Non-idealities in operational amplifiers

João Paulo Carmo, PhD
Principal Researcher
University of Minho
Dept Industrial Electronics
R&D Centre ALGORITMI
Micro/Nanotechnologies
and Biomedical Applications

jcarmo@dei.uminho.pt

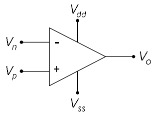
http://lattes.cnpq.br/5589969124054528

CENTROALGORITMI
Micro/Nanotechnologies and Biomedical Applications (MNBA)
Universidade do Minho

Campus de Azurém, 4800-058 Guimarães, PORTUGAL
Phone: +351-253-510190, Fax: +351-253-510189

Ideal OpAmps

(1) Useful for circuit behavior analysis



The symbol of an OpAmp

(2) Because these *golden* rules applies:

(a) Inexistence of input currents

$$\begin{cases} I_p = 0\text{ A} \\ I_n = 0\text{ A} \end{cases}$$

(b) Equal voltages in the both inputs

$$\begin{cases} v_p = v_n \\ v_d = v_p - v_n = 0\text{ V} \end{cases}$$

Non-ideal OpAmps

(1) Ideal behavior useful in initial design steps

(2) Non-idealities must be considered on specific cases:

(a) Signals with very low amplitudes

(b) High-frequency signals

(3) The general method combines:

(a) An ideal OpAmp with

(b) An electric model of the non-ideality

Summary of non-ideal OpAmps

(1) Small signal errors
  - **(a) Differential and common-mode gains**
  - **(b) Input and output resistances**

(2) Frequency limitation
  - **(a) Finite bandwidth**
  - **(b) Product gain×frequency**

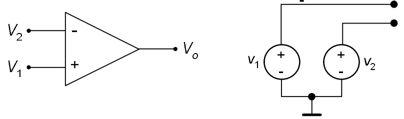
(3) Large signal limitation
  - **(a) Slew-rate**
  - **(b) Voltage distortion due to saturation**

(4) DC imperfections
  - **(a) Input offset voltage**
  - **(b) Input bias and offset currents**

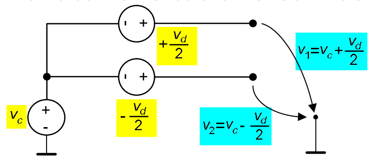
Differential and common-mode gains

(1) Excitations of a differential amplifier:

$$\begin{cases} v_1 \\ v_2 \end{cases}$$



(2) The later excitations can be replaced by:



(3) Where: $v_d = v_1 - v_2$

$$v_c = \frac{1}{2}(v_1+v_2)$$

Differential and common-mode gains

(1) The output of such an amplifier is:

$$v_o = A.v_d + A_c.v_c$$

(2) In an ideal OpAmp we have:

$$A = \infty \text{ and } A_c = 0$$

(3) The *Common-Mode Reject Ratio* (CMRR) is:

CMRR = A/A_c

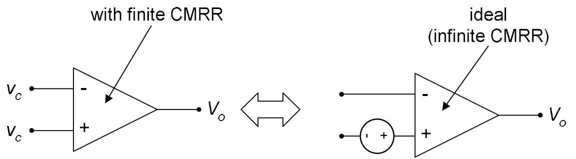
(4) Typical CMRR @ low frequencies :

CMRR = 80-100 dB (10^4-10^5)

PARAMETER		TEST CONDITIONS	T_A†	µA741C			µA741I, µA741M			UNIT
				MIN	TYP	MAX	MIN	TYP	MAX	
CMRR	Common-mode rejection ratio	$V_{IC} = V_{ICR}\text{min}$	25ºC	70	90		70	90		dB
			Full range	70			70			

Differential and common-mode gains

(1) A OpAmp with finite CMRR is equivalent to:



(2) The voltage v_E is:

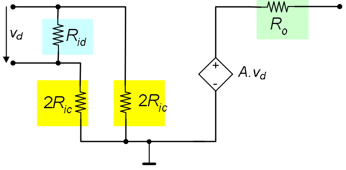
$$v_E = \frac{A_c.v_c}{A} = \frac{v_c}{\text{CMRR}}$$

(3) This effect is important for:

v_d signals with very small amplitudes associated to v_c signals with high amplitudes

Input and output resistances

(1) OA model with input and output resistances



(2) The resistances are such that

$R_{ic} \gg R_{id} \gg R_o$

(3) Typical values for R_{ic}, R_{id} and R_o can be:

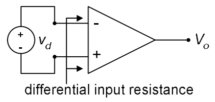
100 MΩ, 1 MΩ and 100 Ω (respectively)

(4) It exists OAs with even highers R_{ic} and R_{id}

Input resistances

Types of input resistances:

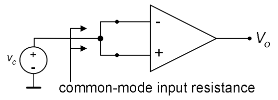
(a) Differential input resistance



differential input resistance

≈ R_{id} because $R_{ic} \gg R_{id}$

(b) Common-mode input resistance

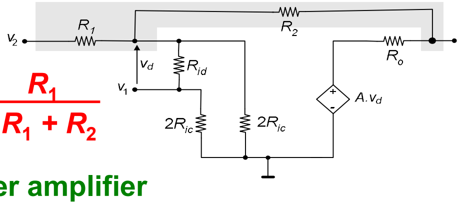


common-mode input resistance

= R_{ic} because is $2R_{ic}$ // $2R_{ic}$

Input resistance

Input resistances of inv & non-inv amplifiers



$$\beta = \frac{R_1}{R_1 + R_2}$$

(a) Inverter amplifier

$v_1 = 0$ V and $v_2 \neq 0 \rightarrow R_{if} \approx R_1$

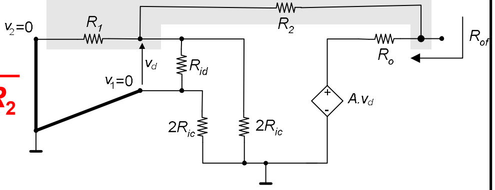
(b) Non-inverter amplifier

$v_1 \neq 0$ V and $v_2 = 0 \rightarrow R_{if} \approx 2R_{ic}$ // $(1+A\beta).R_{id}$

$A\beta \gg 1 \rightarrow R_{if} \gg R_{id}$ IMPROVEMENT!

Output resistances

Output resistance of inv & non-inv amplifiers



$$\beta = \frac{R_1}{R_1 + R_2}$$

(a) It is possible to demonstrate

$$R_{of} \approx \frac{R_o}{1 + A\beta}$$

(b) R_o is low, therefore with feedback ($A\beta \gg 1$)

R_{of} is even more lower IMPROVEMENT!

Input offset voltage

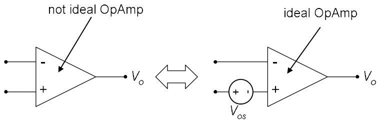
In an ideal OpAmp:

If $v_d = 0$ V → $v_o = 0$ V

Due to internal asymmetries in the OpAmp:

(a) $v_o \neq 0$ V when $v_d = 0$ V

(b) This effect can be modeled by:



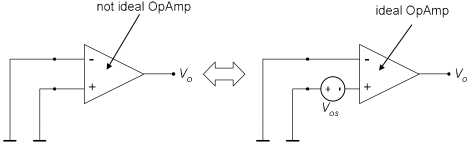
V_{os} is the input offset voltage

Input offset voltage

V_{os}: random variable & asymmetry dependent

In the most common OAs: $|v_{os}|_{max}$ = 1-5 mV

Without feedback: V_{os} saturates the amplifier



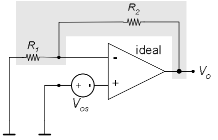
With V_{os} = 1 mV and $A = 10^5$ (100 dB):

(a) $A.V_{os}$ = 100 V

(b) $A.V_{os}$ much higher than the saturation voltage

Input offset voltage

For the inverting and non-inverting amplifiers



The output voltage is:

$$v_O = -\left(1+\frac{R_2}{R_1}\right).V_{os}$$

The effect of V_{os} can be severe on signals with:

(a) reduced amplitudes

(b) low frequencies → masked by V_{os}

Input offset voltage

(1) V_{os} can be compensated:

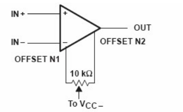
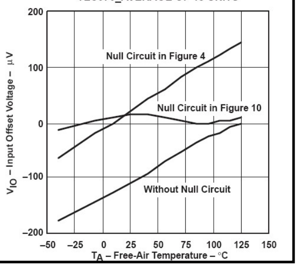


Figure 2. Input Offset Voltage Null Circuit

(2) Not fully effective:

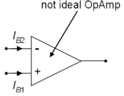
V_{os} mainly affected by T

TLC070_AVERAGE OF 15 UNITS

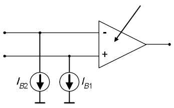


Input bias and offset currents

(1) OAs [on bipolar tech] has input currents:



(a) This non-ideality can be modeled as:



(b) The non-idealities can be quantified as:

- Input bias current: $I_B = \frac{1}{2}(I_{B1}+I_{B2})$
- Input offset current: $I_{OS} = I_{B1}-I_{B2}$

Input bias and offset current

(1) The previous equations results in:

$$\begin{cases} I_{B1} = I_B + \dfrac{I_{OS}}{2} \\ I_{B2} = I_B - \dfrac{I_{OS}}{2} \end{cases}$$

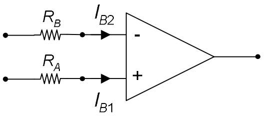
(2) I_{os} is also a random variable

It is possible to have:

$$\begin{cases} I_B = 100 \text{ nA} \\ |I_{OS}| < 10 \text{ nA} \end{cases}$$

Input bias and offset current

The input bias currents can be compensated:



(a) The voltage $V(R_A)$ must be equal to $V(R_B)$:

(b) This can be achieved with:

$R_A I_{B1} = R_B I_{B2}$

(c) $V(R_A)$, $V(R_B)$ are common-mode voltages.

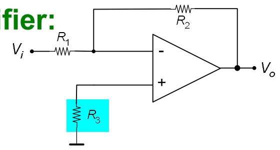
(d) $V(R_A)$, $V(R_B)$ “don’t appear” in the output

Naturally, they are subjected to the CMRR

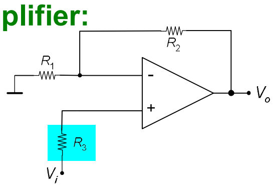
Input bias and offset current

Compensation in basic amplifiers:

(a) Inverting amplifier:

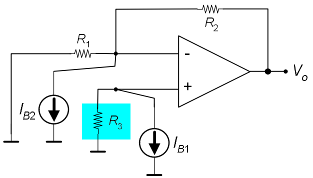


(b) Non-inverting amplifier:



Input bias and offset current

This circuit represent both amplifiers with V_i=0



Applying the superposition principle:

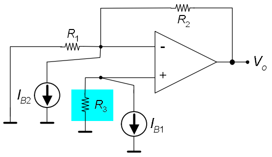
$$v_o = -I_{B1}R_3\times\left(1+\frac{R_2}{R_1}\right) + I_{B2}R_2$$

I_{OS} is random → the compensation is for I_{B1}=I_{B2}

The condition to get v_o = 0 V is:

$$R_3 = R_1 // R_2$$

Input bias and offset current



(1) With: (a) $R_3 = R_1 // R_2$

(b) and $I_{B1} \neq I_{B2}$ →

$$\begin{cases} I_{B1} = I_B + \dfrac{I_{OS}}{2} \\ I_{B2} = I_B - \dfrac{I_{OS}}{2} \end{cases}$$

(2) The output is $v_o = -I_{OS}R_2$

(3) Comparing v_o with $R_3 = 0\ \Omega$:

(a) $v_o \approx -I_BR_2$

(b) A clear reduction in v_o because $|I_{OS}| < 0.1I_B$

Frequency limitation

(1) The differential gain A is not infinite

(2) But even worse, A is frequency dependent

(3) Contrary to others, this one can't be neglected

(4) The frequency response is a critical issue

Can affect the stability of feedback amplifiers

(6) In general purpose OAs, the freq. comp.

(a) Is done internally

(b) Using the dominant pole technique

(c) Whose value is very low (tipically 10 Hz)

Frequency limitation

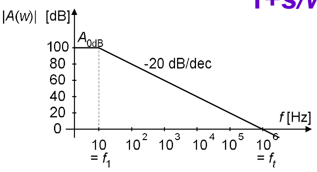
Illustrating the dominant pole technique

(a) Imagining:

- dominant pole in 10 Hz (i.e., f_1 = 10 Hz)
- DC gain of 100 dB (i.e., A_{0dB} = 100 dB)

(b) Dif. gain is (1st order): $A(s) = \dfrac{A_0}{1+s/w_1}$

(c) Therefore:

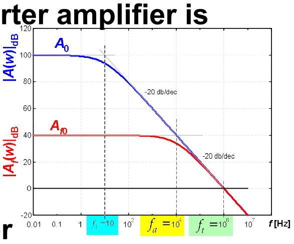


(d) $f_t = f_1.A_0 = f_1\times10^{A_{0dB}/20} = 10^6$ Hz

Frequency limitation

(1) The gain of a non-inverter amplifier is

$$A_f(s) = \frac{A(s)}{1+\beta A(s)}$$



(2) β = 1/100 ∧ A_0=100 dB

→ A_{f0} = 100

(or A_{f0dB} = 40 dB)

(3) $A_f(s)$ is also of 1st order

$$A_f(s) = \frac{A_{f0}}{1+s/w_a} \longrightarrow \begin{cases} A_{f0} = A_0/(1+\beta A_0) \\ w_a = w_1\times(1+\beta A_0) \gg w_1 \end{cases}$$

(4) The small value of f_1 isn't a problem ☺

(5) Increasing A_{f0}

Decreases w_a (i.e., the bandwidth)

Frequency limitation

(1) w_a decreases, but the product *GBP*

(a) Is equal to $A_{f0}.w_a$ and keeps constant

(b) Is equal to $A_0.w_1$

(2) *GBP* constant is a limitation of technology

(3) It is easy to obtain

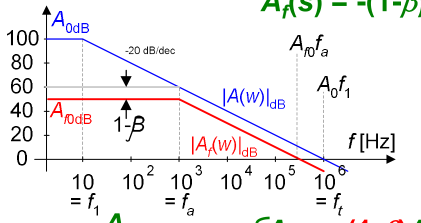
(a) Large gain, low bandwidth

(b) Large bandwidth, low gain

(4) But hard to have both simultaneously large

Frequency limitation

(1) Inverter amplifier: $A_f(s) = -(1-\beta)\times\frac{A(s)}{1+\beta A(s)}$



$$A_f(s) = \frac{A_{f0}}{1+s/w_a} \longrightarrow \begin{cases} A_{f0} = -(1-\beta)A_0/(1+\beta A_0) \\ w_a = w_1\times(1+\beta A_0) \end{cases}$$

(2) For βA_0 »1 → $A_{f0} \approx -\frac{1-\beta}{\beta} = -\frac{R_2}{R_1}$

(3) $GBP = A_{f0}w_a = (1-\beta)A_0w_1$ is not constant

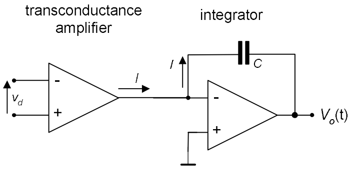
Slew-rate

(1) The output voltage can't change more fast than the slew-rate, *SR*

(2) The slew-rate is defined as

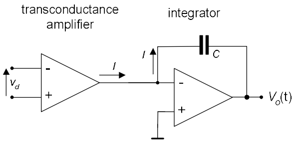
$$SR = \left|\frac{dv_o}{dt}\right|_{max}$$

(3) Internally, a typical OpAmp can be seen as:



Slew-rate

(1) *C* is for internal compensation (dom. pole)



(2) The current *i* is such that

$$i = -C\frac{dv_o}{dt}$$

(3) Therefore

$$SR = \left|\frac{dv_o}{dt}\right|_{max} = \frac{I_{max}}{C}$$

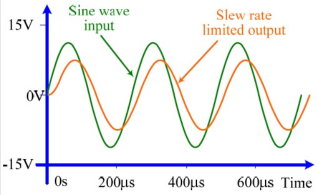
Slew-rate

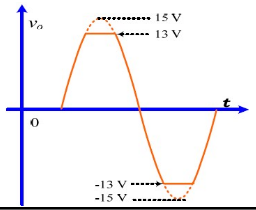
(1) For $v_o(t)=V_{om}cos(wt)$ $\left|\frac{dv_o}{dt}\right|_{max} = v_{om}w < SR$

(2) This means that $w_M = SR/|v_o|_{max}$

(3) w_M is the full power frequency

(4) The *SR* is a not-linear phenomena





Selected bibliography

Tack för er uppmärksamhet

Jag är öppen för frågor