

TEMA 5: AMPLIFICADOR OPERACIONAL Y CIRCUITOS DE APLICACIÓN

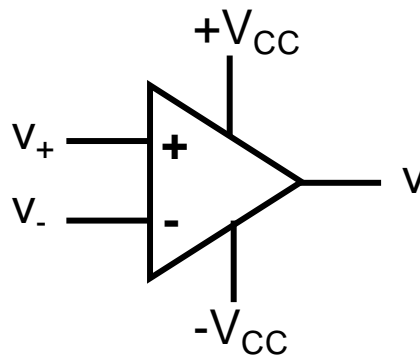
ÍNDICE

- El amplificador operacional ideal (repaso)
- El amplificador operacional real
 - Etapas
 - Errores de continua (V_{iO} , I_B , I_{iO})
 - Características a frecuencias medias (R_i , A_{vd} , R_o , CMRR)
 - Producto Ganancia x Ancho de Banda (GxBW)
 - Slew Rate (SR)
- Aplicaciones lineales de AO (repaso)
- Filtros activos como aplicación lineal de AO
- Aplicaciones no lineales de AO

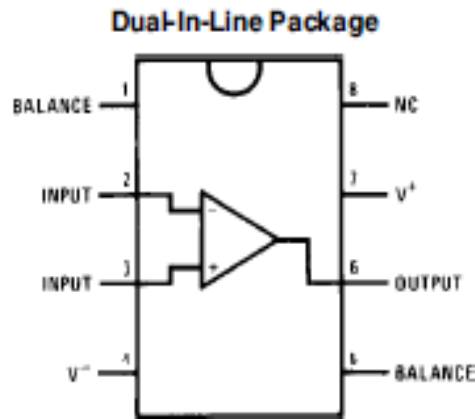
EL AMPLIFICADOR OPERACIONAL IDEAL

AO: Amplificador de tensión integrado con entrada diferencial

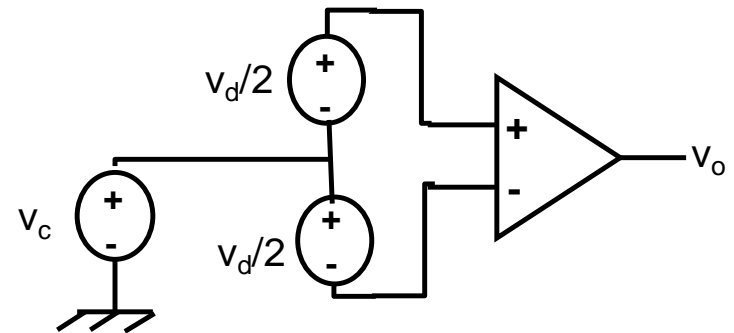
Símbolo



Encapsulado
(DIP8)



Ganancia:
 Modo común y modo
 diferencial



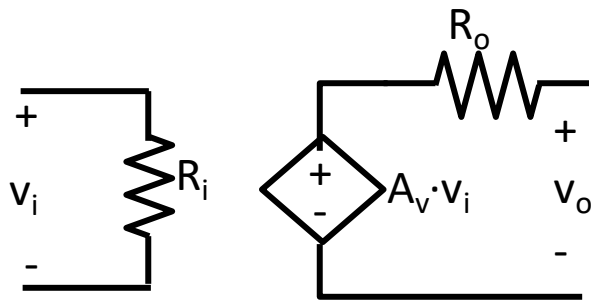
$$v_o = A_{vd} \cdot v_d + A_{vc} \cdot v_c$$

$$\Rightarrow v_o = A_{vd} \cdot (v_+ - v_-) + A_{vc} \cdot \left(\frac{v_+ + v_-}{2} \right)$$

Amplificador operacional ideal

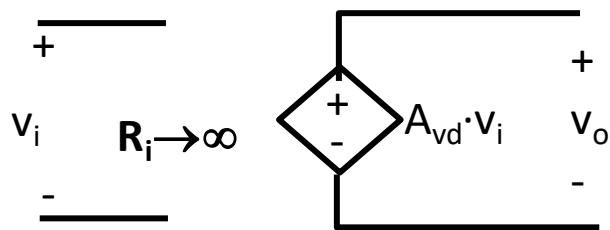
Respuesta a
 frecuencias medias

Amplificador de tensión



AO IDEAL

$R_o = 0$



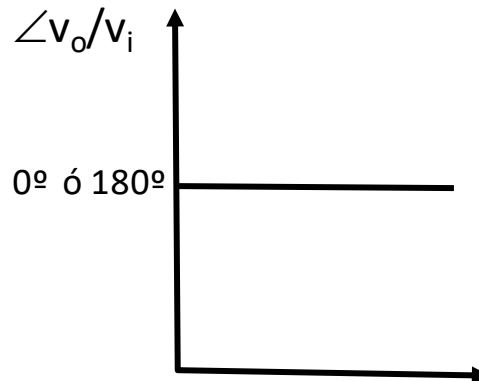
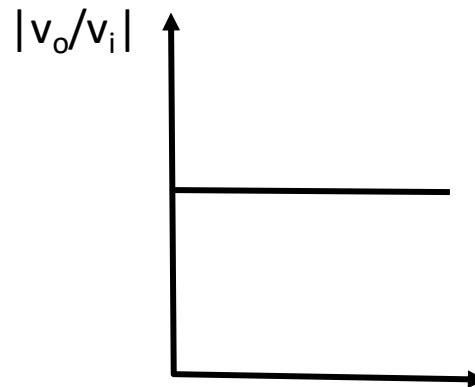
$A_{vd} \rightarrow \infty$

$A_{vc} = 0$

$CMRR = 20 \cdot \log (A_{vd}/A_{vc}) \rightarrow \infty$

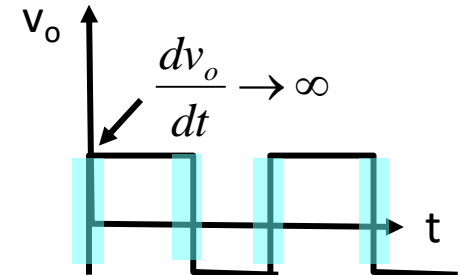
Respuesta en
 frecuencia

$BW \rightarrow \infty$



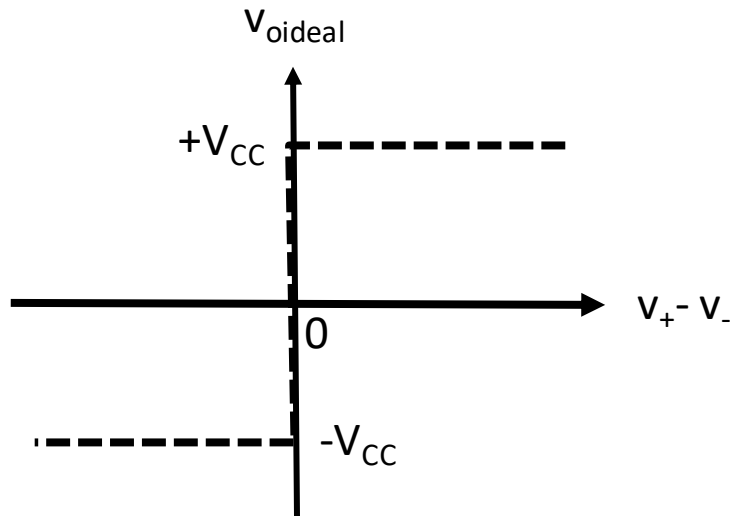
Velocidad de
 respuesta

$$\left. \frac{dv_o}{dt} \right|_{\max} \rightarrow \infty$$



Amplificador operacional ideal

Función de transferencia



Resumen Características

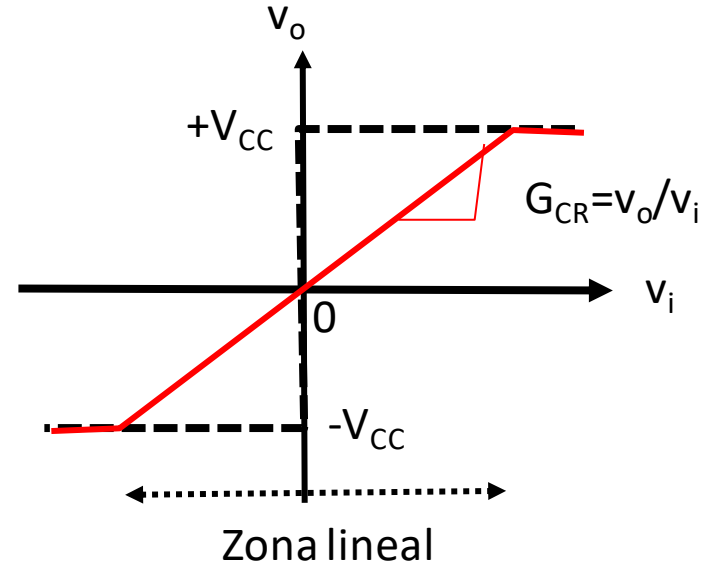
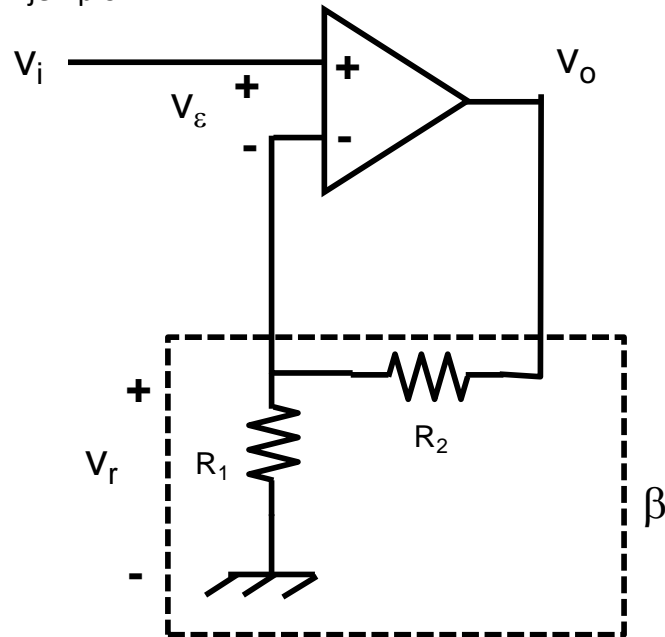
Parámetro	AO ideal	AO real
Ri	∞ ($\Rightarrow i_+ = i_- = 0$)	0.1-5M Ω (par BJT) >10 ¹⁰ (par FET)
Ro	0	20-200 Ω
Avd	∞	10 ⁵ -10 ⁶ V/V
CMRR	∞	80-120dB
BW	∞	1-10MHz (BW ganancia unidad)
$(dv_o/dt)_{max}$	∞	1V/ μ s-30V/ μ s
$(V_+ - V_-)_{DC}$	0	$V_{io} \approx 1-5mV$ (BJT), 20mV (FET)
$I_{+DC}, I_{-DC}, (I_+ - I_-)_{DC}$	0	$I_B \approx nA$ (BJT), μA (FET) $I_{io} \approx 5-10\% I_B$

Amplificador operacional ideal: aplicaciones

Lineales

AO con realimentación
 negativa

Ejemplo:



$$G_{CR} = \frac{v_o}{v_i} = \frac{A}{1 + A \cdot \beta} \left. \vphantom{G_{CR}} \right\} \Rightarrow \frac{v_o}{v_i} \cong \frac{1}{\beta} = \frac{v_o}{v_r} \Rightarrow v_\varepsilon \cong 0 \Rightarrow v_+ = v_-$$

$A \cdot \beta \gg 1$

Principio de cortocircuito virtual

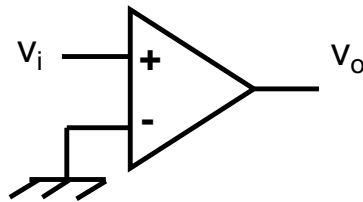
Amplificador operacional ideal: aplicaciones

No Lineales

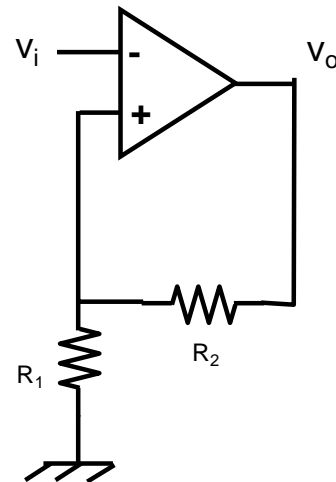
Ej: Comparador

- AO sin realimentar
- AO con realimentación positiva

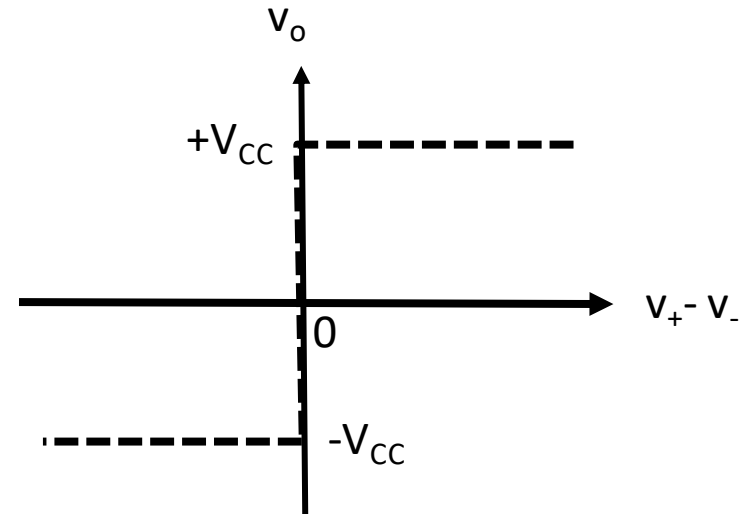
Ejemplo1:



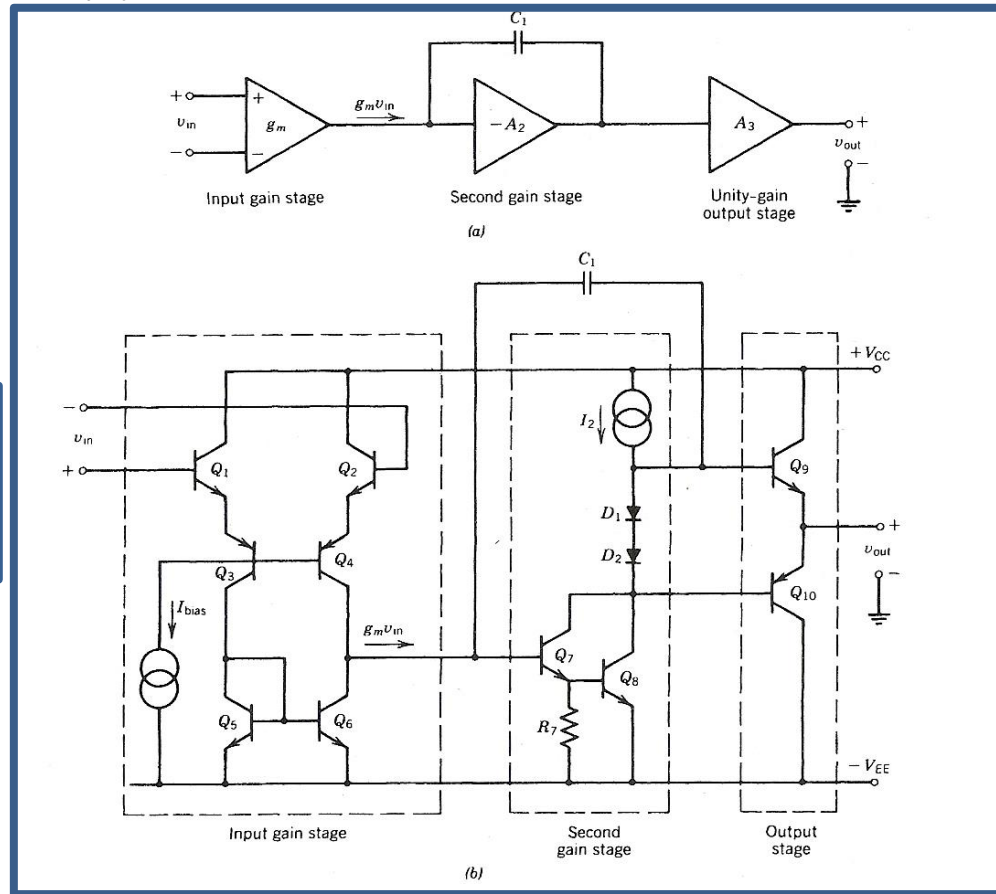
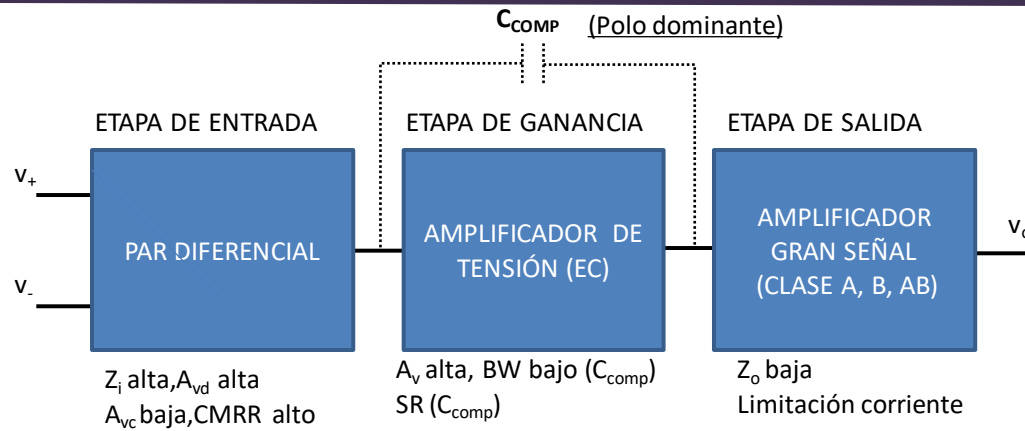
Ejemplo2:



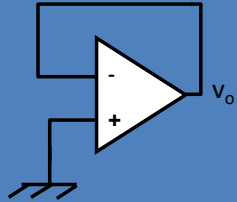
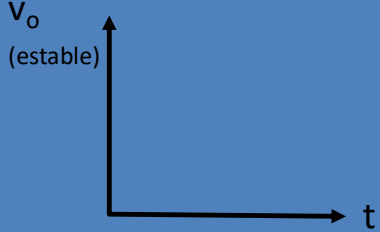
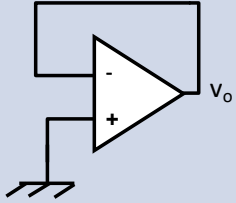
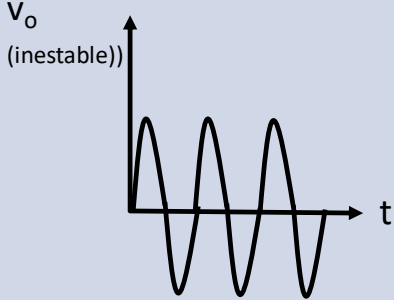
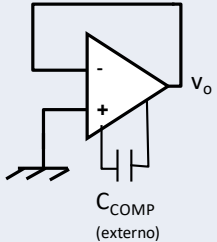
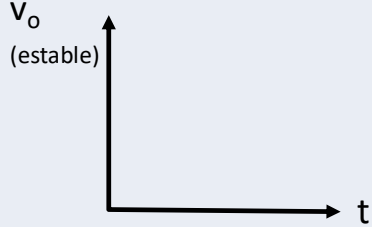
$$v_o \cong \begin{cases} +V_{CC} & v_+ > v_- \\ -V_{CC} & v_+ < v_- \end{cases}$$



ETAPAS DE UN AMPLIFICADOR OPERACIONAL REAL



Esquema interno simplificado

<p>CON COMPENSACIÓN INTERNA (Polo dominante en etapa de ganancia)</p>	<p>-BW bajo - Estabilidad</p> <p>-741, TL081, -LM324</p>		
<p>SIN COMPENSACIÓN INTERNA</p>	<p>-BW ALTO - Inestabilidad</p> <p>-LM301</p>		
			

AMPLIFICADOR OPERACIONAL REAL: ERRORES DE CONTINUA

ERRORES DE CONTINUA (V_{io} , I_B , I_{io})

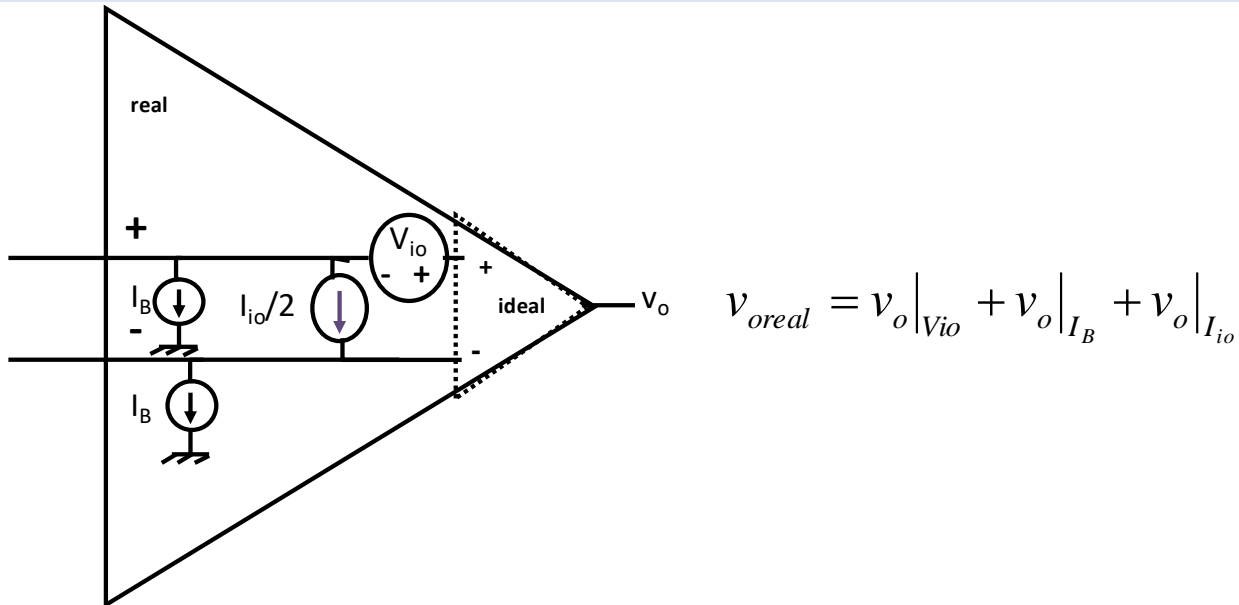
Par diferencial etapa de entrada (Q_1, Q_2):

- TENSIÓN DE OFFSET DE ENTRADA (V_{io})
$$\left. \begin{matrix} V_{BEQ_1} \neq V_{BEQ_2} \\ V_{EQ_1} = V_{EQ_2} \end{matrix} \right\} V_{BQ_1} \neq V_{BQ_2} \Rightarrow (V_+ - V_-)_{DC} = V_{io} (mV)$$

- CORRIENTE DE POLARIZACIÓN DE ENTRADA (I_B) Y CORRIENTE DE OFFSET (I_{io})

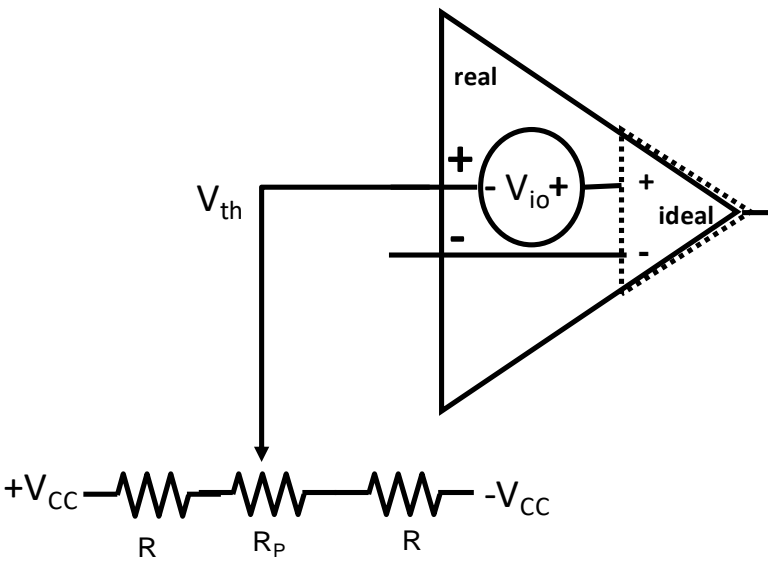
$$\left. \begin{matrix} I_{-DC} \neq 0(I_{BaseQ_1}) \\ I_{+DC} \neq 0(I_{BaseQ_2}) \end{matrix} \right\} I_{BIAS} = I_B (nA, pA)$$

$$+ \quad Q_1 \neq Q_2 \Rightarrow I_{+DC} - I_{-DC} = I_{OFFSET} = I_{io} (nA, pA)$$



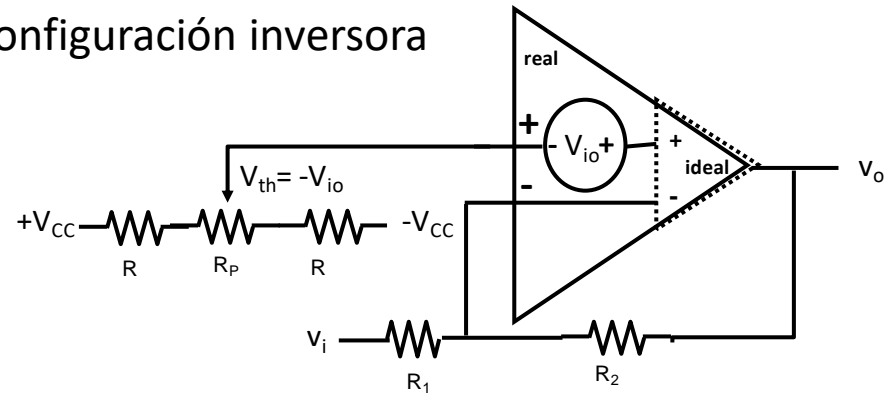
TENSIÓN DE OFFSET DE ENTRADA (V_{io})

COMPENSACIÓN EXTERNA : Eliminación del efecto de V_{io} a la salida del operacional

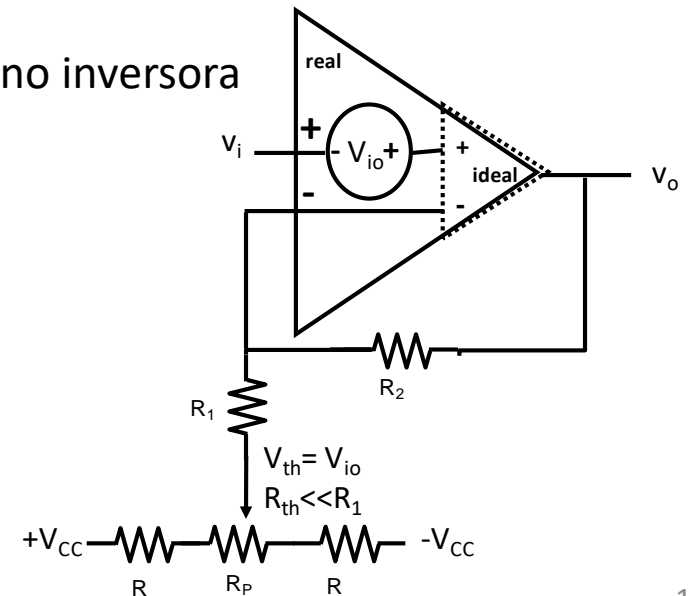


Procedimiento: Ajustar
 potenciómetro hasta
 tener $V_{th} = \pm V_{io}$

Configuración inversora



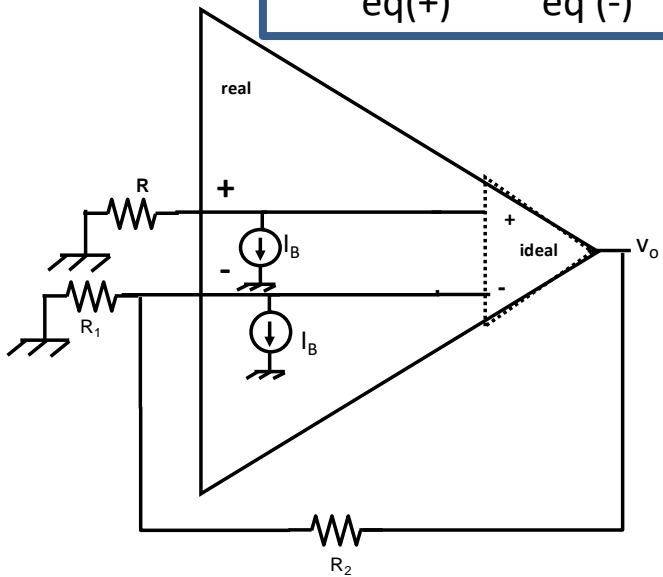
Configuración no inversora



CORRIENTES DE POLARIZACIÓN DE ENTRADA (I_B) Y CORRIENTE DE OFFSET DE ENTRADA (I_{io})

COMPENSACIÓN:
 Eliminación del efecto de I_B a la salida del operacional

$$R_{eq(+)} = R_{eq(-)}$$

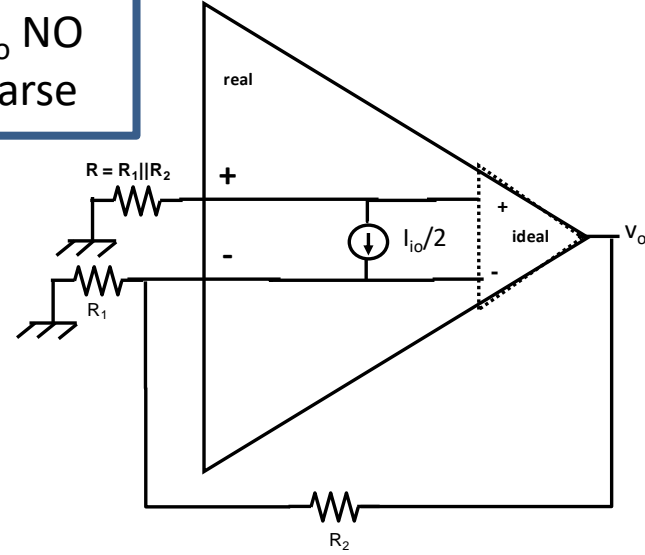


$$v_o = R_2 \cdot I_B - R \cdot I_B \cdot \left(1 + \frac{R_2}{R_1}\right) = 0$$

$$\Rightarrow R_2 - \frac{R(R_1 + R_2)}{R_1} = 0 \Rightarrow R = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

Disminución del efecto de I_{io} a la salida del operacional

El efecto de I_{io} NO puede eliminarse



$$\left. \begin{aligned} v_+ &= -R \frac{I_{io}}{2} \\ \frac{v_o - v_-}{R_2} - \frac{I_{io}}{2} &= \frac{v_-}{R_1} \end{aligned} \right\} \Rightarrow \frac{v_o}{R_2} - \frac{I_{io}}{2} \cdot \left(\frac{R}{R_2} + \frac{R}{R_1} + 1 \right) = 0$$

$$\Rightarrow v_o = R_2 \cdot I_{io}$$

ERRORES DE CONTINUA (V_{io} , I_B , I_{io})

LM741

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	$T_A = 25^\circ\text{C}$ $R_B \leq 10\text{ k}\Omega$ $R_B \leq 50\Omega$		0.8	3.0		1.0	5.0		2.0	6.0	mV mV
	$T_{AMIN} \leq T_A \leq T_{AMAX}$ $R_B \leq 50\Omega$ $R_B \leq 10\text{ k}\Omega$			4.0			6.0			7.5	mV mV
Average Input Offset Voltage Drift				15							$\mu\text{V}/^\circ\text{C}$
Input Offset Voltage Adjustment Range	$T_A = 25^\circ\text{C}$, $V_B = \pm 20\text{V}$	± 10				± 15			± 15		mV
Input Offset Current	$T_A = 25^\circ\text{C}$		3.0	30		20	200		20	200	nA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			70		85	500			300	nA
Average Input Offset Current Drift				0.5							$\text{nA}/^\circ\text{C}$
Input Bias Current	$T_A = 25^\circ\text{C}$		30	80		80	500		80	500	nA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			0.210			1.5			0.8	μA

TL081

Symbol	Parameter	Conditions	TL081C			Units
			Min	Typ	Max	
V_{OS}	Input Offset Voltage	$R_S = 10\text{ k}\Omega$, $T_A = 25^\circ\text{C}$ Over Temperature		5	15 20	mV mV
$\Delta V_{OS}/\Delta T$	Average TC of Input Offset Voltage	$R_S = 10\text{ k}\Omega$		10		$\mu\text{V}/^\circ\text{C}$
I_{OS}	Input Offset Current	$T_j = 25^\circ\text{C}$, (Notes 3, 4) $T_j \leq 70^\circ\text{C}$		25	100 4	pA nA
I_B	Input Bias Current	$T_j = 25^\circ\text{C}$, (Notes 3, 4) $T_j \leq 70^\circ\text{C}$		50	200 8	pA nA

LM301
 ($C_1 = 30\text{pF}$)

Symbol	Parameter	LM101A - LM201A			LM301A			Unit
		Min.	Typ.	Max.	Min.	Typ.	Max.	
V_{io}	Input Offset Voltage ($R_S \leq 10\text{k}\Omega$) $T_{amb} = +25^\circ\text{C}$ $T_{min.} \leq T_{amb} \leq T_{max.}$		0.7	2 3		2	7.5 10	mV
DV_{io}	Input Offset Voltage Drift $T_{min.} \leq T_{amb} \leq T_{max.}$		3	15		6	30	$\mu\text{V}/^\circ\text{C}$
I_b	Input Bias Current $T_{amb} = +25^\circ\text{C}$ $T_{min.} \leq T_{amb} \leq T_{max.}$		25	75 100		70	250 300	nA
I_{io}	Input Offset Current $T_{amb} = +25^\circ\text{C}$ $T_{min.} \leq T_{amb} \leq T_{max.}$		1.5	10 20		2	50 70	nA
DI_{io}	Input Offset Current Drift $25^\circ\text{C} \leq T_{amb} \leq T_{max.}$ $T_{min.} \leq T_{amb} \leq T_{max.}$		10 20	100 200		10 20	300 600	$\text{pA}/^\circ\text{C}$

AMPLIFICADOR OPERACIONAL REAL: RESISTENCIAS DE ENTRADA Y SALIDA, GANANCIA DIFERENCIAL Y CMRR

R_i , R_o , A_{vd} , CMRR

LM741

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Resistance	$T_A = 25^\circ\text{C}$, $V_S = \pm 20\text{V}$	1.0	6.0		0.3	2.0		0.3	2.0		M Ω
	$T_{AMIN} \leq T_A \leq T_{AMAX}$, $V_S = \pm 20\text{V}$	0.5									M Ω
Large Signal Voltage Gain	$T_A = 25^\circ\text{C}$, $R_L \geq 2\text{ k}\Omega$ $V_S = \pm 20\text{V}$, $V_O = \pm 15\text{V}$ $V_S = \pm 15\text{V}$, $V_O = \pm 10\text{V}$	50									V/mV V/mV
	$T_{AMIN} \leq T_A \leq T_{AMAX}$, $R_L \geq 2\text{ k}\Omega$, $V_S = \pm 20\text{V}$, $V_O = \pm 15\text{V}$ $V_S = \pm 15\text{V}$, $V_O = \pm 10\text{V}$	32			25			15			V/mV V/mV
	$V_S = \pm 15\text{V}$, $V_O = \pm 10\text{V}$	10									V/mV
	$V_S = \pm 5\text{V}$, $V_O = \pm 2\text{V}$										
Common-Mode Rejection Ratio	$T_{AMIN} \leq T_A \leq T_{AMAX}$ $R_S \leq 10\text{ k}\Omega$, $V_{CM} = \pm 12\text{V}$				70	90		70	90		dB
	$R_S \leq 50\Omega$, $V_{CM} = \pm 12\text{V}$	80	95								dB
r_o	Output resistance				$V_O = 0$,	See Note 5		75			Ω

TL081

Symbol	Parameter	Conditions	TL081C			Units
			Min	Typ	Max	
R_{IN}	Input Resistance	$T_J = 25^\circ\text{C}$		10 ¹²		Ω
A_{VOL}	Large Signal Voltage Gain	$V_S = \pm 15\text{V}$, $T_A = 25^\circ\text{C}$ $V_O = \pm 10\text{V}$, $R_L = 2\text{ k}\Omega$	25	100		V/mV
		Over Temperature	15			V/mV
CMRR	Common-Mode Rejection Ratio	$R_S \leq 10\text{ k}\Omega$	70	100		dB

LM301
 ($C_1 = 30\text{pF}$)

Symbol	Parameter	LM101A - LM201A			LM301A			Unit
		Min.	Typ.	Max.	Min.	Typ.	Max.	
A_{vd}	Large Signal Voltage Gain * ($V_O \leq 10\text{V}$, $R_L = 2\text{k}\Omega$) $T_{amb} = +25^\circ\text{C}$ $T_{min.} \leq T_{amb} \leq T_{max.}$	50 25	100		25 15	100		V/mV
CMR	Common-mode Rejection Ratio ($R_S \leq 10\text{k}\Omega$) $T_{amb} = +25^\circ\text{C}$ $T_{min.} \leq T_{amb} \leq T_{max.}$	80 80	96		70 70	96		dB
Z_i	Input Impedance *		1.5	4		1.5	4	M Ω
R_o	Output Resistance *			75			75	Ω

R_i , R_o , A_{vd} , CMRR

Common-Mode Rejection Ratio

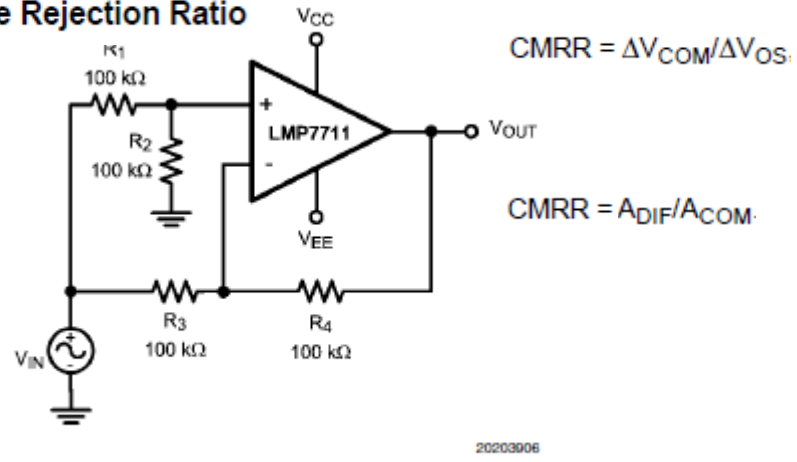


FIGURE 6. CMRR TEST CIRCUIT

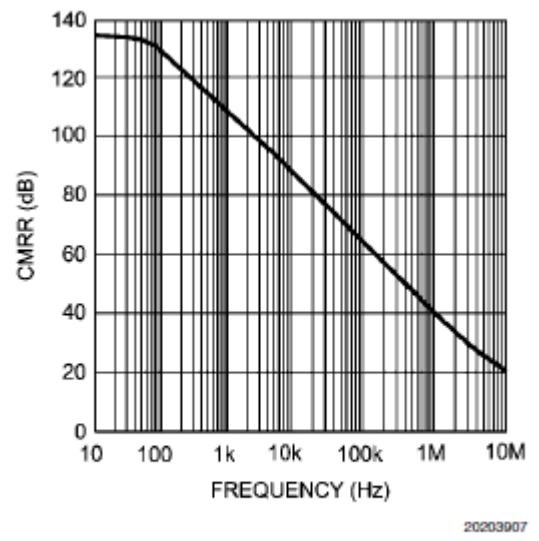


FIGURE 7. SIMULATED CMRR RESPONSE vs. FREQUENCY

Supply Voltage Rejection Ratio

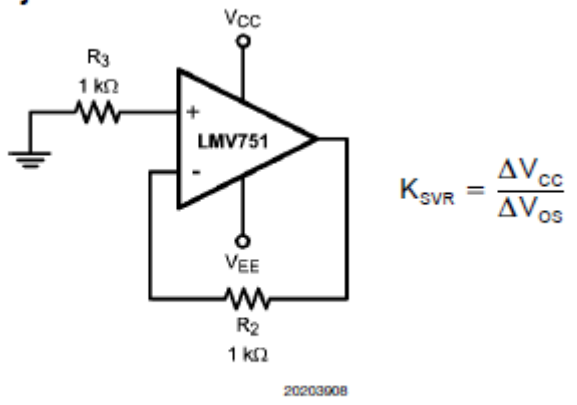


FIGURE 9. PSRR TEST CIRCUIT

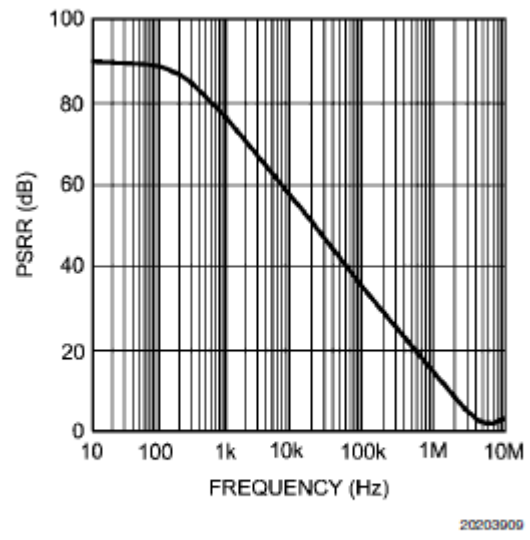


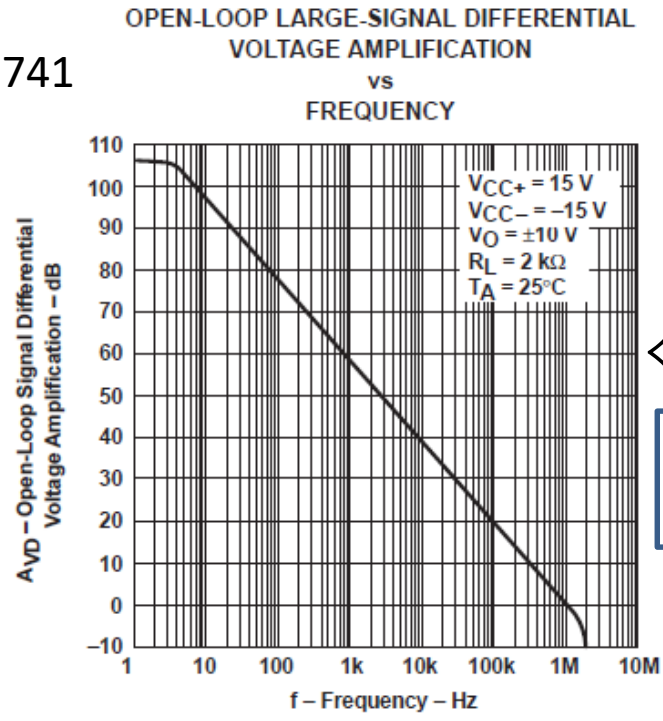
FIGURE 10. SIMULATED PSRR RESPONSE vs. FREQUENCY

AMPLIFICADOR OPERACIONAL REAL: PRODUCTO GANANCIA x ANCHO DE BANDA

Producto GxBW
 SIN REALIMENTAR

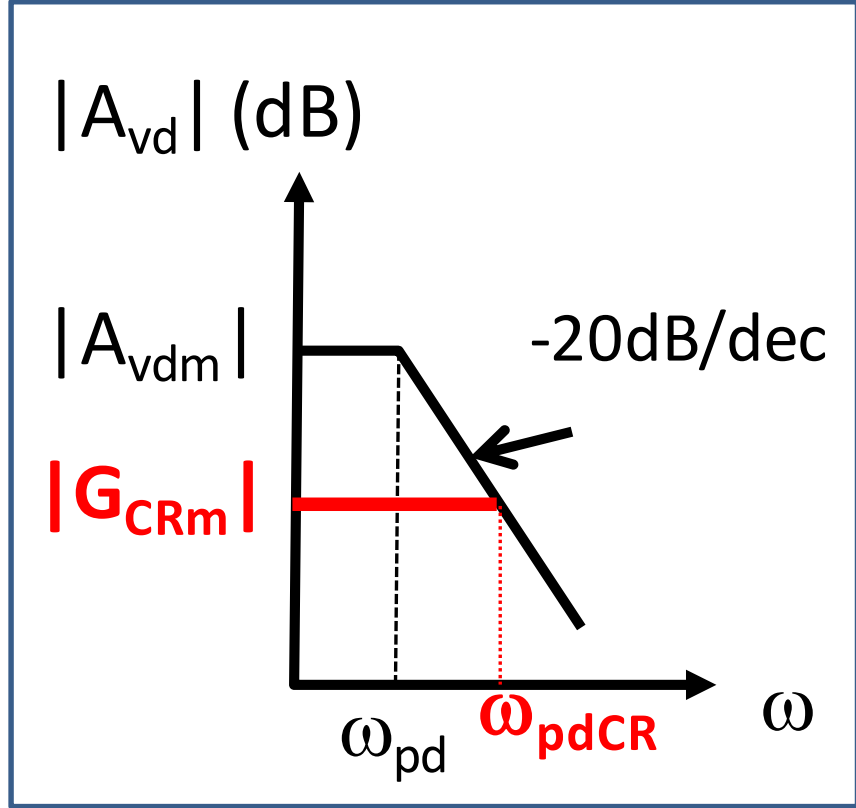
GxBW = cte = 1MHz (741)

Ej: 741



Sistema de primer orden (1 solo polo)

$$A(j\omega) = \frac{A_{vdm}}{1 + j\omega/\omega_{pd}}$$



CON REALIMENTACIÓN NEGATIVA

$$G_{CR}(j\omega) = \frac{A}{1 + A\beta} = \frac{\frac{A_{vdm}}{1 + j\omega/\omega_{pd}}}{1 + \left(\frac{A_{vdm}}{1 + j\omega/\omega_{pd}}\right) \cdot \beta} = \frac{\frac{A_{vdm}}{1 + A_{vdm} \cdot \beta}}{1 + j\omega/\omega_{pd} \cdot (1 + A_{vdm} \cdot \beta)}$$

G_{CRm} (for the numerator term) and ω_{pdCR} (for the denominator term) are indicated with red dashed boxes in the original image.

AMPLIFICADOR OPERACIONAL REAL: SLEW RATE

Slew Rate (SR)

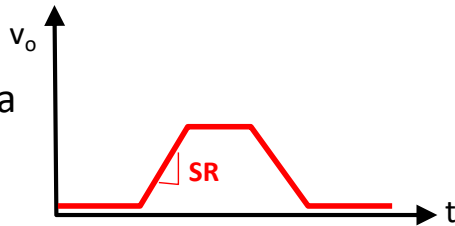
$$SR \left(\frac{V}{\mu s} \right) = \left. \frac{dv_o}{dt} \right|_{m\acute{a}x}$$

• Operación AO “Gran Señal”

• Máxima velocidad de respuesta

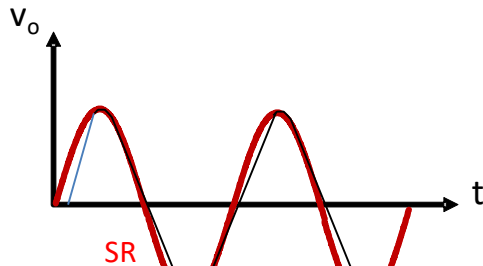
EFFECTO

• v_i cuadrada

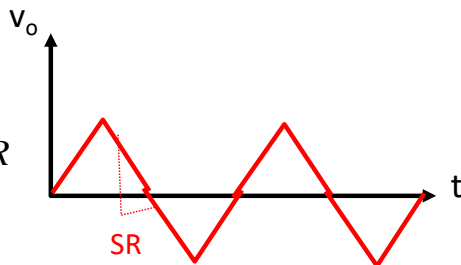


• v_i no cuadrada (ej. Sinusoidal)

si $\left. \frac{dv_o}{dt} \right|_{m\acute{a}x} < SR$

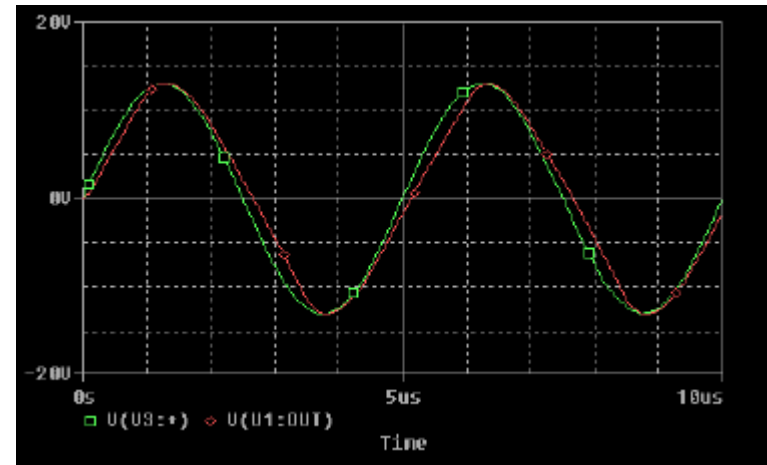


si $\left. \frac{dv_o}{dt} \right|_{m\acute{a}x} > SR$



si $\left. \frac{dv_o}{dt} \right|_{m\acute{a}x} \gg SR$

Simulación en PSpice



Slew Rate (SR)

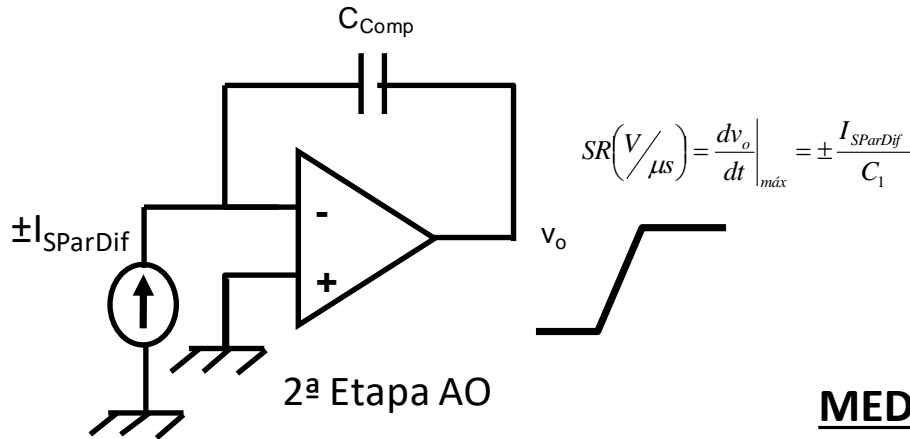
- Operación AO "Gran Señal"

- Máxima velocidad de respuesta

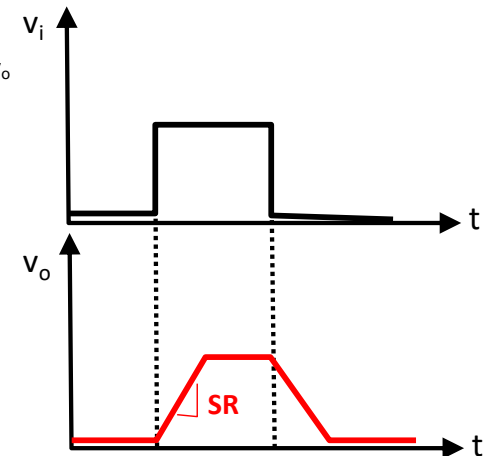
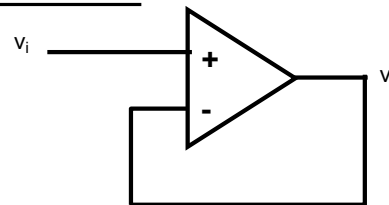
$$SR \left(\frac{V}{\mu s} \right) = \left. \frac{dv_o}{dt} \right|_{máx}$$

ORIGEN

Si $v_{iAO} \gg V_T \Rightarrow Q_1$ o Q_2 ParDif OFF



MEDIDA



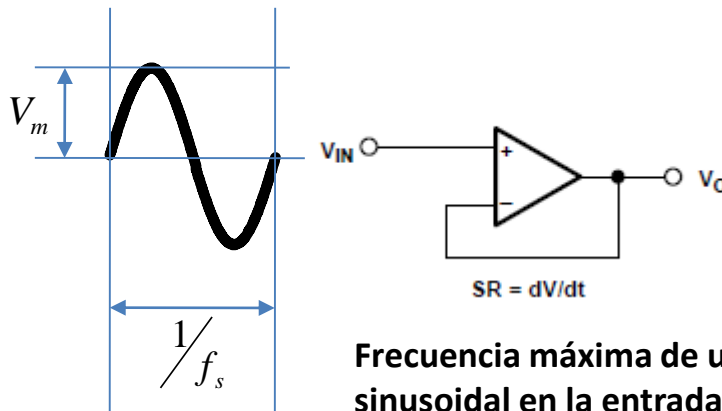
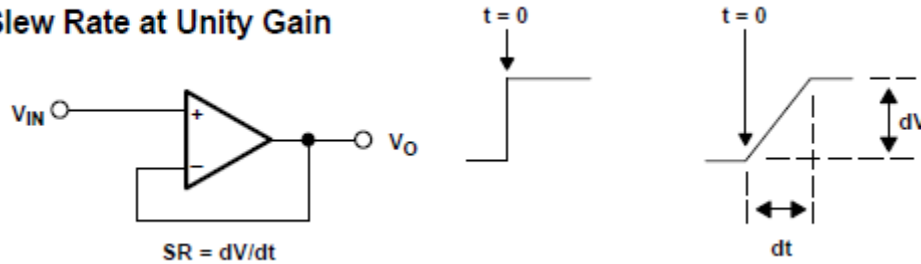
Slew Rate (SR)

- Operación AO "Gran Señal"

- Máxima velocidad de respuesta

$$SR \left(\frac{V}{\mu s} \right) = \left. \frac{dv_o}{dt} \right|_{\text{máx}}$$

Slew Rate at Unity Gain



Frecuencia máxima de una onda
sinusoidal en la entrada

$$f_{s(\text{max})} = \frac{SR}{2\pi \cdot V_m}$$