Chapter4: Passive Sensors Conditioners

4.1 Adaptation of the signal source to the measurement chain

4.2 Linearisation

4.3 Signal Amplification and Reduction of the Common Mode Voltage

4.4 Information Detection

4.5 Reduction of Disturbances in Measurement Systems

Introduction

The sensor and its possible conditioner (potentiometer, bridge, oscillator…) are the source of the electrical signal which the measurement chain must ensure is processed in the most appropriate way.

In this chapter we propose to study on one hand, a certain number of processing devices (signal conditioners), whose function is directly related to the nature of the signal which is a function of the specific characteristics of the sensor and, where applicable, of its conditioner and on the other hand, the practical conditions of the measurement.

The issues that will be examined concern:

- The appropriate type of interface between signal source and the rest of the measurement chain depending on whether this source is a voltage, current, or charge.
- Linearization of the signal.
- Signal amplification in the presence of common mode voltages.
- Extraction of information related to the measurand when its variations modulate the electrical signal.

4.1 Adaptation of the Signal Source to the Measuring Chain

The sensor, associated with its conditioner when it is passive, is equivalent to a **Thevenin generator** consisting of a **source** and an **internal impedance**, and delivering the signal to the circuit that charges it.

In order for the signal to be obtained in the best conditions, sensitivity and stability with respect to possible variations in the internal impedance, the equivalent generator must be loaded with an appropriate impedance.

4.1.1 Sensors providing voltage

When the information corresponding to the measurand m is delivered in the form of an electromotive force *e.m.f.* $e_c(m)$ in series with an impedance *Zc* which can be important and variable (fig. a):

• Thermocouple with long connection

• Resistive sensor mounted in a Wheatstone bridge

The circuit at the terminals of which the signal *Vm* is collected must have an input impedance *Zi* >>*Zc* to minimize the influence of the latter:

$$V_m = e_c \frac{Z_i}{Z_i+Z_c} \approx e_c$$

If $Z_i >> Z_c$

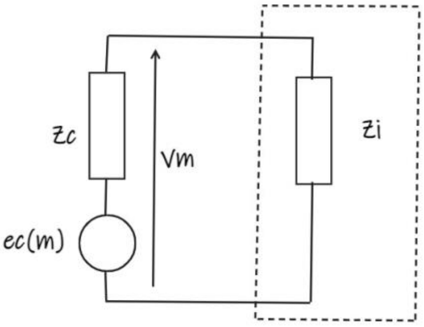


fig a: Schema electrique equivalent

The devices with large input impedances that can be used in this case are:

The operational amplifier in **follower** (fig. b) or **non-inverting** (fig. c) assembly.

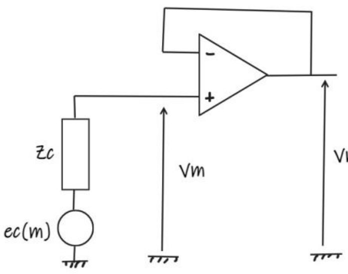


fig b: Montage suiveur

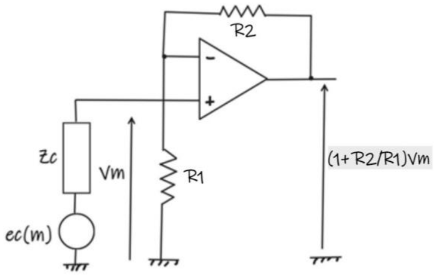


fig c: Montage non-inverseur

4.1.2 Sensors providing current

When the sensor is equivalent to a current source $i_c(m)$ in parallel with an internal impedance Z_C:

- Photodiode
- Photomultiplier

The input impedance *Zi* of the measuring circuit must be much lower than Z_C so that the signal collected i_m is practically equal to i_c and independent of Z_C (fig. a):

$$i_m = i_c \frac{Z_c}{Z_i + Z_c} + i_c \quad \text{for} \quad Z_i \ll Z_c$$

But, the voltage v_m across *Zi* risks in this case being itself very weak.

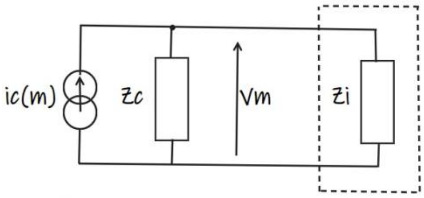


fig a: Schema electrique equivalent

The use of a **current-voltage converter** (fig. b) makes it possible to both reduce the influence of Z_C and obtain a significant voltage v_m.

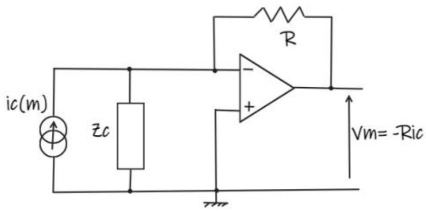


fig b: Convertisseur courant-tension

4.1.3 Sensors providing charge

In the case where the sensor is a generator of charge $q_c(m)$, of internal capacitive impedance (C_C) (fig. a): **piezoelectric crystal**, it is generally not possible to place at its terminals a circuit whose input impedance would be resistive.

Indeed, on the one hand the discharge

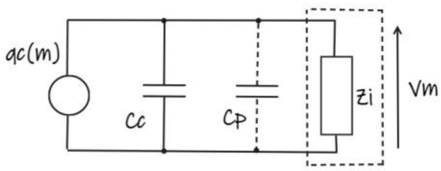


fig a: Schema electrique equivalent

Of the capacity could be too fast to allow the exploitation of the signal,

and on the other hand, the tension collected which depends on all the capacities (C_P) of the assembly (example: cable capacities) would be sensitive to their erratic variations.

The device to be used in this case is the **charge amplifier** (fig. b) which delivers a voltage proportional to the load and independent of the capacitance of the sensor and the connection cables.

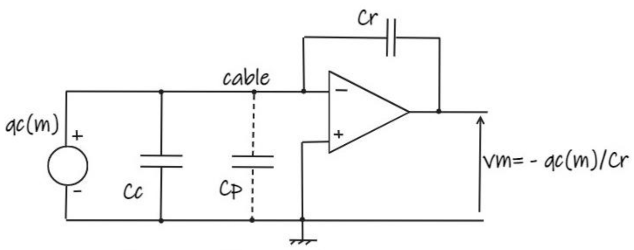


fig b: Amplificateur de charge

4.2 Linearisation

There are a certain number of processes, called linearization prosseses, which make it possible to correct the **linearity defect** of a sensor or its possible conditioner, when they present in their field of use deviations from linearity, prohibiting the sensitivity from being considered as constant to the required measurement precision.

These linearization processes can be classified into two groups:

- On the one hand, those which intervene on the very source of the electrical signal, in order to linearize it from its origin.

- On the other hand, those which intervene downstream of the sensor conditioner.

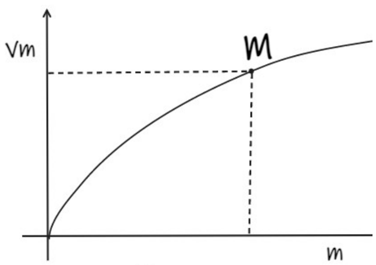
4.2.1 Analog linearization at the signal source

a) Resting point positioning

The process is reminiscent of the

polarization of electronic components.

The transfer characteristic of the



sensor is not linear but has a **rectilinear part**.

It is always possible to position the rest point *M* (fig. a) on this linear range.

The information sought is generated by small variations (small signal regimes in electronics) of the measurand *m* around this rest point (case of photodiodes, phototransistors, etc.)

b) Parallelization on the sensor of an impedance

This method is commonly used to achieve an often limited linear range of an equivalent dipole:

$R_{eq} = R_c \, // \, R$

R_C being a thermistor for example.

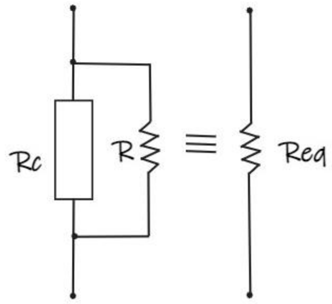


fig b

c) Operation in opposition

Consider two identical R_C sensors, suppose that they are placed in such a way so that they are subject to equal and opposite variations of measurand (fig. c).

At the sensor terminals we have:

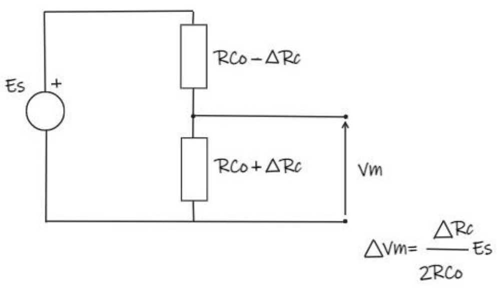


fig c

$V_m = E_s \frac{R_{co}+\Delta R_c}{R_{co}+\Delta R_c+R_{co}-\Delta R_c}$,

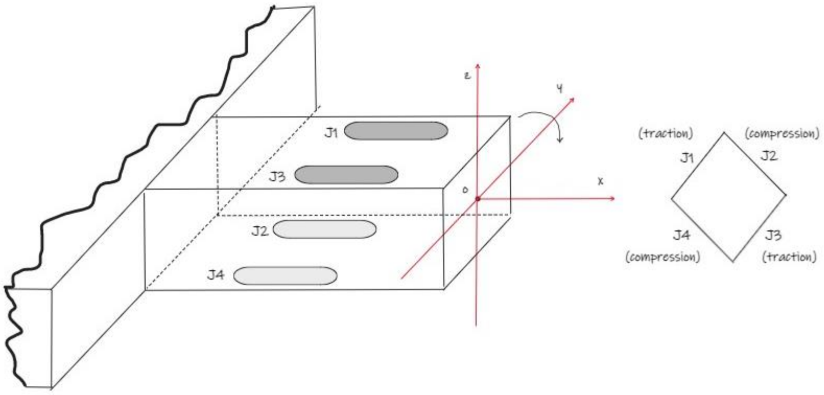
with $\Delta V_m = E_s \frac{\Delta R_c}{2R_{co}}$

Application example

When measuring stresses, it is common for the gauges to be mounted in such a way that two consecutive arms of the bridge work, one in traction and the other in compression.

In simple bending, the upper face of the part works under tension while the lower face undergoes compression.

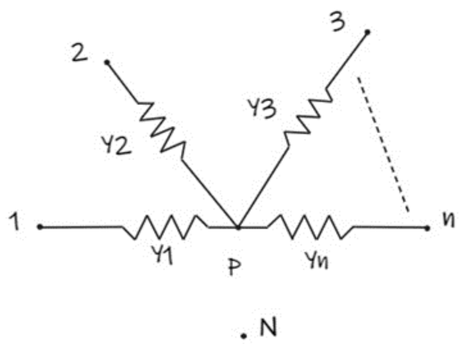
The gauges must be glued as shown in the figure below.



d) Loopback correction (non-linearity of passive sensor conditioner)

Millman's theorem (reminder)

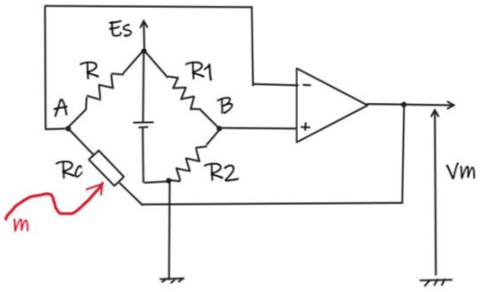
If any number of admittances Y1, Y2, Y3 ... meet at a common point P and the voltages of another point N with respect to the free ends of these admittances are E1, E2, E3 ...



In this case the tension between the two points is given by the following expression:

$$V_{PN} = \frac{E_1 Y_1 + E_2 Y_2 + \cdots + E_n Y_n}{Y_1 + Y_2 + \cdots + Y_n}$$

The sensor is placed in the feedback loop of an op-amp.



When the sensor is at rest, the bridge is balanced:

We have $V_A - V_B = 0$

With $R_{co} = R = R_1 = R_2$

When the measurand varies, we have:

$$R_c = R_{co} + \Delta R_c$$

The bridge is unbalanced:

$$V_B = \frac{E_s}{2}$$

$V_A = \frac{R_c}{R_c+R} E_s + \frac{R}{R_c+R} V_m$ (Millmann)

=> $V_A = \frac{R_{co}+\Delta R_c}{R_{co}+\Delta R_c+R} E_s + \frac{R}{R_{co}+\Delta R_c+R} V_m$

V_m is the measurement voltage at the amplifier output.

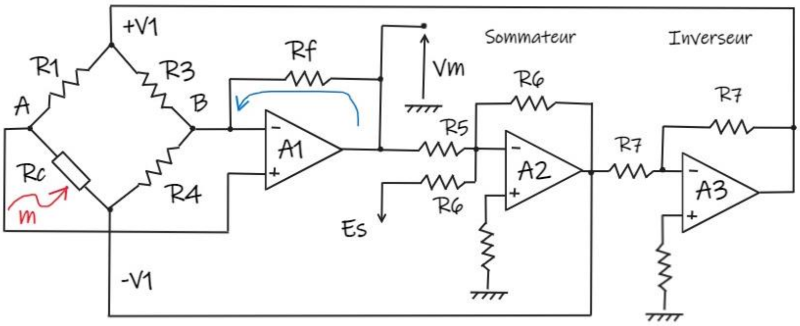
The amplifier being assumed to be ideal, the negative reaction maintains a zero potential difference between its + and – inputs:

$$V_A = V_B$$

$$=> \ V_m = -\frac{E_s}{2} \times \frac{\Delta R_c}{R_{co}}$$

d) Linearization by double feedback: On the unbalance voltage and on the bridge voltage

The following diagram represents the bridge:



With $R_1 = R_3 = R_4 = R_{co}$ and $R_c = R_{co} + \Delta R_c$

The negative reaction carried out through the first stage A1 tends to cancel the unbalance voltage of the bridge, which occurs when the voltage at the output of this stage, which is the measurement voltage, has the value:

$V_m = \mathrm{V}_1 \frac{\mathrm{R_{co}}+2\mathrm{R_f}}{2\mathrm{R_{co}}+\Delta\mathrm{R_c}} \times \frac{\Delta\mathrm{R_c}}{\mathrm{R_{co}}}$ (*Millmann*), when we put V_A=V_B

The bridge supply voltages ±*V1* are supplied by the summing amplifier A2 and the inverter A3 and are such that:

$$V_1 = \mathrm{E_s} + \frac{\mathrm{R_6}}{\mathrm{R_5}} \mathrm{V_m}$$

When the following condition is satisfied:

$$\frac{R_6}{R_5} = \frac{\mathrm{R_{co}}}{\mathrm{R_{co}} + 2\mathrm{R_f}}$$

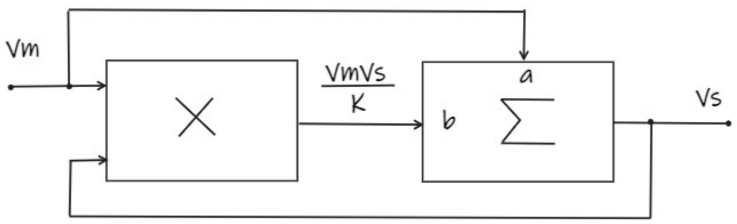
The measuring voltage has the linearized expression:

$$V_m = \frac{\mathrm{E_s}}{2} \left[1 + \frac{2\mathrm{R_f}}{\mathrm{R_{co}}}\right] \frac{\Delta R_c}{R_{co}}$$

d) Linearization by a multiplier followed by a summation downstream of the conditioner

We have seen that in the bridge assembly, the non-linearity error is due to the term $\left(\frac{1}{1+\frac{\Delta R_C}{2R_{co}}}\right)$, which is in the denominator.

The use of a **multiplier** followed by an **adder** provides the solution to the problem.



We can write: $V_s = \frac{V_m V_m}{k} + aV_m$

Let us replace *Vm* with its value $V_m = \frac{E_S}{4}\frac{\Delta R_C}{2R_{co}}\frac{1}{1+\frac{\Delta R_C}{2R_{co}}}$

$$=> \ V_s = a\frac{E_s \Delta R_c}{4R_{co}} \frac{1}{1+\frac{\Delta R_c}{2R_{co}}\left(1 - b\frac{E_S}{2k}\right)}$$

By adjusting the gain b of the Adder to the value $\frac{2k}{E_s}$, we obtain :

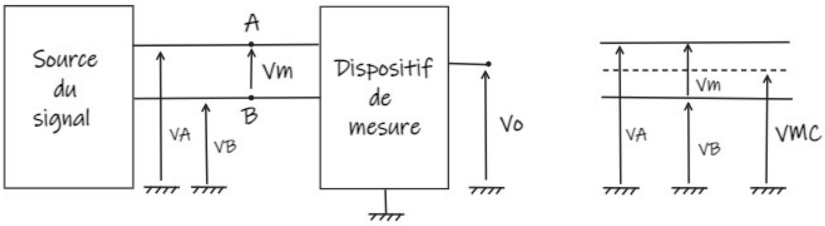
$$V_s = \frac{E_s \Delta R_c}{4R_{co}}$$

4. 3 Signal amplification and common mode voltage reduction

4.3.1 Common mode voltage: Definition and origins

In a circuit where the measurement voltage *Vm* is the differential voltage between two conductors:

$$V_m = V_A - V_B$$



The common mode voltage V_{MC} represents the voltage value common to V_A and V_B, and which does not carry any information.

If we put $V_{MC} = \frac{V_A+V_B}{2}$, we can write:

$$V_A = V_{MC} + \frac{v_m}{2} \text{ , } V_B = V_{MC} - \frac{v_m}{2}$$

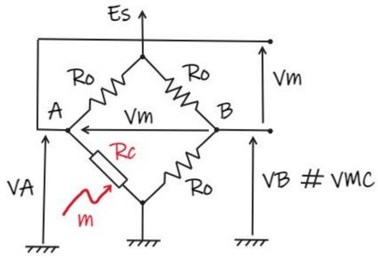
The common mode voltage V_{MC} can be much higher than the signal v_m.

One of the most important problems in instrumentation is the **elimination or rejection of the common mode** in order to obtain and be able to process in the measurement installation a signal proportional to v_m and therefore independent of V_{MC}.

a) Common mode voltage due to power supply

The case arises when the measurement voltage is the differential voltage between two points whose potential has a common term determined by the supply voltage.

Thus for a **Wheatstone bridge**, made up of three fixed resistors R_O and a sensor with a resistance $R_c = R_0 + \Delta R$ we have (when $\Delta R_c \ll R_0$):



$V_A = \frac{E_S}{2} + \frac{E_S}{4}\frac{\Delta R_C}{R_0}$, $V_B = \frac{E_S}{2}$;

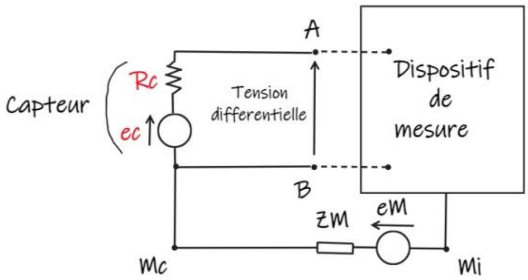
When, for example :

$E_s = 20V$ *and* $\frac{\Delta R_C}{R_0} = 10^{-2}$

The common mode voltage V_{MC} is practically equal to: $\frac{E_S}{2} = 10V$.

The measuring voltage, which is the differential voltage, is: $v_m = \frac{E_S}{4}\frac{\Delta R_C}{R_0} = 5 \times 10^{-2}V$

a) Ground common mode voltage



Between two distant grounding points there are generally:

- A ground impedance Z_M of the order of one Ohm;
- An e.m.f. of mass e_M which has as main origins *em* inductions (of alternating current), and the circulation of return currents from various installations.

The distance between grounding points (*Mi* and *Mc*) can reach hundreds of meters in industrial installations, and the ground *e.m.f.* (e_M) can be greater than several tens of volts.

The *e.m.f.* e_M establishes a common mode voltage for the measuring installation.

At the ends *A* and *B* of the connection we have, in open circuit, relative to the mass *Mi* of the measuring installation:

$V_B = e_M$, $V_A = e_M + e_c$ with in general $e_c \ll e_M$

thus $V_{MC} = e_M$ and $v_m = e_c$

4.3.2 Differential Amplifier and Common Mode Rejection Rate

When the signal appears as a differential voltage at the ends of a link, its processing by a differential amplifier is necessary.

A differential amplifier can be considered to consist of:

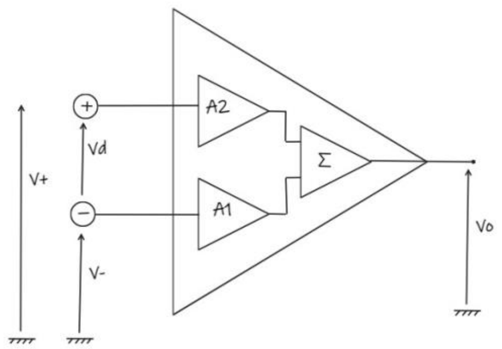


Fig 1: Structure de l'amplificateur differentiel

- Two amplifier channels, one A_1 **inverting**, and the other A_2 **non-inverting**, with the gain $|A_1|=|A_2|$;
- A **summing amplifier**, adding the voltages supplied by A_1 and A_2, and whose output is that of the differential amplifier;

$$v_0 = A_2 v_+ - A_1 v_-$$

With $v_{MC} = \frac{v_+ + v_-}{2}$ et $v_d = v_+ - v_-$

$$\Rightarrow \quad v_o = \frac{A_1 + A_2}{2} v_d + (A_2 - A_1) v_{MC}$$

The differential gain is: $A_d = \frac{A_1 + A_2}{2}$

The common mode gain is: $A_{MC} = A_2 - A_1$

Note1

If $A_2 \approx A_1$ => $v_o \approx \frac{A_1+A_2}{2} v_d$ independant of v_{MC}

The output voltage can be written as:

$$v_o = A_d \left[v_d + \frac{A_{MC}}{A_d} v_{MC} \right]$$

The ratio $\frac{A_d}{A_{MC}} = \tau_r$ is the common mode rejection rate

$$=> \quad v_o = A_d \left[v_d + \frac{1}{\tau_r} v_{MC} \right]$$

Note2

Lim $v_o = A_d v_d$ if $\tau_r \to \infty$

4.3.3 Instrumentation amplifier

It is an operational amplifier module, suitable for processing signals in the presence of relatively high common mode voltages.

The bias currents of the input stages at the + and - terminals must be able to close to **the ground** of the amplifier, there must exist an ohmic line between these input terminals and the ground of the amplifier (fig.1).

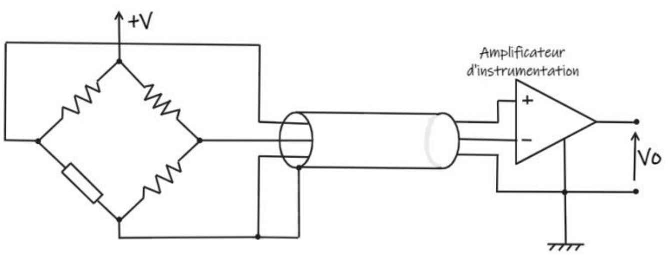


Fig 1: Liaison d'un pont de Weatstone à un amplificateur d'instrumentation

As a result, the common mode voltage applicable to these inputs is limited to values which **must be slightly lower** than the amplifier supply voltages (around ten to a few tens of volts).

The general characteristics of instrumentation amplifiers are given below:

- Adjustable differential gain: $1 \rightarrow 10^4$
- Very high input impedance: 10^{10} *Ω* in // with a few *pF*, allowing the influence of source resistance to be reduced.
- Very low output impedance: *0.1 Ω*, reducing the influence of the load on the gain.
- Very low input bias currents (a few *pA* → a few *nA*) in order to minimize variations in input voltages caused by variations in source or link resistances.
- High thermal stability of performance (*0.0015/°C* for example for the differential gain) in order to avoid output drifts indistinguishable from the signal.
- High common mode rejection rate τ_r: for example 10^5 or *100 dB* continuously or at *50 Hz*, it decreases at high frequencies.

The output voltage V_O of the instrumentation amplifier has the expression:

$$V_o = A_d\left(v_d + \frac{1}{\tau_r}V_{MC}\right)$$

Where $v_d = v_+ - v_-$ and $v_{MC} = \frac{v_+ + v_-}{2}$

In data acquisition sets from several sensors, each of the latter can be associated with an instrumentation amplifier whose gain is fixed according to the average level of the signal delivered and which is located near the sensor. This allows the transmission of a high-level signal, reducing the influence of parasites, which are superimposed on it during transmission and avoiding carrying out multiplexing at low level (Fig.2).

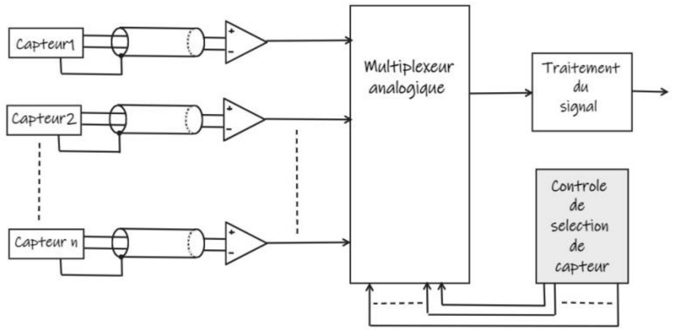


Fig 2: Multiplexage des voies apres amplification des signaux

4.3.3 Isolation Amplifier

The limitation of the common mode voltage applicable to an instrumentation amplifier is due to the need to ensure a return connection to the ground of the amplifier, of the bias currents of the input stages, to which the signal source is linked.

The isolation amplifier makes it possible to increase considerably the maximum value of the common mode voltage by ensuring galvanic isolation between, on the one hand its input circuits connected to the signal source, and on the other hand, the circuit of output connected to the rest of the measurement chain, the power supply and to the common ground (Fig.3).

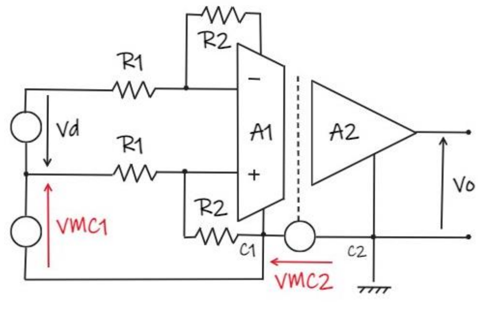


Fig 3: Schema de principe d'un amplificateur d'isolement dont l'etage d'entrée est un ampli. operat. en montage diff. de gain Ad = R2/R1

The isolation amplifier is made up of:

- A stage A_1, whose input is an operational or instrumentation amplifier, powered by a floating source and whose common point C_1 designated as “guard” is connected to the signal ground;

• A stage A_2 whose common point C_2 is connected to the common ground of the downstream processing assembly, and of unity gain;
• An isolation barrier which breaks any ohmic connection between stages A_1 and A_2, while allowing the transfer of the signal between these stages by electromagnetic (transformer) or optoelectronic (photodiode) coupling..

The common mode voltage v_{MC1} relative to the common point C_1 of the input circuit is, as for any amplifier, limited to around ten volts.

The common mode voltage v_{MC2} relative to point C_2 (called insulation voltage) can reach several thousand volts.

The output voltage v_o of a differential gain isolation amplifier A_d is of the form:

$$v_0 = A_d v_d \left[1 + \frac{1}{\tau_{r_1}} \frac{v_{MC_1}}{v_d}\right] + \frac{1}{\tau_{r_2}} v_{MC_2}$$

The orders of magnitude being:

$$\tau_{r_1} \cong 100\, dB \quad et \quad \tau_{r_2} \cong 100\, dB$$

The isolation amplifier finds its applications:

When the e_c signal is superimposed on a very high common mode voltage (fig. a).

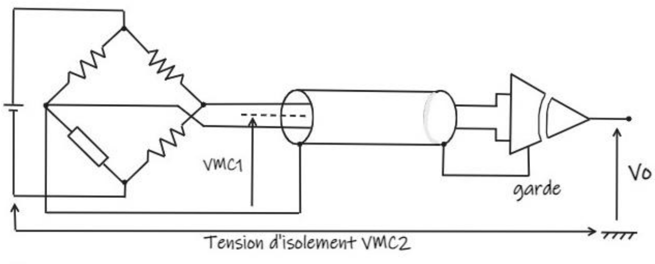


Fig a

When, for security reasons for example, the signal source must be isolated from the processing chain (fig. b).

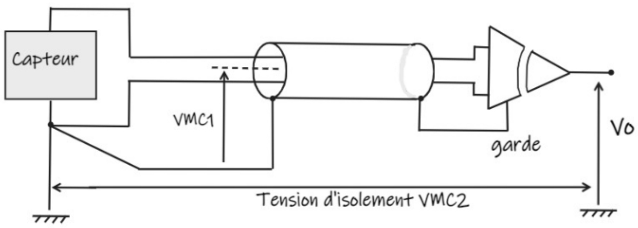


Fig b

4.4 Information detection

Passive sensor conditioners deliver in a certain number of cases a measurement voltage v_m, which is modulated by variations Δm of the measurand.

We propose here to briefly describe the methods, which make it possible to extract information from this modulated tension. That is to say an electrical signal which reflects only variations of the measurand.

4.4.1 Amplitude modulated measuring voltage with carrier conservation

In this case, the evolution over time of the peak value of the measuring voltage exactly reproduces the variations Δm of the measurand (fig. 1).

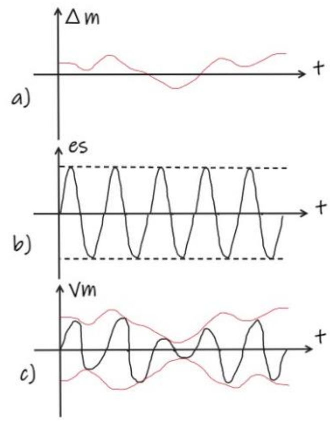


Fig 1: Modulation d'amplitude
a) mesurande b) porteuse c)tension de mesure

When the voltage of the power source is sinusoidal, with pulsation ω_s, we have:

$$v_m = \grave{E_s}(1 + k\Delta m)\cos\omega_s t$$

A peak detector (fig. 2), whose basic elements are a diode and an *R-C* assembly, delivers a voltage v_o:

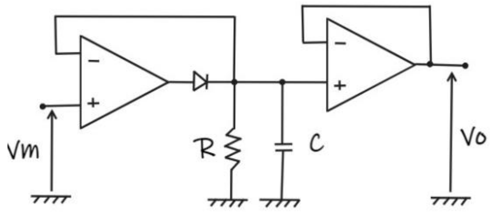


Fig 2: Montage d'un detecteur de crete

$v_o = \eta E_s^{`}(1 + k\Delta m)$

Where η is the detection efficiency ($0 < \eta < 1$).

Note: The DC component of the detected voltage (ηEs`) can be eliminated either by high-pass filtering, or using a subtractor assembly if its value has been determined by a prior measurement when ∆m=0.

4.4.2 Frequency modulated measuring voltage

Devices intended to extract the information contained in a frequency modulated voltage use one of the following three methods:

• Conversion of frequency modulation into amplitude modulation by means of assemblies (discriminators) using anti-resonant circuits and detection of this amplitude modulation.

• Conversion of modulated voltage into synchronous pulses, i.e. of the same instantaneous frequency of which we measure either the average voltage or the frequency.

• *PLL* (phase locked loop) phase locking of a voltage-controlled oscillator to the frequency-modulated signal: the oscillator control voltage varies as the modulating information.

Anti-resonant circuit discriminators

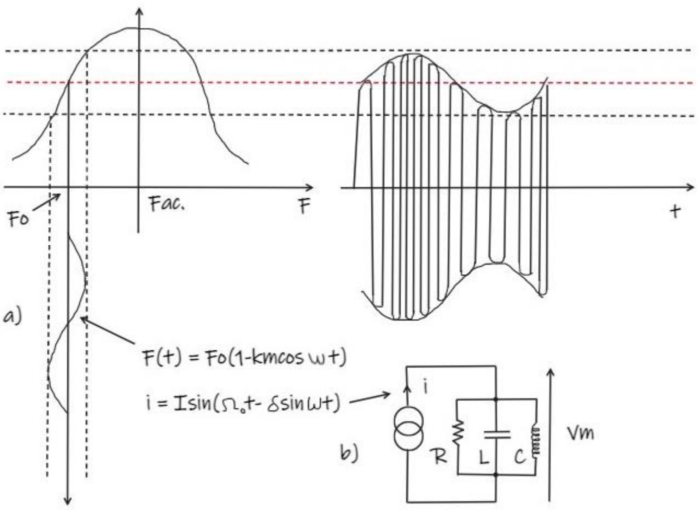


Fig 1: Discriminateur à circuit antirésonant
a) Interpretation graphique du fonctionnement
b) Schema de principe

The amplitude and phase response of an anti-resonant circuit depends on the difference between its tuning frequency ($F_{ac.}$) and the frequency (F) of the signal applied to it.

By properly shifting $F_{ac.}$ and F_0, central frequency of the signal, the variation in amplitude of the voltage across the oscillating circuit is proportional to the variation in frequency of the signal, i.e. the information that modulated it.

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