: Detect the presence or absence of objects.
- Force Sensors: Measure the force or load applied to a surface.
- Acceleration Sensors: Measure acceleration in various directions.
- Humidity Sensors: Measure the moisture content in the air.
- Light Sensors: Measure the intensity or brightness of light.

2- Based on the transduction principle:

- Resistive Sensors: Change resistance in response to a physical change (e.g., strain gauges).
- Capacitive Sensors: Change capacitance in response to a physical change.

- Inductive Sensors: Change inductance in response to a physical change.
- Piezoelectric Sensors: Generate an electric charge when subjected to mechanical stress.
- Optical Sensors: Use light to measure a physical quantity.
- Magnetic Sensors: Detect changes in magnetic fields.
- Ionizing Radiation Sensors: Detect ionizing radiation levels.

3- Based on application:

- Automotive Sensors: Used in vehicles for various applications like engine control, airbag deployment, etc.
- Industrial Sensors: Used in industrial processes for monitoring and control.
- Medical Sensors: Used in healthcare for patient monitoring, diagnostics, etc.
- Environmental Sensors: Monitor environmental parameters like air quality, temperature, humidity, etc.
- Consumer Electronics Sensors: Found in devices like smartphones, wearables, etc., for various purposes such as motion sensing, biometric measurements, etc.

This classification is not exhaustive, but it covers the most common types of sensors based on their working principles.

5.2 Temperature sensors

The thermoresistances

Thermoresistors are temperature sensors that utilize the principle of resistance change with temperature. These devices typically consist of a resistive material whose resistance varies with changes in temperature.
As the temperature increases or decreases, the resistance of the thermoresistor changes accordingly. This change in resistance can be measured and correlated with the temperature of the environment in which the thermoresistor is placed.

Metals	Resistivity at\\ 0°C ($\mu\Omega$)	**Melting Point (°C)**	**Range of Use (°C)**	$\frac{R(100C)}{R(0C)}$
Copper	7	1 083	-190 to 250	1,427
Nickel	6,38	1 453	-60 to 180	1,672
Platinum	9,81	1 769	-250 to 1100	1,392

Table 5.1: Metals used

Thermoresistors are commonly used in various applications for temperature measurement and control, such as in industrial processes, automotive systems, and electronic devices.

1-The metal resistances:

Principle: The resistivity of a metal or alloy depends on the temperature:

$$\rho = \rho_0(1 + \alpha(T - T_0))$$

Where:

- ρ is the resistivity at temperature T
- ρ_0 is the resistivity at reference temperature T_0
- α is the temperature coefficient of resistivity
- T is the current temperature
- T_0 is the reference temperature

Resistance-temperature : Within a measurement range depending on each metal:

$$R(T) = R(0)(1 + AT + BT^2 + CT^3)$$

where:

- $R(0)$: resistance at 0°C;
- 3 other calibration points allow us to determine A, B, C.

Example: The Pt100 probe: a platinum resistance probe of 100Ω at $100°C$.

The Pt100 probe, also known as a platinum resistance thermometer, is a type of temperature sensor commonly used in various industrial and scientific applications. "Pt" stands for platinum, which is the material used for the resistance element, and "100" indicates its nominal resistance at 0°C.

Here is a brief explanation of the Pt100 probe:

1. **Material**:
   Pt100 probes utilize a platinum resistor as the sensing element. Platinum is chosen because of its linear resistance-temperature relationship, stability, and high accuracy over a wide temperature range.

2. **Nominal Resistance**:
   The "100" in Pt100 refers to its nominal resistance at 0°C, which is 100 ohms. At this temperature, the resistance of the Pt100 probe is approximately 100 ohms.

3. **Temperature Measurement**:
   The resistance of the Pt100 probe changes linearly with temperature. By measuring the resistance of the probe, the temperature of the surrounding environment can be accurately determined using appropriate calibration curves or conversion tables.

4. **Accuracy and Precision**:
   Pt100 probes are known for their high accuracy and precision in temperature measurement. They are commonly used in industries where precise temperature control and monitoring are essential, such as pharmaceutical, food processing, automotive, and aerospace industries.

5. **Applications**:
   Pt100 probes find applications in a wide range of industries and processes, including HVAC (heating, ventilation, and air conditionnel) systems, laboratory equipment, environmental monitoring, industrial ovens, and medical devices.

Overall, Pt100 probes offer reliable and accurate temperature measurement capabilities, making them indispensable tools in many fields where precise temperature monitoring is crucial.

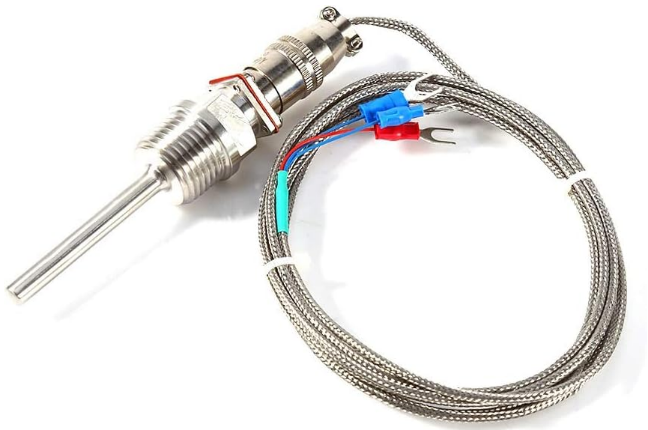


Figure 5.1: PT100 Temperature Sensor, 3 Wire

PT100 Temperature Sensor Specifications. (Figure 5.1)

- Type: PT100
- Wiring Configuration: 3-Wire
- Temperature Range: -40°C to 450°C

Advantages:

- Very precise.
- Easy to implement.
- Can be approximated by a linear law.

Disadvantages:

- Sensitive to self-heating and variations in connection resistances.

2- The thermistors:

A thermistor is an aggregate of sintered metal oxides, which means compacted by high pressure exerted at elevated temperature, typically around 150 bars and 1000°C. The composition of a thermistor can be, for example:

- Fe_2O_3 (ferric oxide)
- $MgAl_2O_4$ (magnesium aluminate)

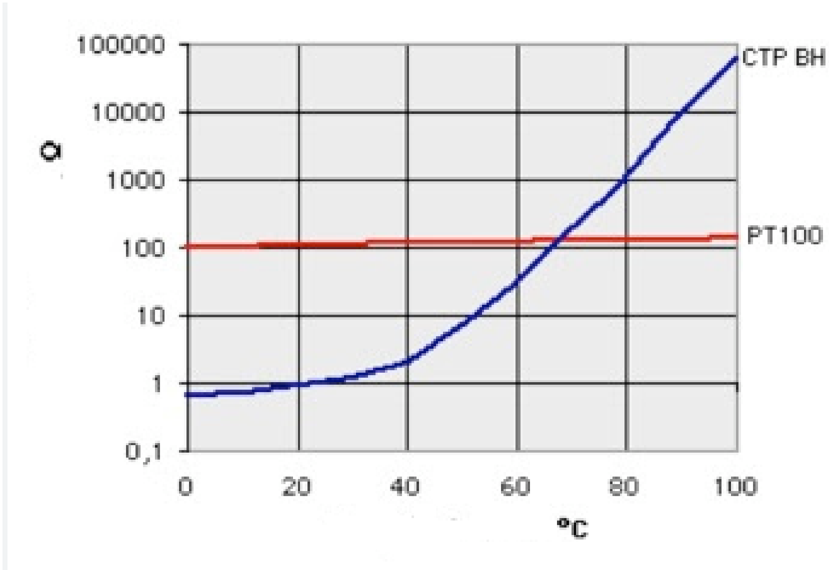


Figure 5.2: Resistance as a function of temperature for a PTC BH thermistor and a platinum Pt100 probe

- Zn2TiO4 (zinc titanate)

The electrical resistance of a thermistor is highly sensitive to temperature. There are two types of thermistors: NTCs (Negative Temperature Coefficient) and PTCs (Positive Temperature Coefficient).
The variation law is of the form:

$$R = a \cdot e^{b/\theta}$$

Where:

- R is the resistance,
- θ is the temperature in Kelvin,
- a and b are constants.

Resistance-temperature relationship of NTCs:

$$R(T) = R(0) \cdot e^{B \cdot T(0)}$$

Where:

- $R(0)$: resistance at 0°C

Advantages: Fast response time, lower cost.

Disadvantages: Non-linear behavior, diversity of characteristics within series, sensitivity to self-heating and variations in connection resistances.

Thermocouples

Principles

Thermoelectric phenomena in chains of metallic or semiconductor conductors describe energy conversions that occur within them, aside from Joule heating, between thermal agitation energy and the electric energy of moving charges. At the junction of two different conductors A and B but at the same temperature, a potential difference is established that depends only on the nature of the conductors and their temperature θ (Seebeck and Peltier effects. Figure 5.3):

$$V_M - V_N = P_{AB}^{\theta}$$

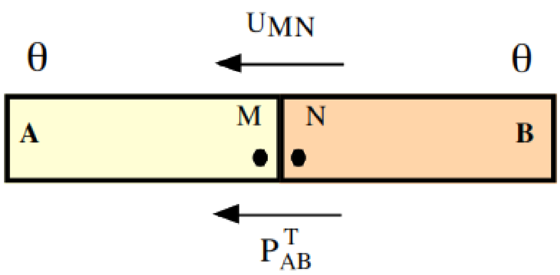


Figure 5.3: Peltier effects

The law of Volta tells us that in an isothermal circuit, consisting of different conductors, the sum of the Peltier electromotive forces (EMF) is zero. Thus:

$$P_{AB}^{\theta} + P_{BC}^{\theta} = P_{AC}^{\theta}$$

Between two points M and N at different temperatures, inside a homogeneous conductor A, an electromotive force is established that depends only on the nature of the conductor and the temperatures at points M and N (Thomson effect. Figure 5.4):

$$T_A^{\theta_M \theta_N} = \int_{\theta_N}^{\theta_M} h_A \times d\theta$$

This is the Thomson electromotive force; h_A the Thomson coefficient of conductor A is a function of temperature. Consider a closed circuit consisting of two conductors A and B whose junctions are at temperatures θ_1 and θ_2. This circuit constitutes a thermoelectric couple. This couple is the site of an

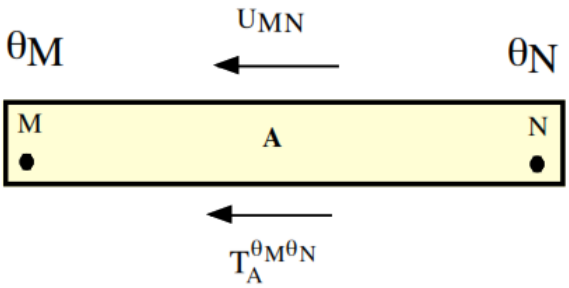


Figure 5.4: Thomson effect

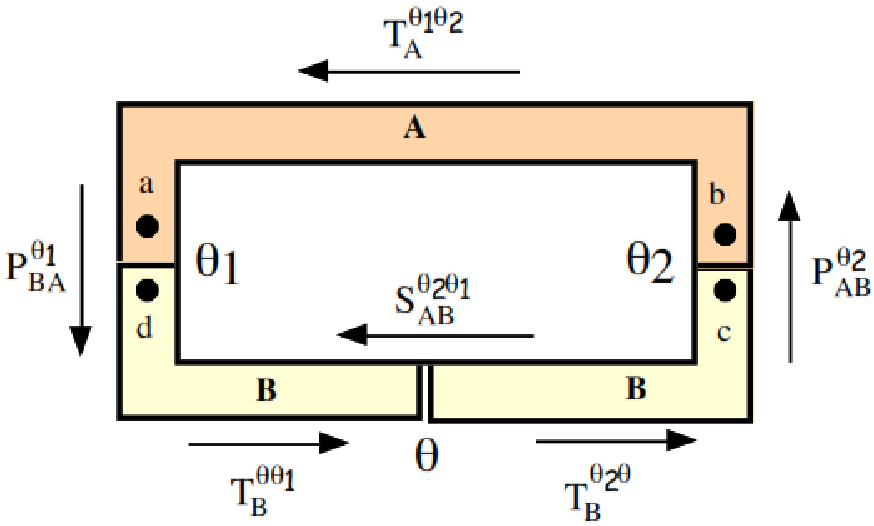


Figure 5.5: Seebeck effect

electromotive force called Seebeck electromotive force, which results from the Peltier and Thomson effects occurring within it.

$$S_{AB}^{\theta_2\theta_1} = T_B^{\theta_2\theta} + P_{AB}^{\theta_2} + T_A^{\theta_1\theta_2} + P_{BA}^{\theta_1} + T_B^{\theta\theta_2}$$

$$S_{AB}^{\theta_2\theta_1} = T_B^{\theta_2\theta_1} - T_B^{\theta_2\theta_2} + P_{AB}^{\theta_2} - P_{BA}^{\theta_1}$$

We demonstrate (composition laws):

$$S_{AC}^{\theta_2\theta_1} = S_{AB}^{\theta_2\theta_1} + S_{BC}^{\theta_2\theta_1}$$

$$S_{AB}^{\theta_3\theta_1} = S_{AB}^{\theta_3\theta_2} + S_{AB}^{\theta_2\theta_1}$$

Example:

We are looking for the EMF provided by the thermocouple for the temperature pair: (4°C; 27°C). We can represent the data as shown in Figure 5.6.
The EMF is equal to $(1381\mu V - 202\mu V)$ which is $1179\mu V$.

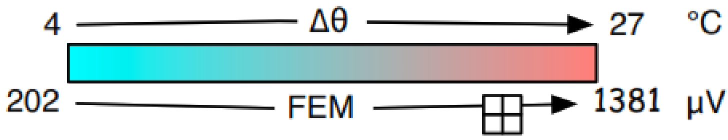


Figure 5.6: Temperature/EMF

Compensation cables

We use compensation cables in two cases:

- When the metals forming the couple are very expensive (precious metals in particular);
- When the distance between the temperature measurement point and the reference junction is large;

It is then appropriate to reduce the resistance of the circuit when the internal resistance of the reading device is higher (galvanometer).
The principle wiring diagram is shown in Figure 5.7. The length of wires A and B of the thermocouple is kept to a minimum.
The connection between the intermediate junction at temperature θ_2 and the reference junction at temperature θ_{ref} is ensured by compensation cables A' and B' associated with metals A and B, respectively. The condition to be met is that the electromotive force at the terminals of the A' and B' conductors combined in a couple is the same as that of the couple (A, B). This condition

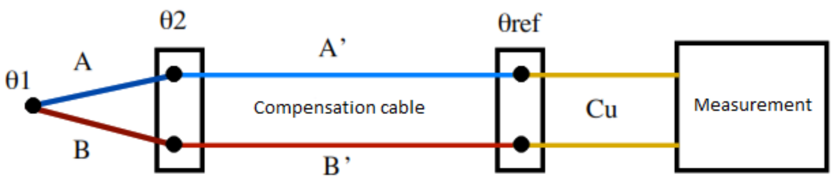


Figure 5.7: Compensation cables

is expressed by the equation:

$$S_{AB}^{\theta_2\theta_{ref}} = S_{A'B'}^{\theta_2\theta_{ref}}$$

In conclusion, compensation cables A' and B' do not modify the voltage delivered by the couple AB provided that:

- Junctions AA' and BB' are at the same temperature T_2;
- Couples $A'B'$ and AB have the same Seebeck electromotive force between T_2 and $0C$.

Measurement methods

Method of opposition: A variable voltage source is placed opposite the EMF to be measured. When the current is zero, the variable source has the same voltage as the EMF to be measured (Figure 5.8).

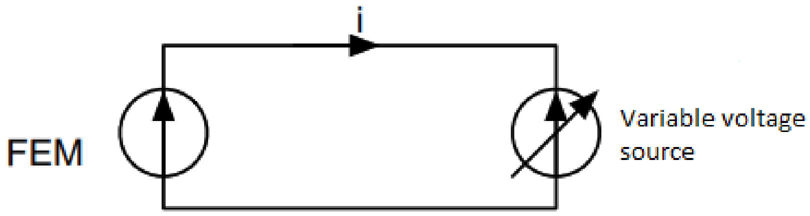


Figure 5.8: Method of opposition

Exercise 1

Consider a thermostatic enclosure which is kept at a constant temperature $T_u = 20°\text{C}$; the surrounding environment temperature is $T_0 = 10°\text{C}$. The enclosure is heated using a heat source whose temperature is T_a (see Figure 1). To measure the temperatures at these points, three Chromel-Alumel thermocouples are used. The reference junctions for these thermocouples are kept at the ambient temperature T_0.

1. **Explain the principle of a thermocouple:**
   A thermocouple operates on the *Seebeck effect*, which states that a voltage (thermoelectric EMF) is generated when two dissimilar metals are joined

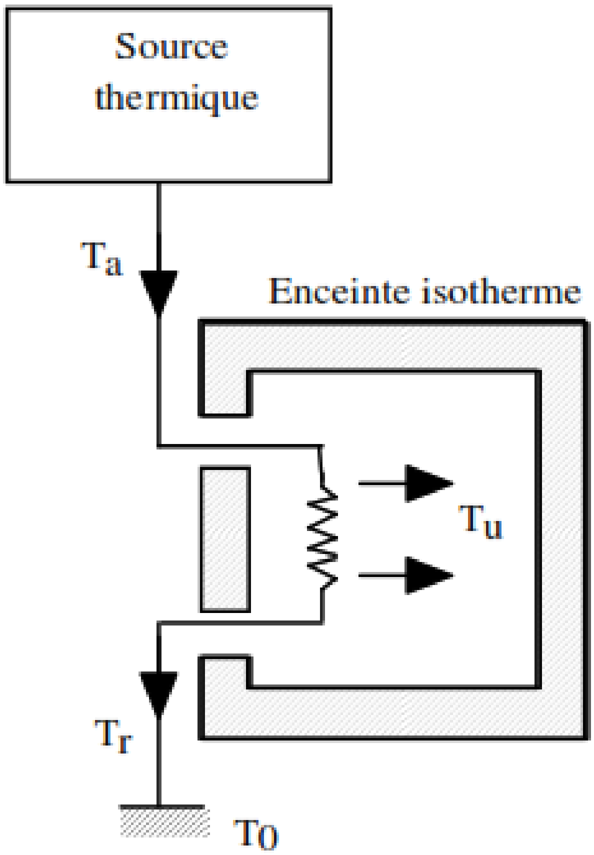


Figure 5.9: Heating of isothermal enclosure

at two junctions and maintained at different temperatures. The generated voltage is proportional to the temperature difference between the two junctions:

$$V = S \cdot (T_{\text{hot}} - T_{\text{cold}}),$$

where S is the Seebeck coefficient, T_{hot} is the temperature of the measuring junction, and T_{cold} is the temperature of the reference junction.

2. **List the names of some other temperature transducers:**
   - Resistance Temperature Detector (RTD)
   - Thermistor
   - Infrared (IR) Thermometer
   - Liquid-in-glass Thermometer
   - Silicon Bandgap Temperature Sensor

3. **The thermocouple measuring the temperature T_u is connected to the terminal of a digital voltmeter. What should be the value**

of the displayed voltage at the voltmeter screen?
Using the Seebeck effect equation and assuming the reference junction temperature $T_0 = 10°\text{C}$ and measuring junction temperature $T_u = 20°\text{C}$, the voltage is given by:

$$V = S \cdot (T_u - T_0).$$

Substituting values and the Seebeck coefficient for Chromel-Alumel thermocouples ($S \approx 41\,\mu\text{V}/°\text{C}$):

$$V = 41 \cdot 10 = 410\,\mu\text{V} = 0.41\,\text{mV}.$$

4. **Actually, the value displayed by the voltmeter is** $0.652\,\text{mV}$**. Explain this result:**
The observed discrepancy arises because the Seebeck coefficient S can vary slightly with temperature. The thermocouple does not have a perfectly linear response, and calibration differences or slight environmental factors (e.g., contact resistance) can affect the measurement.

5. **The voltmeter connected to the thermocouple measuring T_a displays a voltage equal to** $6.112\,\text{mV}$**. What is the heat source temperature T_a?**
Using the Seebeck effect:

$$V = S \cdot (T_a - T_0),$$

solving for T_a:

$$T_a = \frac{V}{S} + T_0.$$

Substituting $V = 6.112\,\text{mV}$, $S = 41\,\mu\text{V}/°\text{C}$, and $T_0 = 10°\text{C}$:

$$T_a = \frac{6112}{41} + 10 \approx 149°\text{C}.$$

Exercise 2

A bi-metallic strip is fabricated from stainless steel and Invar with thickness of 5 mm and 1 mm respectively. This sensor is used in thermostats to control temperatures.

1. Explain the principle of functioning of this sensor in this case

2. Our aim is to maintain a temperature of $T = 120\,°\mathrm{C}$. Determine the expansion of each strip at this temperature. The length of the strip at the initial temperature $T_0 = 10\,°\mathrm{C}$ is $L_0 = 22\,\mathrm{cm}$.

3. Determine the radius of curvature of the strip if it undergoes a temperature of $T = 120\,°\mathrm{C}$.

   The radius of curvature ρ is given by:

$$\rho = \frac{\left[3 \cdot (1 + r_h)^2 + (1 + r_h r_e)\left(r_e^2 - \frac{1}{r_h r_e}\right)\right] \cdot h}{6 \cdot (\alpha_1 - \alpha_2) \cdot (1 + r_h) \cdot \Delta T},$$

   where:

$$r_h = \frac{h_2}{h_1}, \quad \text{the thickness ratio,}$$
$$r_e = \frac{E_2}{E_1}, \quad \text{the modulus of elasticity ratio.}$$

4. Determine the sensitivity of this sensor at 120°C (Write the equation 1 as:

$$\rho = K \cdot \Delta T$$

5. If the smallest length variation that can be measured by the sensor used to measure the radius of curvature is 0.001 mm, determine the resolution of the bimetallic strip at this temperature.

6. We suppose that the length L(T) of the bimetallic strip at the temperature T, is the average of the two strip lengths. The switch controlling the thermostat will be placed at a distance e under the extremity of the strip supposed straight at the temperature T0 (figure 5.10).

7. Demonstrate that if T is the desired temperature, the switch must be placed at the distance:

$$e = \rho(T) \bullet \left(1 - cos\left(\frac{L(T))}{\rho(T)}\right)\right)$$

   Calculate e for T = 120°C

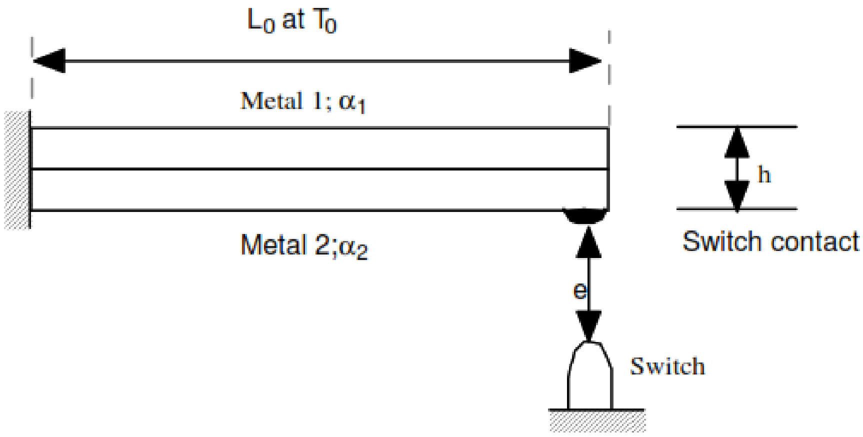


Figure 5.10: Functioning principle of a Bimetallic strip

8. If the error on $L(T)$ and $\rho(T)$ is 1%, determine the possible error on the distance e. The mechanical and thermal properties of stainless steel and Invar are as follows:

   - **Stainless Steel:**
     - $E_1 = 193\,\mathrm{GPa}$
     - $\alpha_1 = 17.3 \times 10^{-6}\,°\mathrm{C}^{-1}$
   - **Invar:**
     - $\alpha_2 = 1.1 \times 10^{-6}\,°\mathrm{C}^{-1}$
     - $E_2 = 145\,\mathrm{GPa}$

Semiconductor temperature sensors

Temperature sensors using semiconductor materials operate based on the principle that the voltage across the semiconductor (forming a diode or a transistor) and the current passing through it depend on the temperature.

$$I = I_0 \cdot e^{\frac{qv}{K_T}}$$

with :

$$I_0 = C \cdot T^m \cdot e^{\frac{-q\Theta}{kT}}$$

- V_Φ: bandgap energy (1.12 eV for silicon)
- C: constant depending on the geometry of the junction

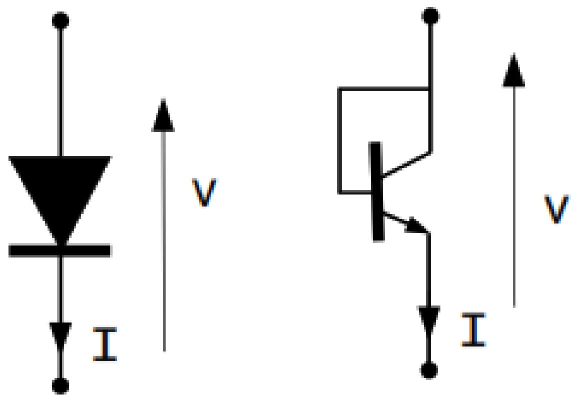


Figure 5.11: Temperature diode sensor

- m: coefficient close to 3
- Boltzmann constant ($1.3806488(13) \times 10^{-23}$ J/K)

At constant current I, the measurement of V is linear with respect to temperature: $V = aT + b$.

- a depends on the sensing element
- $$b = \frac{2k}{q}(lnK - lnI)$$
- $$b \approx -2mV/C$$

K temperature constant.
The sensor is measured for a reference temperature T_1; let v_1 be the voltage for a given current I. The measured voltage at temperature T is:

$$v(T) = v_1\frac{T_1}{T_2} + v_\Phi(1 - \frac{T}{T_1}) + m\frac{KT}{q}\ln\frac{T}{T_1}$$

This relationship is nonlinear, but for specialized components, the error is within 1°C in the range $[0 - 100C]$.
The thermal sensitivity of a 1N4148 diode is approximately $-2.15mV/C$.
An example of a semiconductor temperature sensor is the LM35 precision

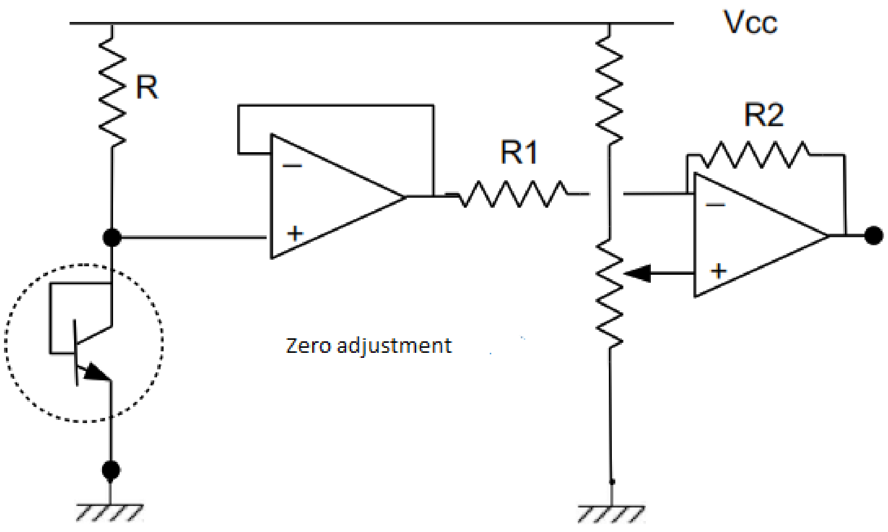


Figure 5.12: Cost-effective circuit with current injection resistor

integrated-circuit temperature sensor.
This sensor provides an accurate voltage output that is linearly proportional to the Celsius (Centigrade) temperature. It doesn't require any external calibration and can measure temperatures ranging from -55°C to +150°C.

5.3 Photoelectric sensors

Passive optical detectors: The photoresistor

Definition:
The photoresistor (or photoconductive cell) is an electronic component whose resistivity ρ varies depending on the amount of incident light. The physical phenomenon underlying its use (photoconduction) results from an internal photoelectric effect:
the release of electric charges within the material under the influence of light and a correlated increase in conductivity (or decrease in resistivity).
The resistance can then be expressed as follows:

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

$$R = \frac{1}{\sigma} \frac{L}{A} = \frac{1}{q \cdot \mu \cdot n} \frac{L}{A}$$

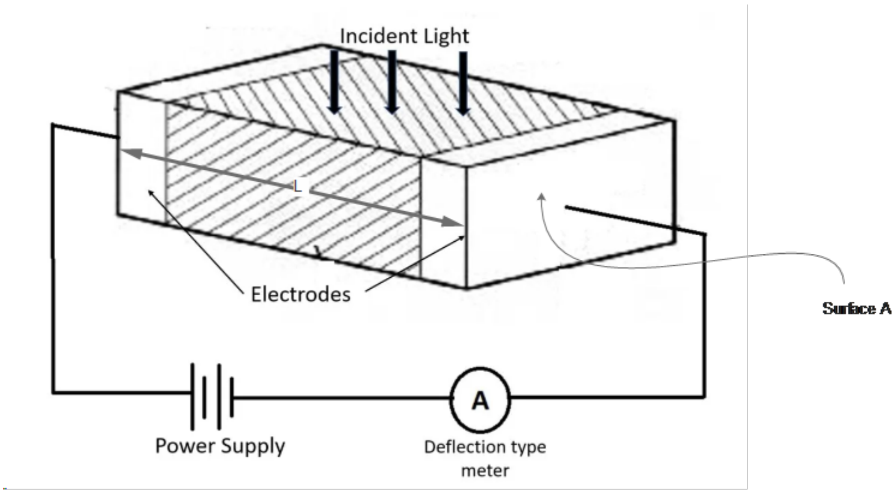


Figure 5.13: Photoconductive cell

where:

σ : conductivity of the material
q : charge of the electron
μ : electron mobility
n : density of electrons present (a function of illumination)
A : surface area of the plate
L : length of the plate

The cells are made using homogeneous polycrystalline or monocrystalline semi-

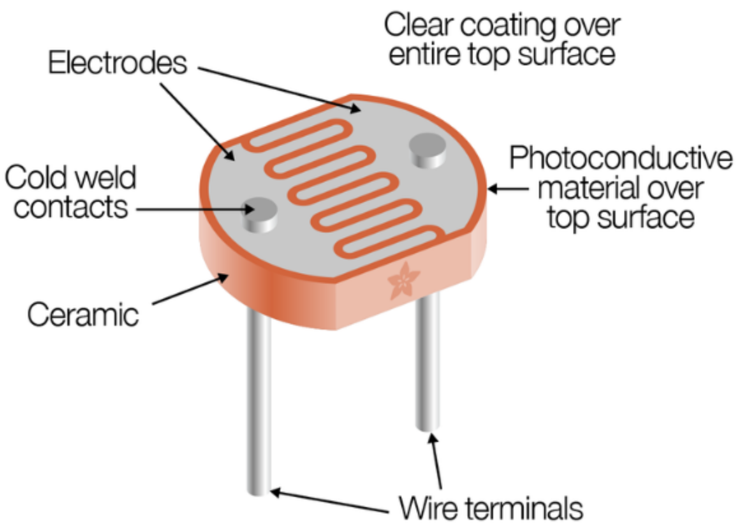


Figure 5.14: The photoresistor or LDR (Light-dependent resistor)

conductor materials, intrinsic (pure) or extrinsic (doped):

- Polycrystalline materials: CdS, CdSe, CdTe, PbS, PbSe, PbTe;
- Monocrystalline materials: Pure Ge and Si or doped with Au, Cu, Sb, Zn, SbIn, AsIn, PIn, CdHgTe.

Light/Resistance Characteristic:

Example:

- Darkness: $R_0 = 20\,\text{M}\Omega$
- Natural light: $R_1 = 100\,\text{k}\Omega$
- Intense light: $R_2 = 100\,\Omega$

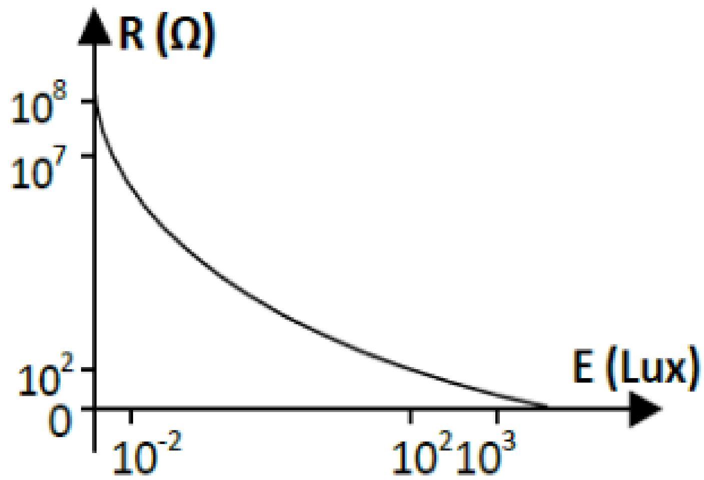


Figure 5.15: Example of variation in the resistance of a photoconductive cell

-Advantages:

- Good sensitivity
- Simplicity of some usage setups
- Low cost and robustness

- Disadvantages:

- Non-linearity of response with respect to flux
- Generally high response time and limited bandwidth

- Susceptible to heat

Usage: Detection of changes from darkness to light (public lighting).

Active optical detectors: The photodiode

Definition: The photodiode is a component based on the junction of a P-type semiconductor and an N-type semiconductor:

- Each photon absorbed by the semiconductor can create an electron-hole pair.
- Under the action of the internal field, the electron diffuses towards the N region and the hole towards the P region.
- Diffusion of holes and electrons in opposite directions.
- These carriers give rise to a generation photocurrent.

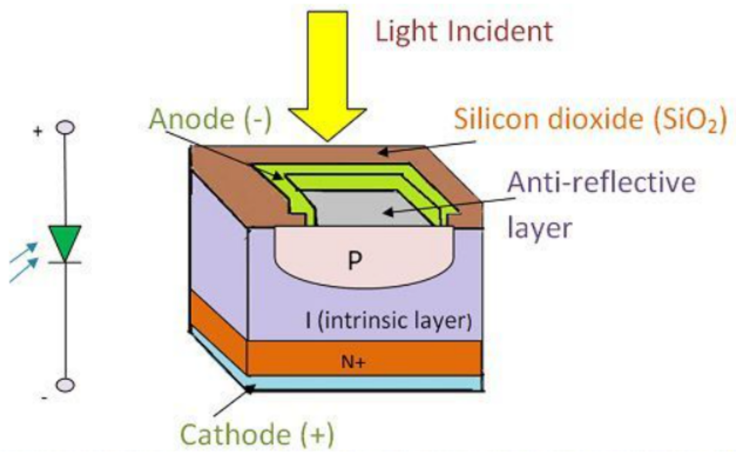


Figure 5.16: Construction photodiode

At the component level, the photodiode consists of a stack of thin layers, with respective thicknesses on the order of micrometers, or even less (Figure 5.16).

Basic configuration

Curve: The graph I = f(U) for a photodiode depends on the illumination of the PN junction.

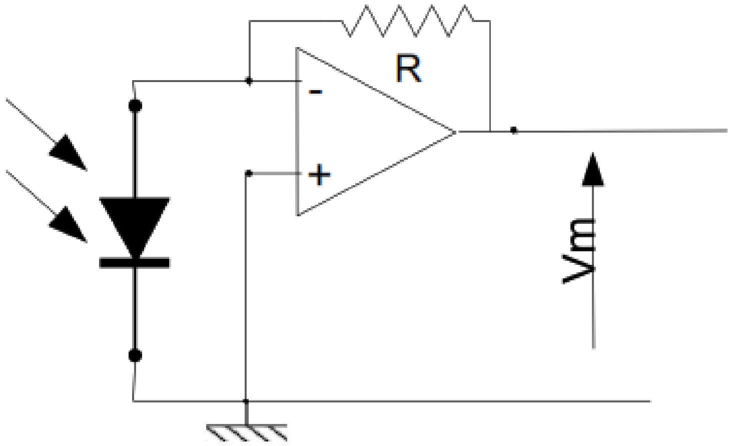


Figure 5.17: Zero-voltage photovoltaic cell configuration with transimpedance amplifier (current amplifier)

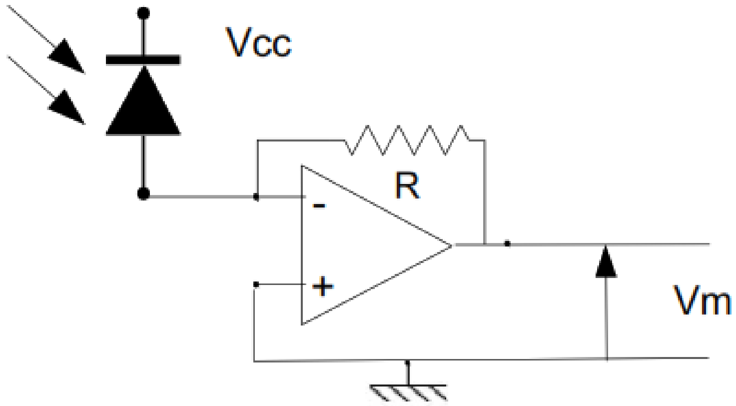


Figure 5.18: Inverse bias configuration with reverse leakage current measurement

Advantages/Disadvantages

Advantages

- Good sensitivity.
- Low response time (high bandwidth).

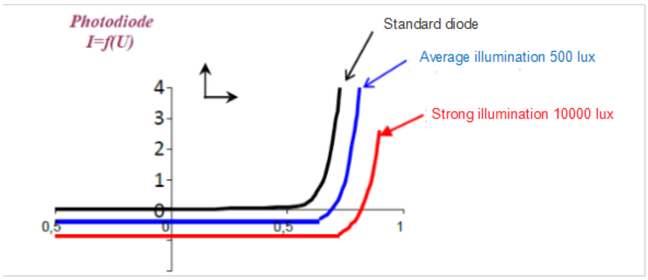


Figure 5.19: Current-voltage characteristic of a photodiode

Disadvantages

- Higher cost compared to a photoresistor.
- Requires a precise biasing circuit.

Applications

- Infrared remote data transmission.
- Passage detection.

BPW34 Photodiode

The BPW34 is a high speed Photodiode that is commonly used in control and driver circuits. Because of it's short switching time (20nS) it can be used in isolated data communication circuits and other remote communications like TV sets, dimmers and other equipments.

Specifications

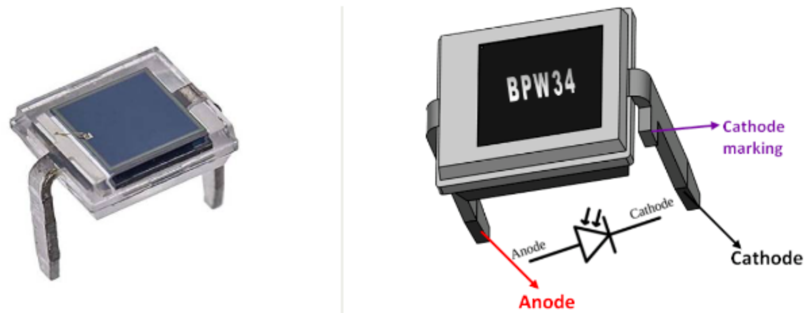


Figure 5.20: BPW34 Photodiode

- **Reverse Breakdown Voltage**: 60V
- **Switching Speed**: 20ns

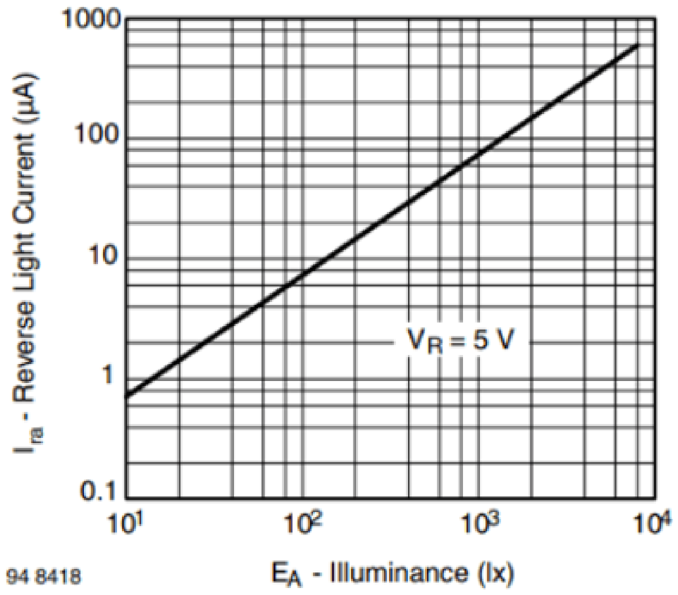


Figure 5.21: Reverse light current vs Ea

- **Diode Capacitance**: 70pF (at 1MHz, Vr=0V)
- **Open Circuit Voltage**: 350mV
- **Rise Time**: 100ns
- **Fall Time**: 100ns

The BPW34 photodiode finds application in various circuits including:

- **Switching Circuits**:
  Due to its high-speed performance, the BPW34 is commonly used in switching circuits where rapid response times are essential.
- **Isolation Circuits**:
  With its capability for fast switching and reliable performance, the BPW34 is ideal for use in isolation circuits to ensure signal integrity and electrical separation.
- **Coupling Circuits**:
  The BPW34 can be employed in coupling circuits to transfer signals between different electronic components or systems while maintaining isolation and minimizing interference.

5.4 Piezoelectric sensors

Piezoelectric effect

Piezoelectric sensors are devices that use the piezoelectric effect to measure changes in pressure, acceleration, temperature, or force by converting them into an electrical charge.
The piezoelectric effect refers to the ability of certain materials to generate an electric charge in response to applied mechanical stress or strain (Figure 5.22).
A force applied to a quartz blade induces a deformation that gives rise to

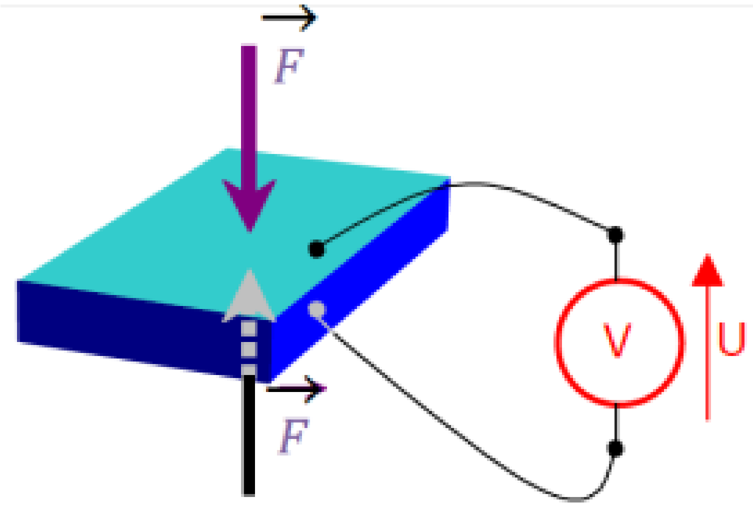


Figure 5.22: Piezoelectric effect

an electrical voltage. The main advantage of piezoelectric sensors is their immediate responsiveness. These are phenomena at the atomic/molecular scale that come into play and are ultra-fast compared to the phenomena studied in the science of motion. Piezo sensors are therefore a good choice when studying dynamic phenomena. They are extremely sensitive to vibrations, which is not always an advantage.

Force sensors

The principle is given by the following Figure 5.23. The output voltage V_S will be proportional to the force F:

$$V_S = k \cdot (F + F) = 2k \cdot F$$

with k constant.
Typically, the appearance of a piezoelectric sensor is illustrated in Figure 5.23.

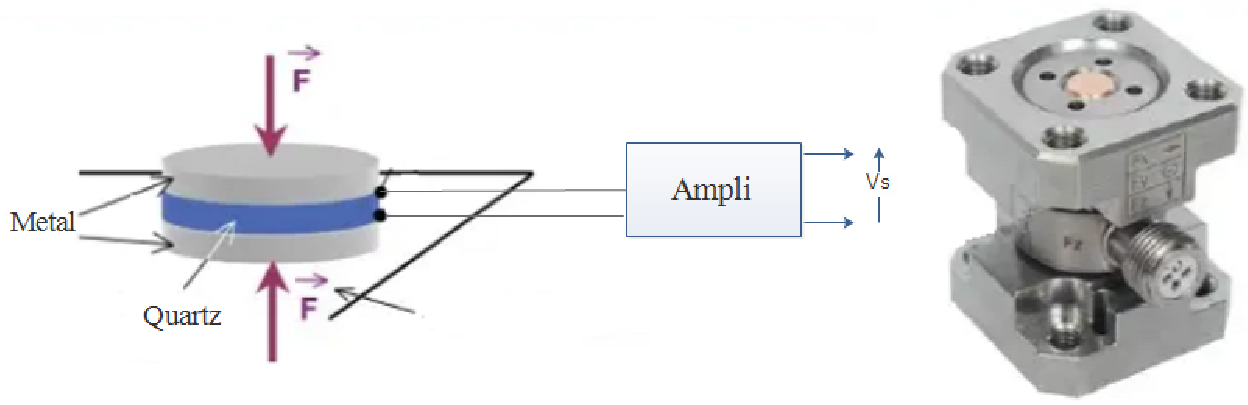


Figure 5.23: Force sensor

The sensor is placed between two metal plates, one resting on the substrate, the other on the plate that will receive the force. The sensor delivers three measurable charges, each corresponding to a direction in space.

Pressure Sensors

When a body (gas, liquid, or solid) exerts a force F on a surface S (area), we can define the pressure P exerted by this body with the following relation:

$$P = \frac{F}{S}$$

With :

$$1Pa = \frac{N}{m^2}$$

and

$$1kg = 9.8N$$

Units:

$$1 \text{ bar} = 10^5 \text{ Pa} = 100,000 \text{ N/m}^2 = 10,000 \text{ kg/m}^2 = 1 \text{ kg/cm}^2$$

Principle: The force sensor is inserted into the wall of a chamber where a pressure P prevails. One side of the sensor is subjected to the force F (pressure P) and the other side is subjected to the force F_0 (external pressure P_0) (Figure 5.24). We have

$$F = P \cdot S \Rightarrow F_0 = P_0 \cdot S_0$$

and

$$u_s = k \cdot (F + F_0)$$

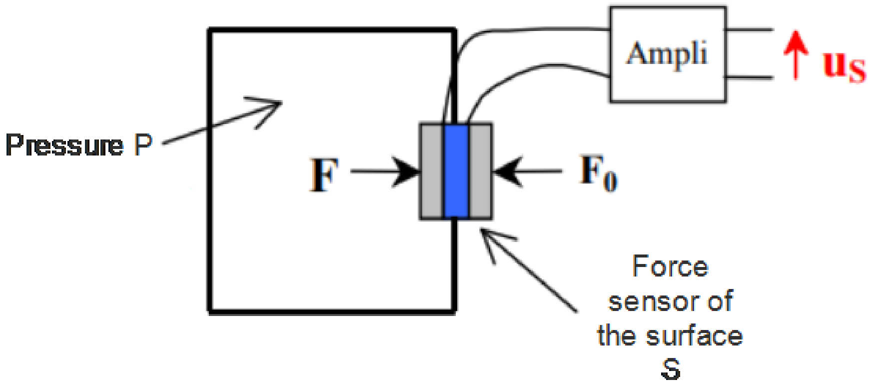


Figure 5.24: Pressure Sensor

k = constant,
So:

$$U_s = k \cdot S(P + P_0) = k'(P + P_0) \Rightarrow U_s = k'(P + P_0)$$

This is a pressure sensor that measures the sum of the external pressure P_0 and the pressure inside the chamber P.

Acceleration sensor

An "acceleration sensor" or "accelerometer" is a device used to measure acceleration, which is the rate of change of velocity of an object. Accelerometers can measure acceleration along one, two, or three axes depending on their design. They are widely used in various applications, including:Motion Sensing,Vehicle Dynamics,Structural Health Monitoring and Medical Devices.
An accelerometer is a device that measures the vibration or acceleration of motion of a structure. The force caused by vibrations or a change in motion (acceleration) pushes the mass to "squeeze" the piezoelectric material, which produces an electric charge proportional to the force exerted on it. Since the charge is proportional to the force, and the mass is constant, the charge is therefore also proportional to the acceleration.
The principle: The increase in velocity V of the vehicle results in an acceleration a which induces a force F exerted by the mass on the sensor. Therefore, we have:

$$F = m \cdot a$$

but

$$U_s = 2K \cdot F$$

Thus

$$U_s = 2K \cdot m \cdot a$$

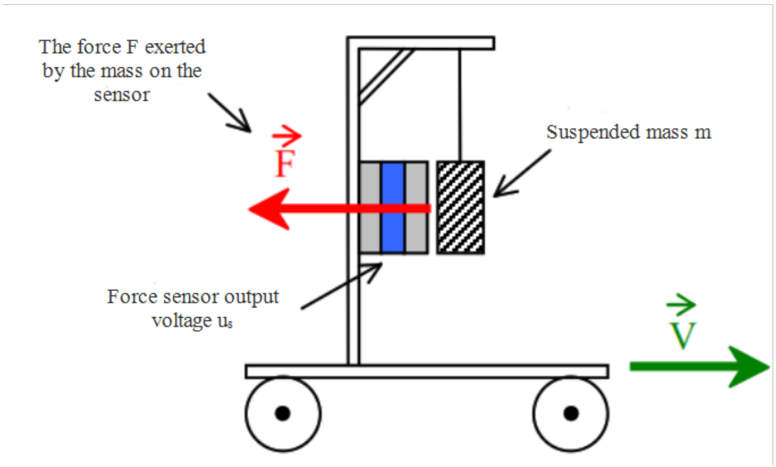


Figure 5.25: Acceleration sensor

Main features:

- Most commonly used for measuring moderate shocks and vibrations. Large bandwidth (0.2Hz-30KHz).
- Very variable size, adaptable to the test configuration (0.2g for the smallest).
- Robust, mature technology.

5.5 Hall Effect Sensors

Their principle is based on an old discovery. In 1879, the American physicist Edwin Herbert Hall discovered that if a current-carrying conductor is introduced into a magnetic field, an electromotive force proportional to the applied magnetic field and the current flowing through the conductor appears. This is the Hall effect.
Principle: A semiconductor bar subjected to a uniform magnetic field B and traversed by a current I, experiences an electromotive force U on two of its faces. The Hall voltage U_H is defined by the equation:

$$U_H = R_H \cdot \frac{IB}{e}$$

with:

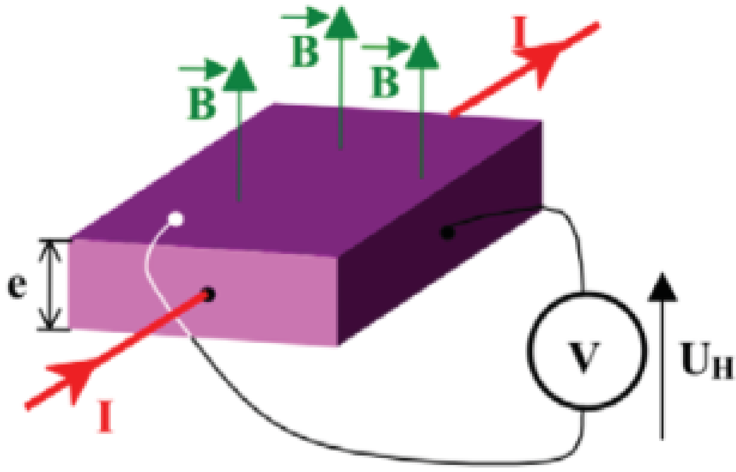


Figure 5.26: Principle of Hall Effect Sensors

- R_H: Hall constant (depends on the semiconductor).
- I: current source intensity (A).
- B: magnetic field intensity (T).
- e: thickness of the silicon bar.

If we maintain the current I constant, we then have a voltage U proportional to the magnetic field B.

$$U_H = k.B$$

With

$$k = \frac{R_H \cdot I}{e}$$

Today, we use this effect for various detection applications (proximity, position, current, rotation speed), as well as for switching applications.

The use of Hall effect sensors offers numerous advantages. They are static sensors (without any contact bouncing) that have a longer lifespan and can be used in high-speed applications. They can also be utilized in challenging conditions, with a lower price level compared to mechanical switches.

Magnetic field sensor

Hall effect sensors allow for the measurement of magnetic fields (in tesla). The typical structure of a magnetic field sensor is as follows: The sensitivity of this sensor can be adjusted by acting on I and on A.

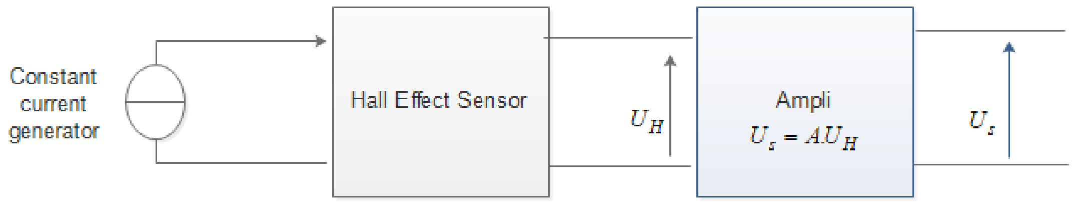


Figure 5.27: Magnetic field sensor

Measurement of the intensity of an electric current

Given that a current can generate a magnetic field, it can also be used to measure the intensity of electric currents. The current I generates a magnetic field proportional to this current:

$$B = \frac{\mu I}{2\pi r}$$

The sensor provides a voltage:

$$U_s = k \cdot B = k' \cdot I$$

with k and k' constants.
This is the principle of ampere clamps (measurement of high currents of 1000A and above).

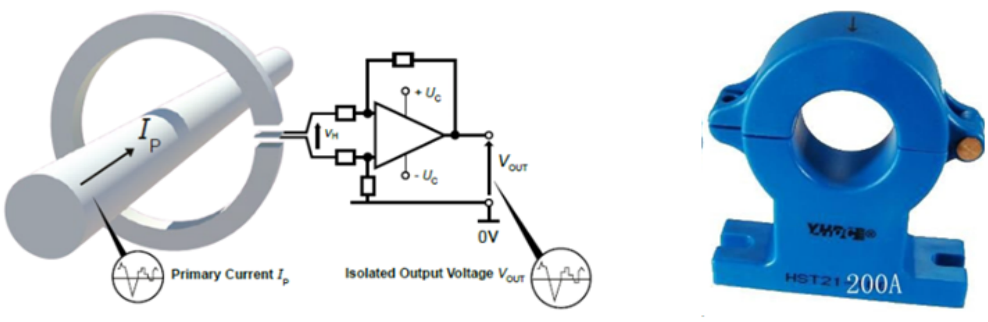


Figure 5.28: Principle of the Hall Effect current sensor

Proximity sensors

These sensors are primarily used in sequential systems. They provide information about the presence or absence of an element. These sensors are also called 'TOR sensors. Examples of proximity sensors include:

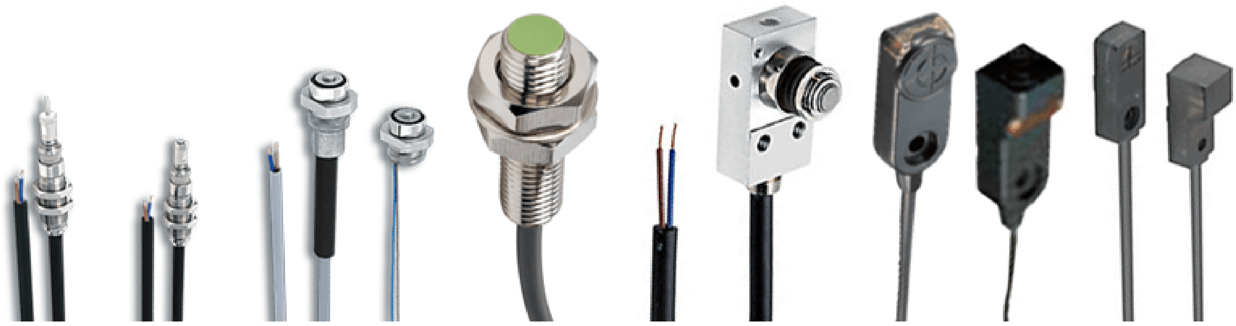


Figure 5.29: Proximity sensors

- **Inductive Proximity Sensors:**
  These sensors detect the presence of metallic objects by generating an electromagnetic field. When a metallic object enters the field, it disrupts the field, causing the sensor to detect the object's presence.

- **Capacitive Proximity Sensors:**
  These sensors detect the presence of both metallic and non-metallic objects by measuring changes in capacitance. When an object enters the sensor's detection range, it changes the capacitance, triggering the sensor to detect its presence.

- **Photoelectric Proximity Sensors:**
  These sensors use light to detect the presence or absence of objects. They emit a beam of light, and when an object interrupts the light beam, the sensor detects the object's presence.

- **Ultrasonic Proximity Sensors:**
  These sensors use ultrasonic waves to detect the presence of objects. They emit high-frequency sound waves and measure the time it takes for the waves to bounce back. The presence of an object is detected when the waves are reflected back to the sensor.

5.6 Conclusion

This chapter provides some examples of sensors and their manufacturing methods, outlining the advantages and disadvantages of each.

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