ANALOG CIRCUITS DESIGN

AE6: Operational Amplifiers V,
Differential circuits – instrumentation amplifiers

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Course overview

1. Single ended versus differential
2. The difference amplifier
3. Common-mode analysis
4. Applications of differential circuits in the digital world

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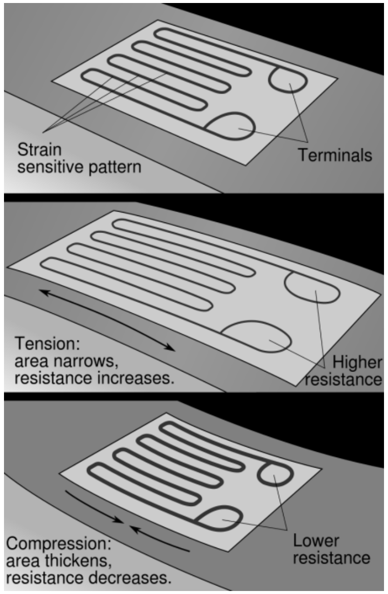
1. Single-ended versus differential: the challenge

The challenge is to measure a mechanical force using a strain gauge which is an insulating flexible backing supporting a metallic foil pattern.



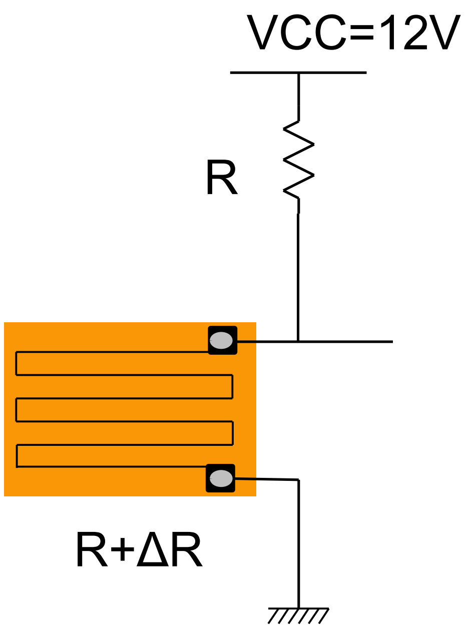
At rest, the metallic pattern exhibits a nominal resistance. The strain causes a deformation of the metallic foil and:

- When stretched, the metal becomes longer and narower: its resistance increases,
- When compressed, the metal becomes shorter and wider: its resistance decreases

The relative variation of the resistance ($\Delta R/R$) is however in the $\pm 10^{-3}$ range, i.e. for a 100Ω nominal resistance, variation is only ±0.1Ω

Source: https://en.wikipedia.org/wiki/Strain_gauge

1. Single-ended versus differential: Single-ended measurement



$$Eg \approx \frac{VCC}{2} + \frac{VCC}{2}\frac{\Delta R}{R} \approx 6V + 6mV$$

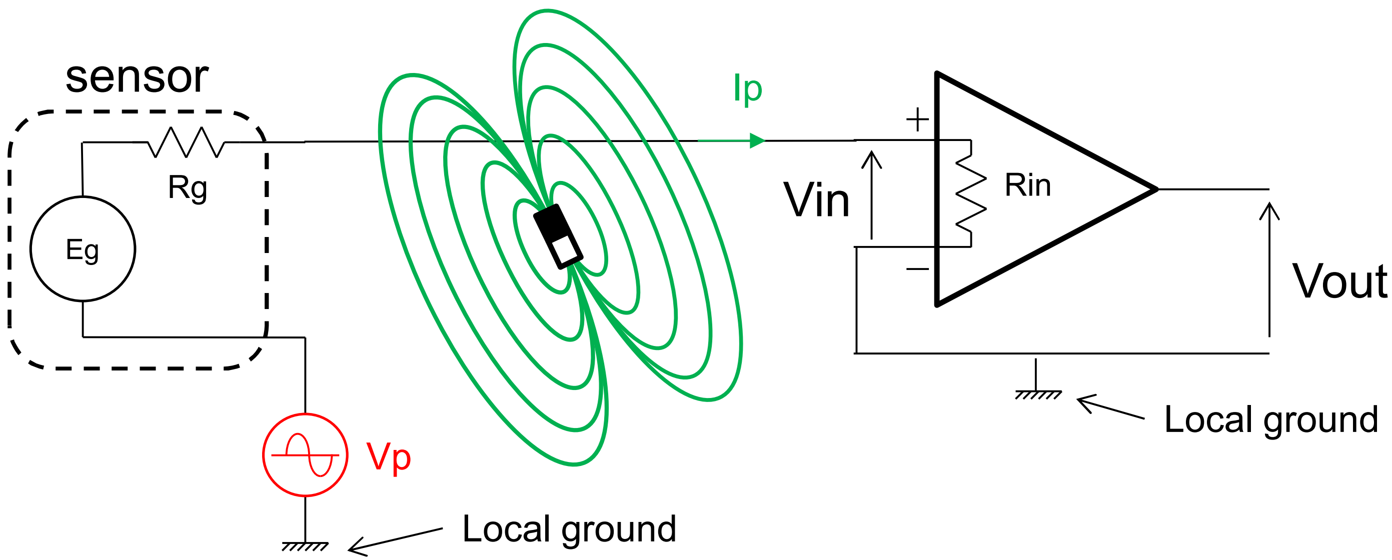
Under strain ($\Delta R/R = 10^{-3}$)

Single-ended arrangement: the signal to measure Eg is referred to the ground

Eg exhibits a large constant bias but very little variation in presence of strain

The large bias, unless it is cancelled, prohibits high gain for the input amplifier

1. Single-ended versus differential: single-ended measurement



Assuming that the bias is cancelled in Eg, only the small variation remains and:

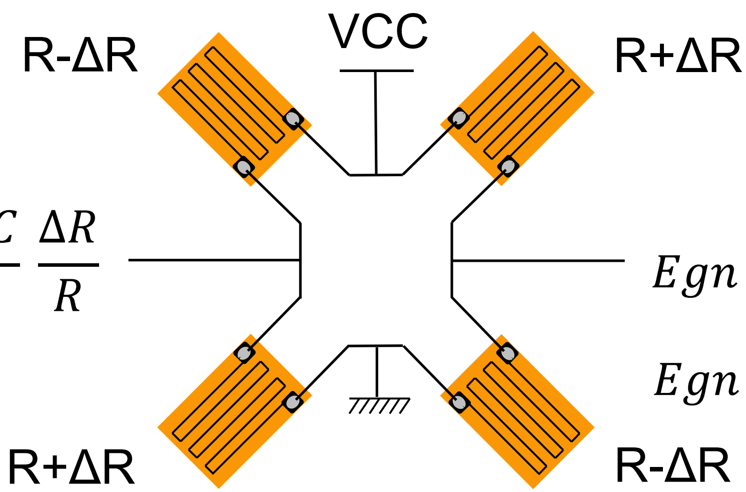
$$Vout = A\,Vin = A\left(Eg\,\frac{Rin}{Rin+Rg} + Vp\,\frac{Rin}{Rin+Rg} + Ip\,Rin \right)$$

Vp: parasitic voltage due to a large distance between the two local ground points

Ip: parasitic current created by an electromagnetic field

1. Single-ended versus differential: differential measurement

Under strain ($\Delta R/R = 10^{-3}$)



$$Egp = \frac{VCC}{2} + \frac{VCC}{2}\frac{\Delta R}{R}$$

$$Egp \approx 6V + 6mV$$

$$Egn = \frac{VCC}{2} - \frac{VCC}{2}\frac{\Delta R}{R}$$

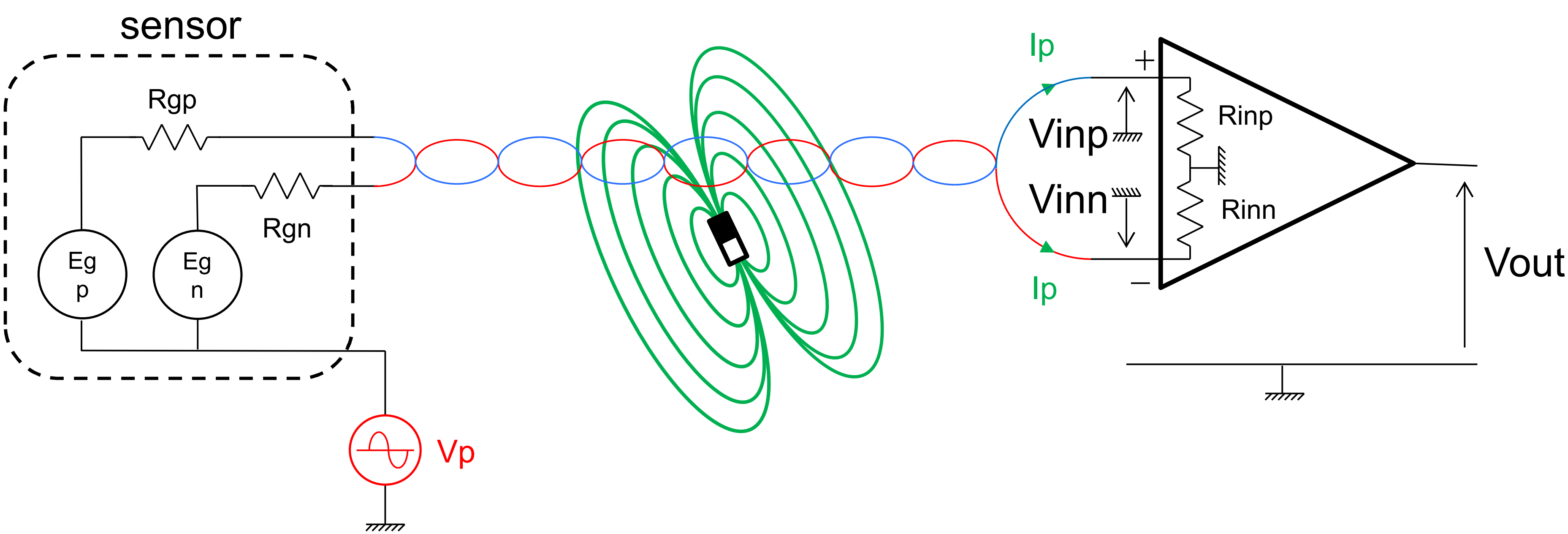
$$Egn \approx 6V - 6mV$$

Differential arrangement: the signal to measure is now Egp – Egn

Ground still exists but is no longer the reference

The bias can be any, only the difference between Egp and Egn matters

1. Single-ended versus differential: differential measurement



$$Vout = Ap\,Vinp\;-An\,Vinn = Ap\,Egp\,\frac{Rinp}{Rinp+Rgp} - An\,Egn\,\frac{Rinn}{Rinn+Rgn}$$

$$+\,Ap\,Vp\,\frac{Rinp}{Rinp+Rgp} - An\,Vp\,\frac{Rinn}{Rinn+Rgn}$$

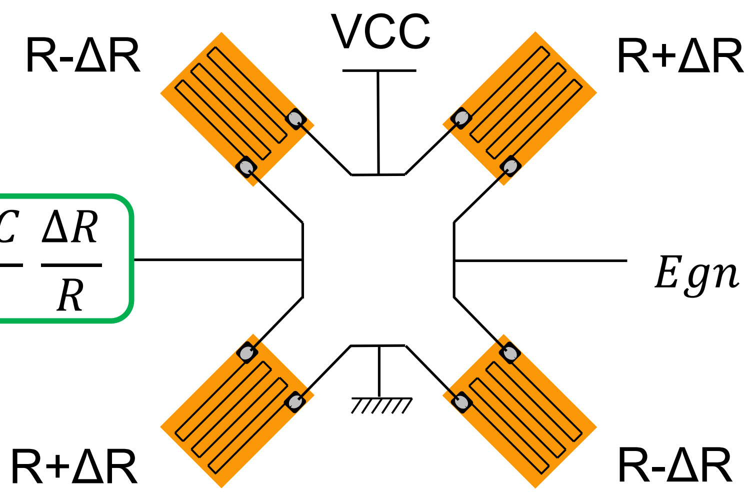
$$+\,Ap\,Ip\,Rinp\;-An\,Ip\,Rinn$$

Parasitic terms cancel if symmetry is ensured :

- At amplifier's level → Ap = An, Rinp = Rinn
- At sensor level → Rgn = Rgp

1. Single-ended versus differential: common mode & differential mode

$$Egp = \boxed{\frac{VCC}{2}} \boxed{+\frac{VCC}{2}\frac{\Delta R}{R}}$$



$$Egn = \boxed{\frac{VCC}{2}} \boxed{-\frac{VCC}{2}\frac{\Delta R}{R}}$$

Differential operation involves two voltages (for example Egp and Egn)

Common-mode voltage (Vcm): the amount which is the same on both Egp and Egn.
→ Here, Vcm = VCC/2

Differential-mode voltage (Vd): the amount which is the difference of the terms having the same value but opposite polarity on both Egp and Egn.
→ Here, Vd = VCC (ΔR/R)

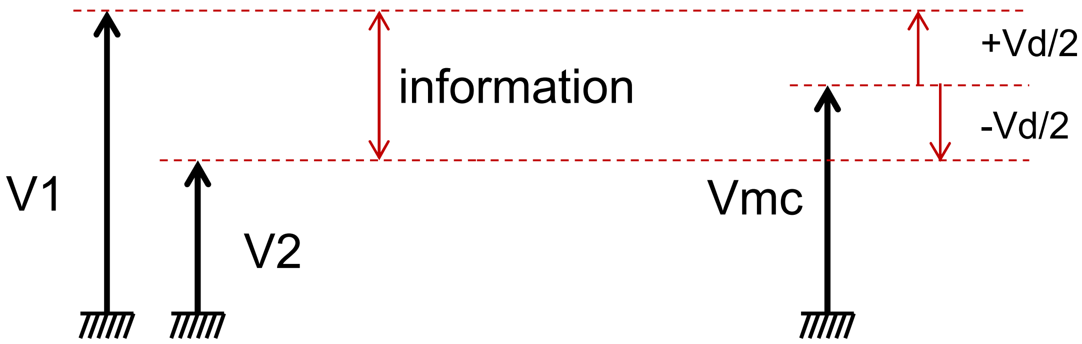
1. Single-ended versus differential: common mode & differential mode

In a general way, when information is conveyed by two voltages V1 and V2:

V1 and V2 can be expressed as $V1 = Vcm + \frac{Vd}{2}$ and $V2 = Vcm - \frac{Vd}{2}$

Information is carried by the differential-mode voltage $Vd = V1 - V2$

Perturbators are carried by the common-mode voltage $Vcm = \frac{V1+V2}{2}$



Goals for the differential amplifier:

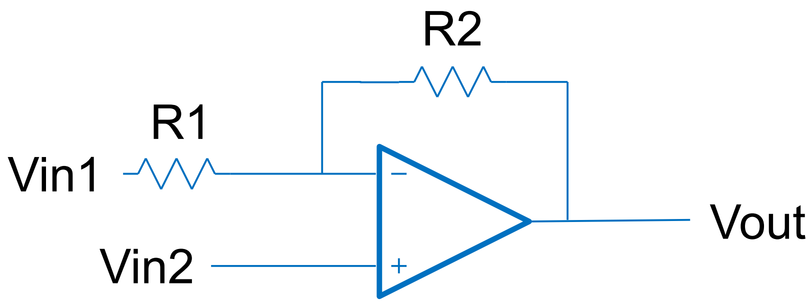
Offering a stable and predictible gain for differential-mode signals

Reducing as much as possible the effects of common-mode perturbators (achieved through circuit symetry)

2. The difference amplifier: basic circuit

Goals: the amplifier must exhibit at both inputs:

- The same gain with opposite sign
- The same (high) impedance

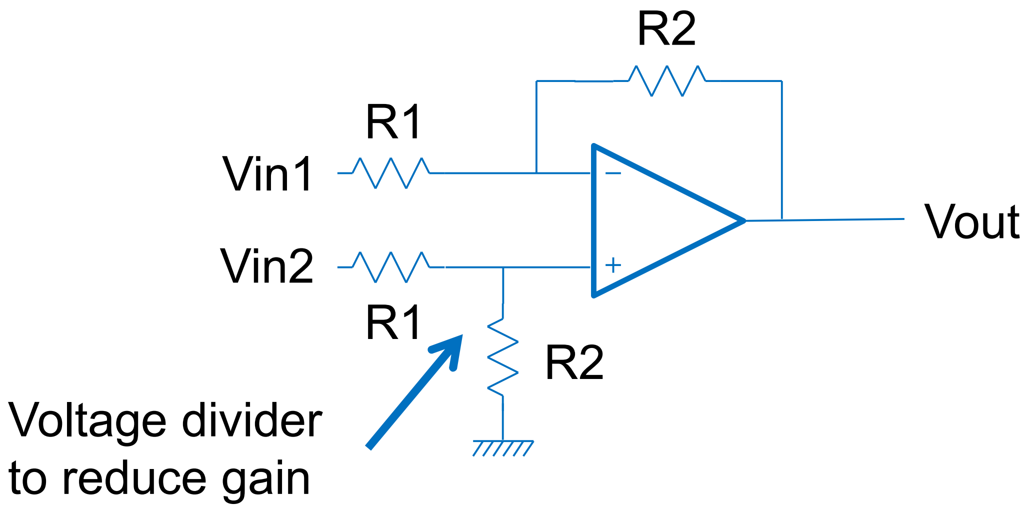


Gain: $$Vout = \frac{-R2}{R1} Vin1 + \left(1 + \frac{R2}{R1}\right) Vin2$$

Input impedance: $Zin1 = R1$ $\quad Zin2 \rightarrow \infty$

This circuit doesn't meet the expectations neither for gain nor input impedance

2. The difference amplifier: improved basic circuit



Gain: $Vout = \frac{R2}{R1}(Vin2 - Vin1)$

Importance of R2/R1 ratio matching

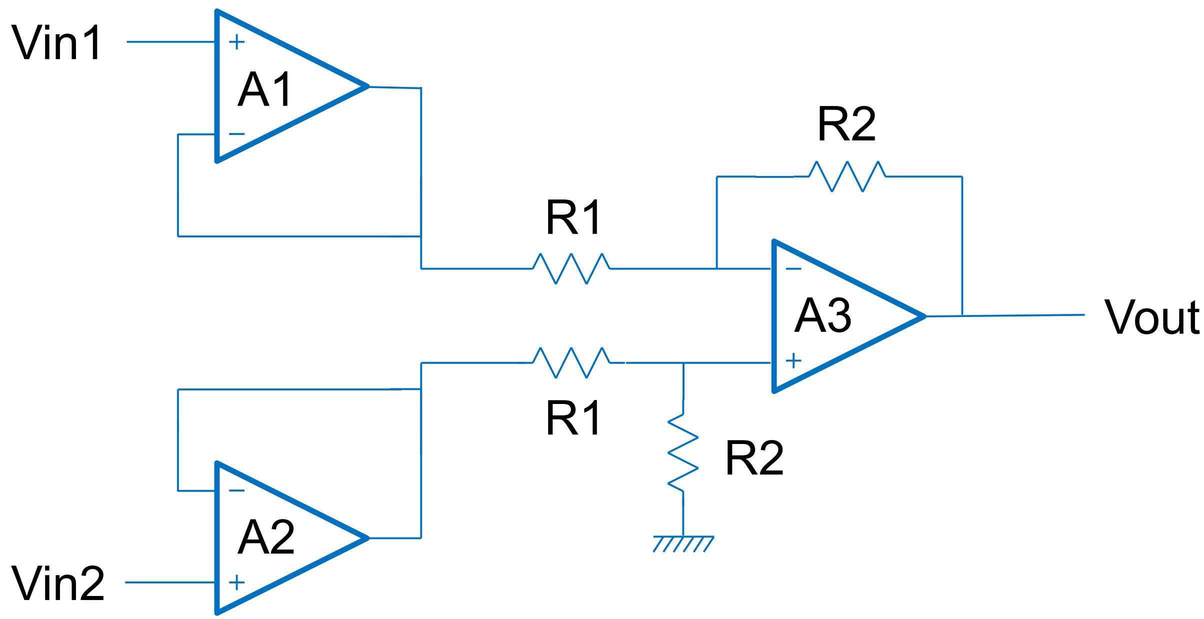
Input impedance: $Zin1 = R1$ $\quad Zin2 = R1 + R2$

This circuit meets the expectations for gain but not for impedance

2. The difference amplifier: the instrumentation amplifier

Adding voltage followers increase and symmetrize input impedances

$Zin1 \rightarrow \infty$



$Zin2 \rightarrow \infty$

Problem: overall gain is only performed by last stage → R2/R1 > 1

→ two external resistors needed

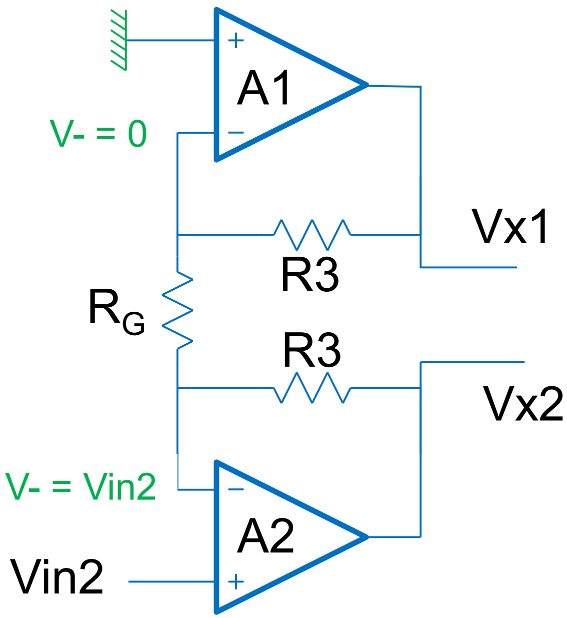
→ matching is difficult for external resistors

Gain of last stage is set to 1 (R1 = R2) → matching greatly improved (internal res.)

Gain is implemented on first stage (A1, A2) with only one external resistor R_G

2. The difference amplifier: the instrumentation amplifier

Which expression for the amplifier's gain?



1/ Amplifier's output voltage is:

$$Vout = \frac{R2}{R1}(Vx2 - Vx1)$$

2/ Vin2=0

$$Vx1a = \left(1 + \frac{R3}{R_G}\right)Vin1$$

$$Vx2a = \frac{-R3}{R_G}Vin1$$

3/ Vin1=0

$$Vx1b = \frac{-R3}{R_G}Vin2$$

$$Vx2b = \left(1 + \frac{R3}{R_G}\right)Vin2$$

4/ Superposition: $Vx1 = \left(1 + \frac{R3}{R_G}\right)Vin1 + \frac{-R3}{R_G}Vin2$ $\quad Vx2 = \frac{-R3}{R_G}Vin1 + \left(1 + \frac{R3}{R_G}\right)Vin2$

5/ Finally:

$$\boxed{Vout = \frac{R2}{R1}\left(1 + \frac{2\,R3}{R_G}\right)(Vin2 - Vin1)}$$

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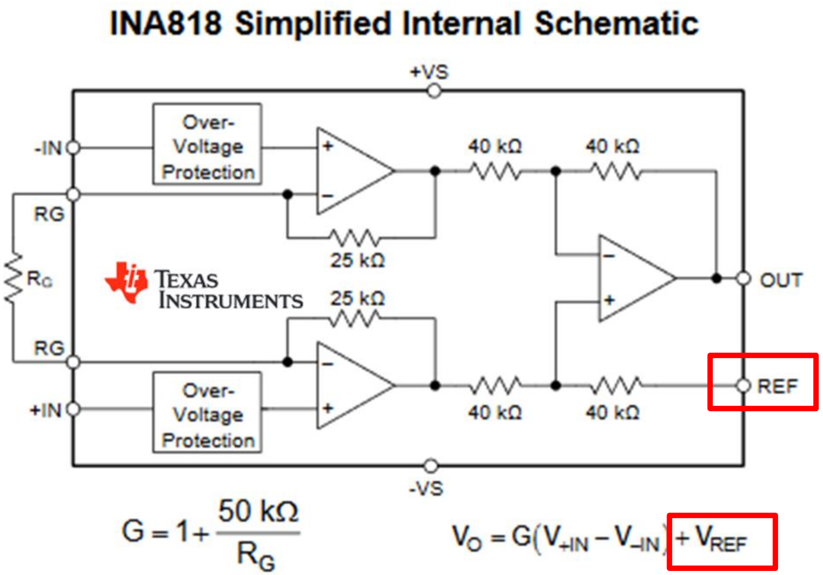
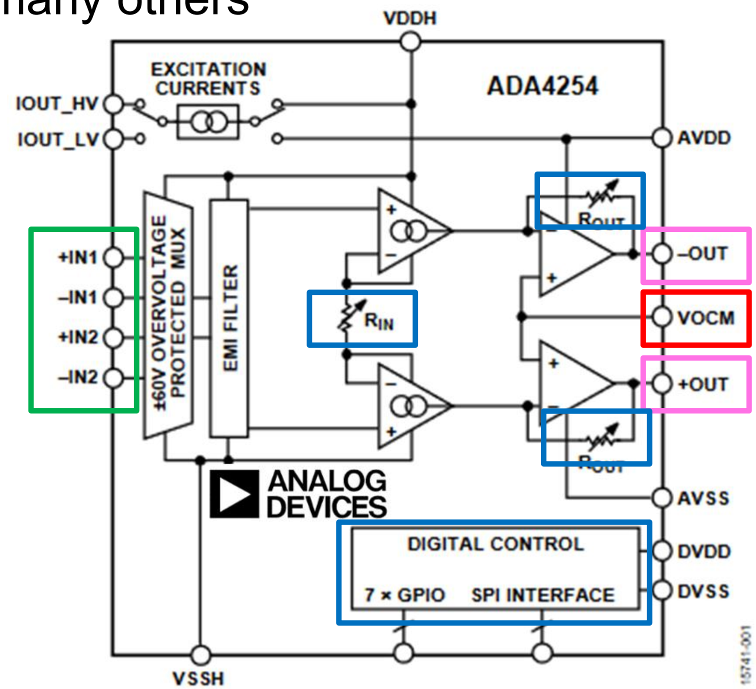
2. The difference amplifier: the instrumentation amplifier

Some commercially available circuits… among many others



$$G = 1 + \frac{50\ k\Omega}{R_G} \qquad V_O = G(V_{+IN} - V_{-IN}) + V_{REF}$$



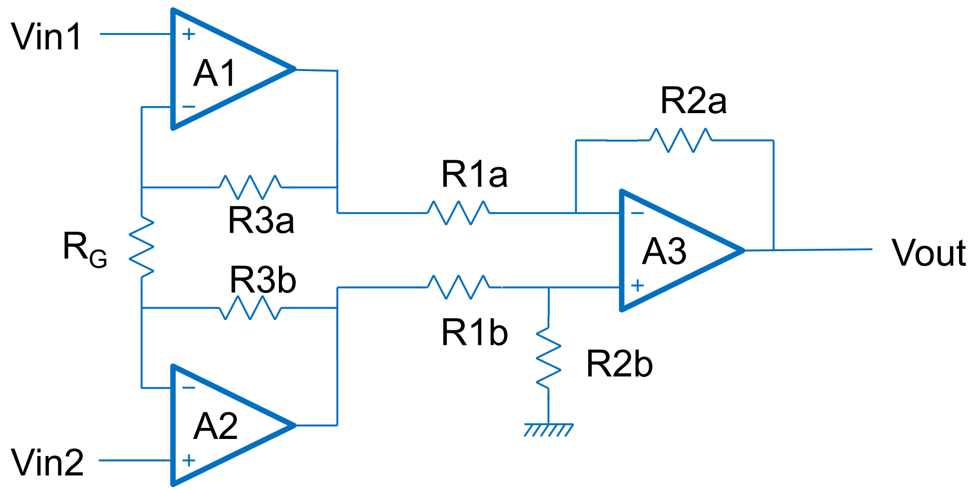
- Second stage gain = 1 (R1=R2=40kΩ)
- R3 (25k Ω) is laser-trimmed to guarantee an accurate absolute value
- Gain can be set between 1 and 1000
- Implements a V_{REF} input* to allow an offset at the output

- Digitally programmable gain (36 different values)
- Calibration register for each gain value
- 2 multiplexed channels
- Differential output
- Implements a V_{OCM} input to allow an offset at the output

*The external voltage source connected to V_{REF} must exhibit a negligible output resistance with respect to 40kΩ

3. Common-mode analysis: when common-mode becomes differential..

Taking into account that resistors haven't exactly their nominal value:



The gain is sligthly different for Vin1 and Vin2: $Vout = G_+ Vin2 - G_- Vin1$

Consequence if Vin1 and Vin2 have a non-zero common mode:

$$Vout = G_+ \left(Vcm + \frac{Vd}{2}\right) - G_- \left(Vcm - \frac{Vd}{2}\right) = \frac{Vd}{2}\boxed{(G_+ + G_-)} + Vcm\boxed{(G_+ - G_-)}$$

Slight gain error for Vd/2

Vmc is not fully canceled

A portion of the common-mode signal is viewed as a differential one

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3. Common-mode analysis: Common-Mode Rejection Ratio

The Common-Mode Rejection Ratio (CMRR) is a measure of the ability of the amplifier to reject (cancel) the common-mode signals

$$CMRR = \frac{Adm}{Acm}$$

Adm: differential-mode gain
Acm: common-mode gain

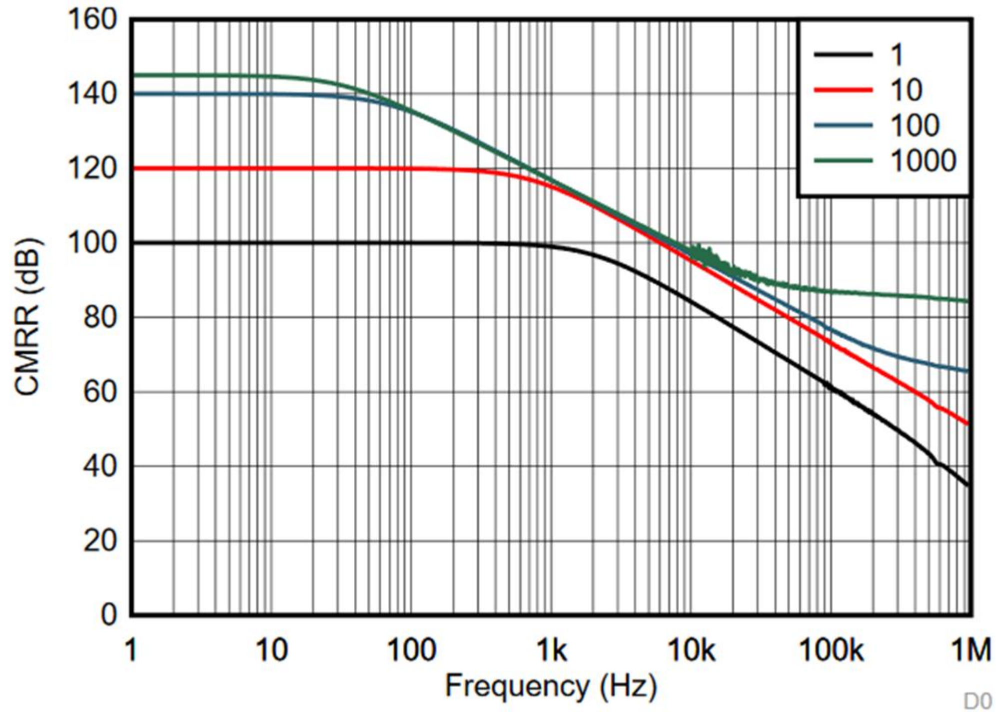
CMRR is frequency depedent

How to use the CMRR value?

CMRR   Adm

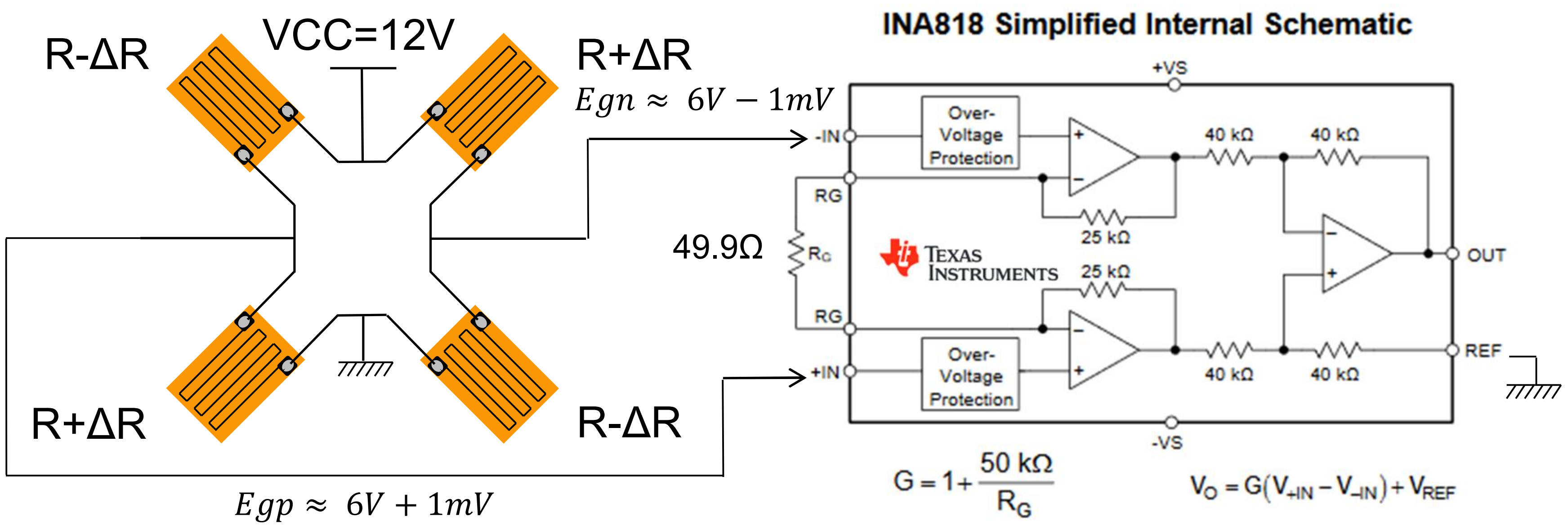
Acm

$$Vout = Adm\,Vd + Acm\,Vcm$$



Example: INA828

Common-mode error calculation example:



Gain = 1003 = Adm Vd = 2mV → Expected value: Vout = 2.006V

CMRR = 140dB (worst case @ G=1000) → CMRR = 10^7 → Acm ≈ 10^{-4}

Real value: Vout = 1003 x 2mV + 10^{-4} 6V = 2.0066V (≈ 0.03% error, <0.5LSB @ 10 bits, Vref = 3.3V)

Vcm range is limited, check datasheet

4. Applications of differential circuits in the digital world

Why differential signals for digital applications?

Because $i = C\,\dfrac{dV}{dt}$

Digital signals → high dV
+ high throughput → low dt
+ Long distance → high capacitance

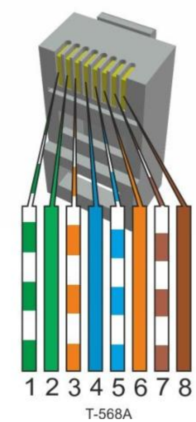
= high current from supply

Reducing dV (lower supply voltage) helps reducing the supply current but also increases susceptibility to perturbators

Perturbators are common-mode signals, thus the interest in using differential signals

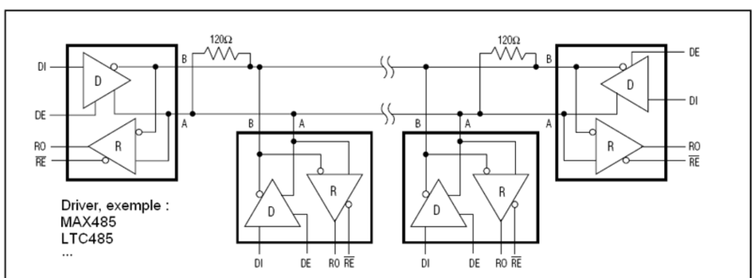
RS485 (computers, industry)
CAN bus (automotive, industry)

Ethernet

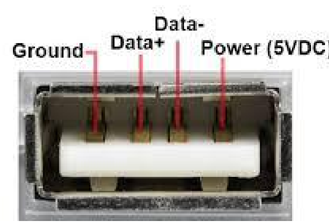


Pin	Description	10base-T	100Base-T	1000Base-T
1	Transmit Data+ or BiDirectional	TX+	TX+	BI_DA+
2	Transmit Data- or BiDirectional	TX-	TX-	BI_DA-
3	Receive Data+ or BiDirectional	RX+	RX+	BI_DB+
4	Not connected or BiDirectional	n/c	n/c	BI_DC+
5	Not connected or BiDirectional	n/c	n/c	BI_DC-
6	Receive Data- or BiDirectional	RX-	RX-	BI_DB-
7	Not connected or BiDirectional	n/c	n/c	BI_DD+
8	Not connected or BiDirectional	n/c	n/c	BI_DD-

PinoutsGuide.com



USB



LVDS