Sensors and conditioning

F. Pépin
www-pepin.ensea.fr

ENSEA
Ecole Nationale
Supérieure
de l'Electronique
et de ses Applications

Electronics and packaging

1. Notion of measurement
2. Constitution of a measurement chain
3. Characteristics of a measurement chain
4. Instrumentation amplifiers
5. Isolation amplifiers
6. Passive sensor conditioners
7. Signal conversion
8. Electronic noise
9. Temperature sensors
10. Integrated conditioners
11. Position and displacement sensors
12. Deformation sensors
13. Pressure and force sensors per test body
14. Piezoelectricity

1. Notion of measurement.

$$\text{Measure} = \frac{\text{Size to be measured}}{\text{Reference size}}$$

International System of Units (S.I.) :

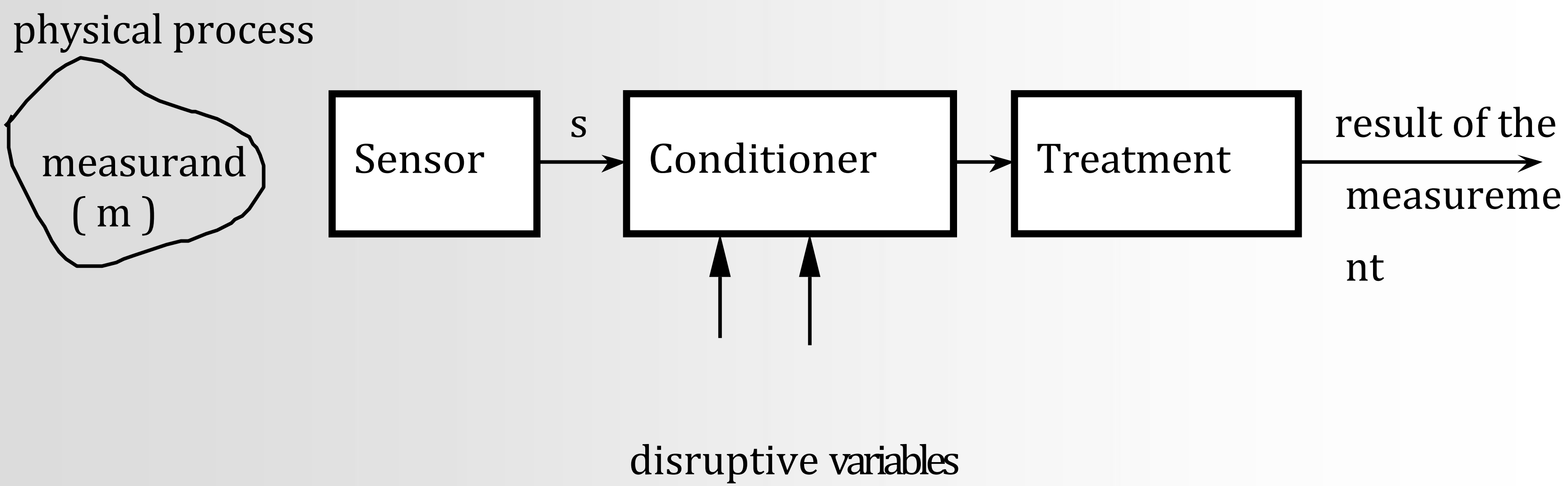
7 basic units: m, kg, s, K, A, cd, mol

Measuring: set of operations to determine the value of a quantity.

Metrology: field of knowledge related to the measurements.

2. Constitution of a measurement chain.

Objective:physical sizeelectrical size



Constitution of a measurement chain

3. Characteristics of a measurement chain.

- Static transfer characteristic.
  - obtained by calibration.
  - Measurement range (MS):

    nominal range of measurand variations.
  - Limit of use of the sensor :

    area of non-deterioration.

- Static sensitivity : $S \left. \frac{\Delta y}{\Delta x} \right|_{x0}$

- Zero offset
- Linearity: describes the degree of agreement between the static calibration diagram and a line chosen as reference.
- Hysteresis.
- Resolution: minimum increase in the input quantity causing a change in the output quantity.
- Derivatives
- Finesse: allows to estimate the influence of the presence of the sensor and the chain of measurement on the value of the measurand.

- Dynamic features :
  - Sensitivity as a function of frequency S(f)
  - Speed: response time.

- Measurement errors.

x_0 :true value

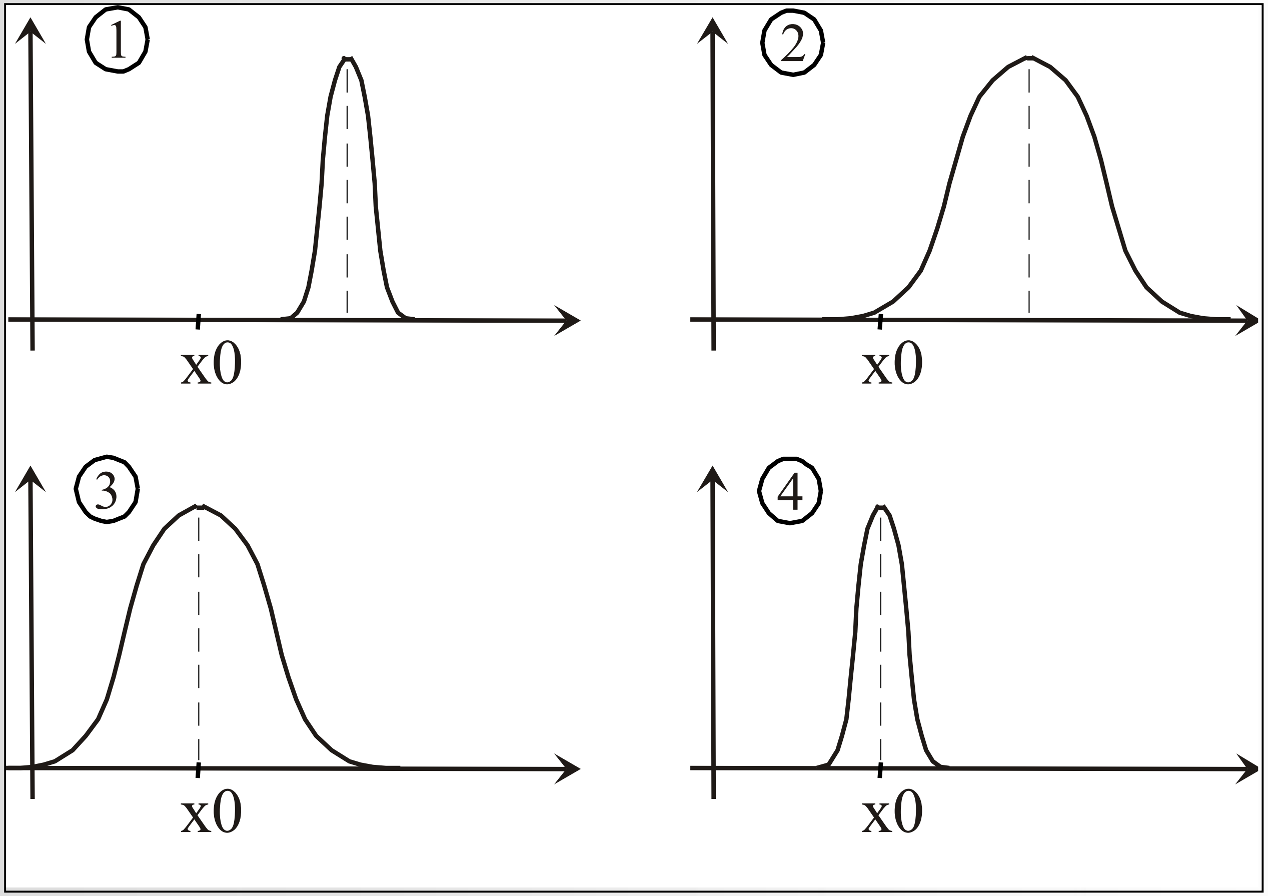
xi: measurement

resultError : $e_i = x_i - x_0$

- ➢ Systematic errors
- ➢ Accidental errors

Experiment:n measurements x1...

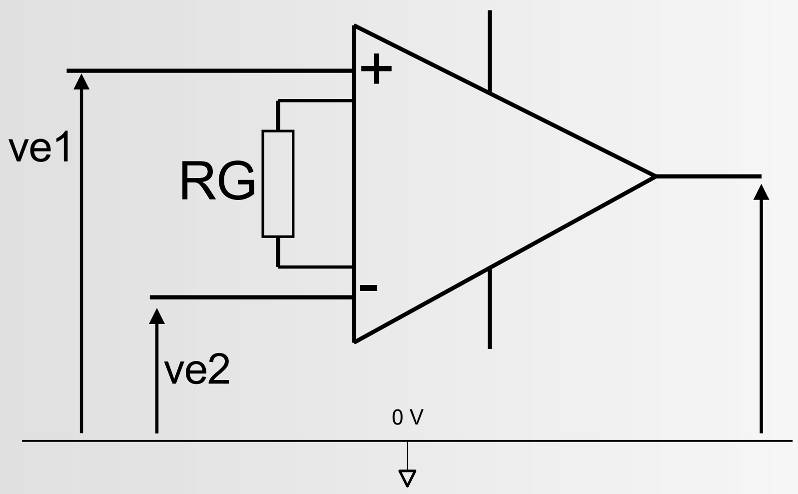
xn



	Cas 1	Cas 2	Cas 3	Cas 4
Justesse	non	non	oui	oui
Fidélité	oui	non	non	oui

4. Instrumentation amplifier.

- Objectives.
  - *amplify the signal to make it more perceptible*
  - Infinite input impedance
  - Zero output impedance
  - An output voltage proportional to the difference between the two inputs:



$$vs = Ad\,(ve1 - ve2)$$

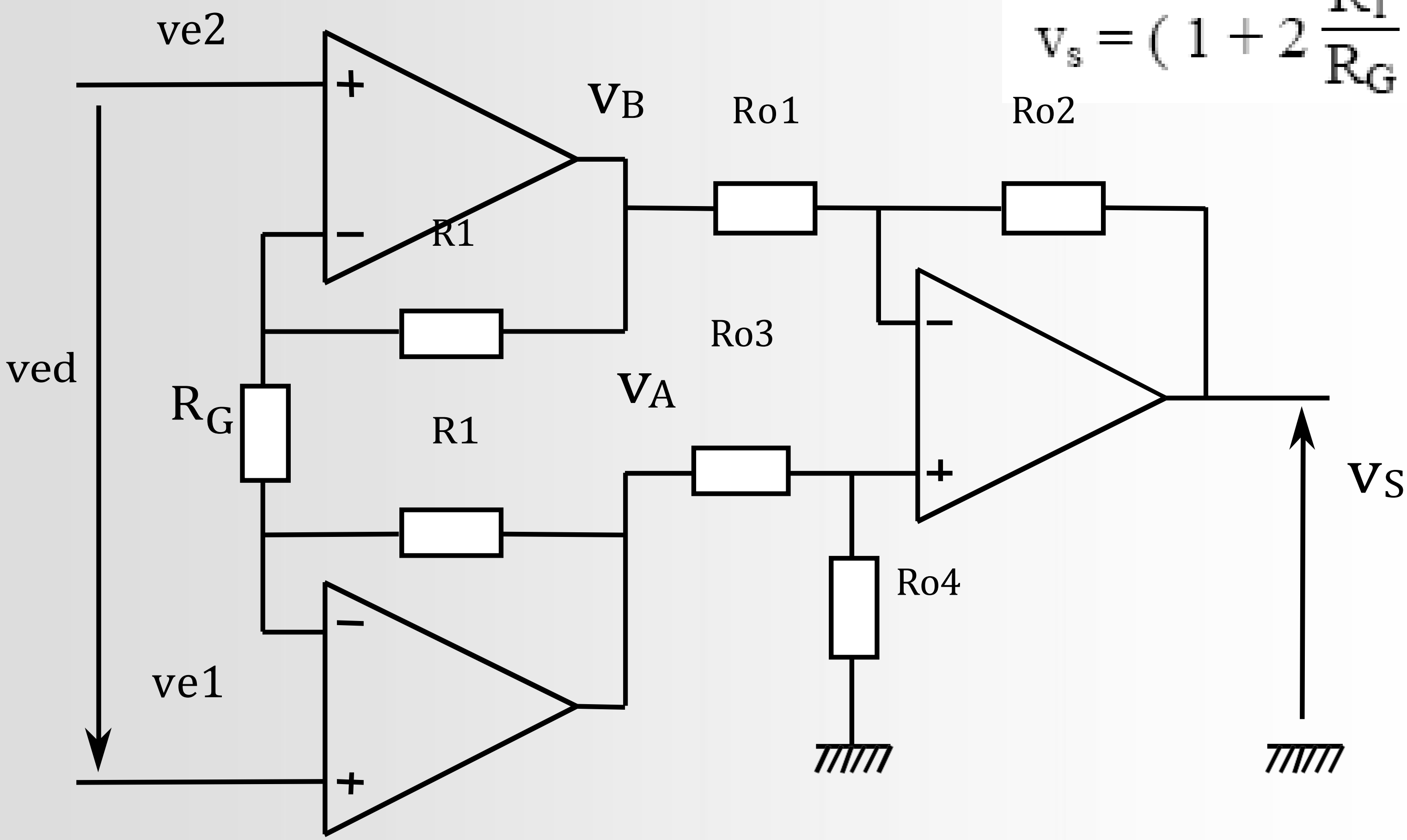
- Reminder on the differential and common mode.

- Instrumentation amplifier :

  Circuit designed to **amplify a signal in a hostile environment**, characterized by deviations from the ideal (temperature, noise, voltage drop of the supply,...).

- Examples of realizations.
  - Three operational amplifier arrangement

$$v_s = \left(1 + 2\frac{R_1}{R_G}\right) v_{ed}$$



  - Assembly with two operational amplifiers : in TD.

- Example: the AD623 circuit

ANALOG DEVICES

Single and Dual-Supply, Rail-to-Rail, Low Cost Instrumentation Amplifier

Data Sheet **AD623**

FEATURES

Easy to use
Rail-to-rail output swing
Input voltage range extends 150 mV below ground (single supply)
Low power, 550 μA maximum supply current
Gain set with one external resistor
- Gain range: 1 to 1000

High accuracy dc performance
- 0.10% gain accuracy (G = 1)
- 0.35% gain accuracy (G > 1)

Noise: 35 nV/√Hz RTI noise at 1 kHz
Excellent dynamic specifications
- 800 kHz bandwidth (G = 1)
- 20 μs settling time to 0.01% (G = 10)

APPLICATIONS

Low power medical instrumentation
Transducer interfaces
Thermocouple amplifiers
Industrial process controls
Difference amplifiers
Low power data acquisition

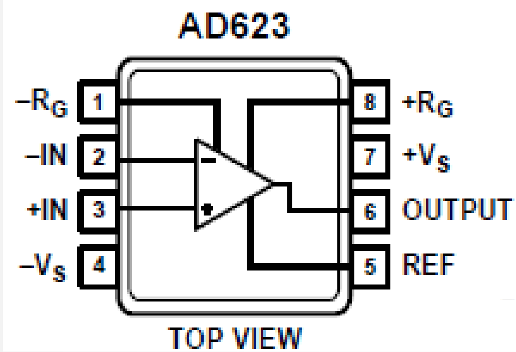
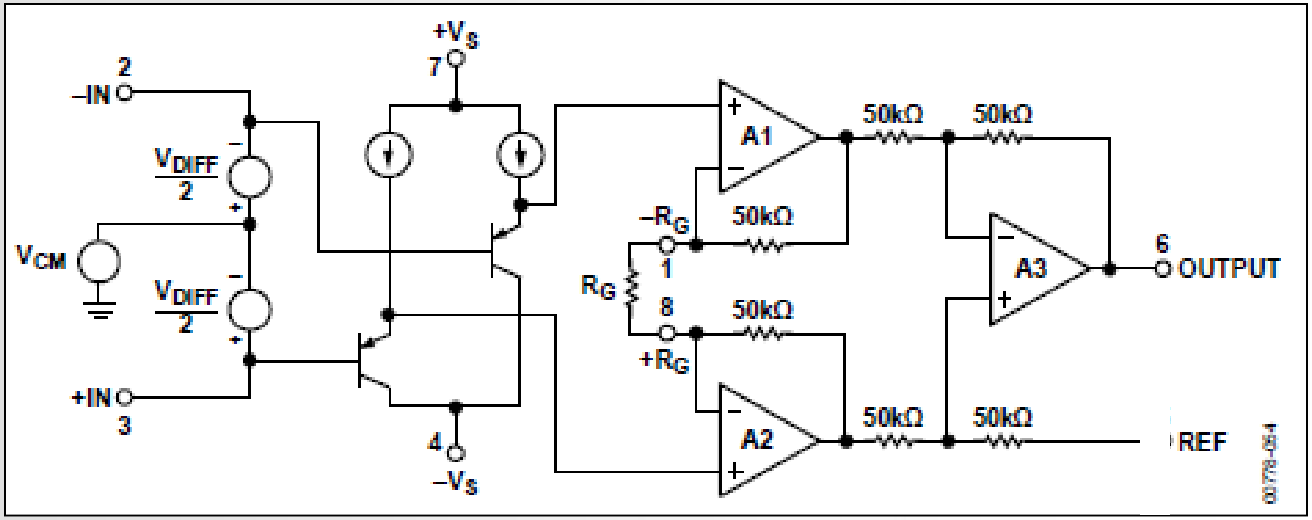


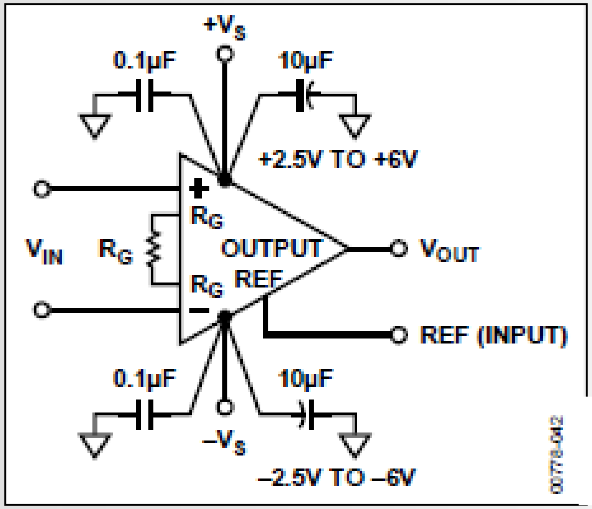
Table 1. Low Power Upgrades for the AD623

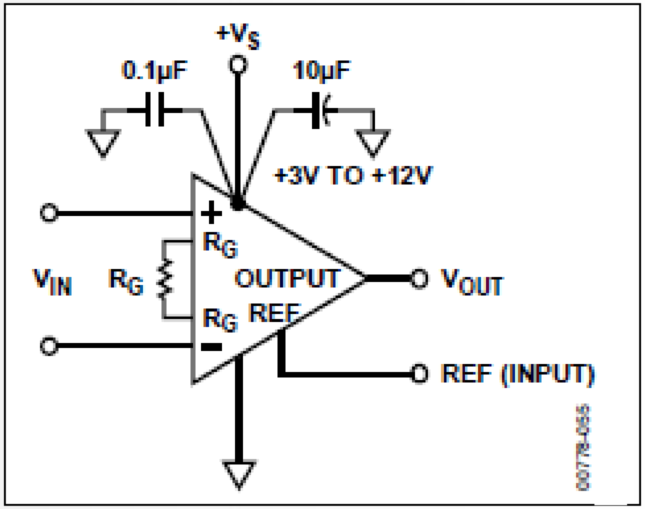
Part No.	Total V_S (V dc)	Typical I_Q (μA)
AD8235	5.5	30
AD8236	5.5	33
AD8237	5.5	33
AD8226	36	350
AD8227	36	325
AD8420	36	85
AD8422	36	300
AD8426	36	325 (per channel)

Simplified internal diagram:

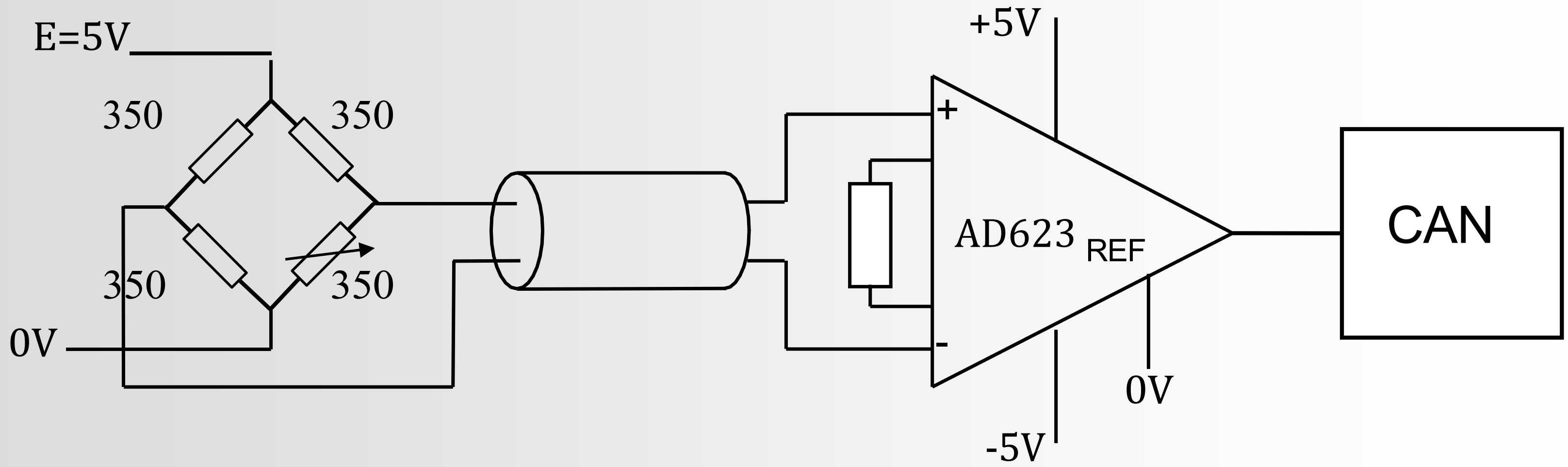


Usage:

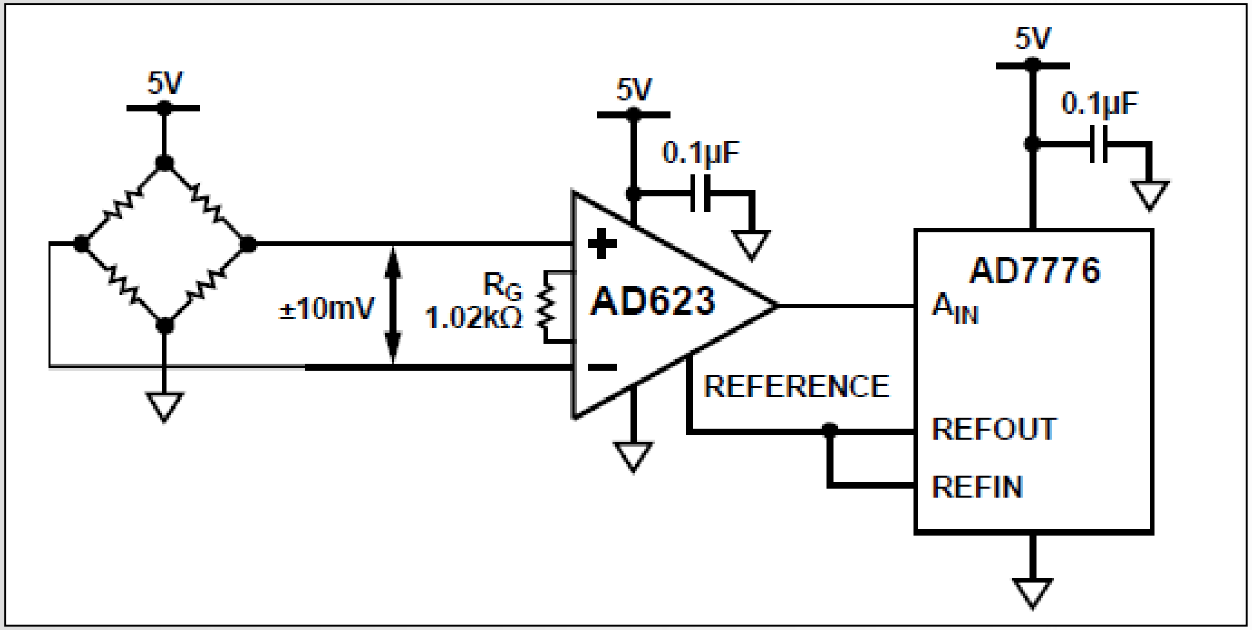


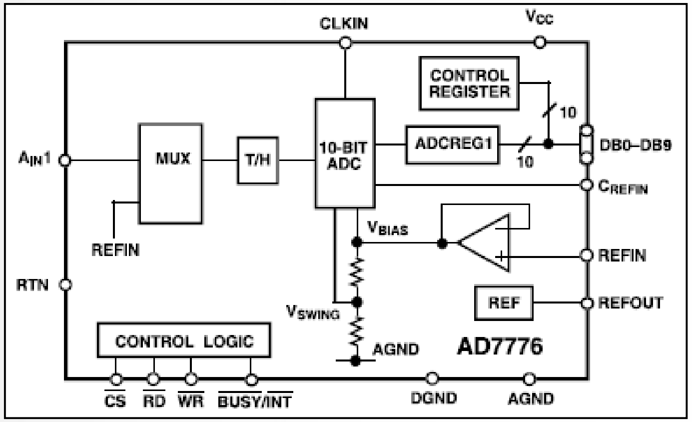


- Application examples:

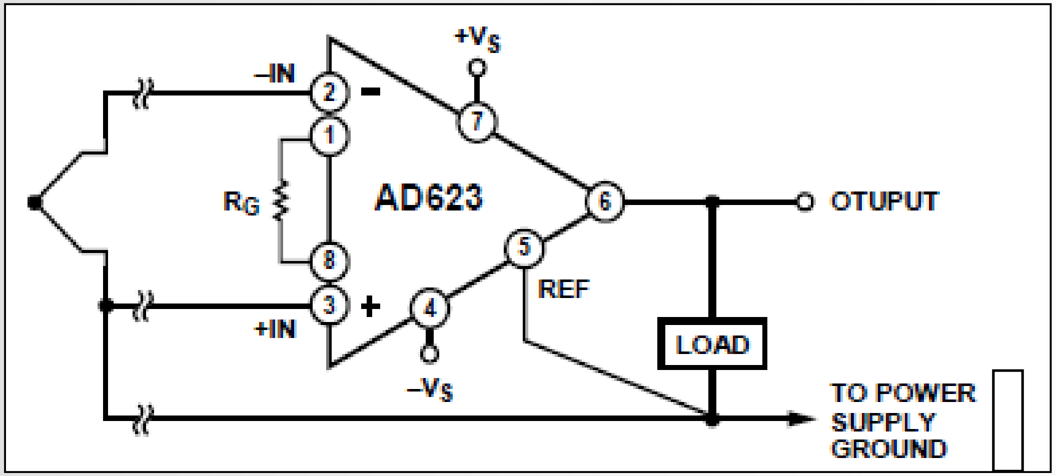


Acquisition system for a passive sensor :

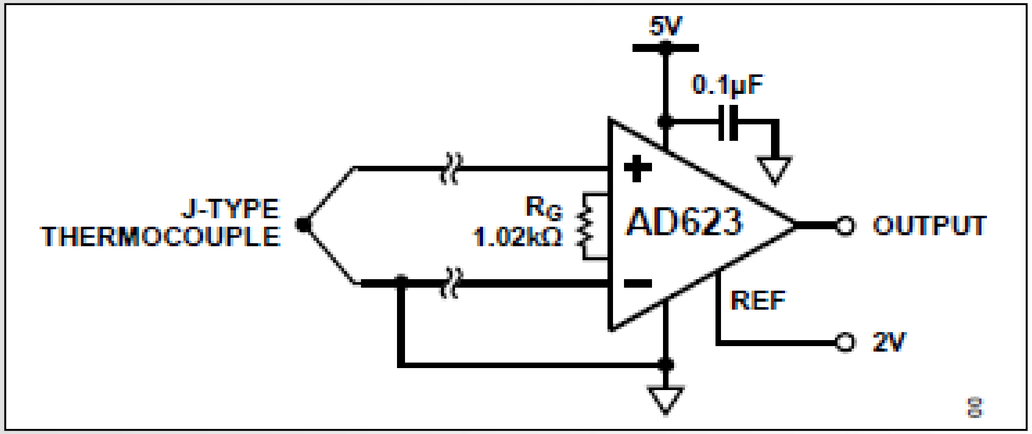




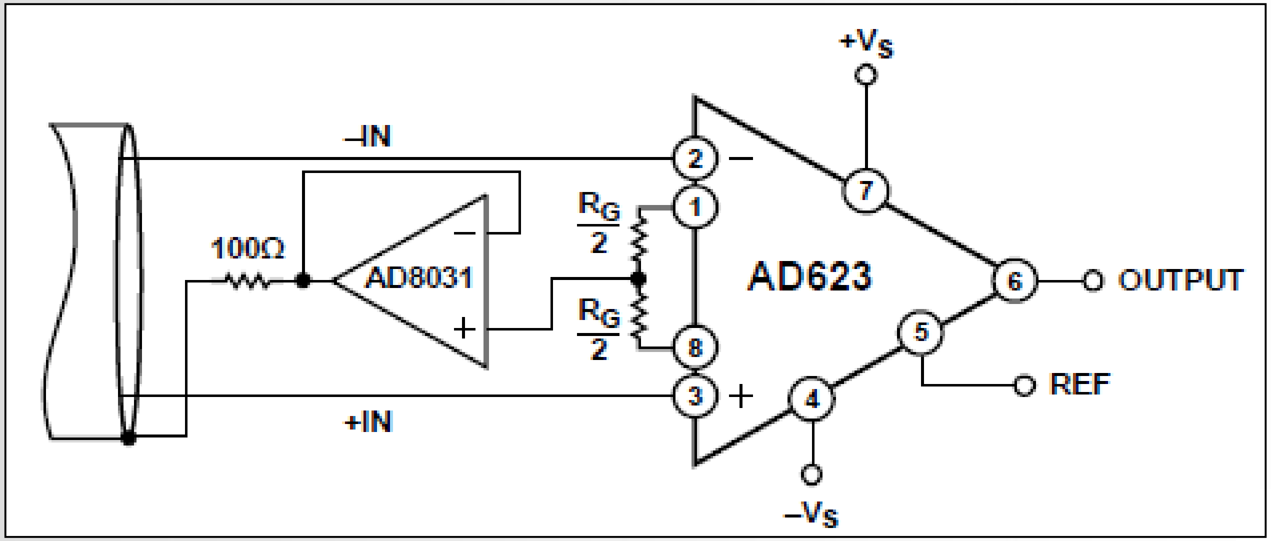
Interfacing a thermocouple :



Temperature measurement from -200°C to +200°C:

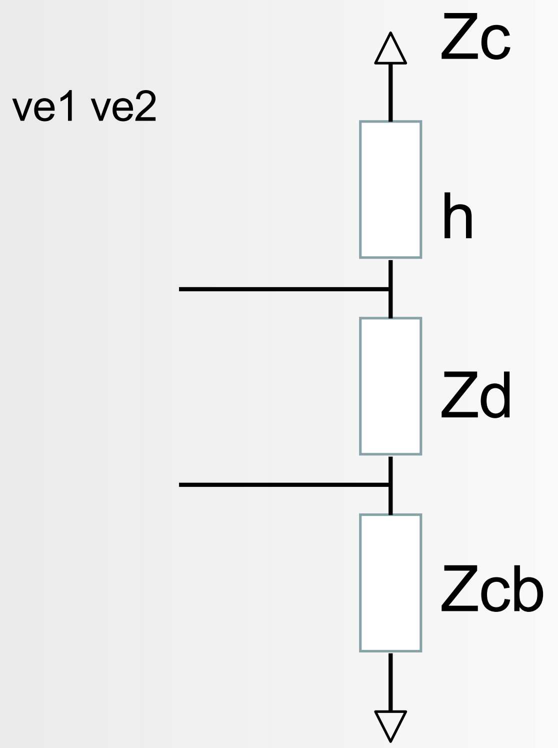


On-call circuit:



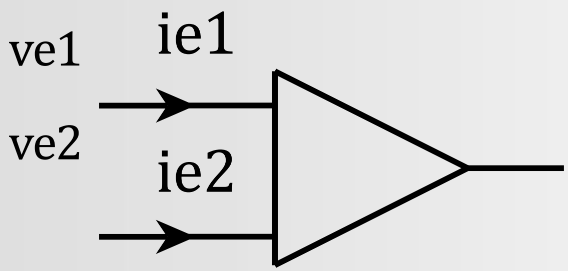
- Equivalent diagram
  - At the entrance

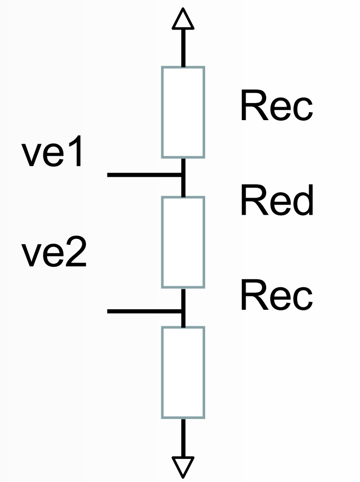
Commonly used scheme:



Instrumentation amplifier: equivalent diagram at the input

Rationale: Let the two input currents be:





$$i_{e1} = G_{11}\, v_{e1} + G_{12}\, v_{e2}$$

$$i_{e2} = G_{21}\, v_{e1} + G_{22}\, v_{e2}$$

$$i_{e1} = \frac{G_{11} - G_{12}}{2}\, v_{ed} + (G_{11} + G_{12})\, v_{ec}$$

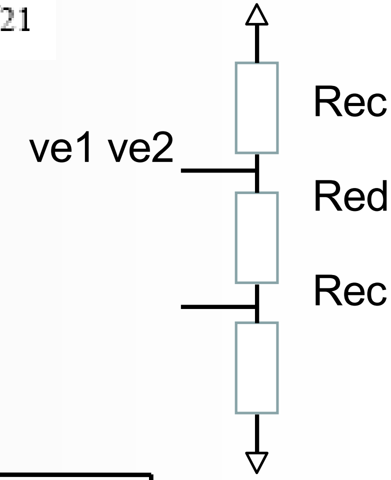
$$i_{e2} = \frac{G_{21} - G_{22}}{2}\, v_{ed} + (G_{22} + G_{21})\, v_{ec}$$

Hypothesis: symmetrical instrumentation amplifier

$$G_{11} = G_{22} \text{ et } G_{12} = G_{21}$$

$$R_{ed} = \frac{2}{G_{11} - G_{12}} = -\frac{2}{G_{21} - G_{22}}$$

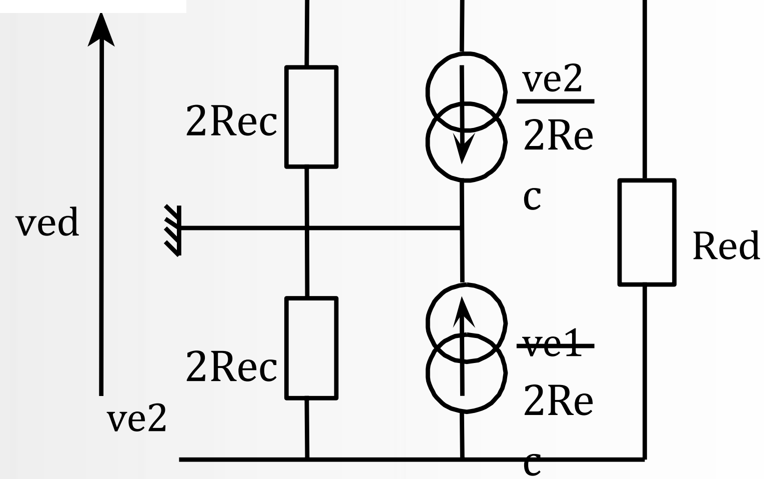
$$R_{ec} = \frac{1}{G_{11} + G_{12}} = \frac{1}{G_{22} + G_{21}}$$

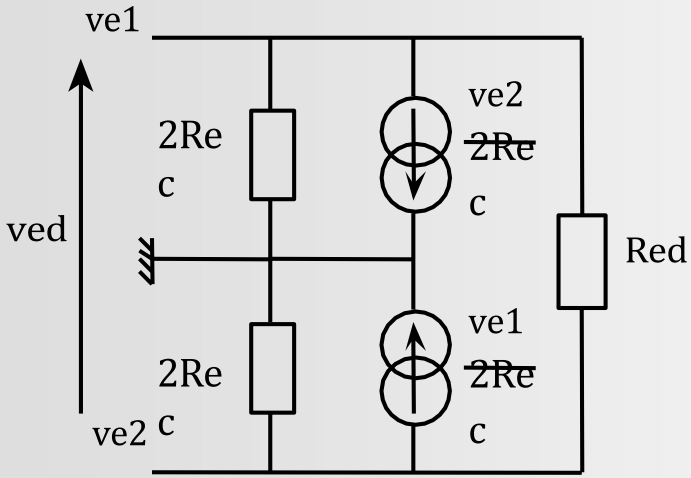


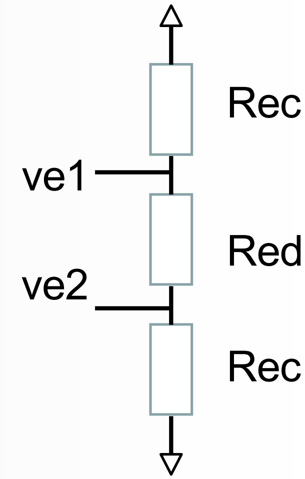
$$i_{e1} = \frac{V_{ed}}{R_{ed}} + \frac{V_{ec}}{R_{ec}} = \frac{V_{ed}}{R_{ed}} + \frac{V_{e1} + V_{e2}}{2\,R_{ec}}$$

$$i_{e2} = -\frac{V_{ed}}{R_{ed}} + \frac{V_{e1} + V_{e2}}{2\,R_{ec}}$$

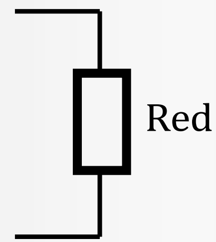
This gives the following diagram.



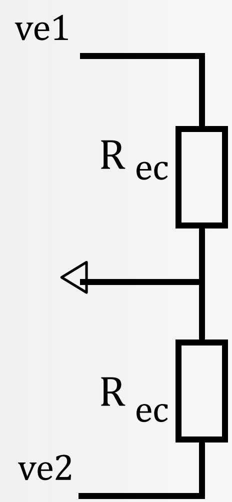




- In differential mode (ve1 = - ve2) :



- In common mode (ve1 = ve2):



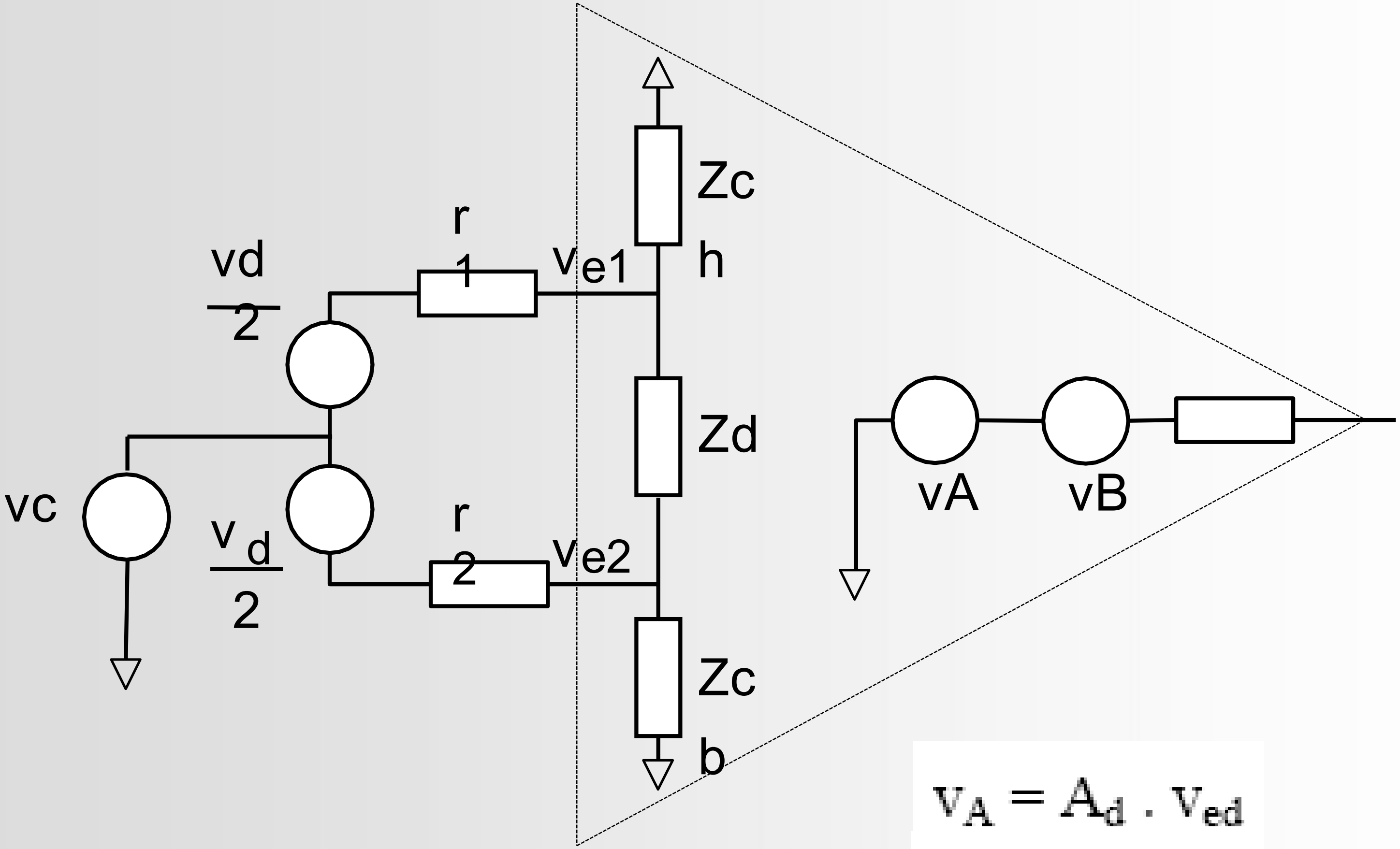
AD623:

Red = 2 Γ

Rec = 2 Γ

- On exit:
  - Output resistor
  - Voltage proportional to the voltage in differential mode
  - Common mode voltage.

- Full diagram:



$$v_A = A_d \,.\, v_{ed}$$
$$v_B = A_c \,.\, v_{ec}$$

- Common mode rejection rate, guard circuit.
  - Definition of the common mode rejection rate (CMR)

$$TRMC = \frac{A_d}{A_c}$$ $$A_d = \frac{V_{sd}}{V_{ed}}$$ $$A_C = \frac{V_{sc}}{V_{ec}}$$

in dB : $$TRMC = 20 \log \frac{A_d}{A_c}$$

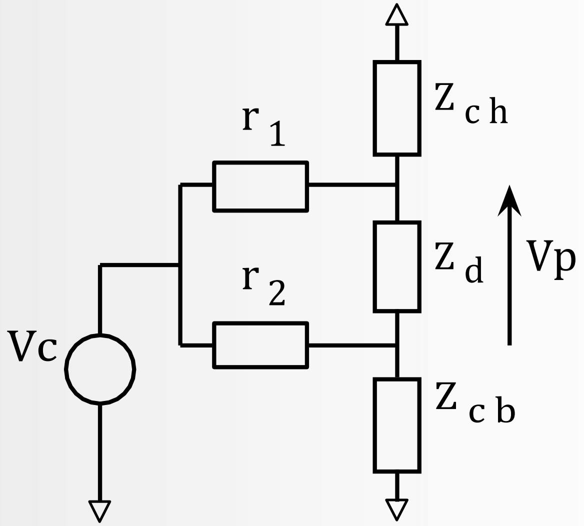
Example : A d = 100ved = 10 mV
vec = 10 VTRMC = 80 dB

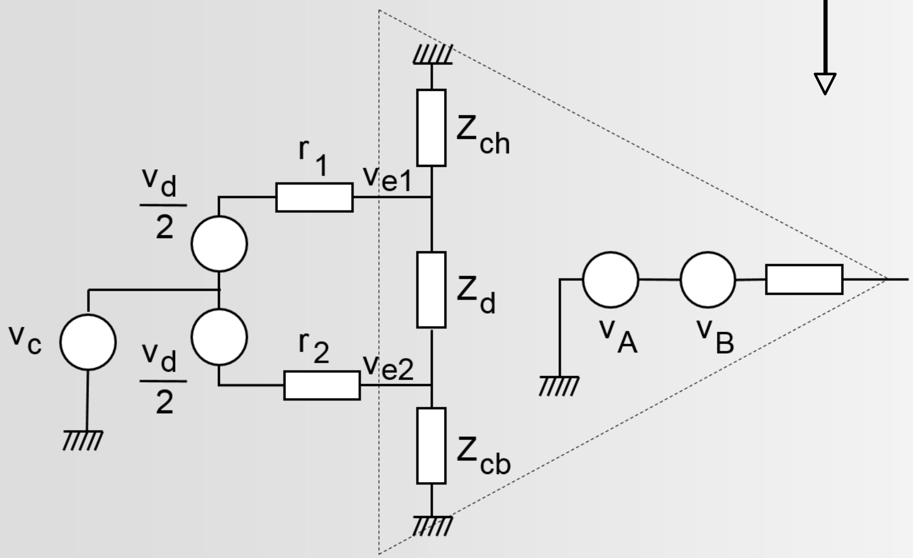
A d . ved = 1 V and $$\frac{A_d}{TRMC} \cdot V_{ec} = 0{,}1\ V$$

which is an **error of 10%!**

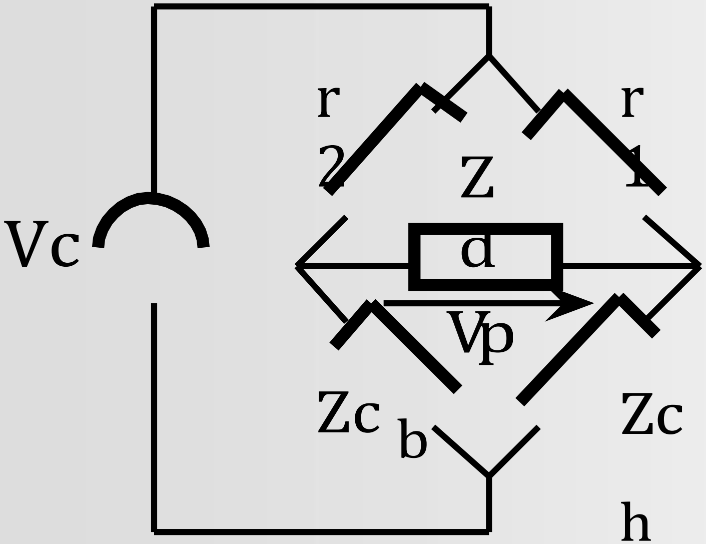
- Functional analysis

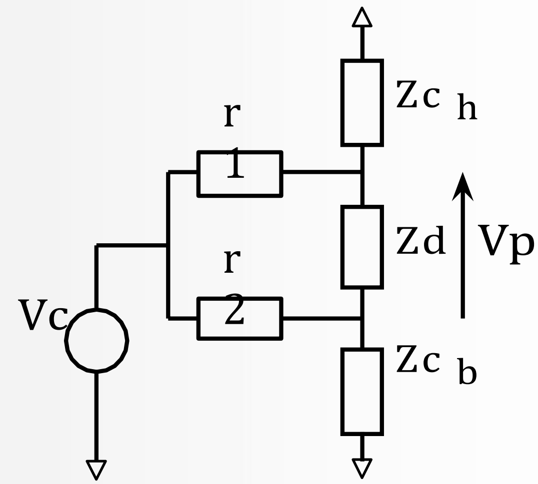
Let's say the following diagram:





By changing the layout of the components in the diagram:



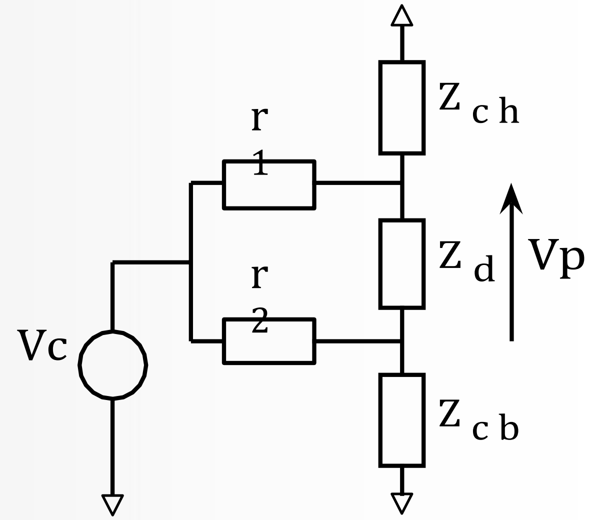


Sir1 = r2 andZch = ZcbVp = 0

Case studied: r1 = 0

$$V_p = \left| \frac{r_2 // Z_d}{r_2 // Z_d + Z_{c\,b}} \right| \cdot V_c$$

and $$TRMC = \left| \frac{r_2 // Z_d + Z_{c\,b}}{r_2 // Z_d} \right|$$



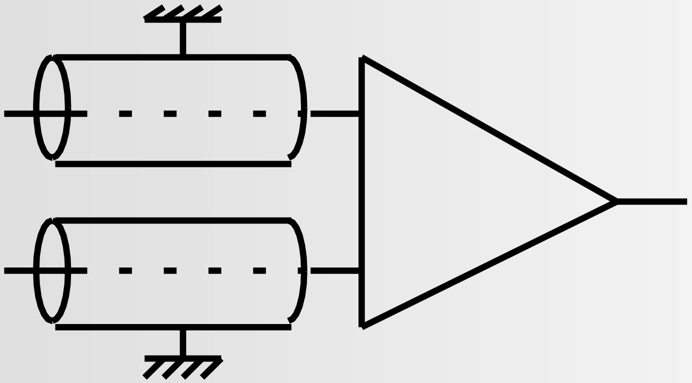
r2 << Zd and Zcb: $$TRMC = \left| \frac{Z_{cb}}{r_2} \right|$$

Example: $Z_{cb} = 1000\ M\Omega\ //\ 10\ pF \quad r_2 = 100\ \Omega$

$Z_{cb} = 1000\ M\Omega\ //\ 10\ pF \quad r_2 = 100\ \Omega$

$$TRMC = \left| \frac{Z_{cb}}{r_2} \right|$$

- for a continuous common mode signal, we have TRMC = 140dB
- for f = 50 Hz, TRMC = 130 dB
- If the signal is brought by a 1m coaxial cable:



TRMC = 109 dB

Solution: **guard circuit**

• Characteristics of an instrumentation amplifier

Data Sheet **AD623**

DUAL SUPPLIES

Typical at 25°C dual supply, $V_S = \pm 5$ V, and $R_L = 10$ kΩ, unless otherwise noted.

Table 3.

Parameter	Test Conditions/ Comments	AD623A Min	AD623A Typ	AD623A Max	AD623ARM Min	AD623ARM Typ	AD623ARM Max	AD623B Min	AD623B Typ	AD623B Max	Unit
GAIN	$G = 1 + (100\ k/R_G)$										
Gain Range		1		1000	1		1000	1		1000	
Gain Error[1]	G1 V_{OUT} = −4.8 V to +3.5 V G > 1 V_{OUT} = 0.05 V to 4.5 V										
G = 1			0.03	0.10		0.03	0.10		0.03	0.05	%
G = 10			0.10	0.35		0.10	0.35		0.10	0.35	%
G = 100			0.10	0.35		0.10	0.35		0.10	0.35	%
G = 1000			0.10	0.35		0.10	0.35		0.10	0.35	%
Nonlinearity	G1 V_{OUT} = −4.8 V to +3.5 V G > 1 V_{OUT} = −4.8 V to +4.5 V										
G = 1 to 1000			50			50			50		ppm
Gain vs. Temperature											
G = 1			5	10		5	10		5	10	ppm/°C
G > 1[1]			50			50			50		ppm/°C

Parameter	Test Conditions/ Comments	AD623A			AD623ARM			AD623B			Unit
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
VOLTAGE OFFSET	Total RTI error = $V_{OSI} + V_{OSO}/G$										
Input Offset, V_{OSI}			25	200		200	500		25	100	µV
Over Temperature				350			650			160	µV
Average Tempco			0.1	2		0.1	2		0.1	1	µV/°C
Output Offset, V_{OSO}			200	1000		500	2000		200	500	µV
Over Temperature				1500			2600			1100	µV
Average Tempco			2.5	10		2.5	10		2.5	10	µV/°C
Offset Referred to the Input vs. Supply (PSR)											
G = 1		80	100		80	100		80	100		dB
G = 10		100	120		100	120		100	120		dB
G = 100		120	140		120	140		120	140		dB
G = 1000		120	140		120	140		120	140		dB
INPUT CURRENT											
Input Bias Current			17	25		17	25		17	25	nA
Over Temperature				27.5			27.5			27.5	nA
Average Tempco			25			25			25		pA/°C
Input Offset Current			0.25	2		0.25	2		0.25	2	nA
Over Temperature				2.5			2.5			2.5	nA
Average Tempco			5			5			5		pA/°C
INPUT											
Input Impedance											
Differential			2‖2			2‖2			2‖2		GΩ‖pF
Common-Mode			2‖2			2‖2			2‖2		GΩ‖pF
Input Voltage Range[2]	V_S = +2.5 V to ±6 V	$(-V_S) - 0.15$		$(+V_S) - 1.5$	$(-V_S) - 0.15$		$(+V_S) - 1.5$	$(-V_S) - 0.15$		$(+V_S) - 1.5$	V

Parameter	Test Conditions/ Comments	AD623A Min	AD623A Typ	AD623A Max	AD623ARM Min	AD623ARM Typ	AD623ARM Max	AD623B Min	AD623B Typ	AD623B Max	Unit
Common-Mode Rejection at 60 Hz with 1 kΩ Source Imbalance											
$G = 1$	V_{CM} = +3.5 V to −5.15 V	70	80		70	80		77	86		dB
$G = 10$	V_{CM} = +3.5 V to −5.15 V	90	100		90	100		94	100		dB
$G = 100$	V_{CM} = +3.5 V to −5.15 V	105	110		105	110		105	110		dB
$G = 1000$	V_{CM} = +3.5 V to −5.15 V	105	110		105	110		105	110		dB
OUTPUT											
Output Swing	$R_L = 10\ k\Omega$, $V_S = \pm 5\ V$	$(-V_S) + 0.2$		$(+V_S) - 0.5$	$(-V_S) + 0.2$		$(+V_S) - 0.5$	$(-V_S) + 0.2$		$(+V_S) - 0.5$	V
	$R_L = 100\ k\Omega$	$(-V_S) + 0.05$		$(+V_S) - 0.15$	$(-V_S) + 0.05$		$(+V_S) - 0.15$	$(-V_S) + 0.05$		$(+V_S) - 0.15$	V
DYNAMIC RESPONSE											
Small Signal −3 dB Bandwidth											
$G = 1$			800			800			800		kHz
$G = 10$			100			100			100		kHz
$G = 100$			10			10			10		kHz
$G = 1000$			2			2			2		kHz
Slew Rate			0.3			0.3			0.3		V/µs
Settling Time to 0.01%	$V_S = \pm 5\ V$, 5 V step										
$G = 1$			30			30			30		µs
$G = 10$			20			20			20		µs

SPECIFICATIONS COMMON TO DUAL AND SINGLE SUPPLIES

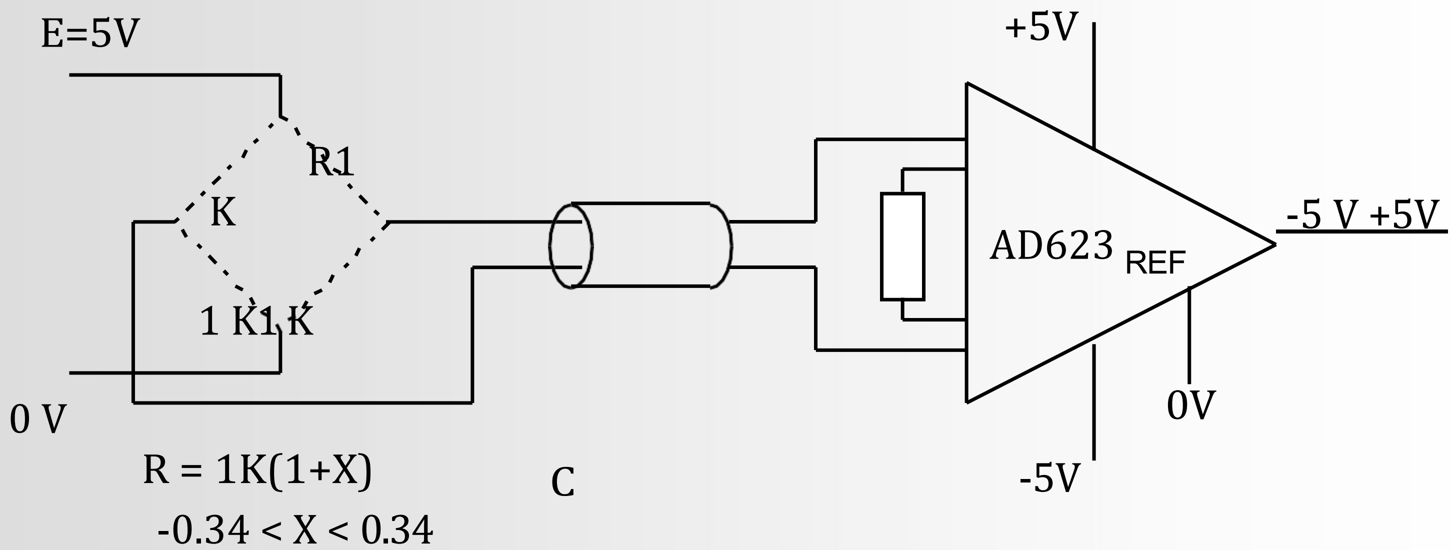
Table 4.

Parameter	Test Conditions/ Comments	AD623A			AD623ARM			AD623B			Unit
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
NOISE											
Voltage Noise, 1 kHz	Total RTI noise = $\sqrt{(e_{ni})^2 + (2e_{no}/G)^2}$										
Input, Voltage Noise, e_{ni}			35			35			35		nV/√Hz
Output, Voltage Noise, e_{no}			50			50			50		nV/√Hz
RTI, 0.1 Hz to 10 Hz											
G = 1			3.0			3.0			3.0		μV p-p
G = 1000			1.5			1.5			1.5		μV p-p
Current Noise	f = 1 kHz		100			100			100		fA/√Hz
0.1 Hz to 10 Hz			1.5			1.5			1.5		pA p-p
REFERENCE INPUT											
R_{IN}			100 ± 20%			100 ± 20%			100 ± 20%		kΩ
I_{IN}	$V_{IN}+$, $V_{REF} = 0$ V		50	60		50	60		50	60	μA
Voltage Range		$-V_S$		$+V_S$	$-V_S$		$+V_S$	$-V_S$		$+V_S$	V
Gain to Output			1 ± 0.0002			1 ± 0.0002			1 ± 0.0002		V
POWER SUPPLY											
Operating Range	Dual supply	±2.5		±6	±2.5		±6	±2.5		±6	V
	Single supply	2.7		12	2.7		12	2.7		12	V
Quiescent Current	Dual supply		375	550		375	550		375	550	μA
	Single supply		305	480		305	480		305	480	μA
Over Temperature				625			625			625	μA
TEMPERATURE RANGE											
For Specified Performance		−40		+85	−40		+85	−40		+85	°C

Instrumentation amplifier: characteristics

- Summary of errors

Application diagram:



Three types of errors:

- the initial errors, easily corrected by an adjustment
- errors that can be reduced by an intelligent system
- irreducible errors

Instrumentation amplifier: error balance

5. Isolation amplifier.

- *Classic* instrumentation amplifier :

  common mode voltage < supply voltage

- An isolation amplifier also ensures galvanic isolation between the source and the rest of the measurement chain.

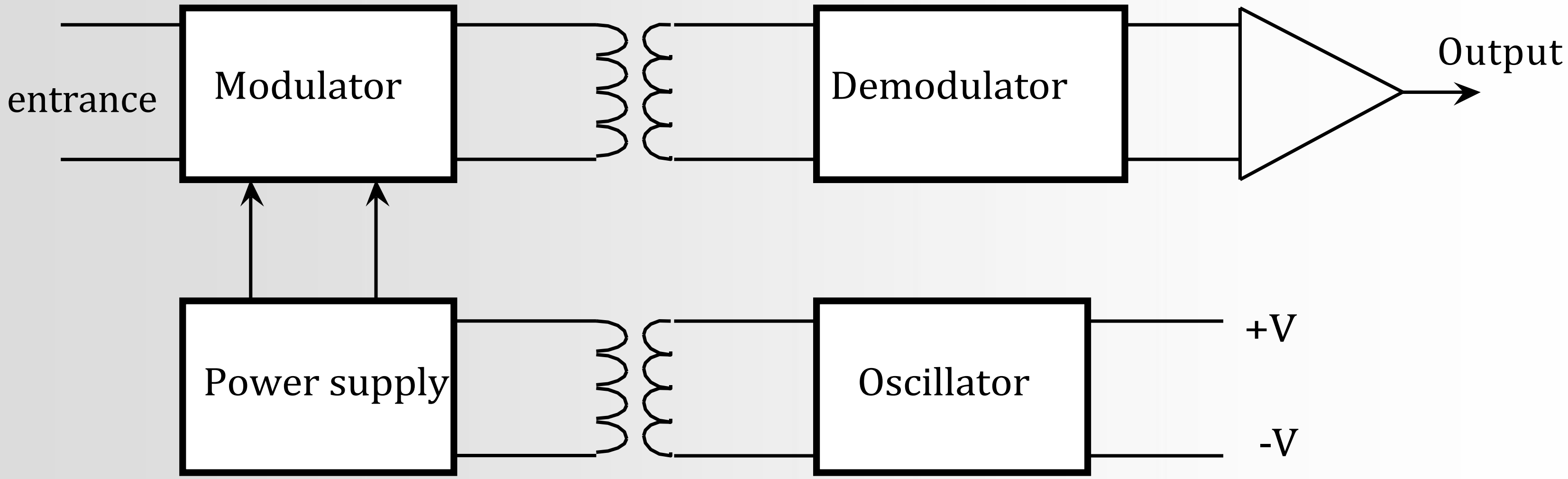
- But it is basically an instrumentation amplifier.

- Application: medical equipment.

- 2 processes : Transformer

  Optical coupling

- Principle:



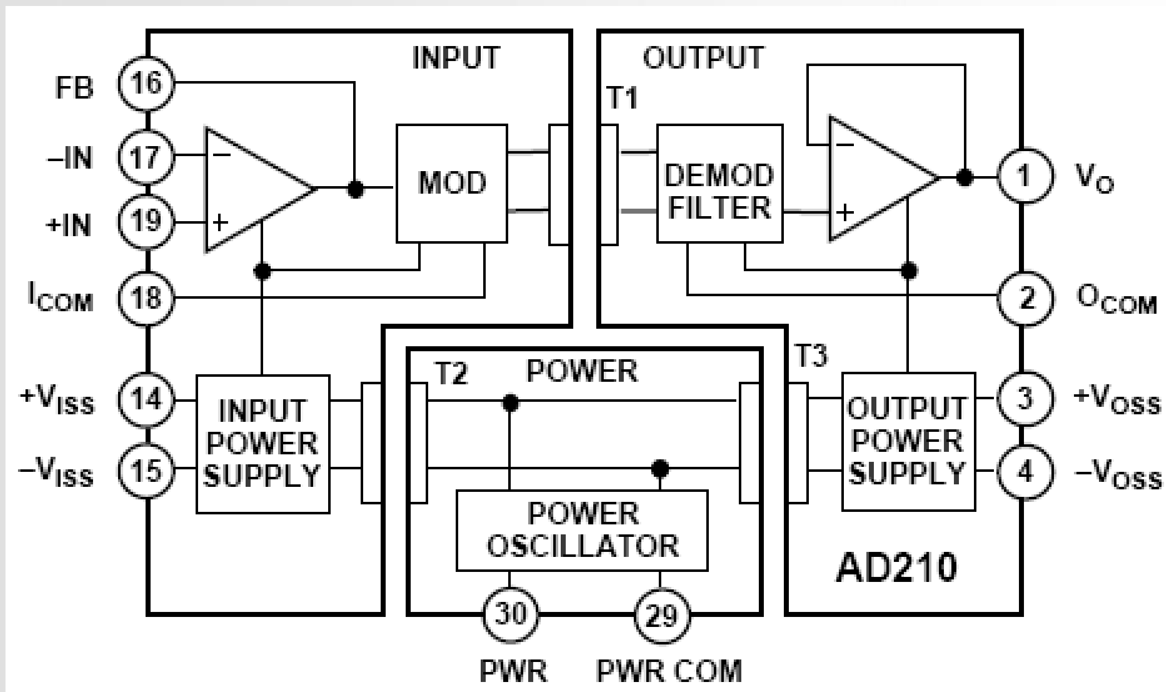
- Example: AD210

ANALOG DEVICES

Precision, Wide Bandwidth
3-Port Isolation Amplifier

AD210*

  - Block diagram:



- Features:

FEATURES

High CMV Isolation: 2500 V rms Continuous
±3500 V Peak Continuous

Small Size: 1.00" × 2.10" × 0.350"

Three-Port Isolation: Input, Output, and Power

Low Nonlinearity: ±0.012% max

Wide Bandwidth: 20 kHz Full-Power (–3 dB)

Low Gain Drift: ±25 ppm/°C max

High CMR: 120 dB (G = 100 V/V)

Isolated Power: ±15 V @ ±5 mA

Uncommitted Input Amplifier

APPLICATIONS

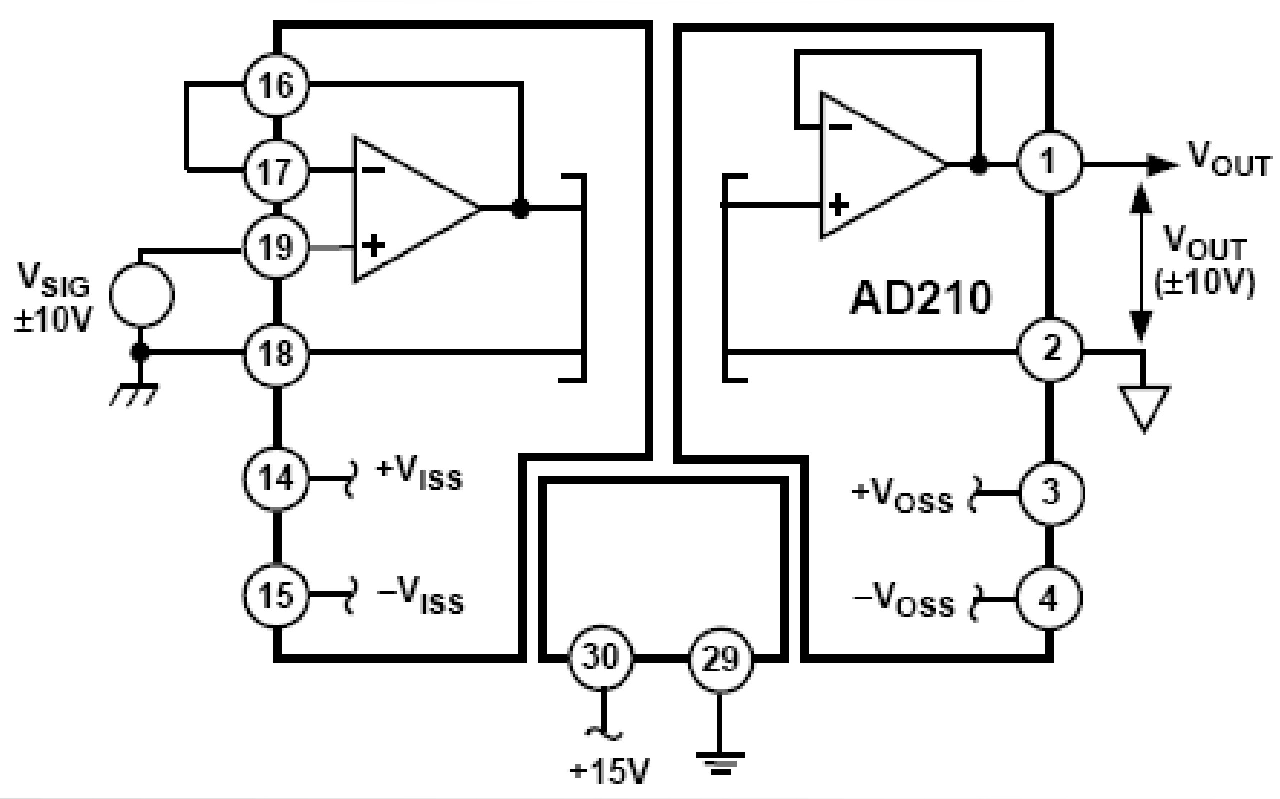
Multichannel Data Acquisition

High Voltage Instrumentation Amplifier

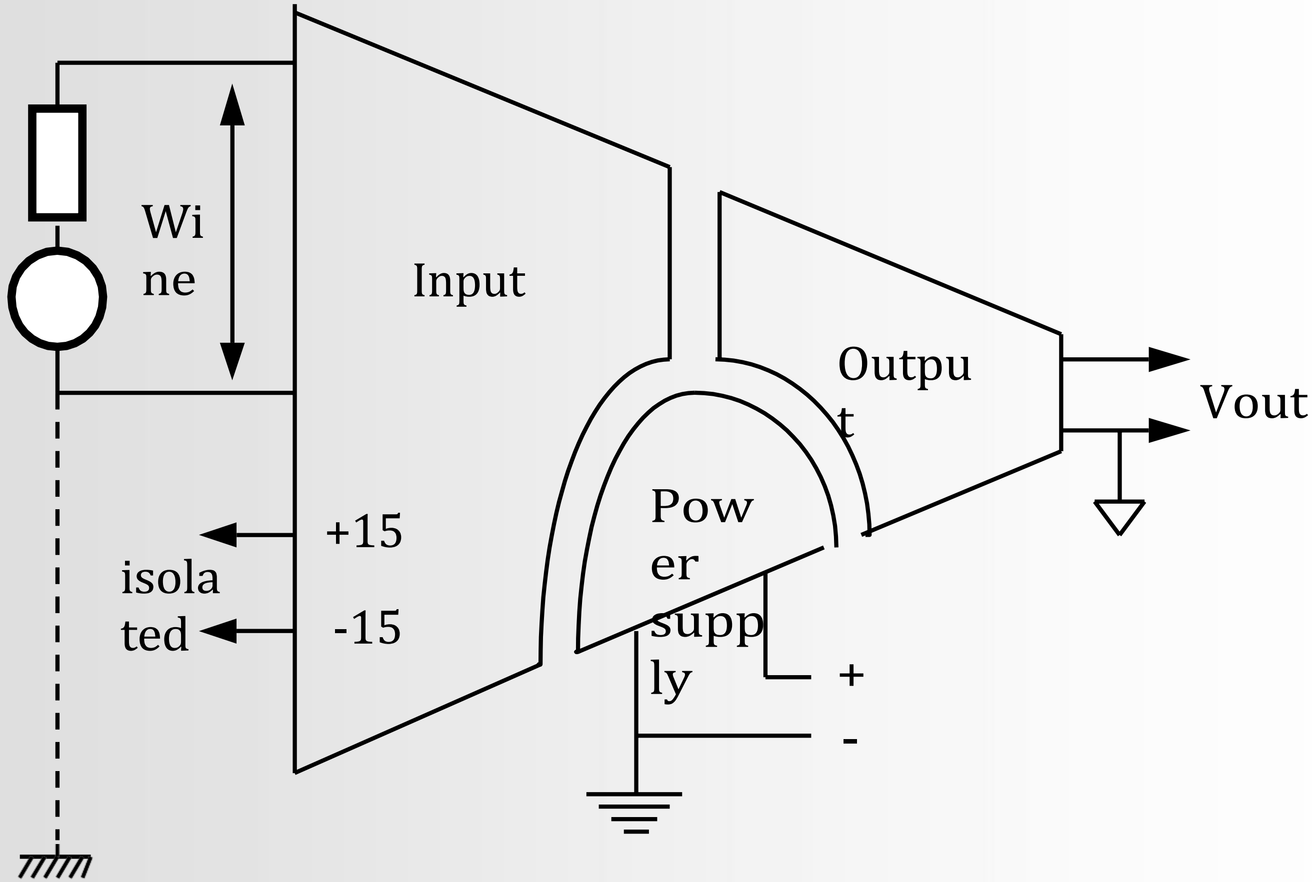
Current Shunt Measurements

Process Signal Isolation

- Example of assembly:



- The concept of isolation therefore allows for the definition of different masses.



Insulation voltage: between input ground and ground output

- AD210 Features:

Model	AD210AN
GAIN	
Range	1 V/V – 100 V/V
Error	±2% max
vs. Temperature(0°C to +70°C)	+25 ppm/°C max
(–25°C to +85°C)	±50 ppm/°C max
vs. Supply Voltage	±0.002%/V
Nonlinearity[1]	±0.025% max
INPUT VOLTAGE RATINGS	
Linear Differential Range	±10 V
Maximum Safe Differential Input	±15 V
Max. CMV Input-to-Output	*
ac, 60 Hz, Continuous	2500 V rms
dc, Continuous	±3500 V peak
Common-Mode Rejection	*
60 Hz, G = 100 V/V	*
$R_S \leq 500\ \Omega$ Impedance Imbalance	120 dB
Leakage Current Input-to-Output	*
@ 240 V rms, 60 Hz	2 µA rms max

INPUT IMPEDANCE	
Differential	$10^{12}\ \Omega$
Common Mode	$5\ G\Omega \| 5\ pF$
INPUT BIAS CURRENT	
Initial, @ +25°C	30 pA typ (400 pA max)
vs. Temperature (0°C to +70°C)	10 nA max
(–25°C to +85°C)	30 nA max
INPUT DIFFERENCE CURRENT	
Initial, @ +25°C	5 pA typ (200 pA max)
vs. Temperature(0°C to + 70°C)	2 nA max
(–25°C to +85°C)	10 nA max
INPUT NOISE	
Voltage (1 kHz)	$18\ nV/\sqrt{Hz}$
(10 Hz to 10 kHz)	4 μV rms
Current (1 kHz)	$0.01\ pA/\sqrt{Hz}$
FREQUENCY RESPONSE	
Bandwidth (–3 dB)	*
G = 1 V/V	20 kHz
G = 100 V/V	15 kHz
Settling Time (±10 mV, 20 V Step)	*
G = 1 V/V	150 μs
G = 100 V/V	500 μs
Slew Rate (G = 1 V/V)	1 V/μs

OFFSET VOLTAGE (RTI)[2]	
Initial, @ +25°C	±15 ±45/G) mV max
vs. Temperature (0°C to +70°C)	(±10 ±30/G) μV/°C
(–25°C to +85°C)	(±10 ±50/G) μV/°C
RATED OUTPUT[3]	
Voltage, 2 kΩ Load	±10 V min
Impedance	1 Ω max
Ripple (Bandwidth = 100 kHz)	10 mV p-p max
ISOLATED POWER OUTPUTS[4]	
Voltage, No Load	±15 V
Accuracy	±10%
Current	±5 mA
Regulation, No Load to Full Load	See Text
Ripple	See Text
POWER SUPPLY	
Voltage, Rated Performance	+15 V dc ± 5%
Voltage, Operating	+15 V dc ± 10%
Current, Quiescent	50 mA
Current, Full Load – Full Signal	80 mA
TEMPERATURE RANGE	
Rated Performance	–25°C to +85°C
Operating	–40°C to +85°C
Storage	–40°C to +85°C

6. Passive sensor conditioners.

- Objectives:

Passive sensor: Zc= f(m   mbeing the

measurand Variation of Zc as a function of the →

measurand

variation of an electrical quantity

by associating the sensor :

- a voltage source $_{es}$ or a current source $_{is}$
- other impedances

Measurement converter: it is a part of the conditioner, whose role is to carry out this transformation.

Two types of output:

- Amplitude   **vm = $_{es}$ f(Zc , Zk)**

- Frequency $f_m = f(Z_c , Z_k)$

- Sensitivity:
  - Overall sensitivity: $$S_t = \frac{\Delta v_m}{\Delta m} = \frac{\Delta v_m}{\Delta Z_c} \frac{\Delta Z_c}{\Delta m}$$

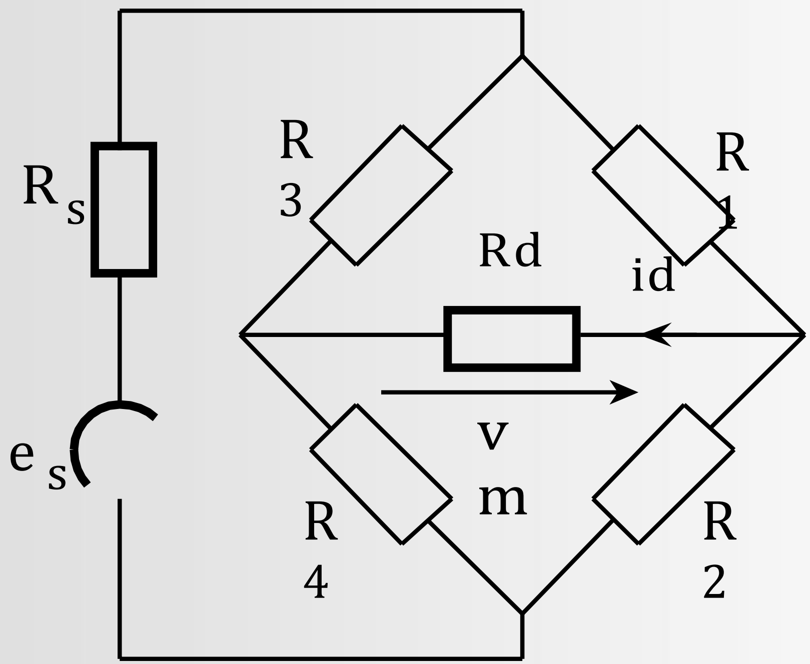
Sensor sensitivity

Sensitivity added by the converter

  - Points to consider:
    - Linearity: $\frac{\Delta v_m}{\Delta Z_c}$ indépendant de Z_c
    - Influence magnitudes

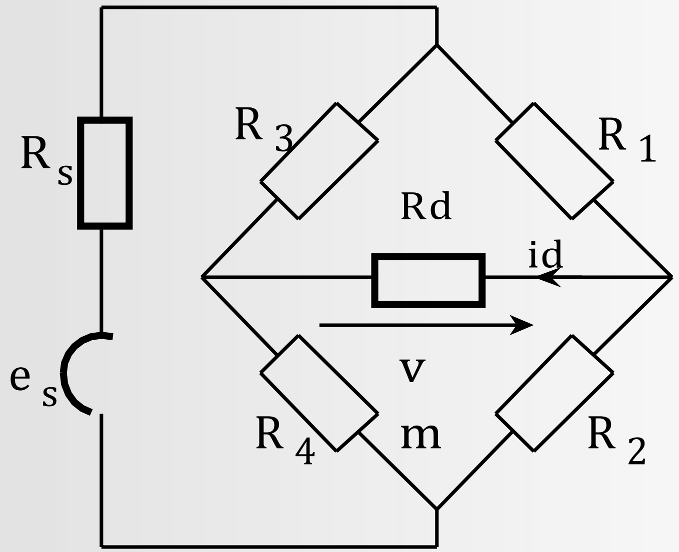
- Bridge mounting :

  $\longrightarrow$ Provide a differential measurement voltage



$i_d = f(R_1, R_2, R_3, R_4, R_s, R_d)$

$i_d = 0$ if $R_1 R_4 = R_2 R_3$ then $v_m = 0$



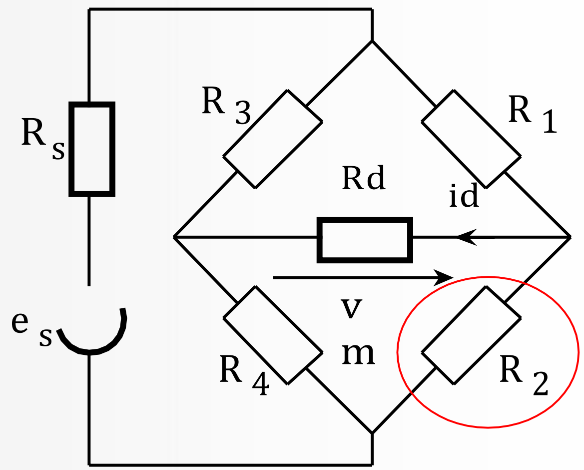
Neglecting the influence of resistances Rs and Rd :

$$v_m = e_s \frac{R_2 R_3 - R_1 R_4}{(R_1 + R_2)(R_3 + R_4)}$$

We will take $R_1=R_2=R_3=R_4=R_o$ *at equilibrium.*

- Sensor: $R_2 = R_o + \Delta R_c$

$$R_1 = R_3 = R_4 = R_o$$



$$v_m = \frac{e_s}{4\,R_o}\,\frac{\Delta R_c}{1+\dfrac{\Delta R_c}{2\,R_o}}$$

With $x = \dfrac{\Delta R_c}{R_o}$

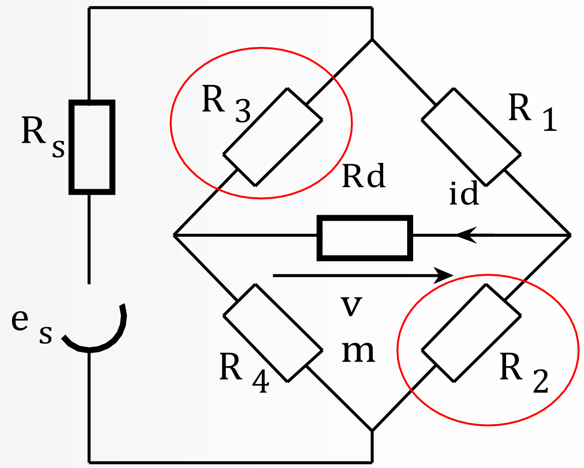
$$v_m = e_s\,\frac{x}{4}\,\frac{1}{1+\dfrac{x}{2}}$$

Non linear!

- Two sensors, with identical variations:

$$R_2 = R_3 = R_0 + \Delta R_c$$

$$R_1 = R_4 = R_0$$



$$\boxed{v_m = \frac{e_s}{2}\,\frac{x}{1+\frac{x}{2}}}$$

Non-linear

- Two sensors, with opposite variations:

$$R_2 = R_0 + \Delta R_c$$

$$R_1 = R_0 - \Delta R_c$$

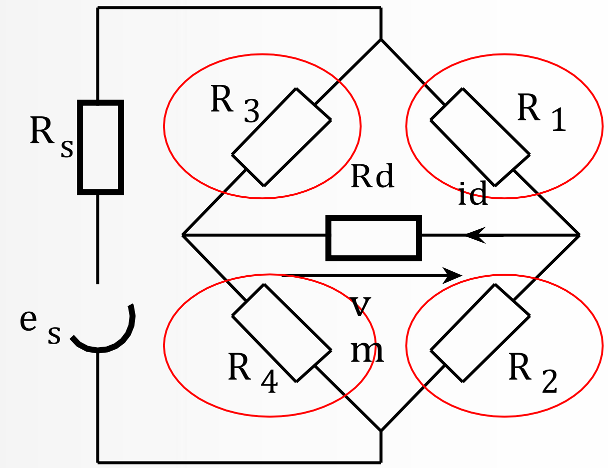
$$\boxed{v_m = e_s\,\frac{x}{2}}$$

Linear

- Push-pull mounting: 4 sensors

$$R_2 = R_3 = R_o + \Delta R_c$$

$$R_1 = R_4 = R_o - \Delta R_c$$



$$\boxed{v_m = e_s\, x}$$

Linear

$$x = \frac{\Delta R_c}{R_o}$$

Application: strain gauges

- Study of the influence of a parasitic quantity (g)

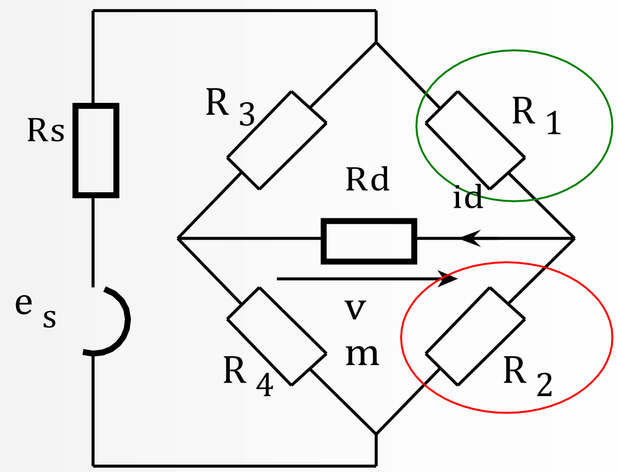
Sensor:

$$\boxed{R_2 = R_o + S\Delta m + S_g \Delta g}$$

A compensation sensor:

$$\boxed{R_1 = R_o + S_g \Delta g}$$

$$v_m = \frac{e_s}{4 R_o} \frac{S\Delta m}{1 + \frac{S\Delta m}{2 R_o} + \frac{S_g \Delta g}{R_o}}$$



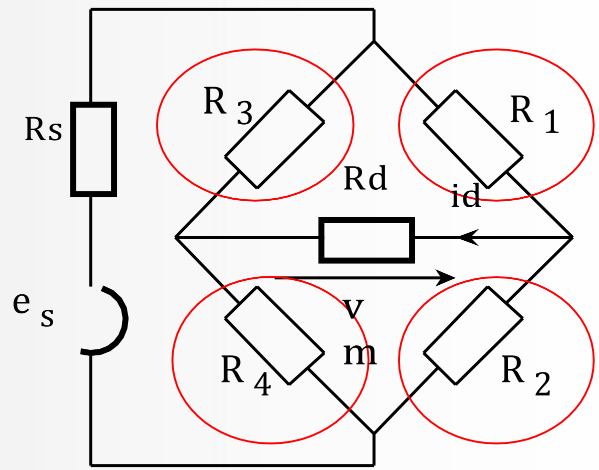
- Study of the influence of a parasitic quantity (g)

Push-pull assembly:

$\Delta R_2 = \Delta R_3 = S\,\Delta m + Sg\,_{\Delta g}\ \Delta R_1$

$= \Delta R_4 = -\,S\,\Delta m + Sg\,_{\Delta g}$

$$v_m = e_s \frac{S\Delta m}{R_o} \frac{1}{1 + S_g \Delta g}$$



The sensitivity depends on the influence quantity

- Example of compensation: g = temperature

$$\Delta g = T - T_o \qquad (T_o \rightarrow R_o)$$

$$R(T) = R_o\,(1 + \alpha_R . \Delta T)$$ so $$S_g = R_o\,\alpha_R$$

S(T) : the sensitivity of the sensor is a function of the temperature

This gives $$v_m = e_s \frac{S(T)}{R(T)} \Delta m$$

Compensation principle: temperature-sensitive source resistance Rs

Compensation principle: temperature-sensitive source resistance Rs

Before : $v_m = e_s \frac{S(T)}{R(T)} \Delta m$

$$v_m = e_s \frac{R_{eq}(T)}{R_{eq}(T) + R_s(T)} \frac{S(T)}{R(T)} \Delta m$$

but $R_{eq}(T) = R(T)$

$$v_m = e_s \frac{S(T)}{R(T) + R_s(T)} \Delta m$$

$$v_m = e_S \frac{S(T)}{R(T) + R_S(T)} \Delta m$$

$$R(T) = R_O\,(\,1 + \alpha_R . \Delta T)$$

$$R_S(T) = R_{SO}\,(\,1 + \alpha_S . \Delta T)$$

Temperature coefficients

$$S(T) = S_O\,(\,1 + \beta . \Delta T)$$

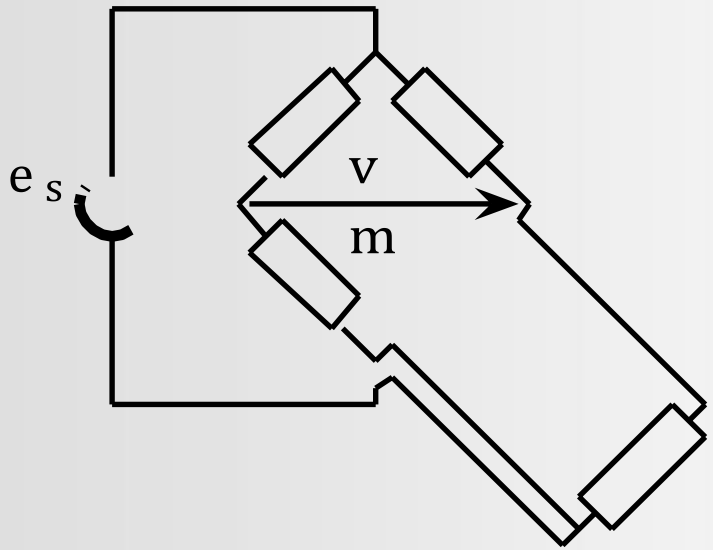
$$R_{SO} = k\,R_O$$

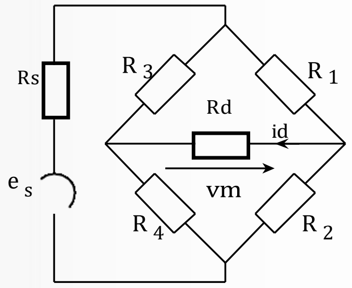
We obtain:

$$\boxed{v_m = e_S \frac{S_O}{R_O(1+k)} \frac{1 + \beta \Delta T}{1 + \frac{\alpha_R + k\,\alpha_s}{1+k} \Delta T} \Delta m}$$

It is necessary $\beta \frac{\alpha_R + k\,\alpha_s}{1+k}$ and $R_{SO} = \frac{\alpha_R - \beta}{\beta - \alpha_s} R_O$

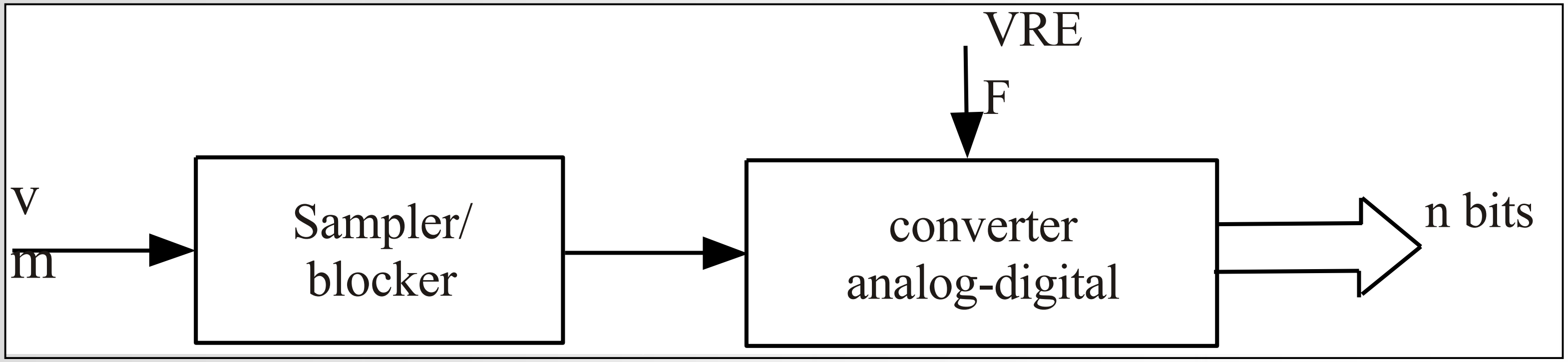
- Elimination of disturbances due to bonding wires:





7. Signal conversion.

- Objective: transform an analog quantity into a "faithful" digital quantity



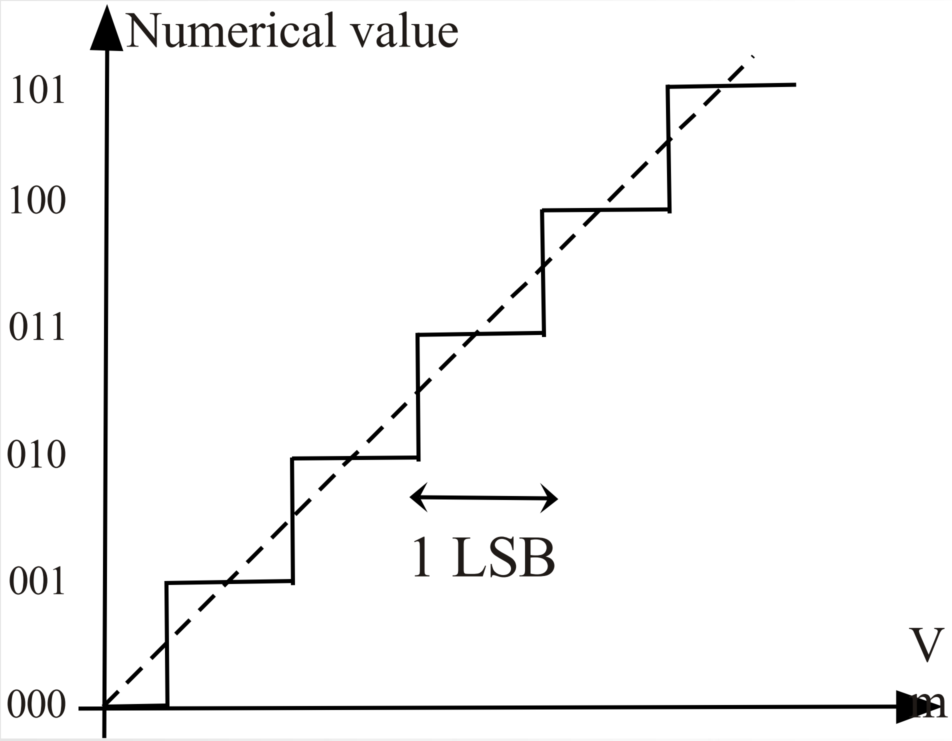
Unsigned word of n bits : an-1 an-2 . . . . a2 a1 a0

$$V_m = \frac{V_{REF}}{2^n}(a_{n-1}.2^{n-1} + a_{n-2}.2^{n-2} + ... + a_1.2^1 + a_0.2^0)$$

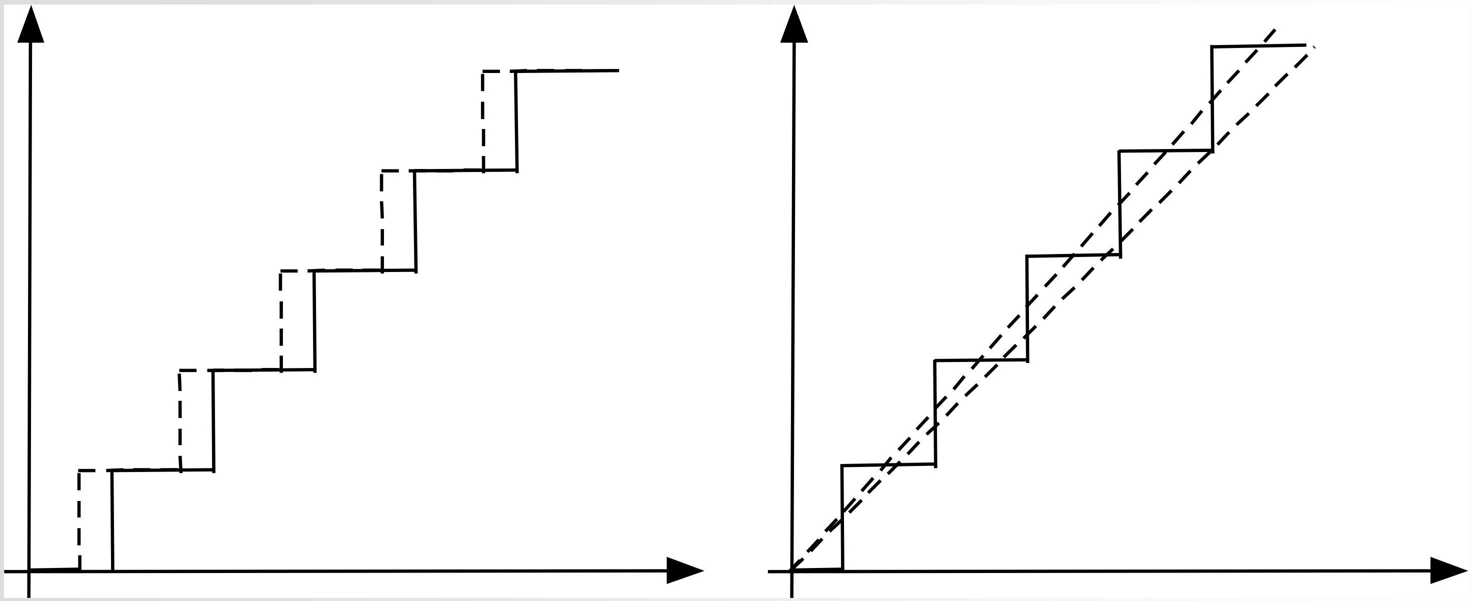
$$V_{m\,max} = V_{REF} \cdot \left(1 - \frac{1}{2^n}\right)$$

$$1 \text{ LSB (quantum)} = \frac{V_{REF}}{2^n}$$

- The different codes:
  - Unipolar operation: natural binary code
  - Bipolar operation: two's complement code
- Ideal transfer function :

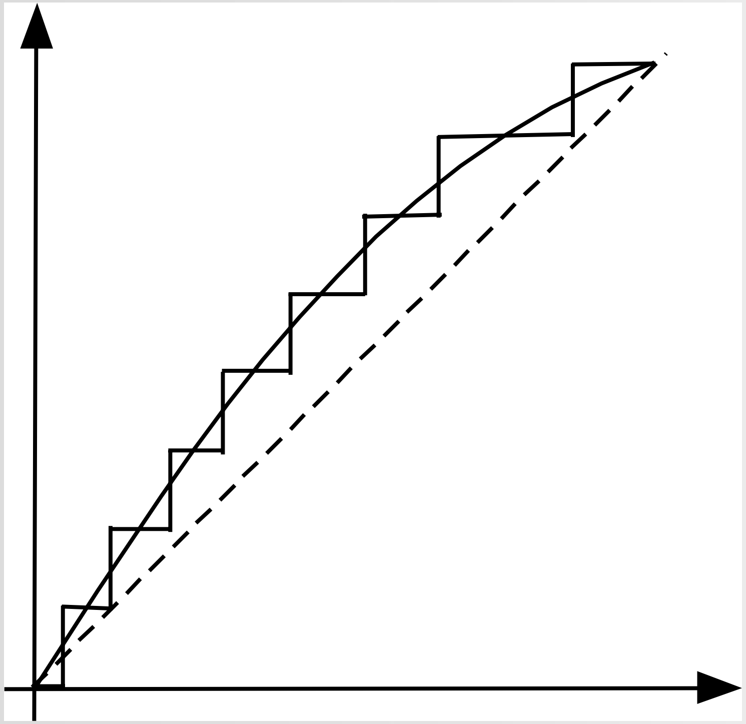


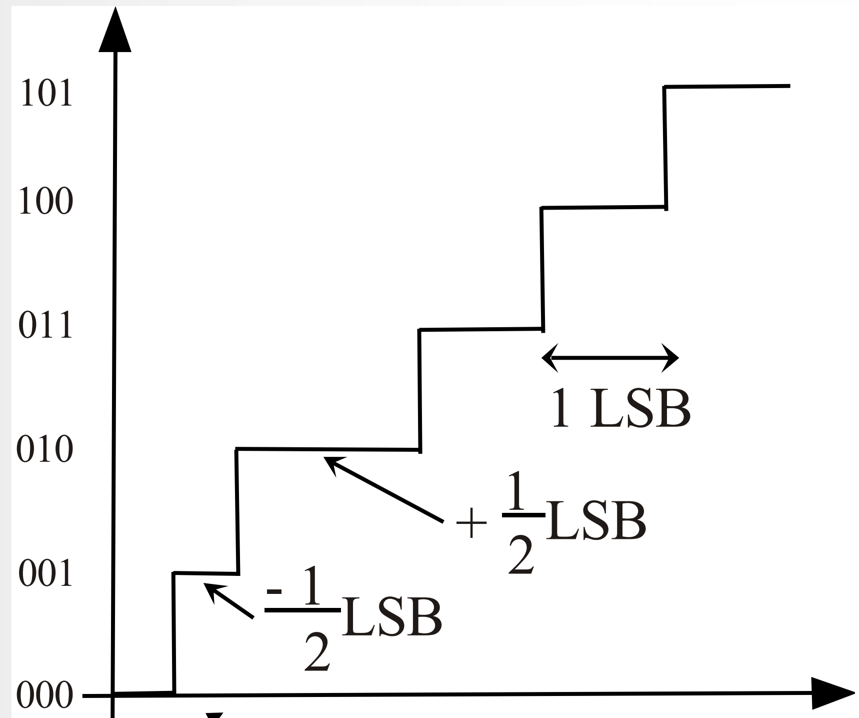
- NAC (and DAC) specifications
  - Offset error, gain error



  - Gain and offset drift

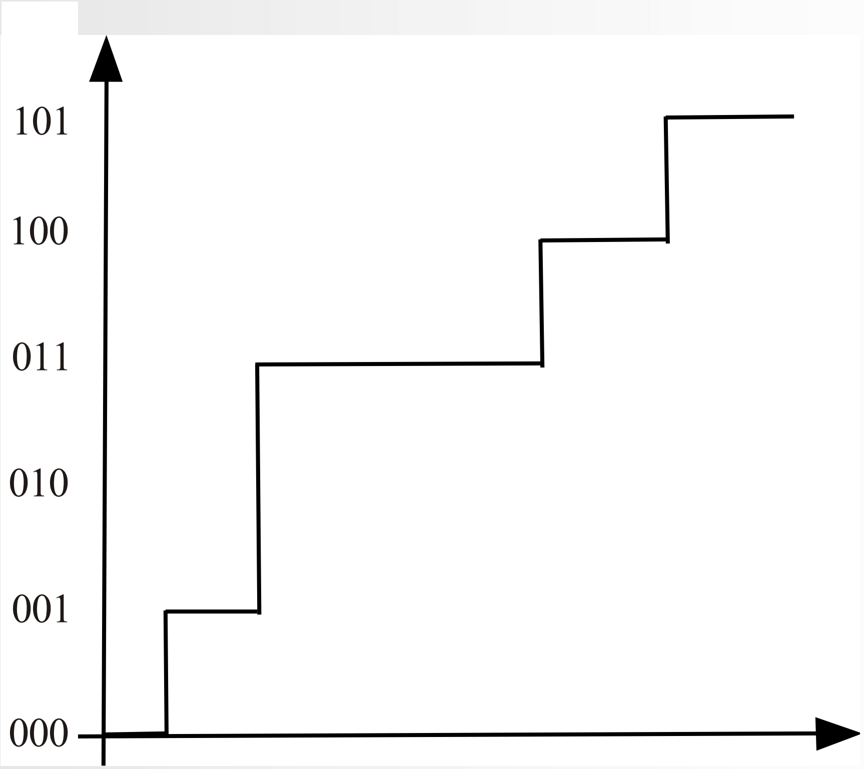
- Integral non-linearity:





- Differential non-linearity :

- Missing code:



An analog-to-digital converter with a differential linearity of 1 LSB must be guaranteed without missing code.

- Error budget

- The different types of converters :
  - Converters with successive approximations
  - Single ramp, double ramp, triple ramp converters
  - Flash" converters
  - Sigma-delta converter.

• Example 1: AD7870

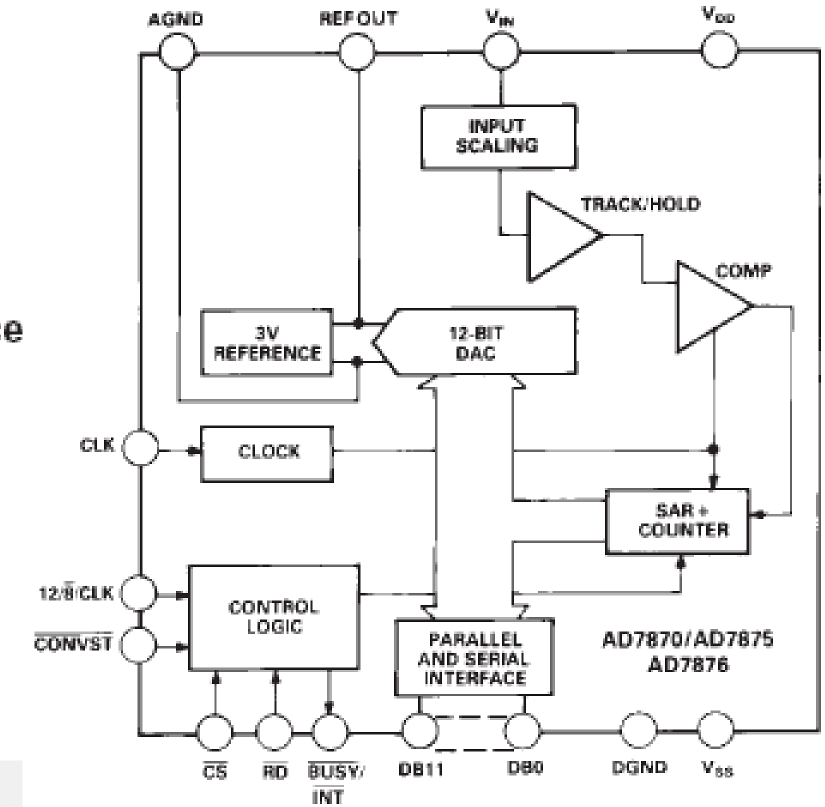
ANALOG DEVICES

LC²MOS
Complete, 12-Bit, 100 kHz, Sampling ADCs

AD7870/AD7875/AD7876

FEATURES
Complete Monolithic 12-Bit ADC with:
- 2 μs Track/Hold Amplifier
- 8 μs A/D Converter
- On-Chip Reference
- Laser-Trimmed Clock
- Parallel, Byte and Serial Digital Interface

72 dB SNR at 10 kHz Input Frequency (AD7870, AD7875)
57 ns Data Access Time
Low Power: –60 mW typ
Variety of Input Ranges:
- ±3 V for AD7870
- 0 V to +5 V for AD7875
- ±10 V for AD7876



- AD7870 Features:

AD7870/AD7875/AD7876–SPECIFICATIONS (V_{DD} = +5 V ± 5%, V_{SS} = –5 V ± 5%, A6ND = DGND = 0 V, f_{CLK} = 2.5 MHz external, unless otherwise stated. All Specifications T_{min} to T_{max} unless otherwise noted.)

Parameter	AD7870 J, A[1]	K, B[1]	L, C[1]	S[1]	T[1]	Units	Test Conditions/Comments
DC ACCURACY							
Resolution	12	12	12	12	12	Bits	
Minimum Resolution for which No Missing Codes are Guaranteed	12	12	12	12	12	Bits	
Integral Nonlinearity	±1/2	±1/2	±1/4	±1/2	±1/2	LSB typ	
Integral Nonlinearity		±1	±1/2		±1	LSB max	
Differential Nonlinearity		±1	±1		±1	LSB max	
Bipolar Zero Error	±5	±5	±5	±5	±5	LSB max	
Positive Full-Scale Error[4]	±5	±5	±5	±5	±5	LSB max	
Negative Full-Scale Error[4]	±5	±5	±5	±5	±5	LSB max	
ANALOG INPUT							
Input Voltage Range	±3	±3	±3	±3	±3	Volts	
Input Current	±500	±500	±500	±500	±500	µA max	

- Example 2: AD7874

3 V/5 V, CMOS, 500 μA Signal Conditioning ADC

AD7714*

FEATURES

Charge Balancing ADC
- 24 Bits No Missing Codes
- 0.0015% Nonlinearity

Five-Channel Programmable Gain Front End
- Gains from 1 to 128
- Can Be Configured as Three Fully Differential Inputs or Five Pseudo-Differential Inputs

Three-Wire Serial Interface
- SPI™, QSPI™, MICROWIRE™ and DSP Compatible

3 V (AD7714-3) or 5 V (AD7714-5) Operation

Low Noise (<150 nV rms)

Low Current (350 μA typ) with Power-Down (5 μA typ)

AD7714Y Grade:
- +2.7 V to 3.3 V or +4.75 V to +5.25 V Operation
- 0.0010% Linearity Error
- –40°C to +105°C Temperature Range
- Schmitt Trigger on SCLK and DIN
- Low Current (226 μA typ) with Power-Down (4 μA typ)
- Lower Power Dissipation than Standard AD7714
- Available in 24-Lead TSSOP Package

Low-Pass Filter with Programmable Filter Cutoffs

Ability to Read/Write Calibration Coefficients

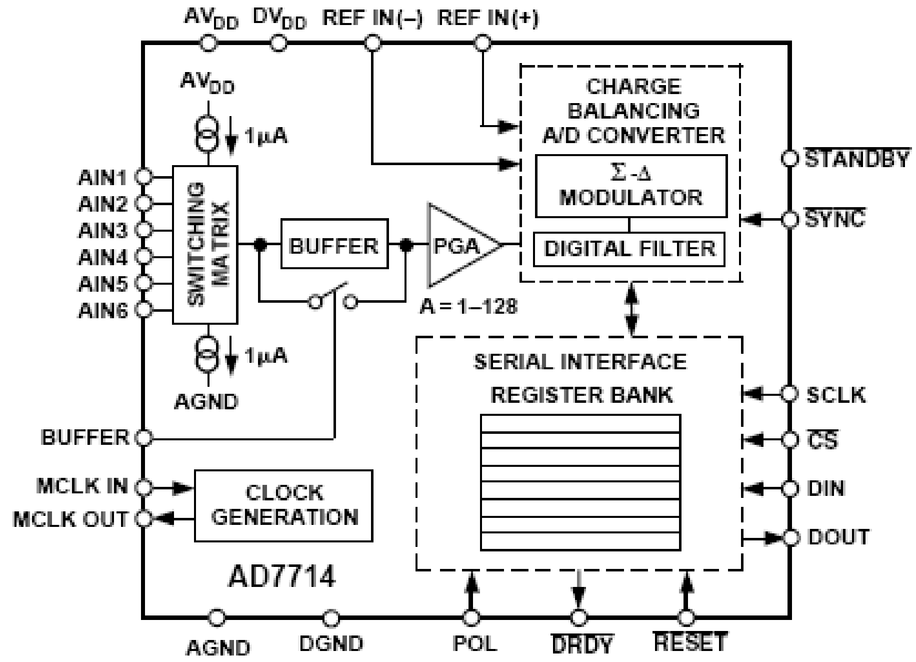
APPLICATIONS

Portable Industrial Instruments

Portable Weigh Scales

Loop-Powered Systems

Pressure Transducers



- AD7874 Features:

Parameter	A Versions[1]	Units
STATIC PERFORMANCE		
No Missing Codes	24	Bits min
	22	Bits min
	18	Bits min
	15	Bits min
	12	Bits min
Output Noise	See Tables I to IV	
Integral Nonlinearity	±0.0015	% of FSR max
Unipolar Offset Error	See Note 2	
Unipolar Offset Drift[3]	0.5	μV/°C typ
	0.3	μV/°C typ
Bipolar Zero Error	See Note 2	
Bipolar Zero Drift[3]	0.5	μV/°C typ
	0.3	μV/°C typ
Positive Full-Scale Error[4]	See Note 2	
Full-Scale Drift[3, 5]	0.5	μV/°C typ
	0.3	μV/°C typ
Gain Error[6]	See Note 2	
Gain Drift[3, 7]	0.5	ppm of FSR/°C typ
Bipolar Negative Full-Scale Error	±0.0015	% of FSR max
Bipolar Negative Full-Scale Drift[3]	1	μV/°C typ
	0.6	μV/°C typ

8. Electronic noise.

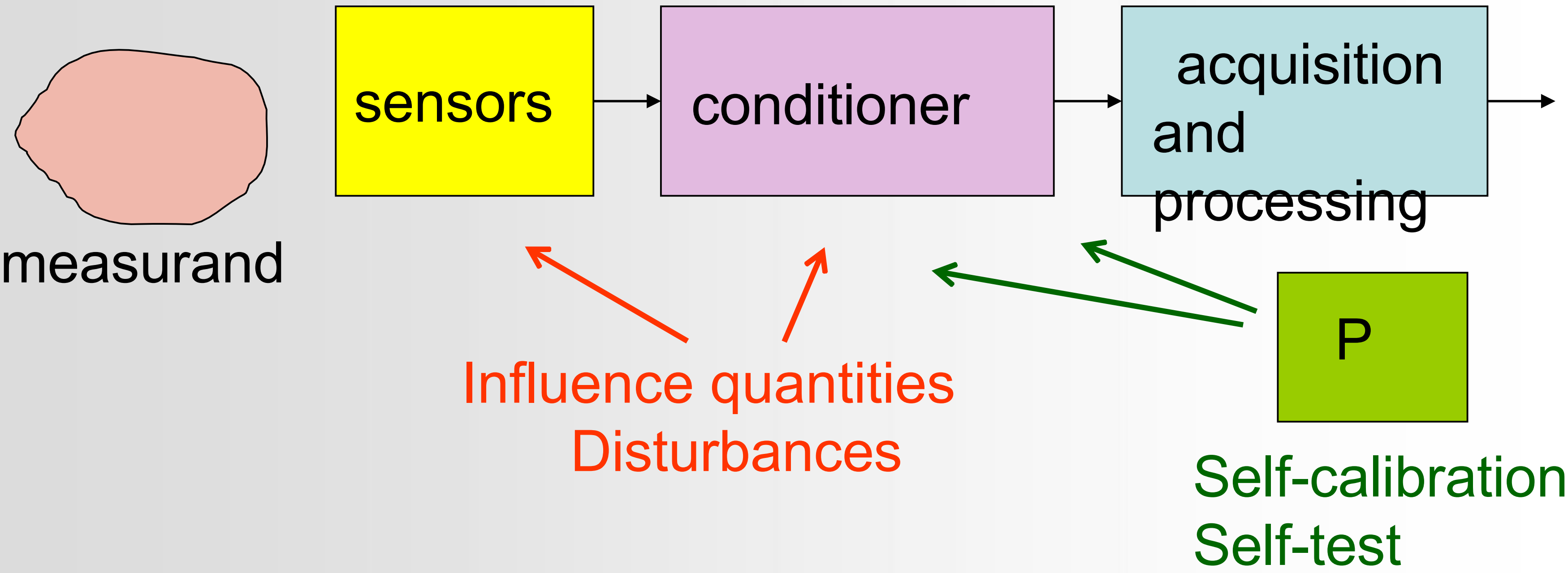
Instrumentation amplifier AD623 :

SPECIFICATIONS COMMON TO DUAL AND SINGLE SUPPLIES

Table 4.

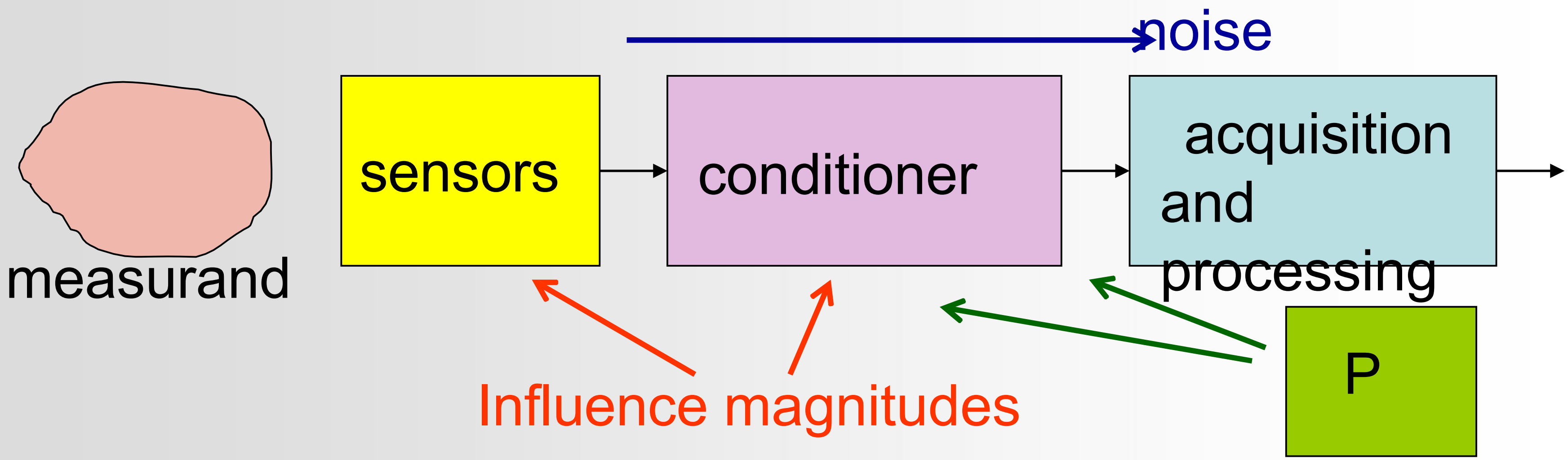
Parameter	Test Conditions/ Comments	AD623A			AD623ARM			AD623B			Unit
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
NOISE											
Voltage Noise, 1 kHz	Total RTI noise = $\sqrt{(e_{ni})^2 + (\cancel{2}e_{no}/G)^2}$										
Input, Voltage Noise, e_{ni}			35			35			35		nV/√Hz
Output, Voltage Noise, e_{no}			50			50			50		nV/√Hz
RTI, 0.1 Hz to 10 Hz											
G = 1			3.0			3.0			3.0		µV p-p
G = 1000			1.5			1.5			1.5		µV p-p
Current Noise	f = 1 kHz		100			100			100		fA/√Hz
0.1 Hz to 10 Hz			1.5			1.5			1.5		pA p-p

Reminders:



Purpose of a measurement chain: to provide as accurate a representation of the measurand as possible

BUT imperfections ... errors → BUDGET OF ERRORS



Self-calibration
Self-test

Influence quantities :

- temperature
- humidity
- atmospheric pressure
- shocks and vibrations
- ...
- Common mode disturbance

Electromagnetic disturbance (EMC)

Electronic noise (internal)

9. Temperature sensors.

9.1. Temperature scales.

- Thermometer scale
- Thermodynamic (or absolute) scale: Kelvin (K)

Derived scales :

	Kelvin (K)	Celsius (°C)	Rankin (°R)	Fahrenheit (°F)
Zéro absolu	0	-273,15	0	-459,67
Température d'équilibre du mélange eau-glace sous pression atmosphérique normale	273,15	0	491,67	32
Point triple de l'eau	273,16	0,01	491,69	32,02
Température d'ébullition de l'eau sous p.a.m.	373,15	100	471,67	212

- International Practical Temperature Scale

  - ➢ Choice of three physical quantities: resistance, e.m.f. of a thermocouple and black body radiation

  - ➢ 11 primary fixed points, 27 secondary points

    Example:

Example:	triple point of hydrogen:	13.31 K
	Triple point of oxygen:	54.361K
	Boiling point of water:	373.15 K

  - ➢ interpolation formulas

Entre 0°C et 630,74 °C : $R(T) = R_o.(1 + a.T + b.T^2)$

a et b : à partir de deux points fixes

9.2. Metallic temperature probes.

- Resistance - temperature relationship :

$$R = \rho.\frac{L}{S} \qquad L = L_o.(1 + a.\theta) \qquad S = S_o.(1 + a.\theta)^2 \qquad \theta \text{ en}°C$$

$$\rho = \rho_o.(1 + \lambda.\theta)$$

a : coefficient moyen de dilatation linéaire du matériau

λ : coefficient moyen de température de la résistivité du métal

$$R(\theta) = \frac{\rho_o.L_o}{S_o}.\frac{1 + \lambda.\theta}{1 + a.\theta}$$

a: de l'ordre de 10^{-5} $(°C)^{-1}$

λ : peu variable pour les métaux $\approx 4\ 10^{-4}$ $(°C)^{-1}$

$$R(\theta) = R_o.\left(1 + (\lambda - a).\theta - \lambda.a.\theta^2\right)$$

In general:

$$\boxed{R(\theta) = R_o.(1 + a.\theta + b.\theta^2)}$$

- Desired characteristics for the metal:
  - high temperature coefficient for greater sensitivity,
  - high resistivity,
  - stability.

Note: thelinearity of the resistance-temperature relationship is no longer an imperative for the choice of the metal.

	R(100°C)/R(0°C)	Résistivité à 0°C	Domaine d'utilisation
Platine	1,3850	$9{,}81\ 10^{-8}\ \Omega m$	-200 à 850 °C
Nickel	1,618	$5{,}75\ 10^{-8}\ \Omega m$	-60 à 180 °C

- Platinum: The most inalterable, the most stainless and the most invariable.
  - melting temperature : 1769 °C
  - can be obtained very pure (99.999%): characteristics identical from one probe to another
  - simple law of variation

- DIN 43760 standard (published by AFNOR): governs temperature sensors for scientific and industrial use with a platinum or nickel wire resistance
  - value table
  - for platinum between 0°C and 850°C :

$$\boxed{R(\theta) = 100.(1 + 3{,}90802.10^{-3}.\theta - 0{,}580195.10^{-6}.\theta^2) \quad \text{en } \Omega}$$

9.3. Thermistors.

Semiconductor resistors :

- High sensitivity
- Non-linear
- Range of application: -100°C to 450°C approx.
- Interchangeability has increased significantly (from 0.1 to 0.2°C)

- Resistance - temperature relationship

$$R = a.\exp\left(\frac{b}{T}\right) \text{ avec } b > 0$$

$$\text{si } R_o \text{ connue à } T_o : \qquad R = R_o.\exp\left(b.\left(\frac{1}{T} - \frac{1}{T_o}\right)\right)$$

$$\text{Coefficient de température } \alpha \ : \ \alpha = \frac{1}{R(T)}.\frac{dR}{dT} = -\frac{b}{T^2}$$

  - < 0 for a NTC
  - large if T small : use in the left part of the characteristic

- :   -5.10-2 K-1 to -1.10-2 K-1
  Note: for a platinum probe 3.9.10-3 K-1

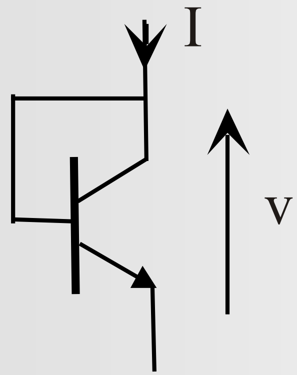
- A thermistor is given by
  - a resistance value at a given temperature
  - the temperature coefficient at this temperature.

Example :$_{R298K}$ = 12 κ $_{298K}$ = -5.10-2 K-1

- Low thermal time constant

- Example of assembly

9.4. Sensors with diodes or transistors :

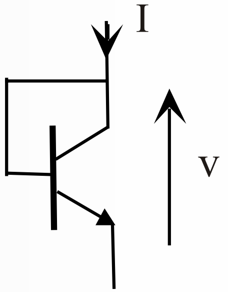


Sensitivity: $$S = \frac{dv}{dT}$$

not constant as a function of temperature

⟶ Use of matched transistors

- Voltage - temperature relationship



$$I = I_S.\left(\exp\left(\frac{q.v}{k.T}\right) - 1\right)$$

T in K
q elementary charge of the electron (1.6.10-19 C), k Boltzmann constant (1.38.10-23 J.K-1)
Is saturation current

In direct polarization :

$$I = I_S.\exp\left(\frac{q.v}{k.T}\right)$$

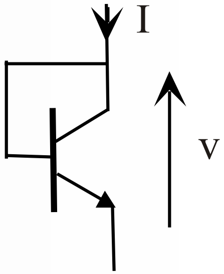
$$I_S = C.T^m.\exp\left(-\frac{q.V_\Phi}{k.T}\right)$$

V�: height of the band gap expressed in V (1.12 V for silicon) m close to 3
C constant independent of T.

$$\longrightarrow \quad v = V_\Phi - \frac{k.T}{q}(m.\ln T - \ln\frac{I}{C})$$

- Sensitivity

$$v = V_\Phi - \frac{k.T}{q}(m.\ln T - \ln\frac{I}{C})$$



$$\frac{dv}{dT} = \frac{k}{q}(\ln\frac{I}{C} - m.\ln T) - \frac{m.k}{q}$$

$$\boxed{\frac{dv}{dT} = \frac{v - V_\Phi}{T} - \frac{m.k}{q}}$$

Numerical application:

$$\boxed{v = 0{,}6\ \mathrm{V} \quad V_\Phi = 1{,}12\ \mathrm{V} \qquad \frac{dv}{dT} = -2\ \mathrm{mV.K}^{-1}}$$

- Use of matched transistors

Q1, Q2 I1, I2 v1, v2 current $_{Is}$ identical

$$I_1 = I_s.\exp\left(\frac{q.v_1}{k.T}\right)$$

$$I_2 = I_s.\exp\left(\frac{q.v_2}{k.T}\right)$$

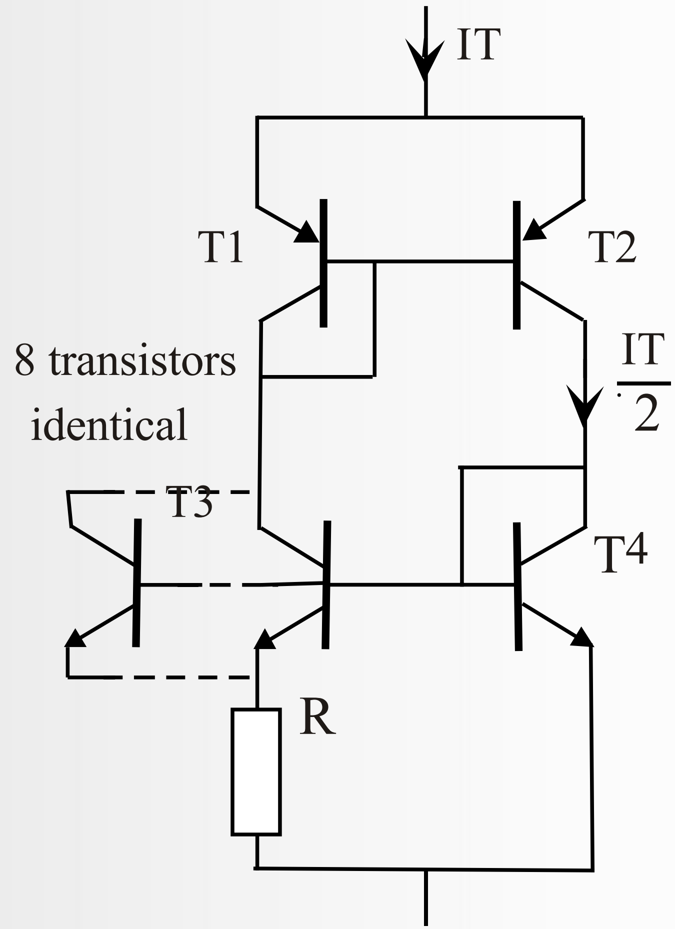
$$\longrightarrow \frac{I_1}{I_2} = \exp\left(\frac{q}{k.T}(v_1 - v_2)\right)$$

$$\boxed{v_d = v_1 - v_2 = \frac{k.T}{q}.\ln\frac{I_1}{I_2}}$$

Example: $\frac{I_1}{I_2} = 2$ v_d=59,78.T en µV

- Integrated sensors: for example the AD590.

Simplified diagram:



$$I_T = \left(\frac{k}{q} \cdot \frac{2}{R} . Ln\, 8 \right) . T$$

avec $R = 358\ \Omega$, on obtient $1\, \mu A.K^{-1}$

Technical documentation:

FEATURES

Linear current output: 1 µA/K
Wide temperature range: −55°C to +150°C
Probe-compatible ceramic sensor package
2-terminal device: voltage in/current out
Laser trimmed to ±0.5°C calibration accuracy (AD590M)
Excellent linearity: ±0.3°C over full range (AD590M)
Wide power supply range: 4 V to 30 V
Sensor isolation from case
Low cost

PIN CONFIGURATIONS

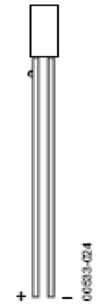


Figure 1. 2-Lead CQFP

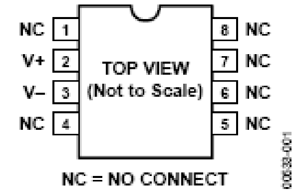


Figure 2. 8-Lead SOIC

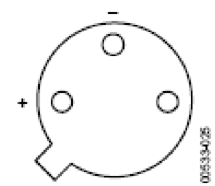
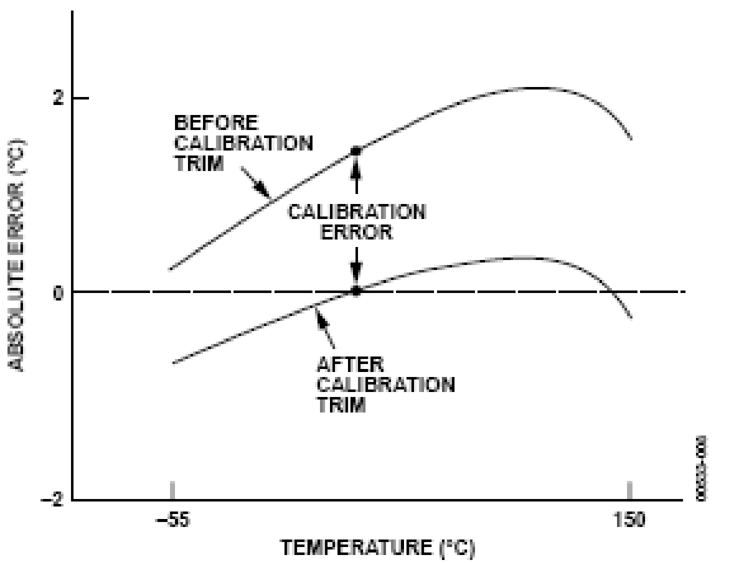


Figure 3. 3-Pin TO-52

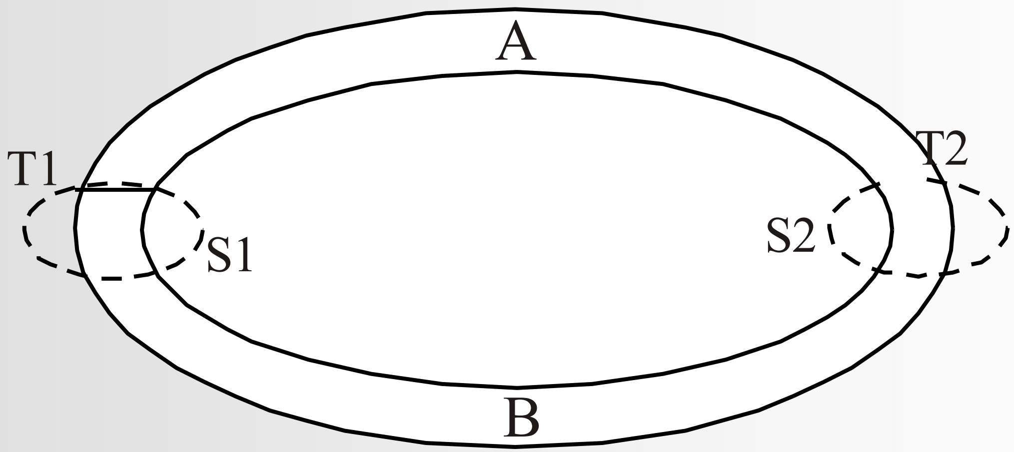


Features:

Parameter	AD590J Min	AD590J Typ	AD590J Max	AD590K Min	AD590K Typ	AD590K Max	Unit
POWER SUPPLY							
Operating Voltage Range	4		30	4		30	V
OUTPUT							
Nominal Current Output @ 25°C (298.2K)		298.2			298.2		μA
Nominal Temperature Coefficient		1			1		μA/K
Calibration Error @ 25°C			±5.0			±2.5	°C
Absolute Error (Over Rated Performance Temperature Range)							
Without External Calibration Adjustment			±10			±5.5	°C
With 25°C Calibration Error Set to Zero			±3.0			±2.0	°C
Nonlinearity							
For TO-52 and CQFP Packages			±1.5			±0.8	°C
For 8-Lead SOIC Package			±1.5			±1.0	°C
Repeatability[2]			±0.1			±0.1	°C
Long-Term Drift[3]			±0.1			±0.1	°C
Current Noise		40			40		pA/√Hz
Power Supply Rejection							
$4\ V \le V_S \le 5\ V$		0.5			0.5		μA/V
$5\ V \le V_S \le 15\ V$		0.2			0.2		μV/V
$15\ V \le V_S \le 30\ V$		0.1			0.1		μA/V
Case Isolation to Either Lead		10^{10}			10^{10}		Ω
Effective Shunt Capacitance		100			100		pF
Electrical Turn-On Time		20			20		μs
Reverse Bias Leakage Current (Reverse Voltage = 10 V)[4]		10			10		pA

9.5. Thermocouple.

- Statement of the Seebeck effect (1821):



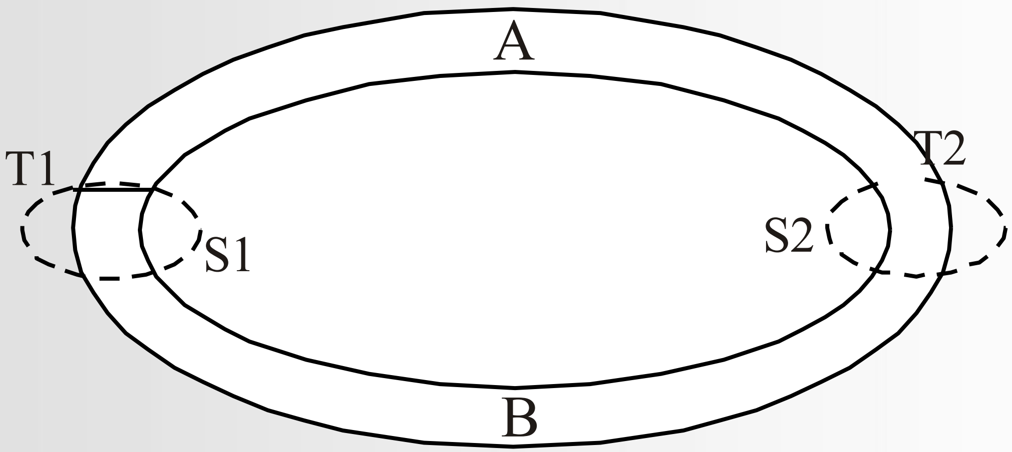
The circuit is the seat of an e.m.f. function of the two temperatures T1 and T2, but also of the two materials A and B:

e(T1, T2, A, B)   e.m.f. thermocouple

Thermoelectric torque, or thermocouple

Application:

T2 constant, measurement of T1 through the e.m.f.

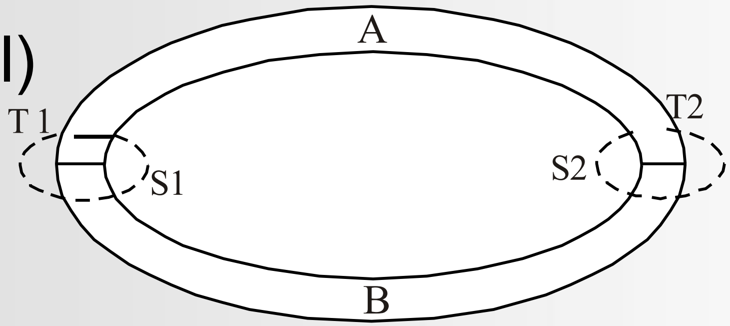


Properties:

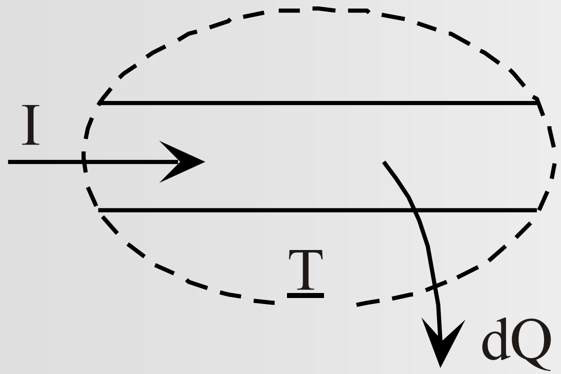
- *e(T1, T1)=0*
- *e(T1, T2) = - e(T2, T1)*
- *the electrical power is completely transformed into Joule effect*

• Study of the Seebeck effect: the Peltier effect and the

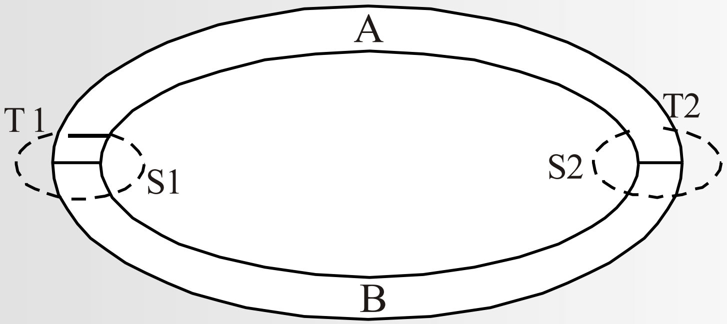
⟶ Thomson effect. Energy balance (electrical and thermal)



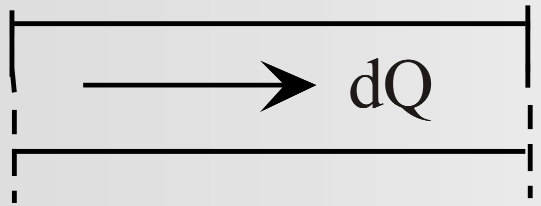
1. Joule effect :



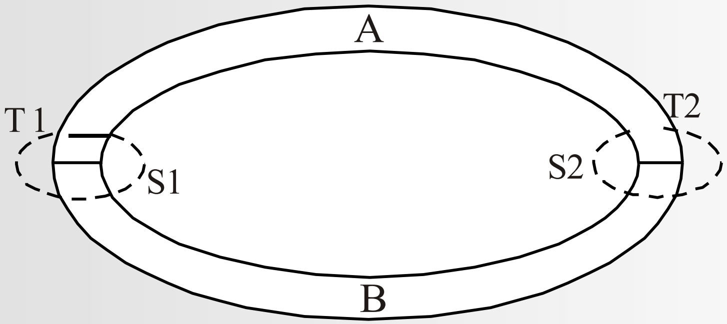
$$\boxed{\frac{dQ}{dt} = r.i^2}$$



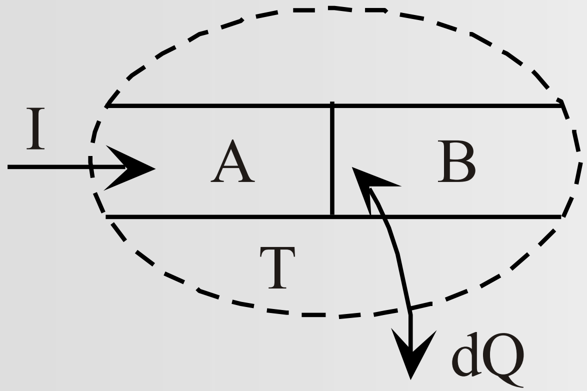
2. Thermal Conduction:



$$\boxed{\frac{dQ}{dt} = -k \, . \, S \, . \, \frac{dT}{dx}}$$

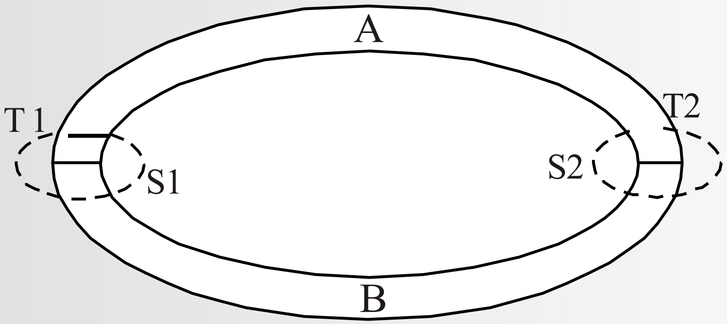


3. Peltier effect:

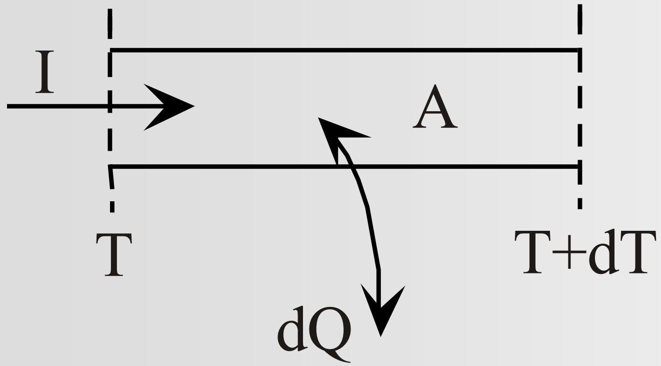


$$\frac{dQ}{dt} = \pi(A,B,T).i$$

Application: Peltier module

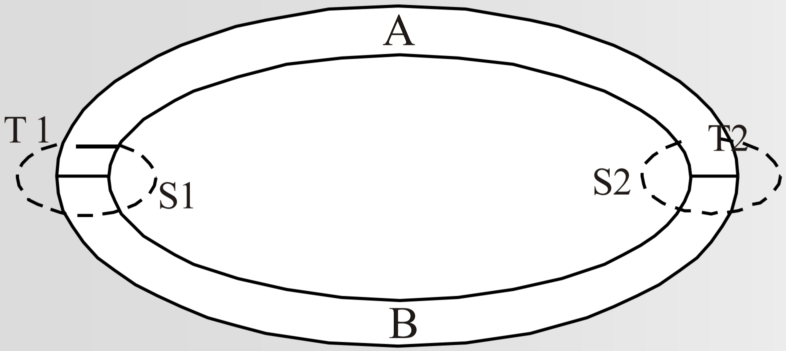


4. Thomson effect:



$$\boxed{d\left(\frac{dQ}{dt}\right) = h_A \, . \, i \, . \, dT}$$

- Thermocouple laws: T_2 = constant, T_1 = T to be measured



Assumptions: no Joule effect,
no thermal conduction

$$\frac{dQ}{dt} = \pi(A,B,T).i \quad (= V . I)$$

$$d\left(\frac{dQ}{dt}\right) = h_A . i . dT$$

Energy balance

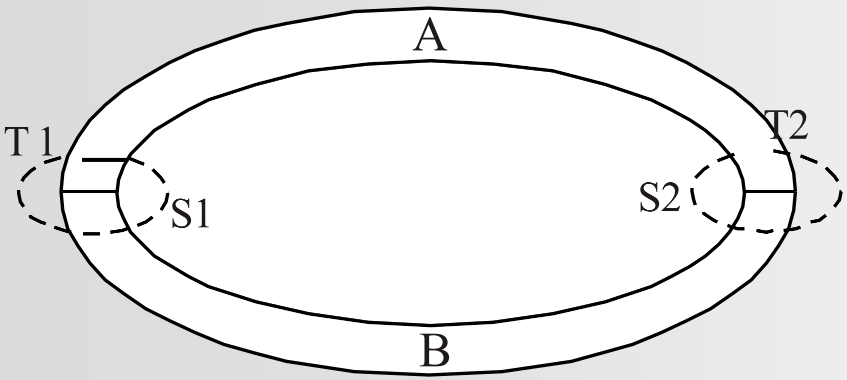
$$\boxed{\frac{de}{dT} = \frac{\pi(A,B,T)}{T}}$$

Entropic balance

$$\boxed{\frac{d^2e}{dT^2} = \frac{h_A - h_B}{T}}$$

- e.m.f. of a thermocouple :

Assumptions: no Joule effect,
no thermal conduction

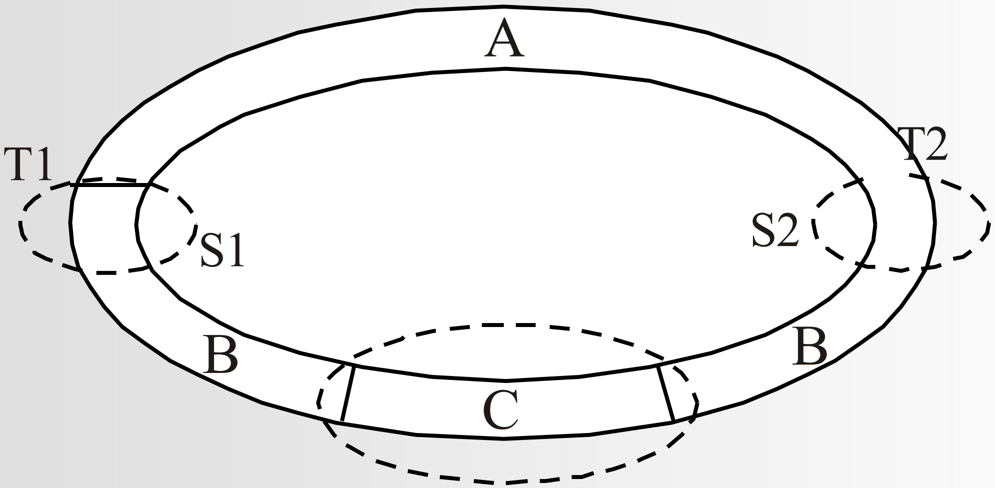


$$\frac{dQ}{dt} = \pi(A, B, T).i$$

$$d\left(\frac{dQ}{dt}\right) = h_A\,.\,i\,.\,dT$$

$$\boxed{e(T_1, T_2) = e_{AB}^{T_1} - e_{AB}^{T_2} + \int_{T_1}^{T_2} (h_A - h_B).dT}$$

- Law of intermediate metals:



Part of the isothermal circuit

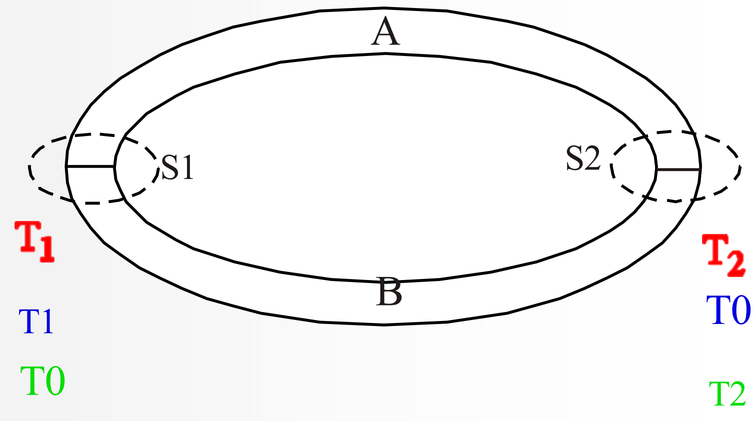
⟶ The e.m.f. is unchanged

- Law of successive temperatures:

$$e(T_1,T_2)=e_{AB}^{T_1}-e_{AB}^{T_2}+\int_{T_1}^{T_2}(h_A-h_B).dT$$

$$e(T_1,T_0)=e_{AB}^{T_1}-e_{AB}^{T_0}+\int_{T_1}^{T_0}(h_A-h_B).dT$$

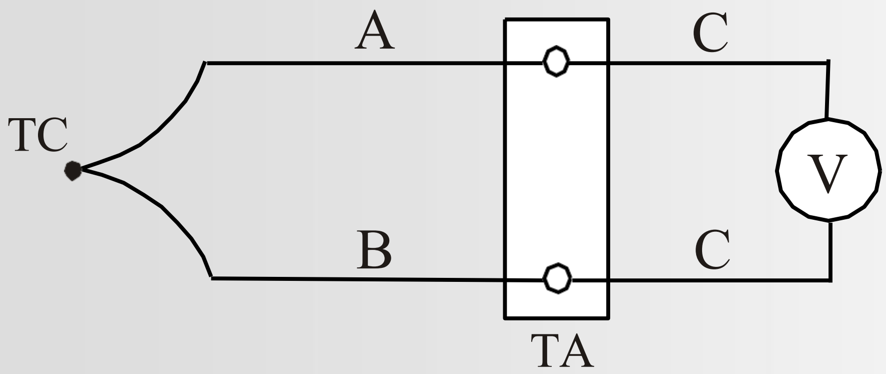
$$e(T_0,T_2)=e_{AB}^{T_0}-e_{AB}^{T_2}+\int_{T0}^{T_2}(h_A-h_B).dT$$



$$e(T_1,T_2)=e_{AB}^{T_1}-e_{AB}^{T_0}+e_{AB}^{T_0}-e_{AB}^{T_2}+\int_{T_1}^{T_0}(h_A-h_B).dT+\int_{T0}^{T_2}(h_A-h_B).dT$$

so $$\boxed{e(T_1,T_2)=e(T_1,T_0)+e(T_0,T_2)}$$

- Use of a thermocouple :

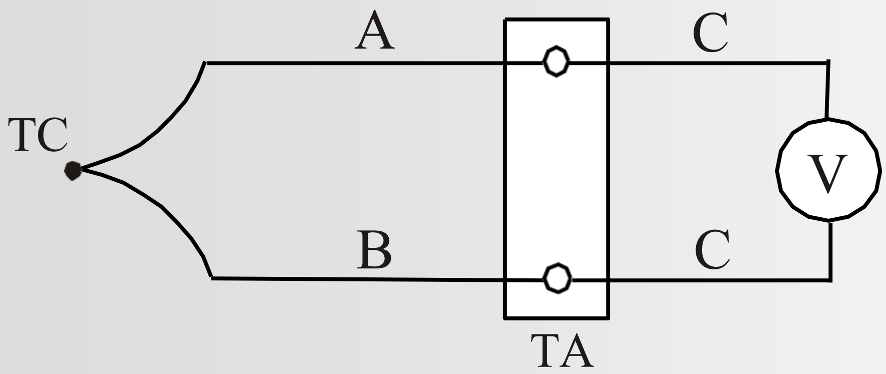


$$e = e_{AB}^{T_C} + \int_{T_c}^{T_A} h_A . dT + e_{CB}^{T_A} + \int_{T_A}^{T_V} h_C . dT + 0 + \int_{T_V}^{T_A} h_C . dT + e_{BC}^{T_A} + \int_{T_A}^{T_C} h_B . dT$$

but $$e_{BC}^{T_A} + e_{CA}^{T_A} = e_{BA}^{T_A} = -e_{AB}^{T_A}$$

$$\boxed{e = e_{AB}^{T_C} - e_{AB}^{T_A} + \int_{T_C}^{T_A} (h_A - h_B) . dT = e(T_C , T_A)}$$

• Using a thermocouple (continued) :



$$e = e_{AB}^{T_C} - e_{AB}^{T_A} + \int_{T_C}^{T_A} (h_A - h_B).dT = e(T_C, T_A)$$

and $$e(T_C, 0°C) = e(T_C, T_A) + e(T_A, 0°C)$$

Compensation for the cold junction

- ➢ Measurement of e($_{TC}$,$_{TA}$)
- ➢ Calculation of e($_{TC}$,0°C)
- ➢ Table or relationship: determination of $_{TC}$

- Common thermocouples :
  - type J: Iron / Copper-Nickel

    -210°C to 800°C-8 .096 mV to 45.498 mV

  - type K : Nickel-Chromium/Nickel-Aluminium

    -270°C to 1250°C-5 .354 mV to 50.633 mV

and others like :

  - type R : Platinum-13%Rhodium / Platinum

    -50°C to 1500°C-0 .226 mV to 17.445 mV

- Integrated conditioners for type J and K: AD594 and AD595

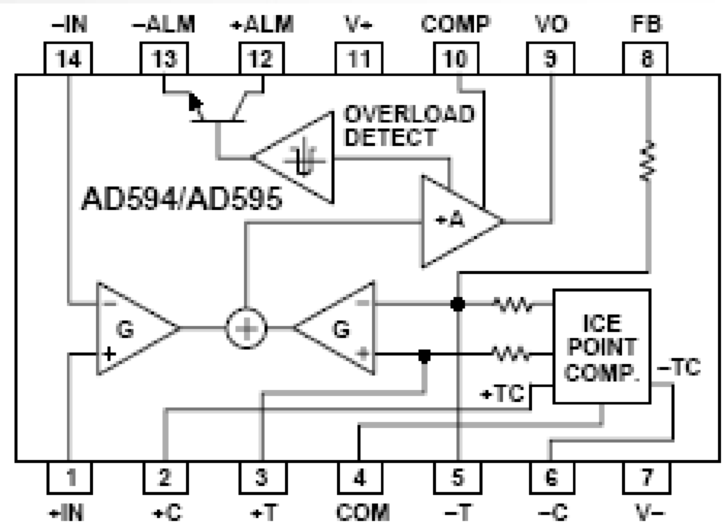
ANALOG DEVICES

Monolithic Thermocouple Amplifiers with Cold Junction Compensation

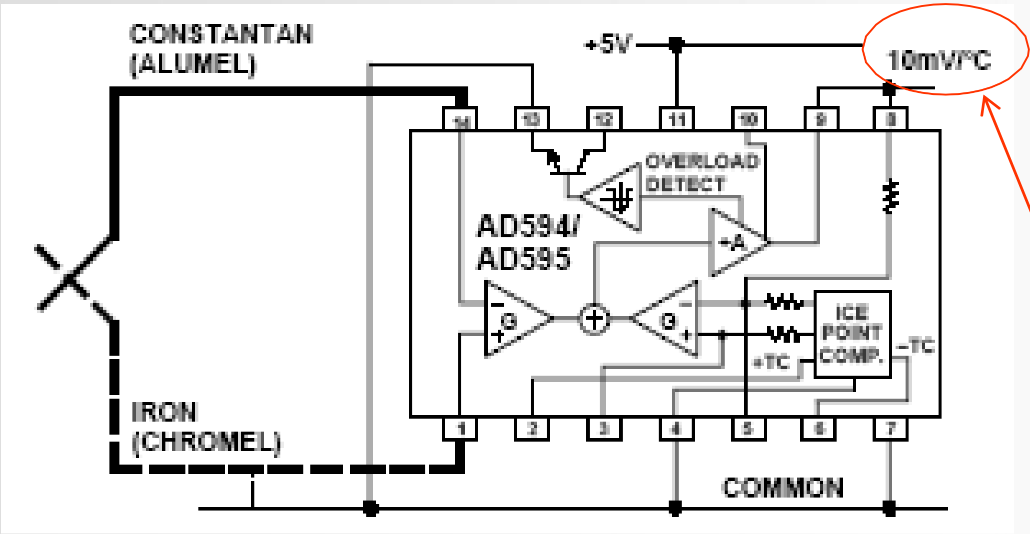
AD594/AD595

FEATURES

Pretrimmed for Type J (AD594) or Type K (AD595) Thermocouples
Can Be Used with Type T Thermocouple Inputs
Low Impedance Voltage Output: 10 mV/°C
Built-In Ice Point Compensation
Wide Power Supply Range: +5 V to ±15 V
Low Power: <1 mW typical
Thermocouple Failure Alarm
Laser Wafer Trimmed to 1°C Calibration Accuracy
Setpoint Mode Operation
Self-Contained Celsius Thermometer Operation
High Impedance Differential Input
Side-Brazed DIP or Low Cost Cerdip



Editing:



Sensitivity of this measurement chain

Thermocouple Temperature °C	Type J Voltage mV	AD594 Output mV	Type K Voltage mV	AD595 Output mV
–200	–7.890	–1523	–5.891	–1454
–180	–7.402	–1428	–5.550	–1370
–160	–6.821	–1316	–5.141	–1269
–140	–6.159	–1188	–4.669	–1152
–120	–5.426	–1046	–4.138	–1021
–100	–4.632	–893	–3.553	–876
–80	–3.785	–729	–2.920	–719
–60	–2.892	–556	–2.243	–552
–40	–1.960	–376	–1.527	–375
–20	–.995	–189	–.777	–189
–10	–.501	–94	–.392	–94
0	0	3.1	0	2.7
10	.507	101	.397	101
20	1.019	200	.798	200
25	1.277	250	1.000	250
30	1.536	300	1.203	300
40	2.058	401	1.611	401
50	2.585	503	2.022	503
60	3.115	606	2.436	605
80	4.186	813	3.266	810
100	5.268	1022	4.095	1015
120	6.359	1233	4.919	1219
140	7.457	1445	5.733	1420
160	8.560	1659	6.539	1620
180	9.667	1873	7.338	1817
200	10.777	2087	8.137	2015
220	11.887	2302	8.938	2213
240	12.998	2517	9.745	2413
260	14.108	2732	10.560	2614
280	15.217	2946	11.381	2817
300	16.325	3160	12.207	3022
320	17.432	3374	13.039	3227
340	18.537	3588	13.874	3434
360	19.640	3801	14.712	3641
380	20.743	4015	15.552	3849
400	21.846	4228	16.395	4057
420	22.949	4441	17.241	4266
440	24.054	4655	18.088	4476
460	25.161	4869	18.938	4686
480	26.272	5084	19.788	4896
500	27.388	5300	20.640	5107
520	28.511	5517	21.493	5318
540	29.642	5736	22.346	5529
560	30.782	5956	23.198	5740
580	31.933	6179	24.050	5950
600	33.096	6404	24.902	6161
620	34.273	6632	25.751	6371
640	35.464	6862	26.599	6581
660	36.671	7095	27.445	6790
680	37.893	7332	28.288	6998
700	39.130	7571	29.128	7206
720	40.382	7813	29.965	7413
740	41.647	8058	30.799	7619
750	42.283	8181	31.214	7722
760	–	–	31.629	7825
780	–	–	32.455	8029
800	–	–	33.277	8232
820	–	–	34.095	8434
840	–	–	34.909	8636
860	–	–	35.718	8836
880	–	–	36.524	9035
900	–	–	37.325	9233
920	–	–	38.122	9430
940	–	–	38.915	9626
960	–	–	39.703	9821
980	–	–	40.488	10015
1000	–	–	41.269	10209
1020	–	–	42.045	10400
1040	–	–	42.817	10591
1060	–	–	43.585	10781
1080	–	–	44.439	10970
1100	–	–	45.108	11158
1120	–	–	45.863	11345
1140	–	–	46.612	11530
1160	–	–	47.356	11714
1180	–	–	48.095	11897
1200	–	–	48.828	12078
1220	–	–	49.555	12258
1240	–	–	50.276	12436
1250	–	–	50.633	12524

9.6. Influence of the mounting of a temperature sensor.

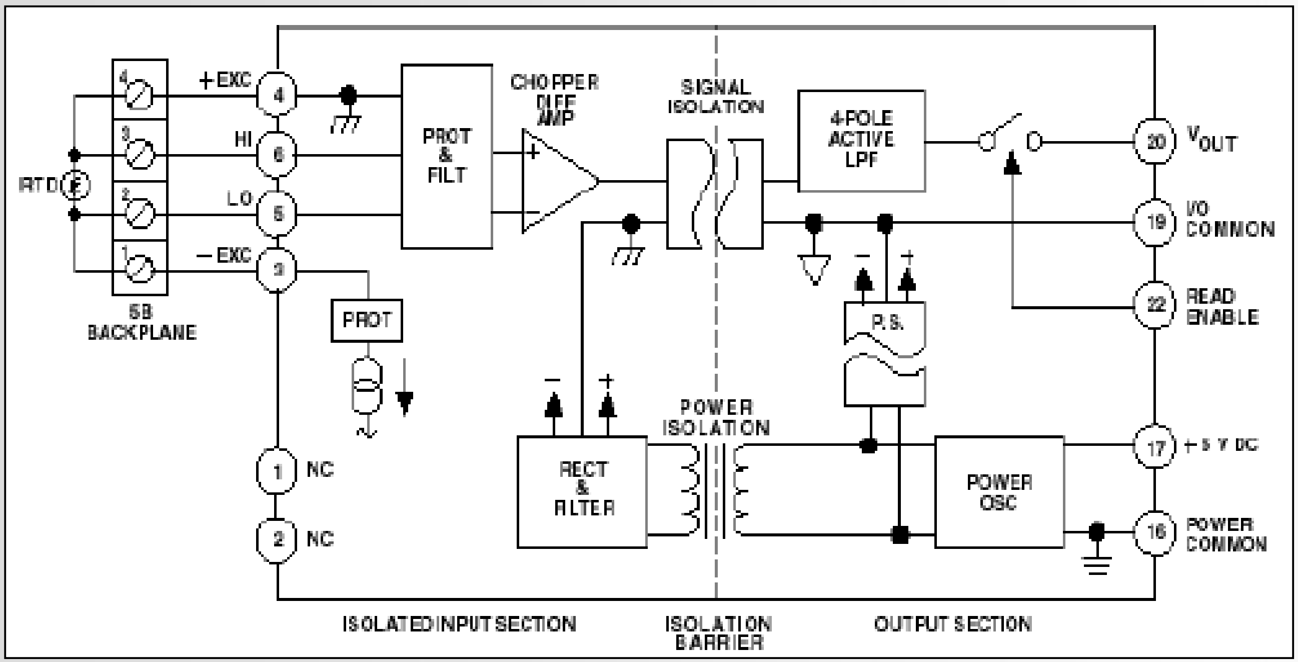
Industrial sensor :

10. Integrated conditioners.

ANALOG DEVICES

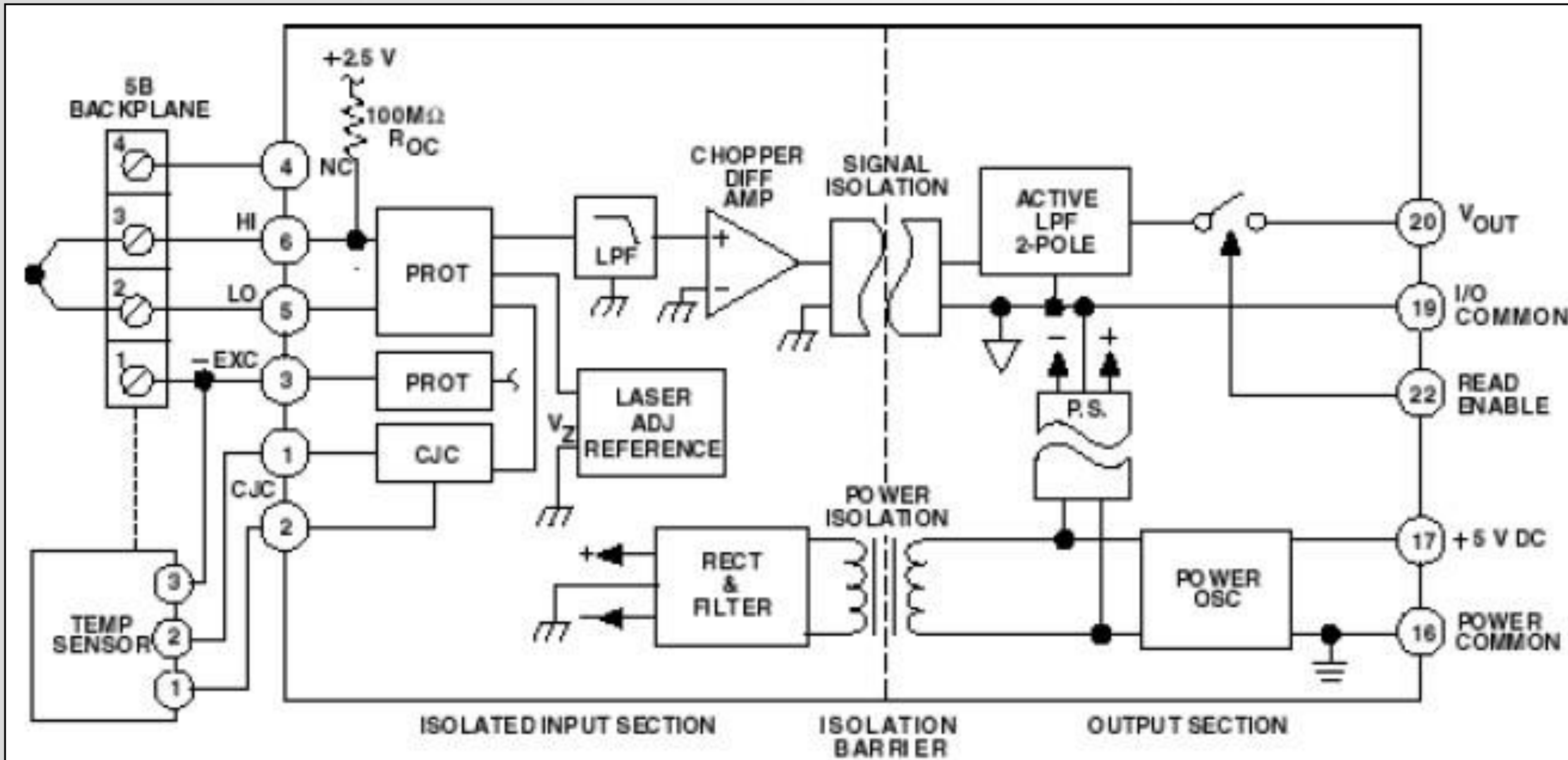
Isolated Linearized 4-Wire RTD Input

5B35



Isolated Thermocouple Input

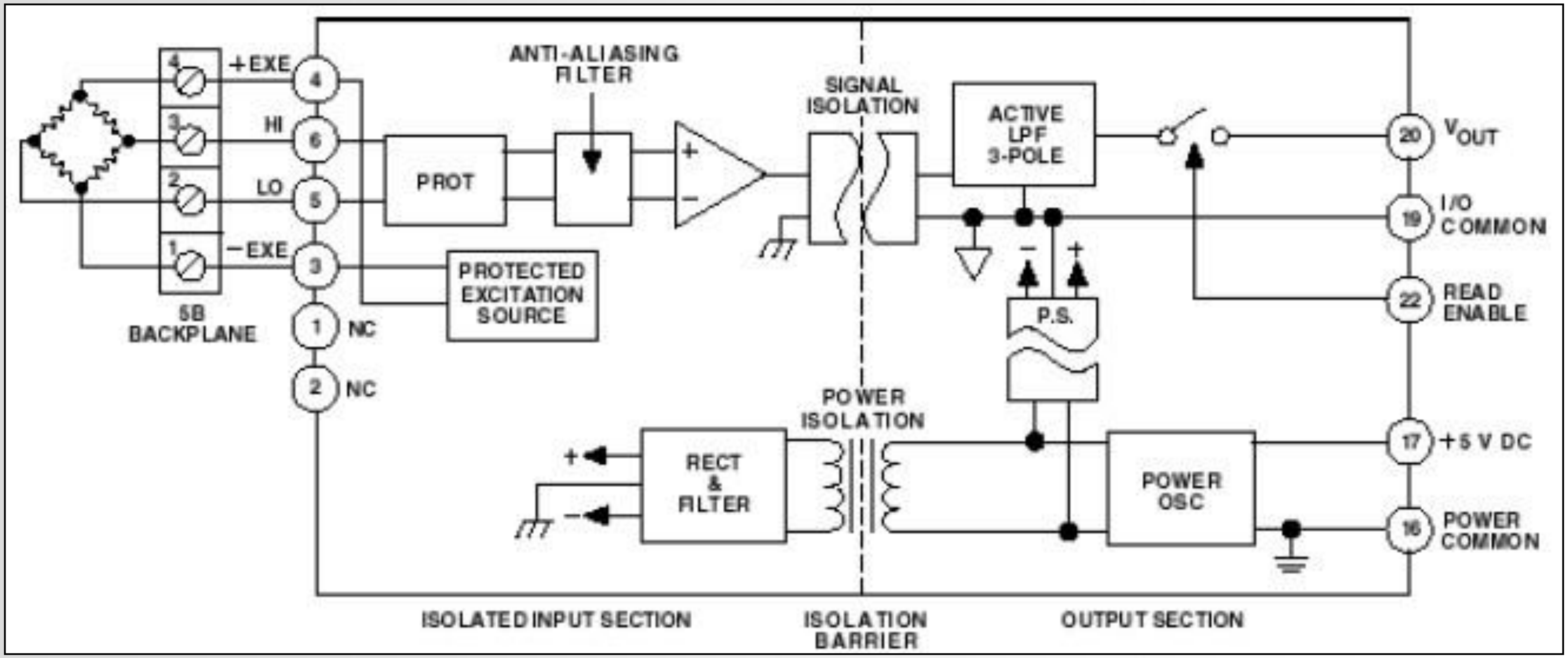
5B37



Model	Input Type	Input Range
5B37-J-01	Type J	-100°C to +760°C (-148°F to +1400°F)
5B37-K-02	Type K	-100°C to +1350°C (-148°F to +2462°F)
5B37-T-03	Type T	-100°C to +400°C (-148°F to +752°F)
5B37-E-04	Type E	0°C to +900°C (+32°F to +1652°F)
5B37-R-05	Type R	0°C to +1750°C (+32°F to +3182°F)
5B37-S-05	Type S	0°C to +1750°C (+32°F to +3182°F)
5B37-B-06	Type B	0°C to +1800°C (+32°F to +3272°F)
5B37-N-08	Type N	0°C to +1300°C (+32°F to +2372°F)
5B37-Custom	Type J, K, T, E, R, S, B, N, C	*

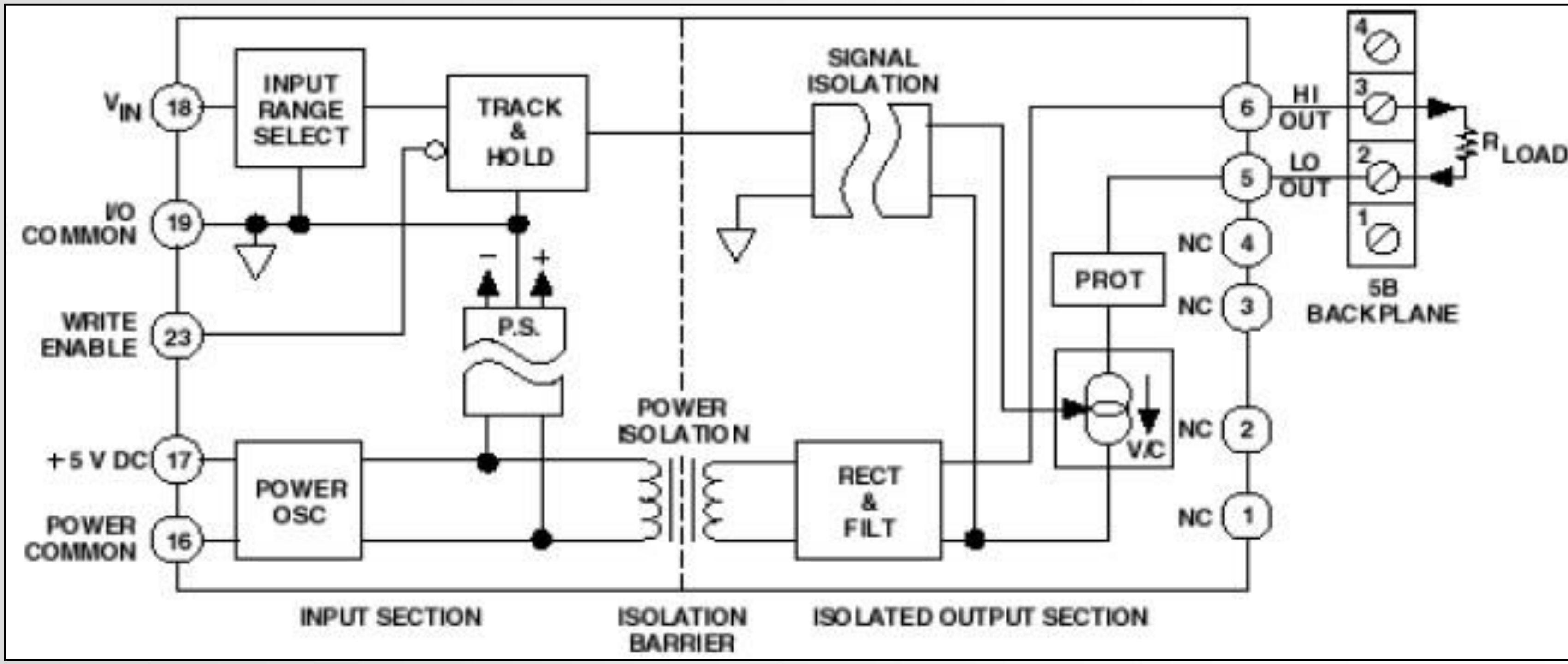
Isolated, Wide-Bandwidth Strain Gage Input

5B38



Isolated Current Output

5B39



11. Position and displacement sensors.

- Position or displacement control

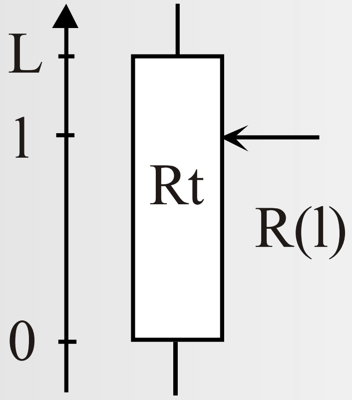
  example : machine tool

- To measure another physical quantity

  example: force, acceleration

11.1. Potentiometer.

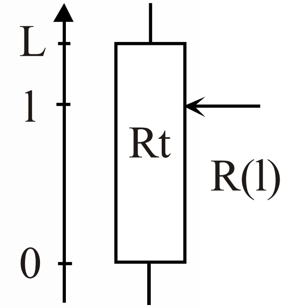
- Principle:



$$R(l) = \frac{l}{L} . R_t$$

Note: linear or angular displacement

- ➢ Simplicity of the principle
- ➢ High signal level, therefore no specific circuit
- ➢ Friction, therefore error of fineness and wear.



- Wound wire :

  Low temperature coefficient Resolution:

  n turns   2n-2positions

  for example 10 m

  Maximum speed of the cursor (thus maximum frequency)

  for example 1.25 m/s

  Good linearity

  Lifetime: ^{106} to ^{107} maneuvers.

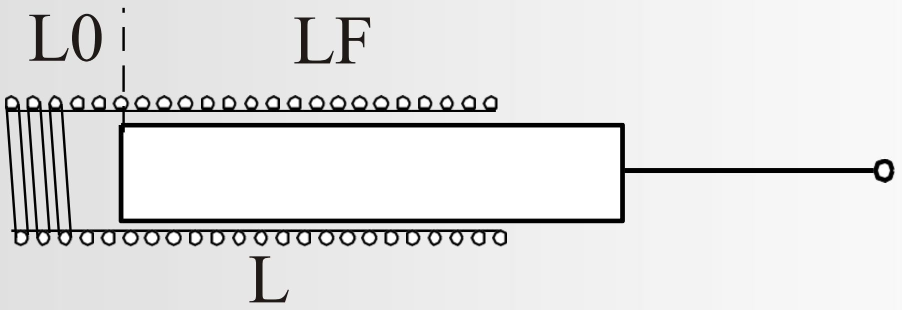
- Conductive track: higher temperature coefficient.

Note: Ratio-metric   assembly to eliminate the influence of the supply voltage.

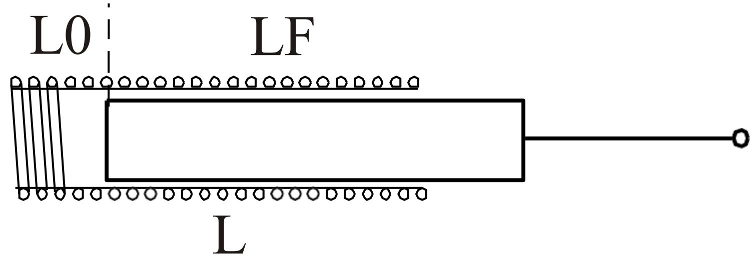
11.2. Inductive sensors.

- Principle: moving element = ferromagnetic core
  - ➢ Modification of the self-induction coefficient
  - ➢ Change of the coupling between the primary and secondary windings of a transformer.

- Plunger Core Coil :



→Measurement of L to get the position of the core



Putting it into equation:

$$L = L_0 + L_F + 2.M \qquad M = k.\sqrt{L_0.L_F} \qquad 0 \le k \le 1$$

$$L_0 = \mu_0.\frac{N_0^2.s_0}{l_0} \qquad N_0 = N.\frac{l_0}{l}$$

$$L_0 = \mu_0.\frac{N^2.s_0.l_0}{l^2} = \mu_0.\frac{N^2.s_0}{l^2}.(l - l_F)$$

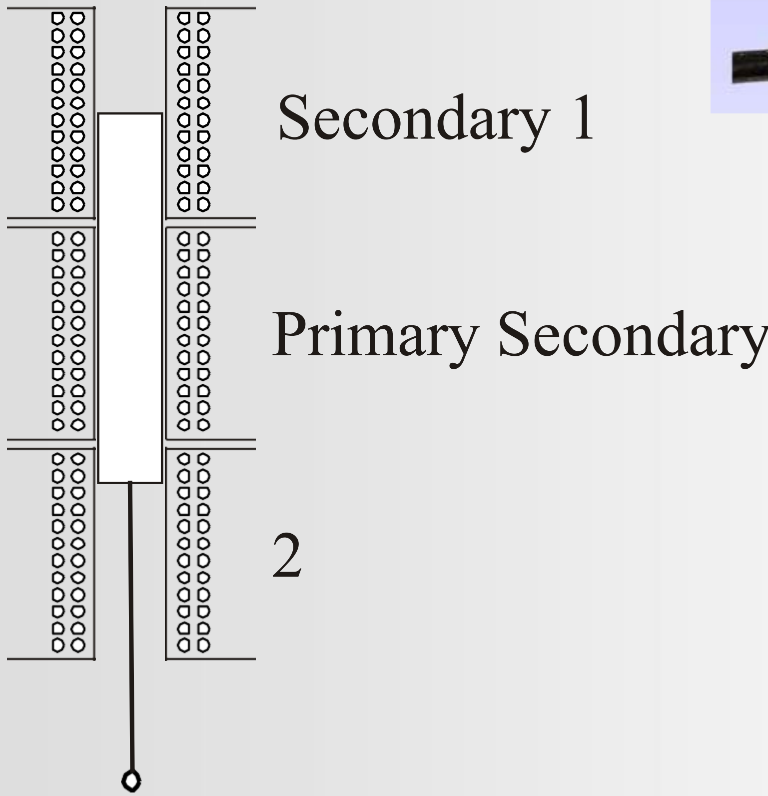
$$L_F = \mu_0.\mu_r.\frac{N^2.s_F.l_F}{l^2}$$

$$L = \mu_0.\frac{N^2}{l^2}\left(s_0.(l - l_F) + \mu_r.s_F.l_F + k.\sqrt{s_0.(l - l_F)}.\sqrt{\mu_r.s_F.l_F}\right)$$

Non linear!

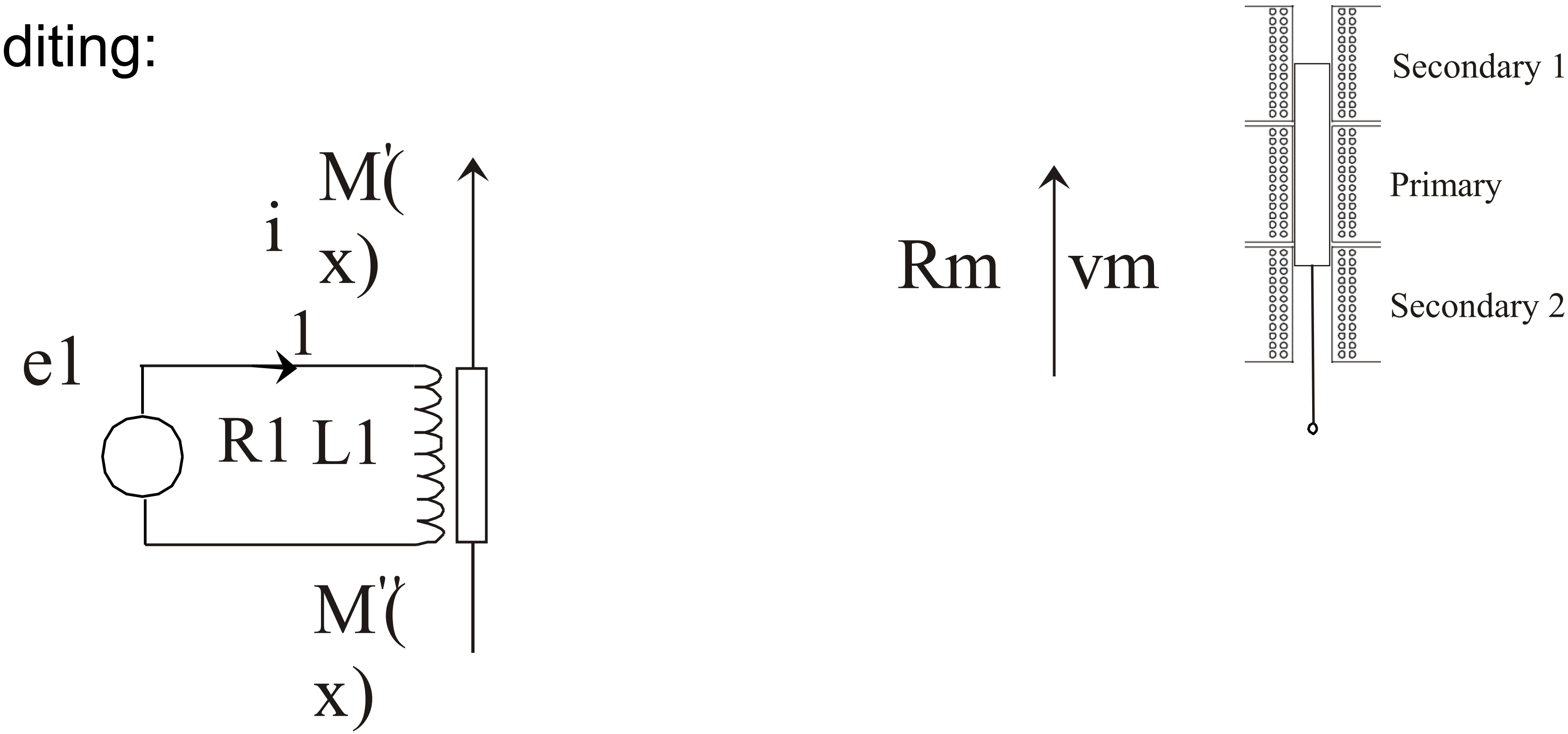
Position and displacement sensors: inductance

• Differential transformer :



→ Modification of the coupling between the primary and each secondary.

Editing:

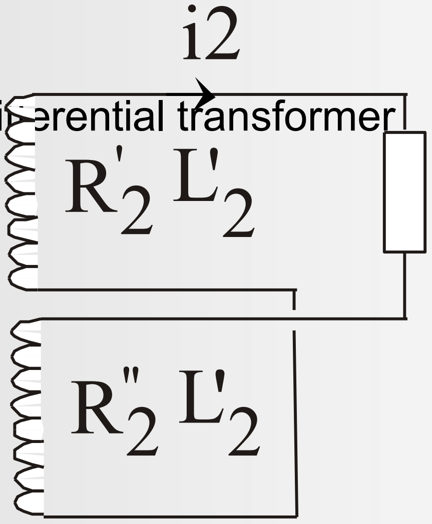


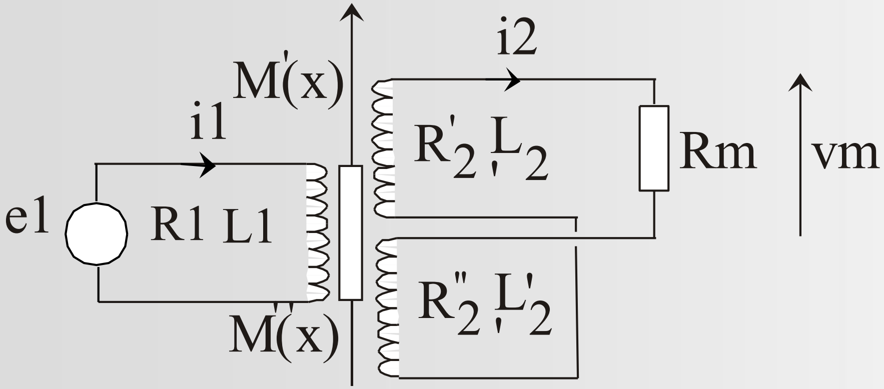
$$e_1 = (R_1 + j.L_1.\omega).I_1 + j\omega(M'(x) - M''(x)).I_2$$

$$0 = \left(R_2^{'} + R_2^{''} + R_m\right).I_2 + j.\omega.\left(L_2^{'} + L_2^{''}\right).I_2 + j.\omega.(M'(x) - M''(x)).I_2$$

$$v_m = R_m.I_2$$

Si R_m très grande : $I_2 \approx 0$ donc $\boxed{v_m = \frac{j.\omega.(M'(x) - M''(x))}{R_1 + j.L_1.\omega}.e_1}$


i2
R'2 L'2
R"2 L'2



$$v_m = \frac{j.\omega.(M'(x) - M''(x))}{R_1 + j.L_1.\omega}.e_1$$

$$M'(x) = M(0) + a.x + b.x^2$$

$$M''(x) = M(0) + a.x - b.x^2$$

$$\boxed{v_m = \frac{-2\,j\,a\,\omega\,e_1}{R_1 + j.L_1.\omega}.x}$$

Sensitivity:

$$\boxed{\frac{\Delta v_m}{\Delta x} = \frac{2.a.\omega.a_1}{\sqrt{R_1^2 + (L_1.\omega)^2}}}$$

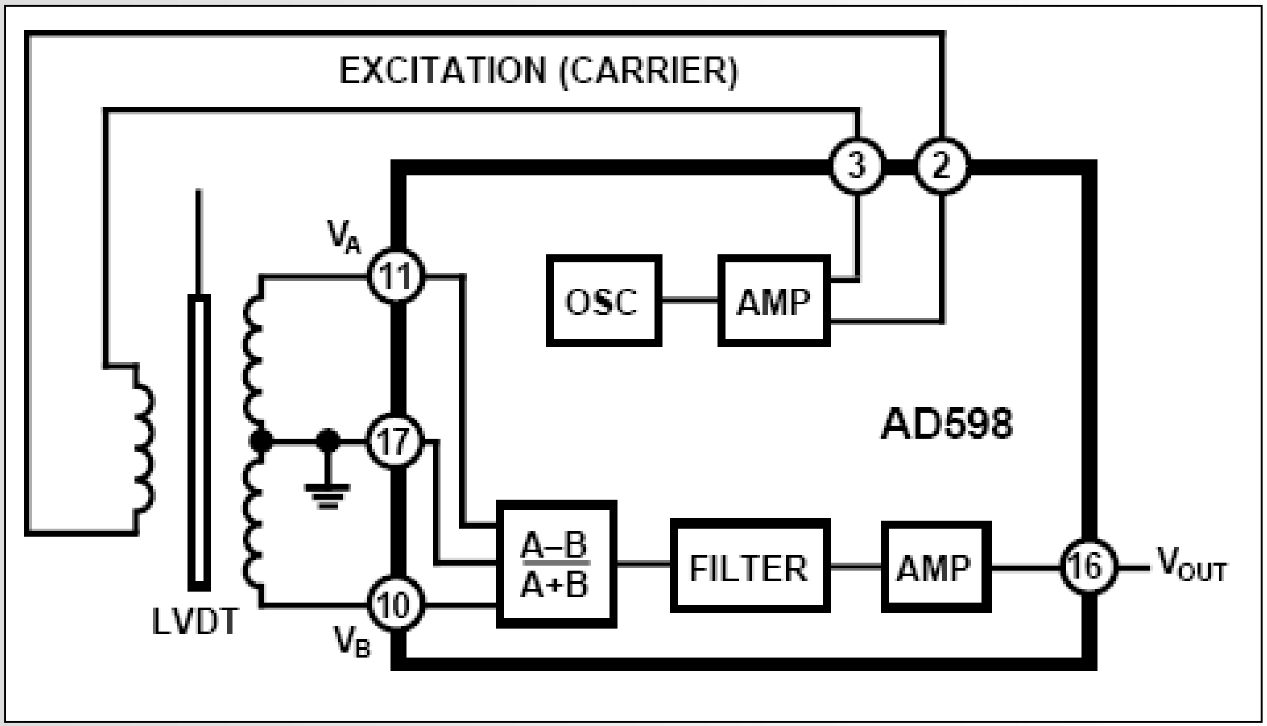
Assembly: synchronous demodulation.

Integrated conditioner :

ANALOG DEVICES

LVDT Signal Conditioner

AD598



12. Deformation sensors.

Deformation: $\varepsilon = \dfrac{\Delta l}{l}$ $\qquad \dfrac{\Delta R}{R_0} = K.\varepsilon$

K : gauge factor

Use: - materials testing,
- in other sensors.

12.1. Some relations of mechanics of continuous media.

- Constraint: vector field $\vec{\sigma}(M, \vec{n}) = \lim\limits_{dS \to 0} \dfrac{d\vec{F}}{dS}$

- Normal and tangential stresses: $\vec{\sigma}_n(M, \vec{n})$ et $\vec{\sigma}_t(M, \vec{n})$

- Stress Tensor

$$\vec{\sigma}(M,\vec{n})=\begin{pmatrix}\vec{\sigma}_1(M,\vec{n})\\ \vec{\sigma}_2(M,\vec{n})\\ \vec{\sigma}3(M,\vec{n})\end{pmatrix}=\begin{pmatrix}\sigma_{11} & \sigma_{12} & \sigma_{13}\\ \sigma_{21} & \sigma_{22} & \sigma_{23}\\ \sigma_{31} & \sigma_{32} & \sigma_{33}\end{pmatrix}.\begin{pmatrix}n_1\\ n_2\\ n_3\end{pmatrix}$$

- Main stress and direction:

by diagonalization of the matrix σ_{ij}

- Deformation in the vicinity of a point

$$\vec{\varepsilon}(M,\vec{n})=\frac{|M'N'|-|MN|}{|MN|}=\frac{dl'-dl}{dl}$$

- Laws of behavior: elastic, isotropic and linear medium.
  - Young's modulus (Y): either a tensile test

$$\left(\sigma_{ij}\right)=\begin{pmatrix}\sigma_{11} & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

with $\sigma_{11}=\frac{F}{S}$

we have $\boxed{\sigma_{11}=Y.\varepsilon_{11}}$

  - Poisson's ratio: $\boxed{\varepsilon_{22}=\varepsilon_{33}=-\nu.\varepsilon_{11}}$

12.2. Metal gauges.

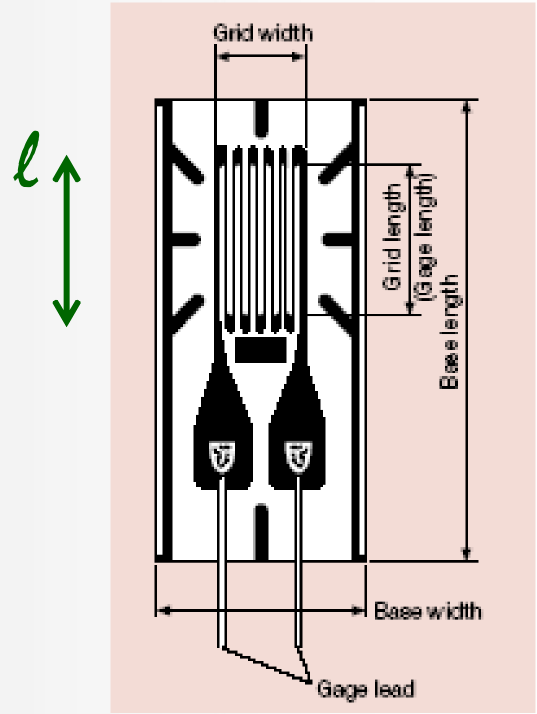
It is a passive sensor:deformation $\longrightarrow$ resistance variation

Orderof magnitude of measurable deformations : $\pm 10^{-5}$ à $\pm 10^{-1}$

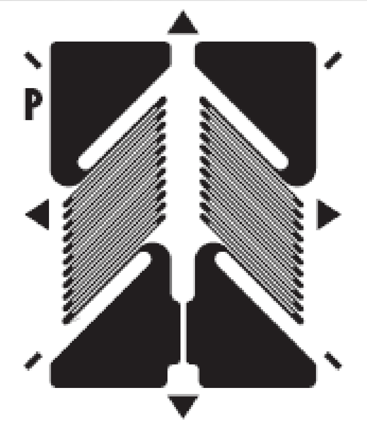
• Film screen gauges :

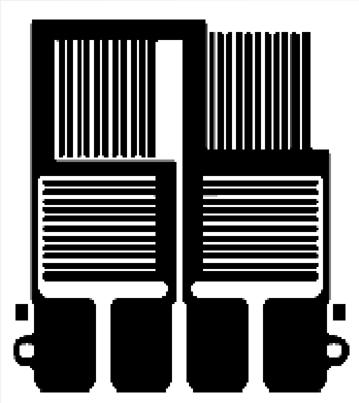
$$\frac{\Delta R}{R_0} = K.\varepsilon$$

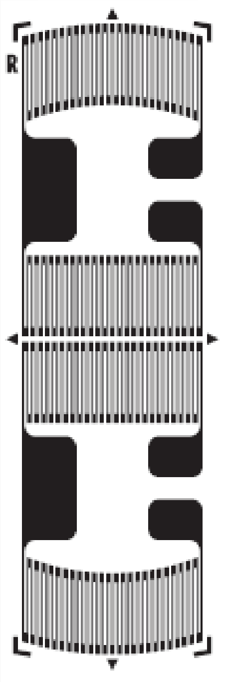
$$\varepsilon = \frac{\Delta l}{l}$$

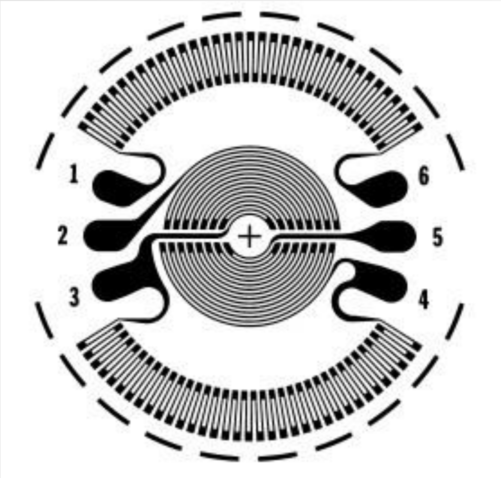


• Some examples of gauges:









- Sensitivity calculation:

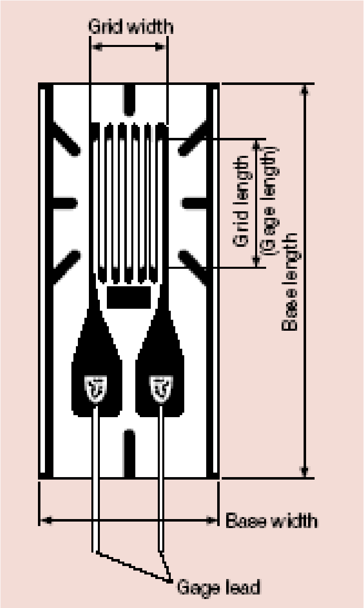
length l, n strands, section s = a .b

$$R = \rho.\frac{n.l}{s} \qquad \frac{\Delta R}{R} = \frac{\Delta\rho}{l\rho} + \frac{\Delta l}{l} - \frac{\Delta s}{s}$$

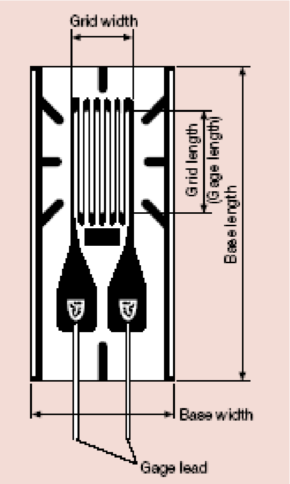
$$\frac{\Delta s}{s} = \frac{\Delta a}{a} + \frac{\Delta b}{b} = -2.\nu.\frac{\Delta l}{l}$$

$$\frac{\Delta\rho}{\rho} = C.\frac{\Delta V}{V} = (1-2.\nu).\frac{\Delta l}{l}$$

$$\boxed{\frac{\Delta R}{R} = (1+2.\nu+C.(1-2.\nu)).\frac{\Delta l}{l} = K.\frac{\Delta l}{l}}$$



- Influence of temperature:



  - On the gauge factor:

$$K(T) = K_0.(1 + \alpha_K.(T - T_0))$$

Constantan: $\alpha_K = 0{,}01\%/°C$

  - On the resistance of the gauge fixed on a structure.

4 variations to take into account:

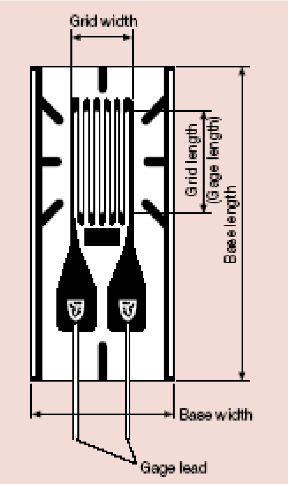
$$\rho(T) = \rho_0.(1 + \alpha_\rho.(T - T_0))$$

$$l(T) = l_0.(1 + \lambda_j.(T - T_0))$$

$$a(T) = a_0.(1 + \lambda_j.(T - T_0)) \text{ et } b(T) = b_0.(1 + \lambda_j.(T - T_0))$$

Dilatation thermique de la ~~jauge~~ structure (λ_s).

- Influence of temperature (continued) :



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

$$l(T) = l_0.(1 + \lambda_j.(T - T_0))$$

$$a(T) = a_0.(1 + \lambda_j.(T - T_0)) \quad \text{et} \quad b(T) = b_0.(1 + \lambda_j.(T - T_0))$$

Dilatation thermique de la ~~jauge~~ (λ_s).
structure

$$\boxed{\frac{\Delta R}{R} = \left(\left(\alpha_\rho - \lambda_j\right) + K.\left(\lambda_s - \lambda_j\right)\right).\Delta T}$$

Self-compensating temperature gauge:

by a suitable choice and a specific heat treatment of the alloy constituting the gauge compared to the material of the structure.

12.3. Semi-conductive gauges.

Piezoresistivity: phenomenon linking the relative variation of the volume

of a metal or semiconductor to its relative variation of resistivity.

Semi-conductor :

$$\frac{\Delta\rho}{\rho} = \pi.\sigma = \pi.Y.\frac{\Delta l}{l}$$

π : coefficient piézorésistif

$$\boxed{\frac{\Delta R}{R} = (1 + 2.\nu + \pi.Y).\frac{\Delta l}{l} = K.\frac{\Delta l}{l}}$$

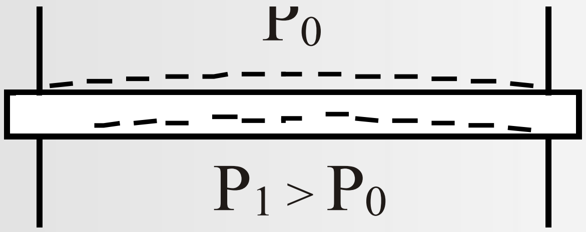
K: 50 to 100, but higher temperature coefficient compared to metal gauges.

Strain sensors: semiconductor gauges

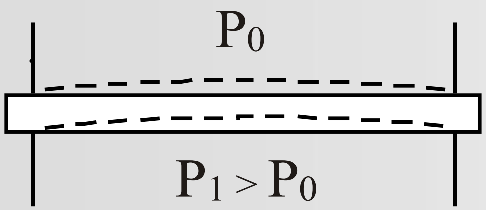
13. Pressure and force sensors per test body.

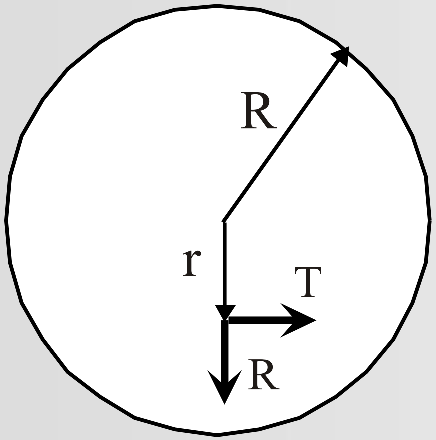
13.1. Fluid pressure sensors.

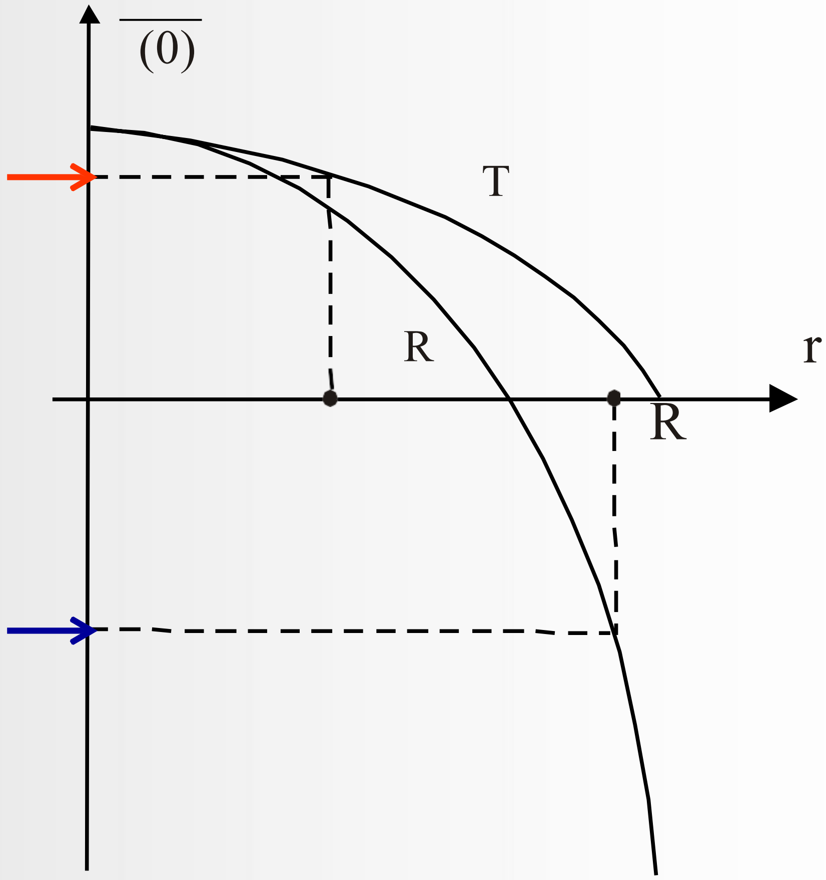
- Direct measurement: by fixing strain gauges on the wall or on the pipe.
- Through a test body :



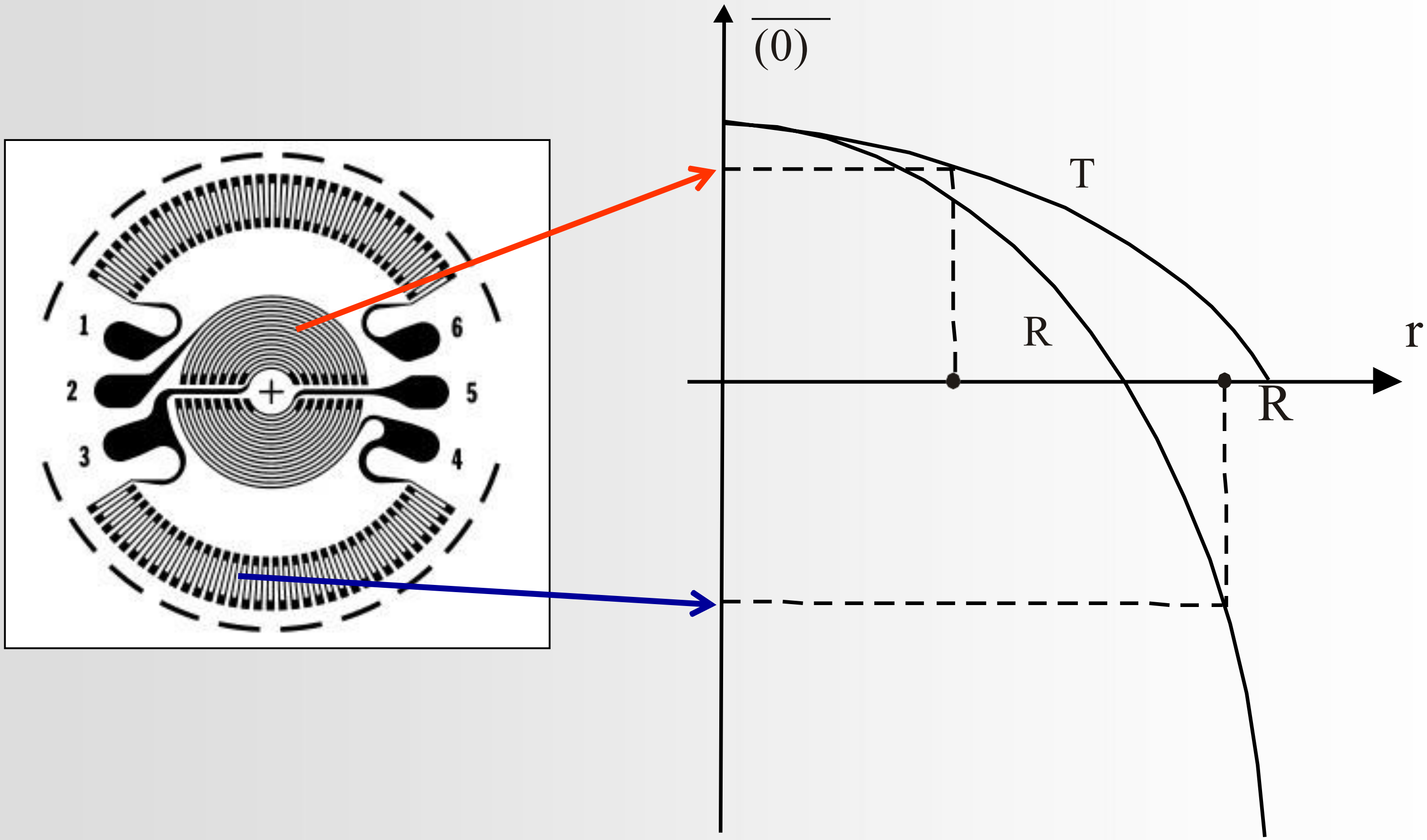
- Through a test body :







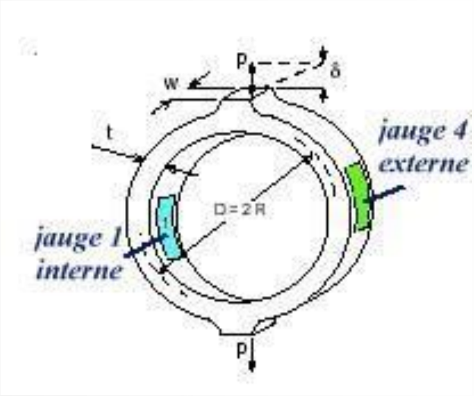
• Shape of the strain gauges :

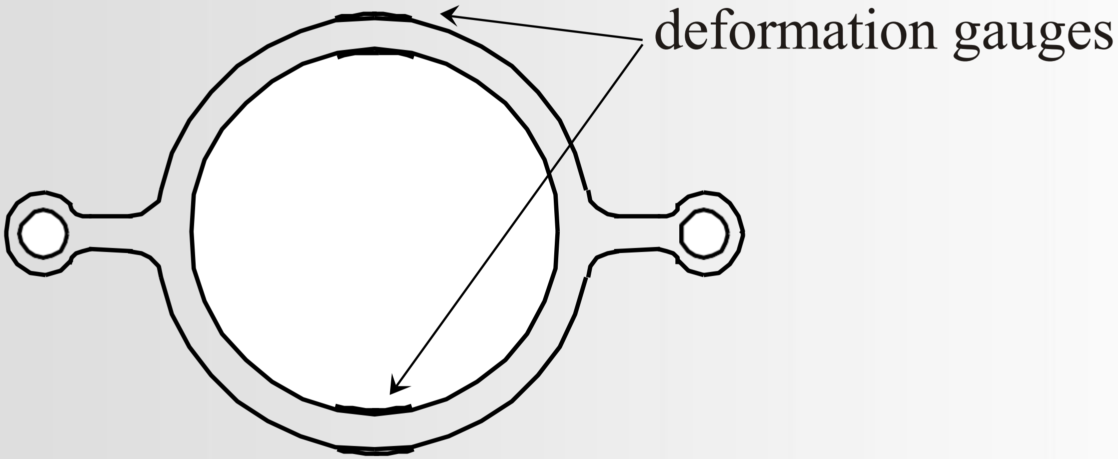


• Example of an industrial sensor:

13.2. Force sensors.

Example of a test body:





Example of an industrial sensor:

Example of a load cell data sheet:

SUPPLIER:	TECHNOLOGIES_AND_INDUSTRIAL_EQUIPMENT
TRADE MARK:	L'ESSOR_FRANCAIS_ELECTRONIQUE
MANUFACTURER:	L'ESSOR_FRANCAIS_ELECTRONIQUE
DESIGNATION:	F 121 TC
MEASURED QUANTITY:	force
MEASURING RANGE (N):	100 250 500 1000 2500
MODE OF ACTION:	traction-compression
GENERAL SHAPE:	cylinder
LENGTH or DIAMETER (mm):	20
HEIGHT (mm):	45
MASS:	100
MATERIAL:stainless	steel
APPLIC. DEVICEEFFORT:	threaded endsM6
OUTPUT SIGNAL:	low level
NUMBER OF OUTPUT SIGNALS:	1
SENSITIVITY:	1.5 to 2mV/V/EM
POWER SUPPLY:	10Vdc
INPUT IMPEDANCE (Ohms):	350
OUTPUT IMPEDANCE (Ohms):	350
ELECTRICAL CONNECTION: cable	gland and cable
TEMP. MIN. COMP. RANGE (°C):	0
TEMP. MAX. COMP. RANGE (°C):	60
TEMP. MINIMUM OPERATING TEMPERATURE (°C):	-40
TEMP. MAX. USE (°C):	100
PROTECTION CLASS:	IP65
ATMOSPH. EXPLOSIVE:	noSAFETY
LIMIT CHARGE:	150%of EM
INTEGRATED OVERLOADING:	no
TYPE OF TEST BODY:	membrane in flexionTYPE
OF SENSITIVE ELEMENT:	gauges... film weft
INCERTITUDE MEASURE (% EM):	+/-0.35
DERIVE TEMP. ZERO (% EM/°C):	+/-0.01
DERIV TEMP SENSIB(% mes/°C):	+/-0.02
MAX TRANSV LOAD (% E.M.):	10%
MAX DECENTRATION (mm) :	+/-1mm

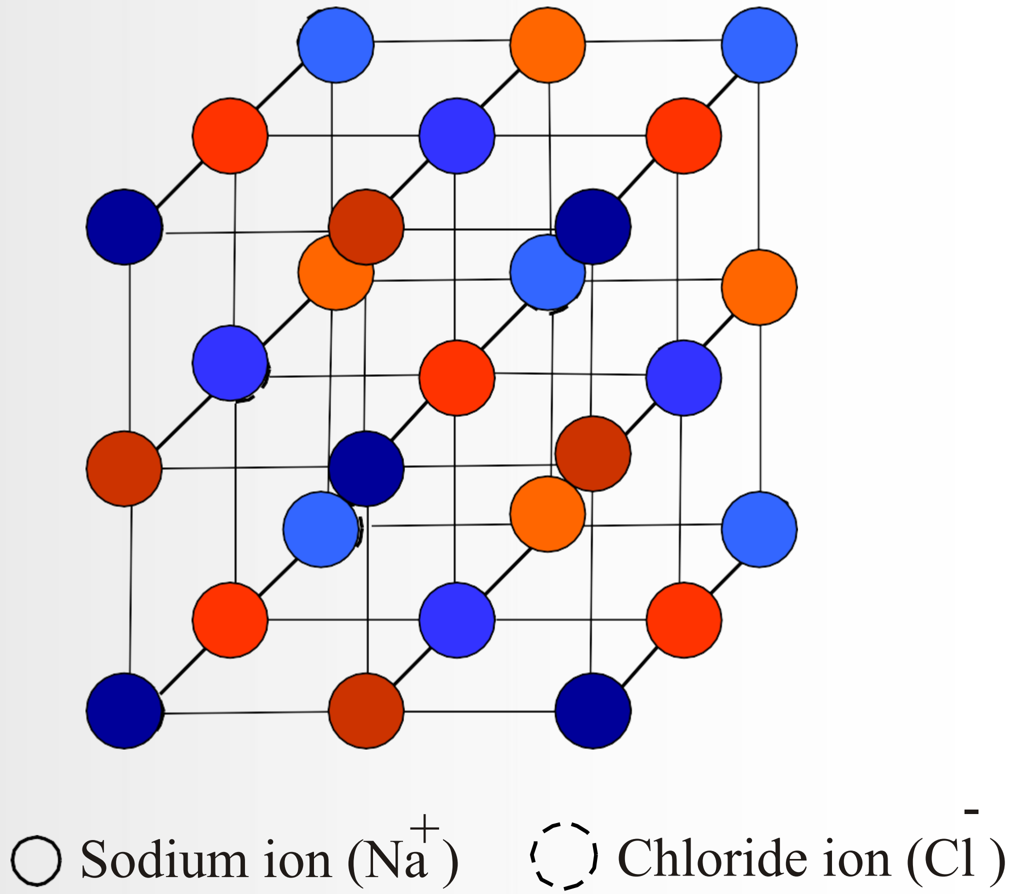
14. Piezoelectricity.

- Crystal structure: 7 primitive and 7 derived meshes Cubic mesh, rhombohedral mesh, ...

Example: Sodium chloride

Sodium ion (Na+)

Chloride ion (Cl-)



• Polarization of a dielectric :

$\overrightarrow{dm} = P \; . \; dv\overrightarrow{P}$: polarization vectordv : volume

• Statement of piezoelectricity: appearance of an electrical polarization (or variation of a polarization) in certain anisotropic dielectrics when they are deformed under the action of a stress of suitable direction.

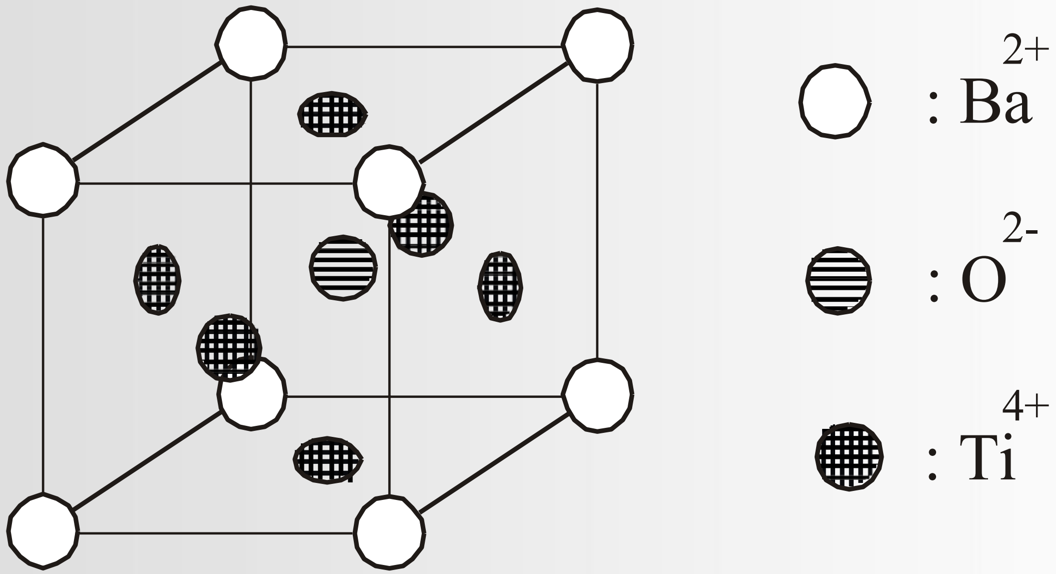
Armatures → appearance of charges→potential

differenceApplication: measurement of force, pressure,

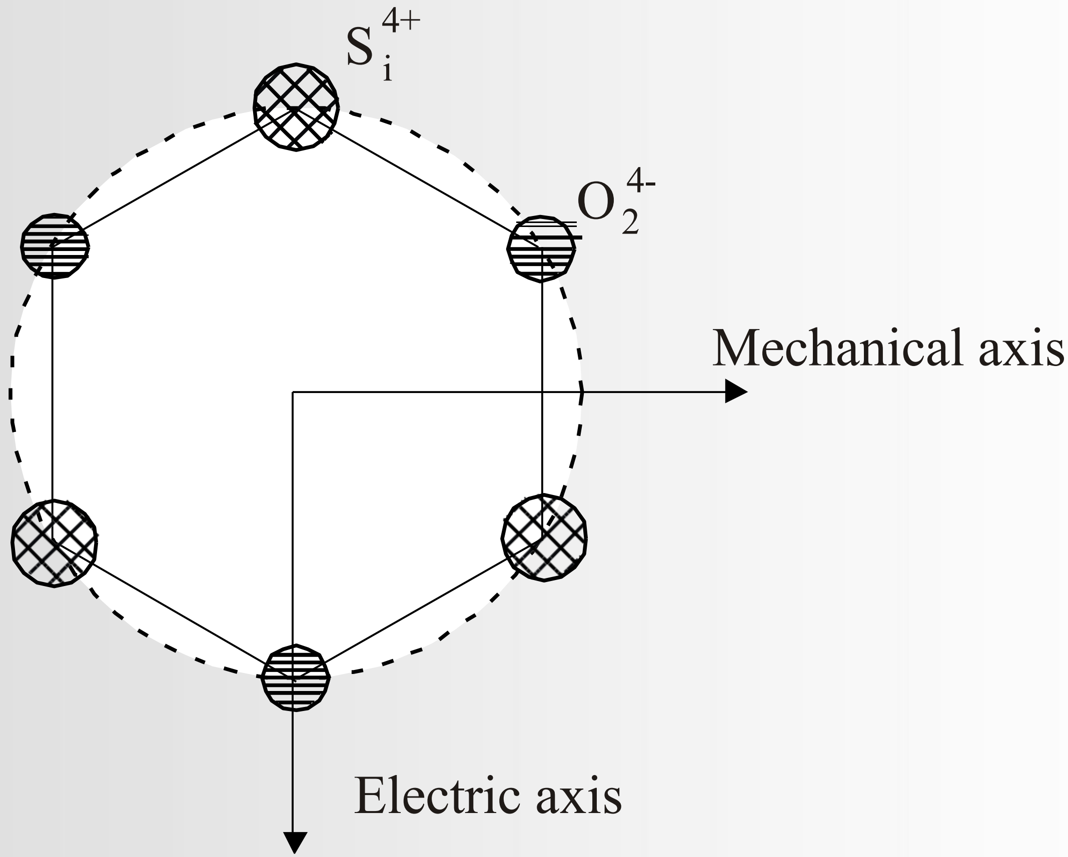
acceleration.

- Ferroelectric bodies.

  Barium titanate :



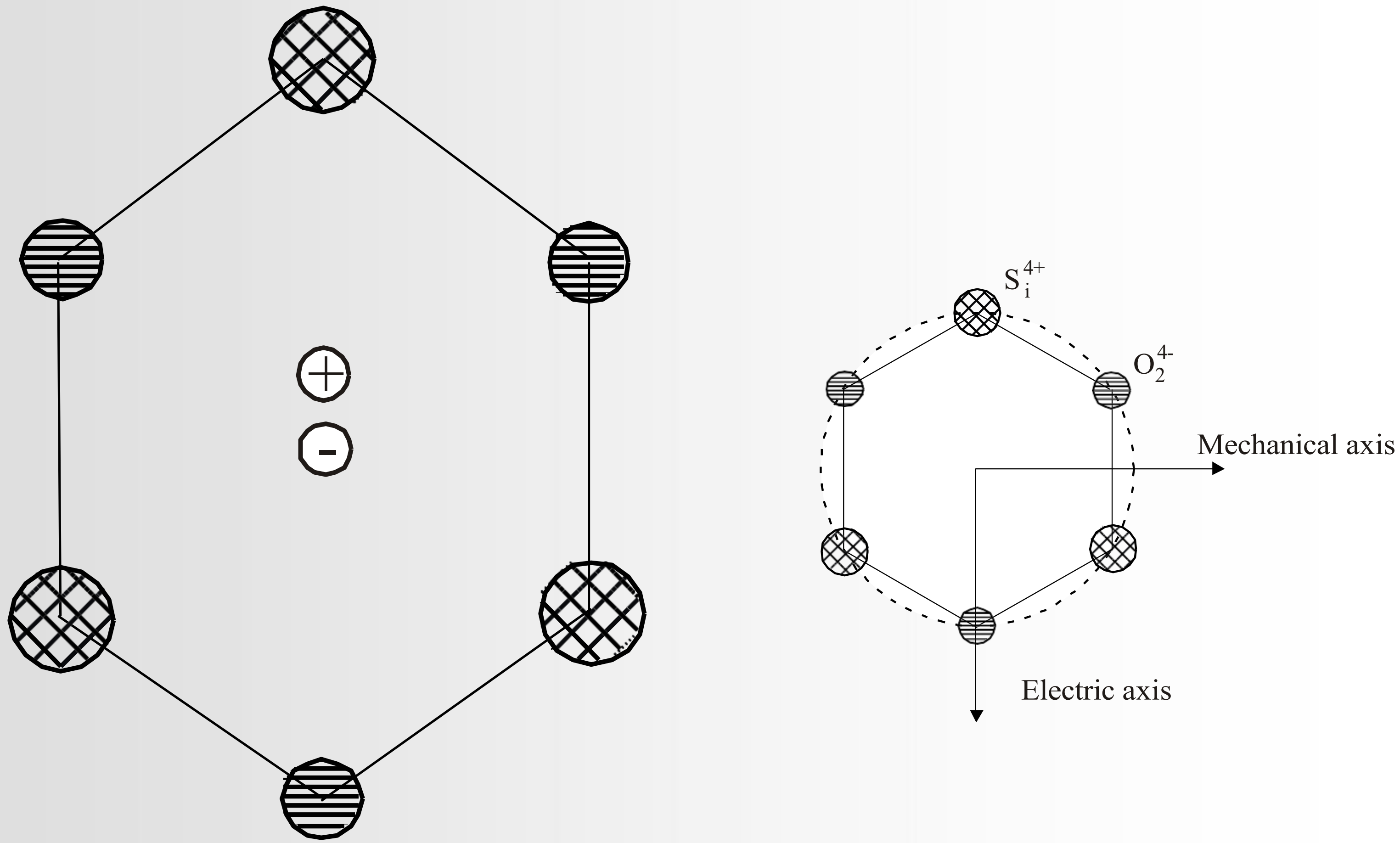
- Quartz :



- At rest : barycentre of positive charges = barycenter of negative charges

  so no polarization

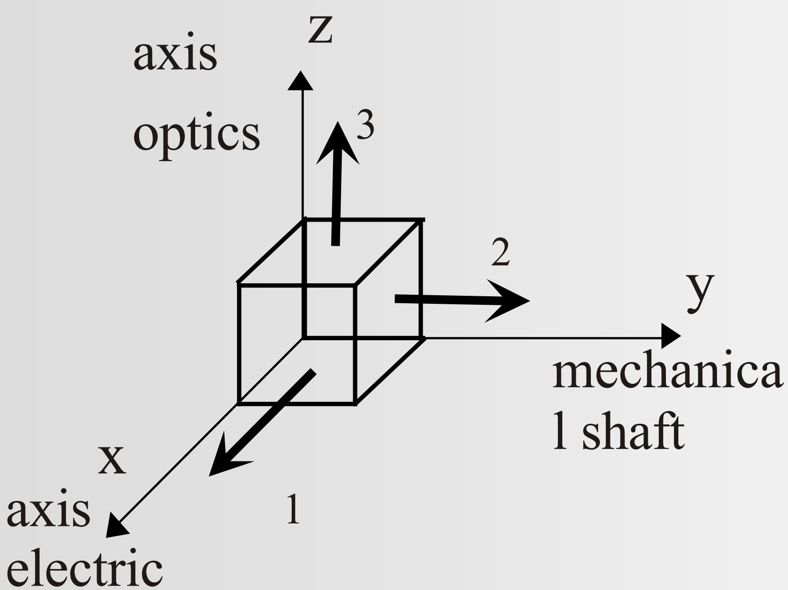
▪ If constrained along the mechanical axis :

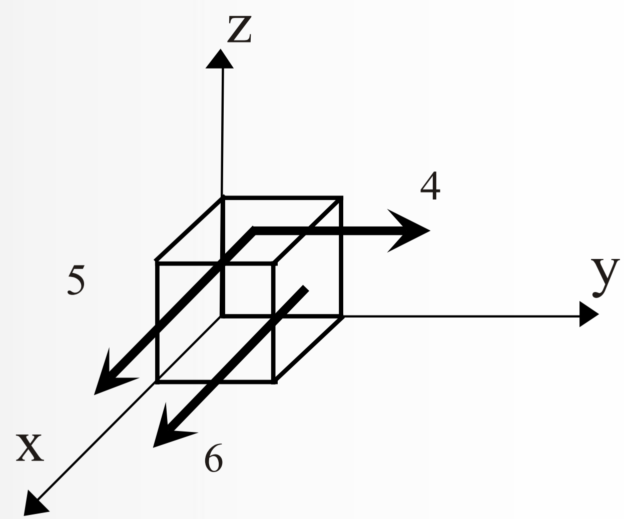


→ Polarization along the electrical axis.

• Piezoelectric coefficients

Constraints:





1, 2 and 3: normal constraints

1, 2 and 3: tangential constraints

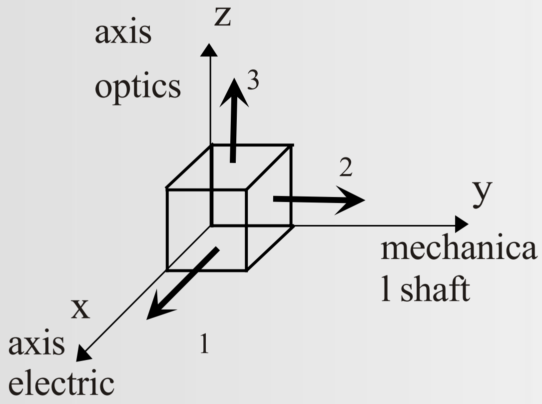
• Piezoelectric coefficients (continued)

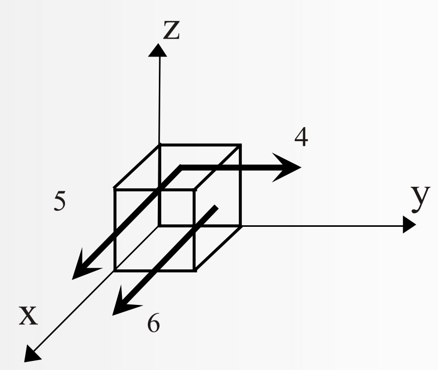
q1 : density of charges recovered along the electrical axis q2 : density of charges recovered along the mechanical axis q3 : density of charges recovered along the optical axis

$$q_1 = h_{11}.\sigma_1 + h_{12}.\sigma_2 + h_{13}.\sigma_3 + h_{14}.\tau_4 + h_{15}.\tau_5 + h_{16}.\tau_6$$

$$q_2 = h_{21}.\sigma_1 + h_{22}.\sigma_2 + h_{23}.\sigma_3 + h_{24}.\tau_4 + h_{25}.\tau_5 + h_{26}.\tau_6$$

$$q_3 = h_{31}.\sigma_1 + h_{32}.\sigma_2 + h_{33}.\sigma_3 + h_{34}.\tau_4 + h_{35}.\tau_5 + h_{36}.\tau_6$$





For quartz, the coefficient matrix is of the form :

$$\begin{pmatrix} h_{11} & -h_{11} & 0 & h_{14} & 0 & 0 \\ 0 & 0 & 0 & 0 & -h_{14} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

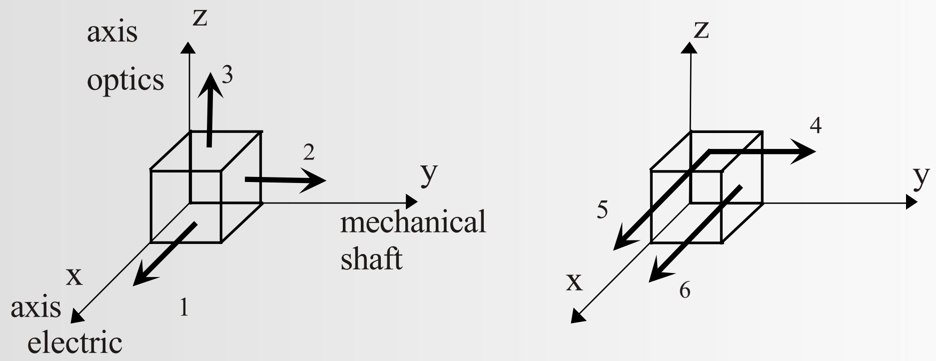
h11 = 2.3.10-12 C.N-1

h14 = -0.7.10-12 C.N-1

$$q_1 = h_{11}.\sigma_1 + h_{12}.\sigma_2 + h_{13}.\sigma_3 + h_{14}.\tau_4 + h_{15}.\tau_5 + h_{16}.\tau_6$$

$$q_2 = h_{21}.\sigma_1 + h_{22}.\sigma_2 + h_{23}.\sigma_3 + h_{24}.\tau_4 + h_{25}.\tau_5 + h_{26}.\tau_6$$

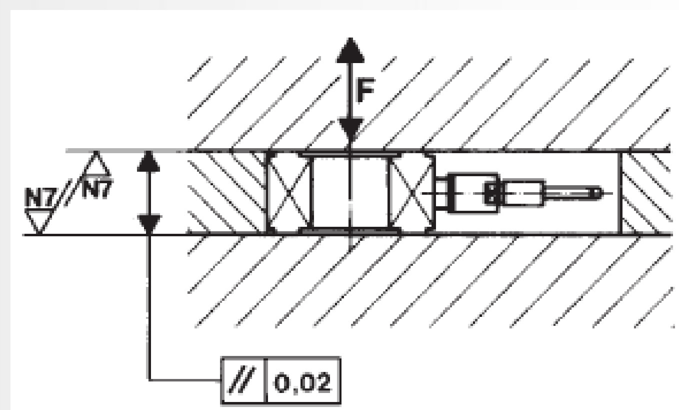
$$q_3 = h_{31}.\sigma_1 + h_{32}.\sigma_2 + h_{33}.\sigma_3 + h_{34}.\tau_4 + h_{35}.\tau_5 + h_{36}.\tau_6$$



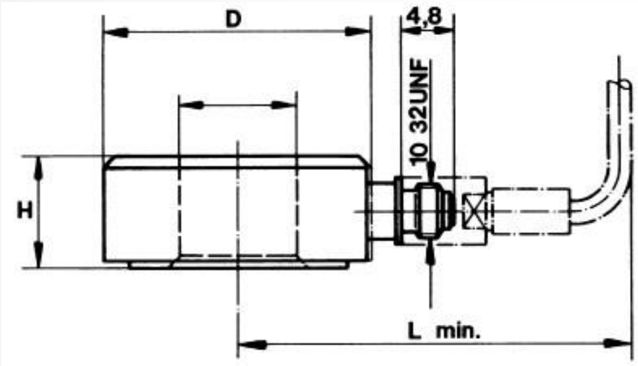
- Example of piezoelectric sensors:

Force – FSN

KISTLER



Features:



Type	Bereich F_z / Gamme F_z / Range F_z kN	Überlast / Surcharge / Overload kN	Max. Biegemoment M_x, M_y / Couple de flexion max. M_x, M_y / Max. bending moment M_x, M_y Nm	Steifheit / Rigidité / Rigidity kN / µm	Kapazität / Capacité / Capacitance pF	Gewicht / Poids / Weight g	d (mm)	D (mm)	H (mm)	L (mm)
9101A	0 ... 20	25	15	≈1,8	23	8	6,5	14,5	8	30
9102A	0 ... 50	60	60	≈3,5	37	21	10,5	22,5	10	34
9103A	0 ... 100	120	130	≈6,0	54	38	13	28,5	11	37
9104A	0 ... 140	160	240	≈7,5	55	57	17	34,5	12	40

Allgemeine Daten	*Données générales*	*General Data*		
Empfindlichkeit	**Sensibilité**	**Sensitivity**	pC / N	≈–4,3
Linearität	**Linéarité**	**Linearity**	% FSO	<±2
Hysterese	**Hystérésis**	**Hysteresis**	% FSO	<1
Ansprechschwelle	**Seuil de réponse**	**Threshold**	N	<0,01
Isolationswiderstand	**Résistance d'isolement**	**Insulation resistance**	TΩ	>10
Temperaturkoeffizient	**Coefficient de température**	**Temperature coefficient**	% / °C	0,01
Betriebstemperaturbereich	**Gamme de température d'utilisation**	**Operating temperature range**	°C	–50 ... 120
Max. Schubkraft	**Force de cisaillement max.**	**Max. shear force**	kN	±0,1 Fv*

* Fv = Vorspannung / Précontrainte / Preload

- Piezoelectric accelerometer :

KISTLER

Type	Unit	8202A10	8203A50
Acceleration Range	g	±2000	±1000
Threshold nom. (noise 100μVrms)	grms	0,001	0,001
Sensitivity	pC/g	-10	-50
Resonant Frequency mounted, nom.	kHz	45	24
Frequency Response ±5%	Hz	5 … 10000	5 … 4000
Amplitude Non-linearity	%FSO	±1	±1
Insulation Resistance (24°C)	Ω	$\geq 1 \times 10^8$	$\geq 1 \times 10^8$
Capacitance	pF	500	1400
Transverse Sensitivity nom., (max. 5%)	%	1,5	1,5
Long Term Stability	%	±1	±1
Environmental:			
Base Strain Sensitivity @ 250με	g/με	0,005	0,005
Shock Limit (1ms pulse) gpk	5000	5000	
Temperature Coefficient of Sensitivity	%/°C	0,13	0,13
Temperature Range Operating	°C	-70 … 245	-70 … 245
Construction:			
Sensing Element	type	Ceramic Shear	Ceramic Shear
Housing/Base	material	St. Stl.	St. Stl.
Sealing-housing/connector	type	Hermetic/ceramic	Hermetic/ceramic
Connector	type	10-32 neg	10-32 neg
Weight	grams	14,5	44,5
Mounting	type	10-32 UNF-2B thread	1/4 - 28 thread

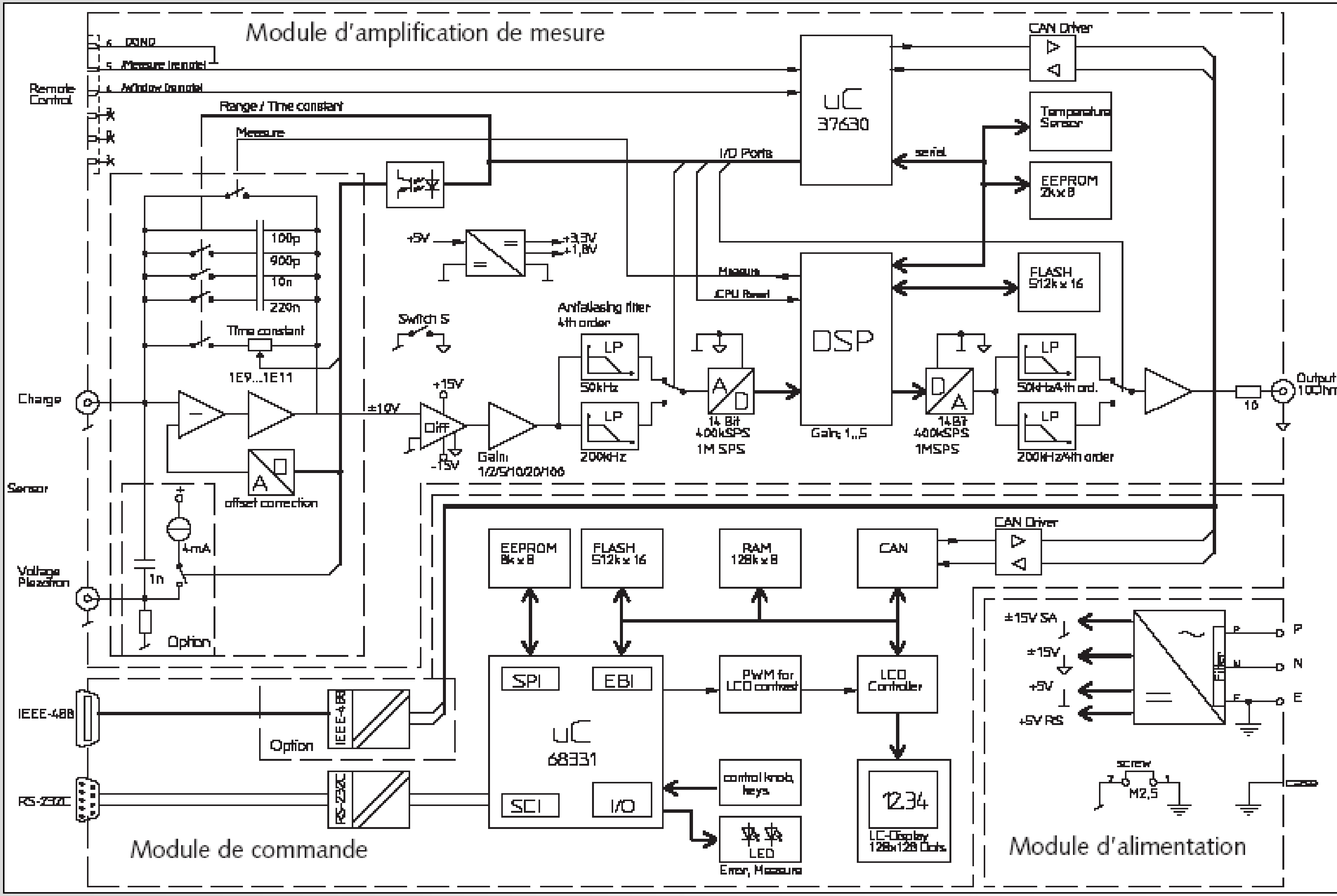
- Mounting: charge amplifier

- Amplificateur de charge à un canal
- Entrée Piezotron® (Option)
- Saut de zéro compensé
- Affichage à cristaux liquides (128x128 pixels)
- Commande par menus
- Evaluation directe du signal
- Filtres passe-haut et passe-bas à réglage convivial
- Compatible avec l'amplificateur de charge de type 5011B
- Logiciel pour PC et Virtual Instrument Driver pour LabVIEW™

KISTLER
Chargemètre

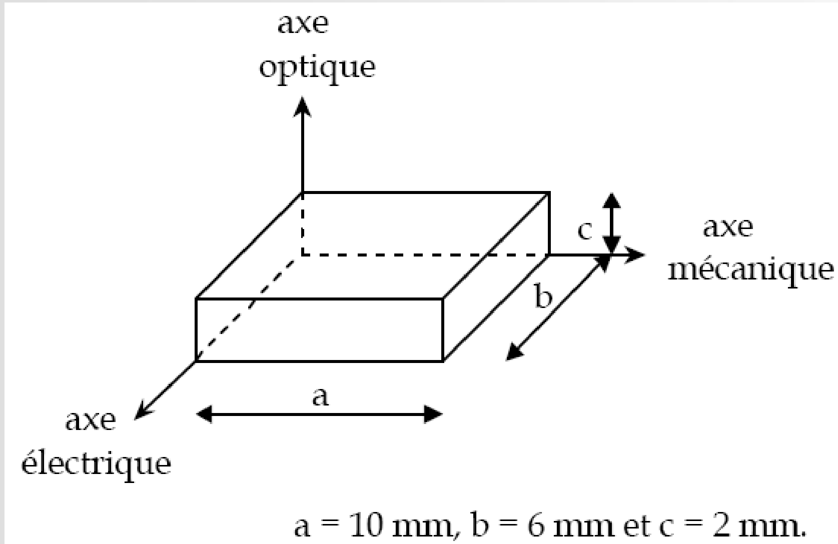
Entrée de charge		
Type de connecteur	BNC neg.	
Plage de mesure FS	pC	±2 … 2'200'000
Erreur de mesure		
Plage FS <10 pC	%	<±3
Plage FS <100 pC	%	<±1
Plage FS ≥100 pC	%	<±0,5
Dérive, mode de mesure DC (Long)		
à 25 °C	pC/s	<±0,03
à 50 °C	pC/s	<±0,3
Tension de mode commun max. entre masse d'entrée et masse de sortie	V	<±30

Block diagram :



• TD n°8 : We want to design a vibration sensor using a quartz blade, in other words a piezoelectric accelerometer.

1. We cut a quartz blade as follows:



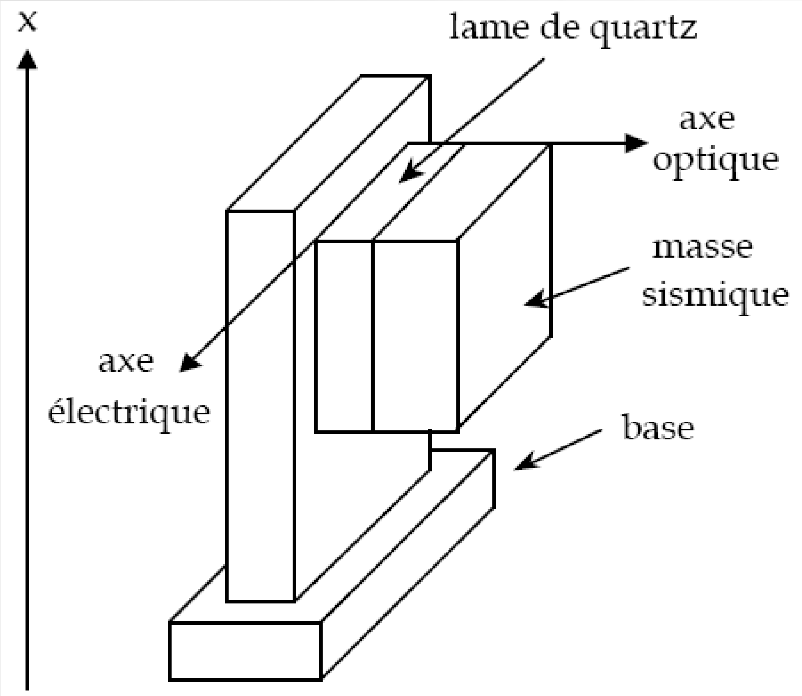
A shear stress is applied on the two horizontal faces in the direction of the mechanical axis (i.e. 4) and the charges generated along the electrical axis are recovered.

The piezoelectric coefficients of quartz are: h11 =2 ,3 pC/N

h14 = - 0.7 pC/N

Determine the amount of charge recovered as a function of the shear force (denoted F).

2. This blade is mounted as follows:

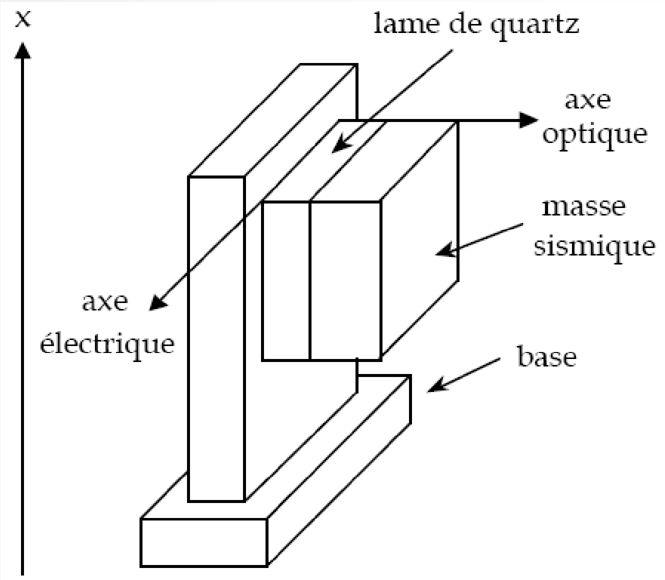


The objective is to measure the acceleration (noted b) of the sensor base. The quartz blade is mounted between a structure attached to the base and a seismic mass (of mass m). This blade is characterized by a mechanical rigidity noted k.

We give: m = 50 g k = 3 kN/mm

2.1. Show, with a simple model of this mechanical system, that the transfer function (in Laplace) giving the force on the quartz blade as a function of the acceleration of the base is :

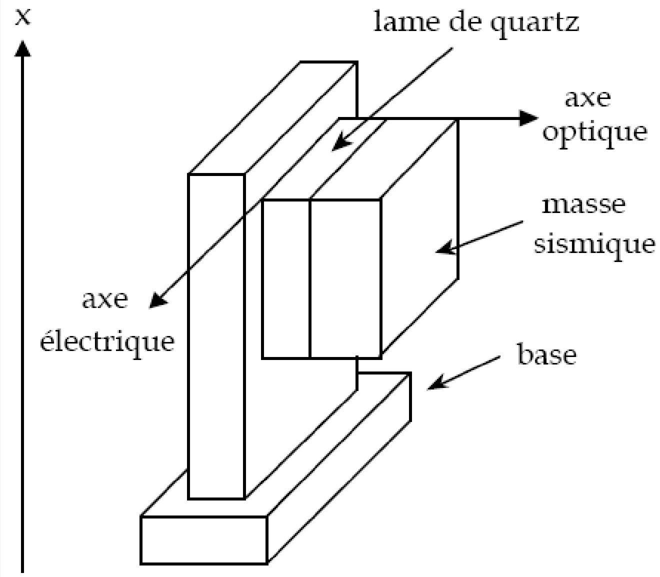
$$\frac{F(p)}{\gamma_b(p)} = m\frac{1}{1+\frac{m}{k}p^2}$$



2.2. Determine the transfer function giving the amount of charge recovered (noted Q) as a function of the acceleration.

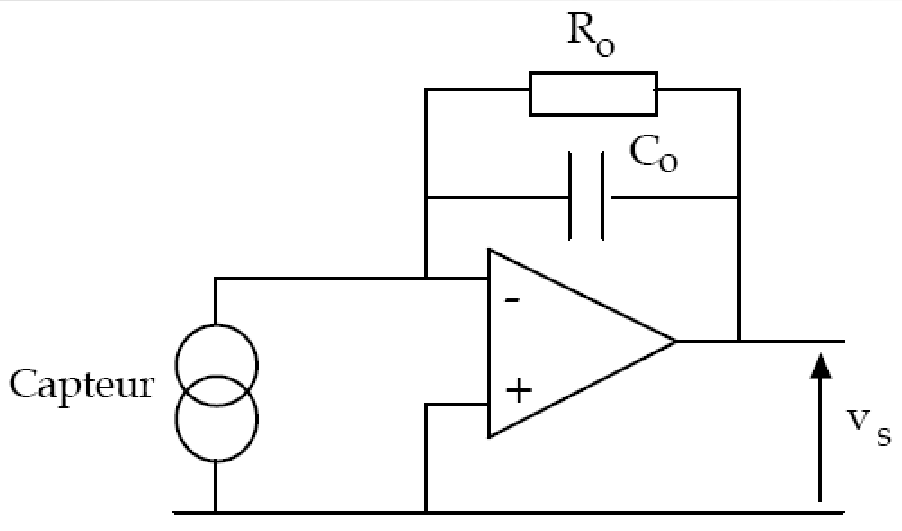
What is the sensitivity of this sensor in the bandwidth (expressed in pC/g, g being the acceleration of gravity, g = 9.81 ms-2) ? Numerical application.

Calculate the resonant frequency of this sensor.



$$\frac{F(p)}{\gamma_b(p)} = m \frac{1}{1 + \frac{m}{k} p^2}$$

3. This sensor is connected to a charge amplifier:



Assuming an ideal operational amplifier, determine the function of transfer $\dfrac{Vs(p)}{_b(p)}$

Sketch its gain Bode diagram.

Determine the components to have a sensitivity of 1 mV/g, and allowing to measure an acceleration higher than 10 Hz.