EE 230
Lecture 15

Nonideal Op Amp Characteristics

Nonideal op amp characteristics

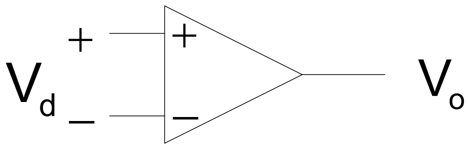
- Finite Gain
- Finite BW

GB

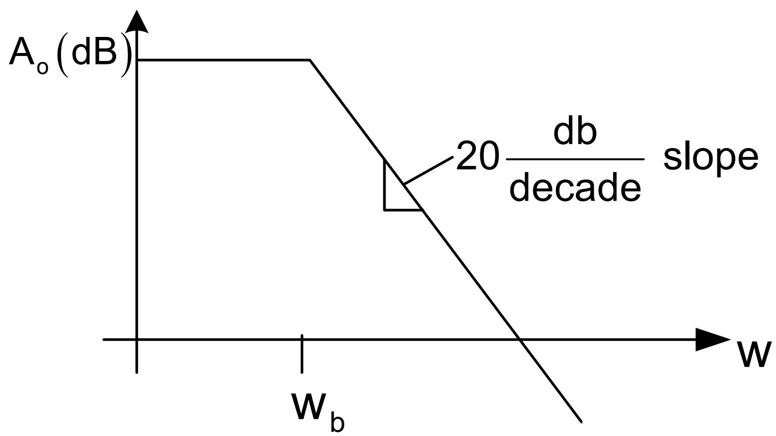
- Compensation
- Output Saturation
- Slew Rate
- R_{IN} & R_{OUT}
- Offset Voltage
- Bias Currents

- CMRR
- PSRR
- Offset Current
- Full Power Bandwidth

Finite GB and BW



For $\omega \gg \omega_b$, $A(s) \simeq \dfrac{A_o}{\dfrac{s}{\omega_b}} = \dfrac{A_o \omega_b}{s}$



$$\left|A(j\omega)\right| = \frac{A_o \omega_b}{\omega}$$

$A_o \omega_b = GB$

GB termed Gain-Bandwidth Product

$$A(s) = \frac{V_o(s)}{V_d(s)} = \frac{A_o}{\dfrac{s}{\omega_b} + 1}$$

$\omega_b \sim$ BW of OA

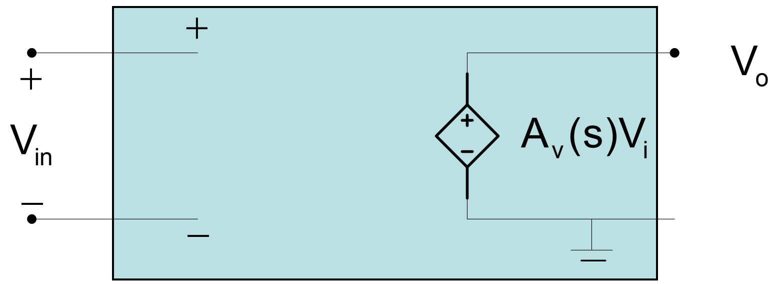
$$\left|A(j\omega)\right| = \frac{A_o}{\sqrt{\left(\dfrac{\omega}{\omega_b}\right)^2 + 1}}$$

$$A(s) = \frac{GB}{s} \quad \Longleftrightarrow \quad A(s) = \frac{A_o}{\dfrac{s}{\omega_b} + 1}$$

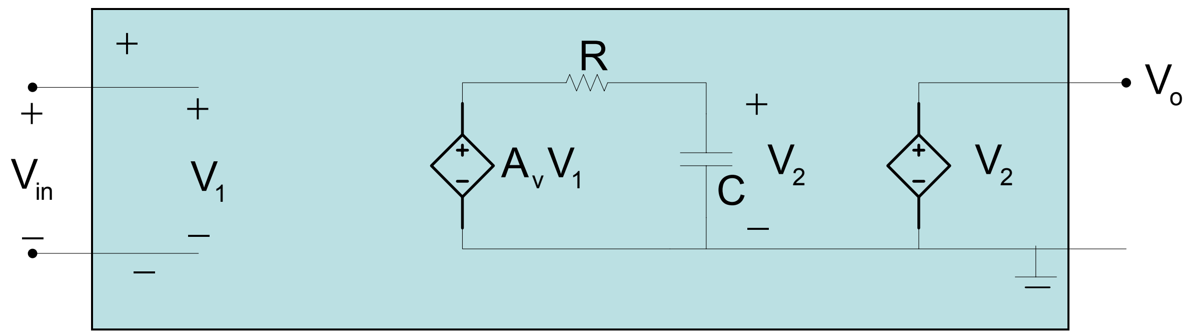
Macromodel

- Equivalent circuit that mimics the behavior of an actual circuit
- Not necessarily (usually no) relationship between elements in macromodel and the circuit of interest

Macromodel of op amp that includes effects of frequency dependent gain



$$A_v(s) = \frac{A_o}{\frac{s}{\omega_b} + 1}$$



$$V_o = A_o V_i \left(\frac{\frac{1}{sC}}{R + \frac{1}{sC}} \right) = V_i \left[\frac{A_o}{1 + RCs} \right]$$

If C=1F

$$R = \frac{1}{\omega_b}$$

$$\frac{V_o}{V_i} = \frac{A_o}{1 + \frac{s}{\omega_b}}$$

Measurement of GB

Most direct: measure A_o $\Rightarrow$ $GB = A_o w_b$

measure ω_b

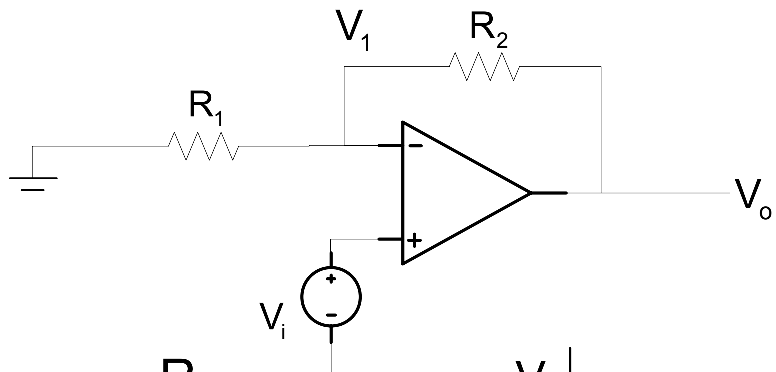
A_o is difficult to measure

ω_b is difficult to measure

Direct method of determining GB is not practical

If a circuit is adversely affected be a parameter, then this circuit is often useful for measuring that parameter provided relationship between performance and parameter is determined/known.

Noninverting Finite Gain Amplifier



$$K_o = 1 + \frac{R_2}{R_1} \qquad \left.\frac{V_o}{V_i}\right|_{A_o=\infty} = K_o$$

If not ideal:

$$\left.\begin{aligned} V_1 &= \frac{R_1}{R_1+R_2}V_o \\ V_o &= A(s)(V_i - V_1) \end{aligned}\right\} \frac{V_o(s)}{V_i(s)} = \frac{K_o}{1+\dfrac{K_o}{A(s)}}$$

$$A(s) = \frac{A_o}{\dfrac{s}{w_b}+1}$$

$$A_{FB}(s) = \frac{K_o}{1+\dfrac{K_o\left(\dfrac{s}{w_b}+1\right)}{A_o}} = \frac{K_oA_o}{A_o + K_o + \dfrac{sK_o}{w_b}}$$

but since $A_o \gg K_o$

$$A_{FB}(s) \simeq \frac{A_oK_o}{A_o + s\dfrac{K_o}{w_b}} = \frac{A_ow_bK_o}{A_ow_b + sK_o} = \frac{K_oGB}{sK_o + GB}$$

$$BW = \frac{GB}{K_0}$$

$$\boxed{K_0 \bullet BW = GB}$$

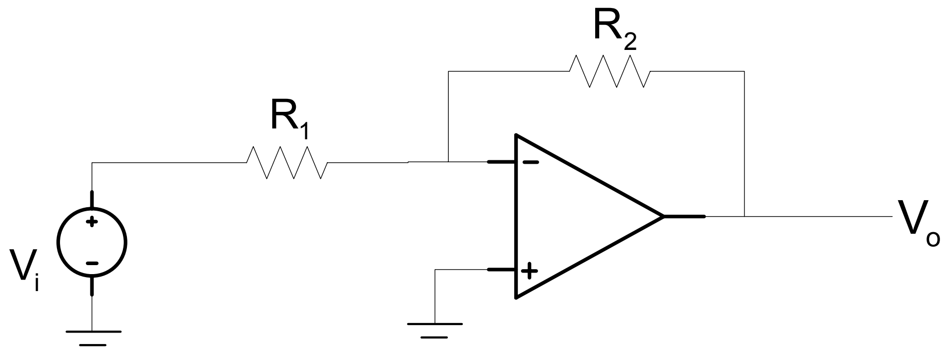
Example: If an op amp has a GB of 1MHz and a dc gain of a closed loop amplifier of 10, what is the BW of the closed loop amplifier?

Solution: $Bw = \frac{GB}{K_o} = \frac{1MHz}{10} = 100kHz$

Example: Determine the maximun dc gain of a noninverting FB amplifier if designed with an OA with GB=1MHz, if the closed loop BW must be greater than 20 kHz.

Solution: $K_0BW = GB \Rightarrow K_o = \frac{GB}{BW} = \frac{1\,MHz}{20kHz} = 50$

Inverting Amplifier



$$K_o = \frac{R_2}{R_1}$$ $\therefore$ ideal dc gain is $-K_o$

Effects of GB of OA on closed loop amplifier

$$A_{fb}(s) = \frac{-K_o}{1 + \frac{1+K_o}{A(s)}}$$

$$A_{FB}(s) \simeq \frac{-K_o}{1 + s\frac{1+K_o}{GB}}$$

$$A(s) \simeq \frac{GB}{s}$$

$$BW_{CL} = \frac{GB}{1+K_o}$$

$$\boxed{(1+K_o)BW = GB}$$

How do bandwidths compare for inverting and noninverting amplifiers?

$$\text{Inverting: BW} = \frac{\text{GB}}{1+K_o}$$

$$\text{Noninverting: BW} = \frac{\text{GB}}{K_o}$$

If $K_o = 1$ $\qquad BW_{INV} = \frac{1}{2} BW_{NONINV}$

K_o is large, $BW_{INV} \simeq BW_{NONINV}$

Strategy for Measuring GB

1. Build FB noninverting amplifier with gain K_o
2. Measure BW
3. $GB=(K_0)(BW)$

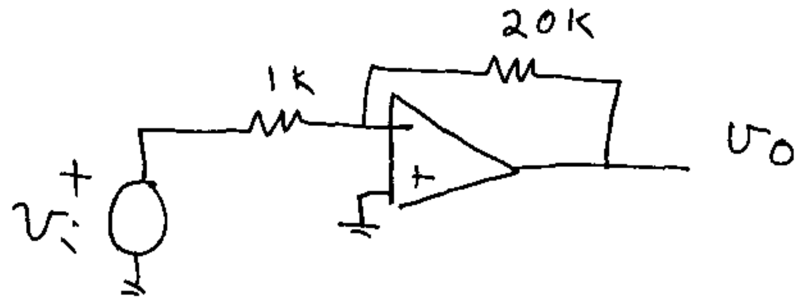
Review: Noninverting Amplifier

$$(BW)(K_o) = GB$$

Inverting Amplifier

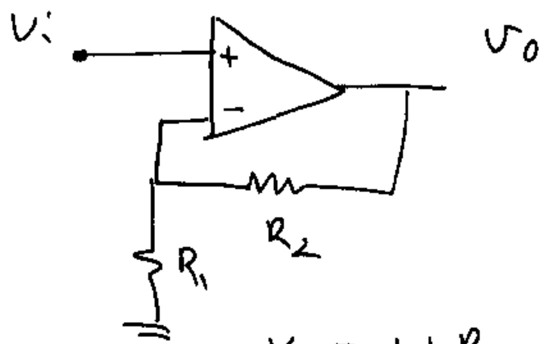
$$(BW)(1+K_o) = GB$$

Example: Determine the 3dB bandwidth of the amplifier shown if GB = 500KHz.



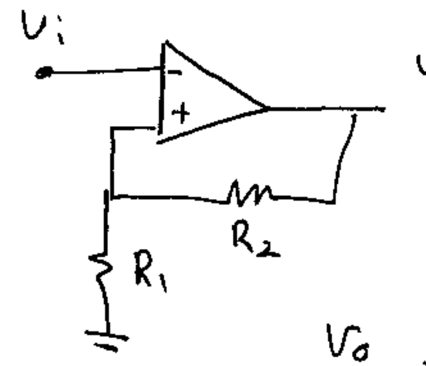
$$BW = \frac{500KHz}{1+20} = \frac{500KHz}{21}$$

Compensation provided the 1st-order roll-off characteristic



$$K_o = 1 + \frac{R_2}{R_1}$$

Good Circuit!



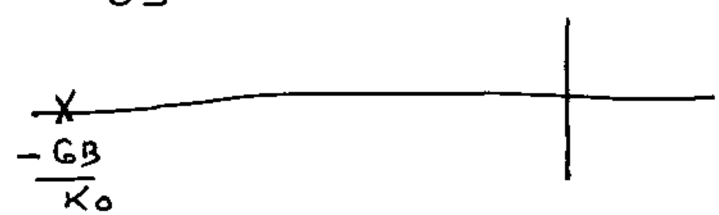
$$\frac{V_o}{V_i} \overset{\text{ideal}}{\underset{\text{op amp}}{=}} 1 + \frac{R_2}{R_1}$$

Not a good amplifier

Recall: A system is stable iff all poles lie in the LHP

Consider First Circuit

$$A_{FB}(s) = \frac{K_o}{1 + \frac{K_o}{A(s)}} = \frac{K_o}{1 + s\frac{K_o}{GB}} \Longrightarrow \text{pole at } s = -\frac{GB}{K_o}$$



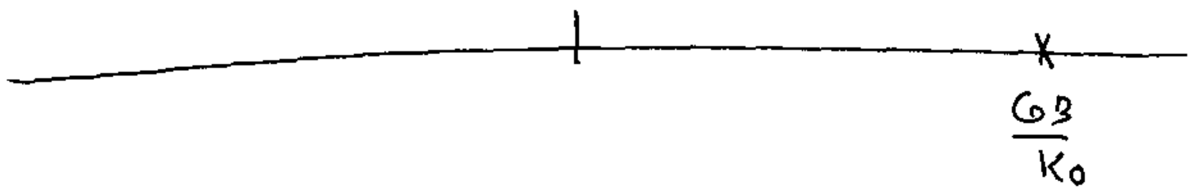
∴ This amplifier is stable

Consider Second Circuit

$$A_{FB}(s) = \frac{K_o}{1 + \frac{K_o}{-A(s)}} \overset{A(s)=\frac{GB}{s}}{=\!=} \frac{K_o}{1 + \frac{K_o}{-GB/s}}$$

$$= \frac{K_o}{1 - s\frac{K_o}{GB}}$$

pole at $s = +\frac{GB}{K_o}$



This "amplifier" is unstable

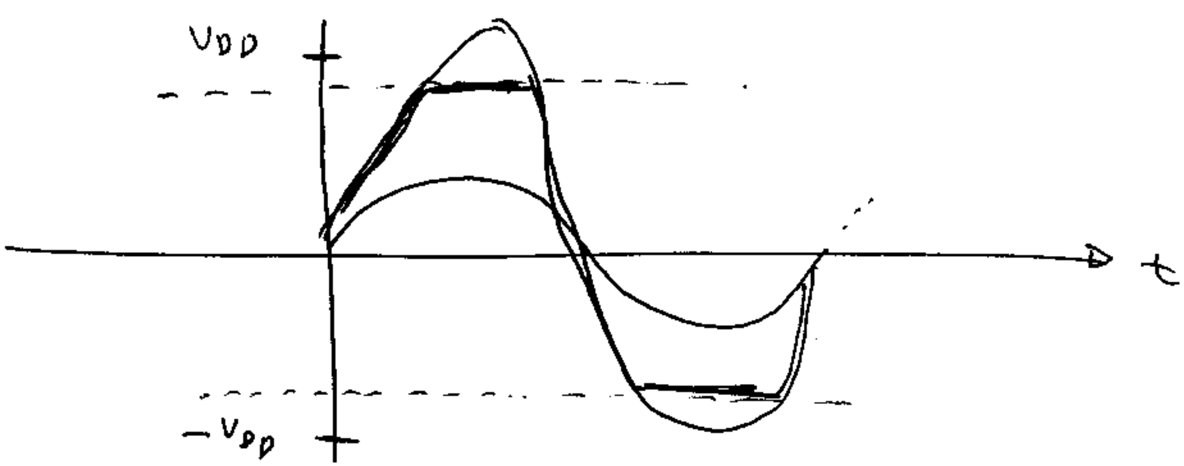
This circuit is not useful as an amplifier

Output Saturation

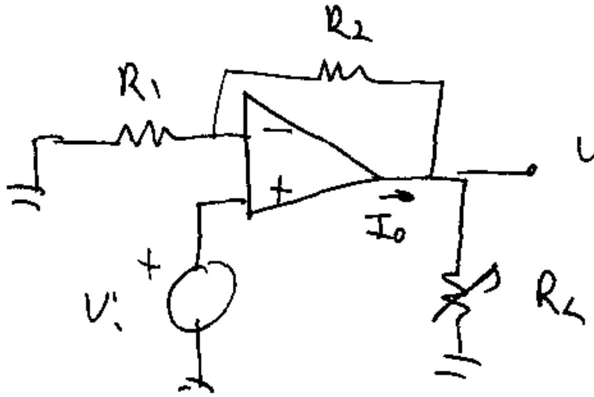
- Voltage Limit → Maximum or minimum output voltages an op amp can provide
- Current Limit → Maximum or minimum output currents an op amp can provide

Often $V_{Omax} \simeq V_{DD} - 1.2\,V$

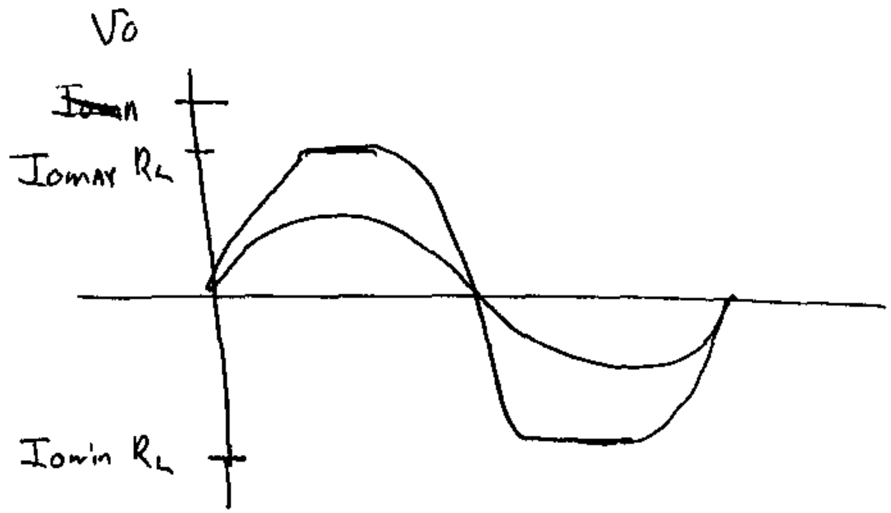
$V_{Omin} \simeq V_{SS} + 1.2\,V$



Nonlinear distortion is introduced



$$I_o = \frac{V_o - V_i}{R_2} + \frac{V_o}{R_L} \approx \frac{V_o}{R_L}$$

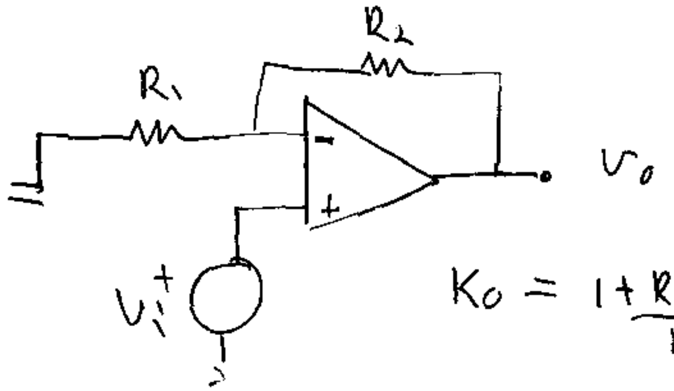


Output current saturation provides similar limits to what was seen with output voltage saturation

Usually tell difference between voltage & current saturation by looking at saturation voltage

Slew Rate

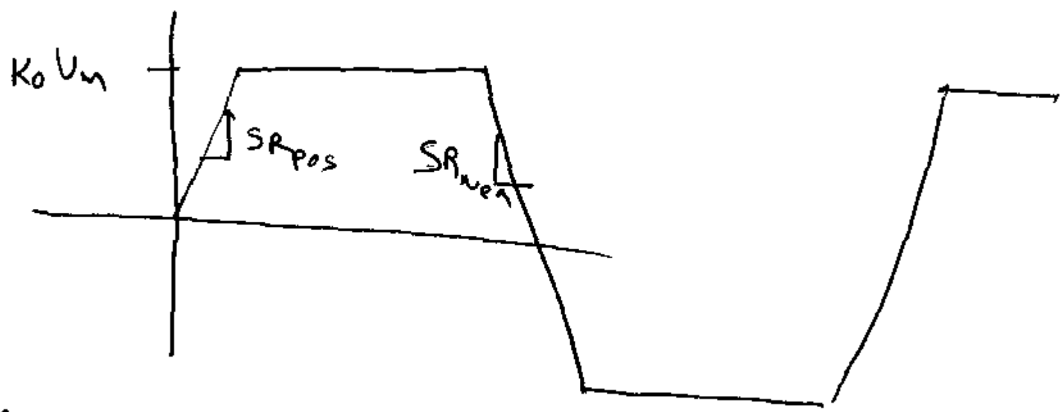
Maximum Rate of Change at Output of Op Amp.



$K_o = 1 + \frac{R_2}{R_1}$

If $V_i(t)$ is a square wave of hight V_m, $V_o(t)$ will ideally be a square wave of height $K_o V_m$

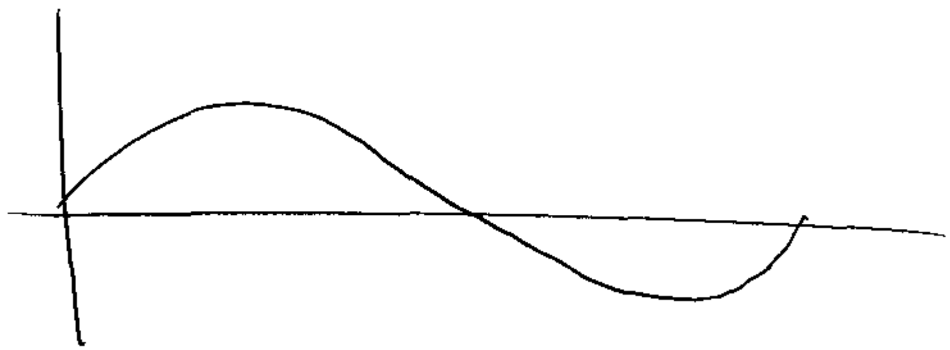
Actual Output.

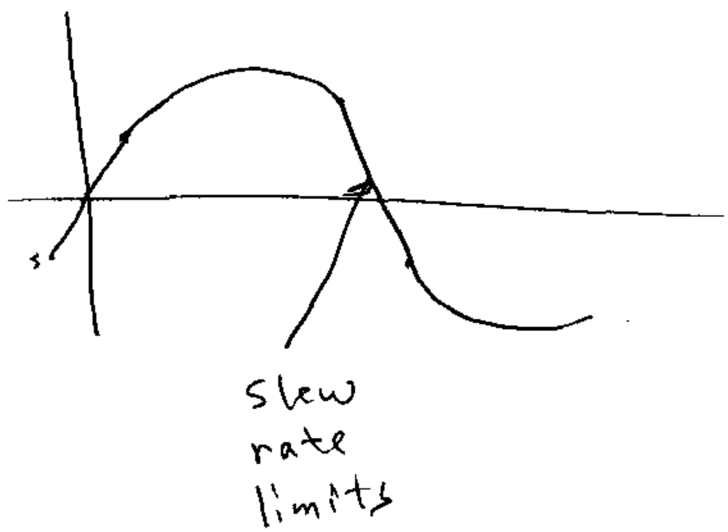


SR in V/μsec

1V/μsec to 100V/μsec

SR with sinusoidal signals





$$V_o = V_m \sin(\omega t + \theta)$$

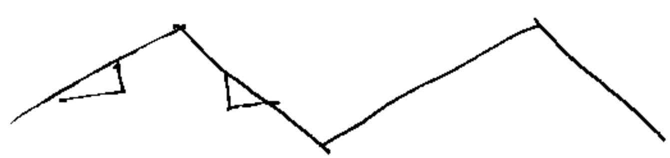
$$\frac{dV_o}{dt} = V_m \cos(\omega t + \theta)\,\omega < SR$$

To avoid slew distortion

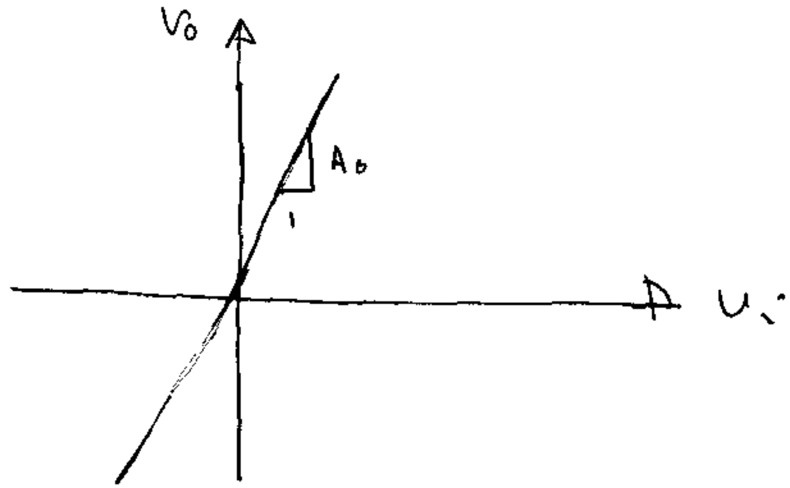
$$V_m \omega < SR$$

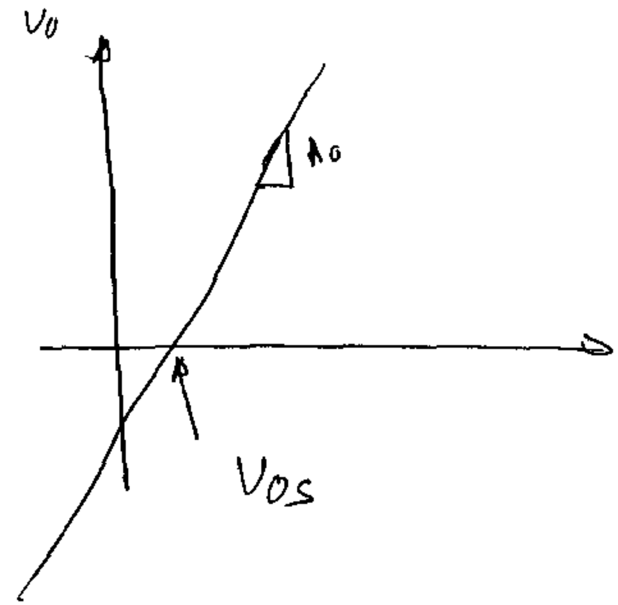
If $V_m \omega$ significantly larger than SR

Output will become a triangle wave



Offset Voltage (Input Referred Offset Voltage)

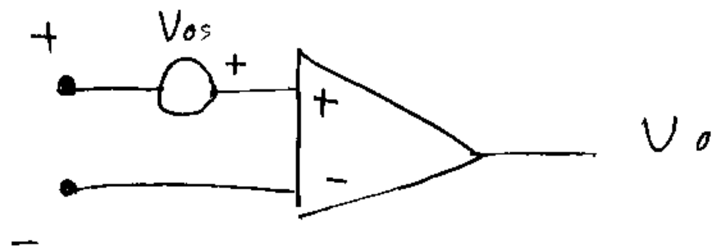




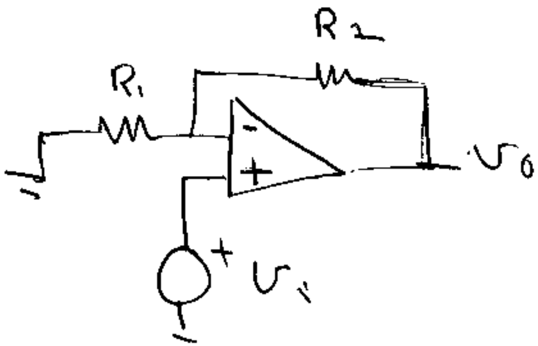
V_{os} can be positive or negative

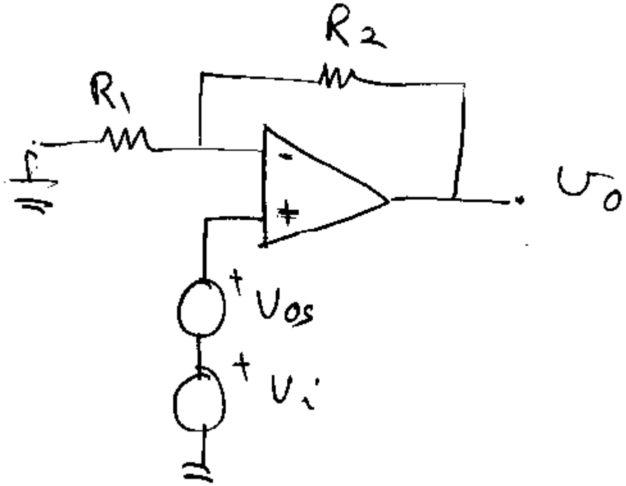
V_{os} is a random variable

V_{os} can be modeled with a dc voltage source in series with input terminal



Effects of V_{os} on basic noninverting amplifier





$$v_o = V_i\left(1+\frac{R_2}{R_1}\right) + V_{os}\left(1+\frac{R_2}{R_1}\right)$$

If $V_i >> V_{os}$, V_{os} does not aduercely affect performarce

$V_i \sim V_{os}$, V_{os} presents a major problem

$V_i << V_{os}$, V_{os} is very diffficult to manage

$$V_o = V_i\left(1 + \frac{R_2}{R_1}\right) + V_{os}\left(1 + \frac{R_2}{R_1}\right)$$

If $V_{os} = 3\,mV$

$V_i = 3\,mV$

$1 + \frac{R_2}{R_1} = 1000$

$V_{o\,desired} = (3mV)(1000) = 3V$

$V_{o\,actual} = (3mV)(1000) + (3mV)1000 = 6V$

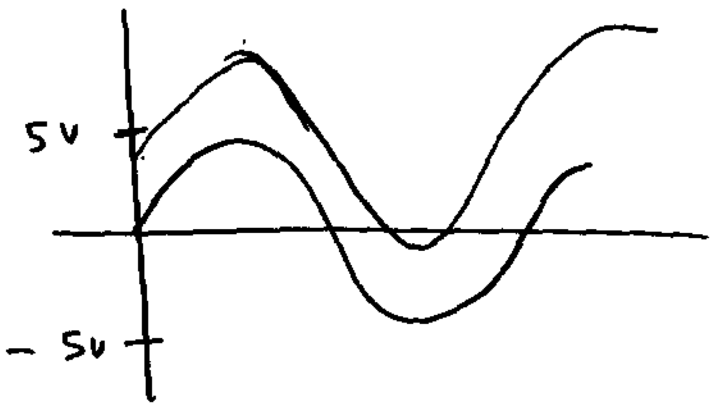
Methods of managing V_{os}

1) Cap. Coupling

2) trimming V_{os}

3) use the premium OA

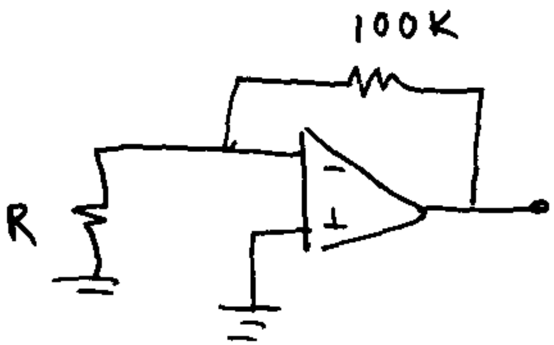
If $V_i = V_m \sin \omega t$



$V_{os} = 3\,mV$

$A_v = 1000$

Measurement of V_{os} (must be on every device if of concern)

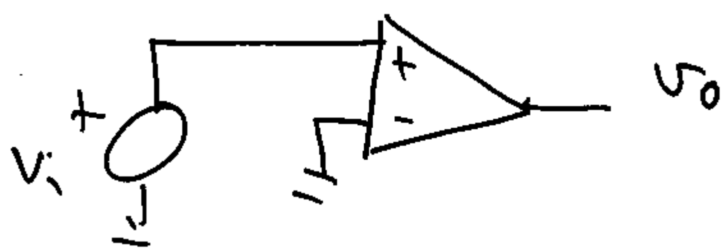


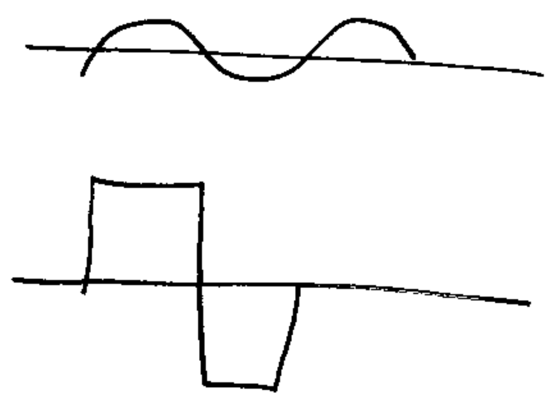
$$V_o = V_{os}(1 + 100)$$

$$V_{os} = \frac{V_o}{101}$$

Nonlinear Op Amp Applications

Op Amp almost never used as amplifier open loop





Comparator