VE311 Mid Review - Op Amp

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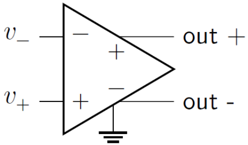
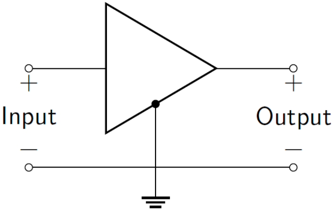
Overview

Intro

- Op Amp is a nonlinear circuit element
  - Low input signal $\rightarrow$ Linear
  - High input signal $\rightarrow$ Saturation
- Op Amp $\leftrightarrows$ Differential & Single-ended amplifier
  Single-ended: the output appears between terminal 3 and ground (not differential)



Differential Amplifier



single-ended Amplifier

Intro

An amplifier receives a signal from a source and delivers it to a load. Gains are dimensionless, and are usually expressed in terms of decibels (dB):

$$A_v = \frac{v_o}{v_i} \tag{1}$$

$$A_i = \frac{i_o}{i_i} \tag{2}$$

$$A_p = A_v A_i \tag{3}$$

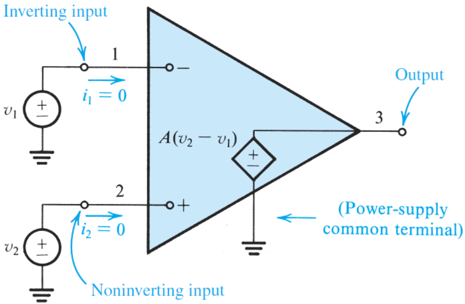
$$A_v(dB) = 20 \log A_v \tag{4}$$

$$A_i(dB) = 20 \log A_i \tag{5}$$

$$A_p(dB) = 10 \log A_p \tag{6}$$

Ideal op amp

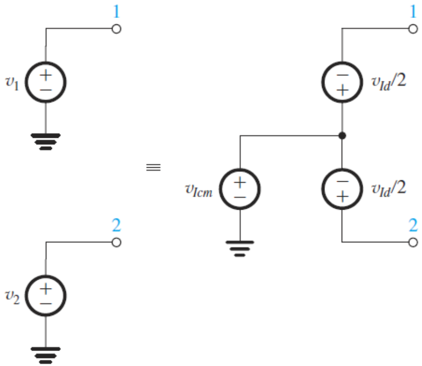
- Infinite input impedance
- Zero output impedance
- Zero common-mode gain or, equivalently, infinite common-mode rejection
- Infinite open-loop gain A
- Infinite bandwidth



Differential and Common-Mode Signals

$$v_{Id} = v_2 - v_1 \quad v_{Icm} = \frac{1}{2}(v_1 + v_2) \tag{7}$$

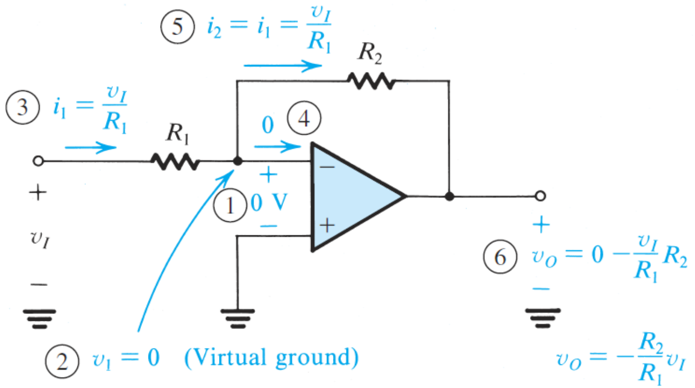
$$v_1 = v_{Icm} - \frac{v_{Id}}{2} \quad v_2 = v_{Icm} + \frac{v_{Id}}{2} \tag{8}$$



The inverting configuration

Determine the closed-loop gain using virtual ground ($v_- = v_+ = 0$)

$$v_O = -\frac{R_2}{R_1} v_I \tag{9}$$

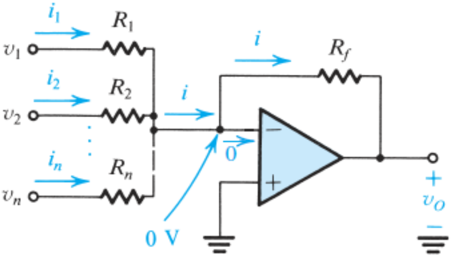


Example

Hw3 Question 2

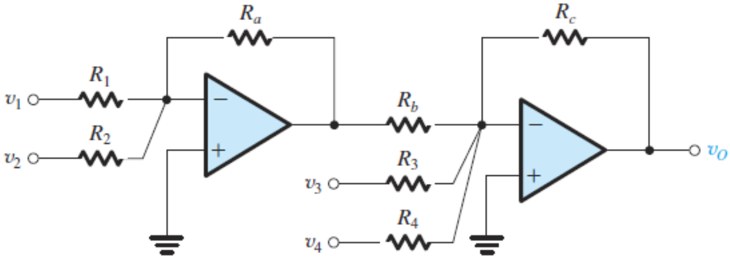
The Weighted Summer

$$v_O = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \cdots + \frac{R_f}{R_n}v_n\right) \tag{10}$$



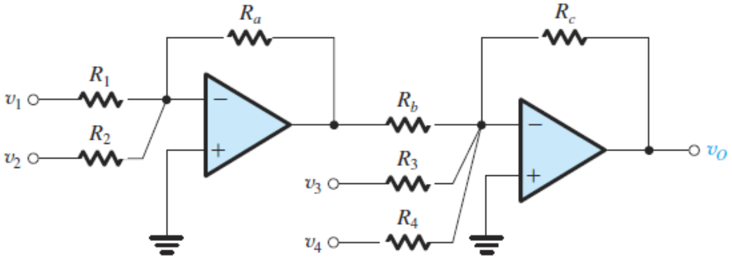
Exercise

$R_1 = 5\mathrm{k}\Omega$, $R_2 = 10\mathrm{k}\Omega$, $R_a = 10\mathrm{k}\Omega$, $R_b = 10\mathrm{k}\Omega$, $R_3 = 2.5\mathrm{k}\Omega$, $R_c = 10\mathrm{k}\Omega$, $R_4 = 10\mathrm{k}\Omega$, determine v_O



Exercise

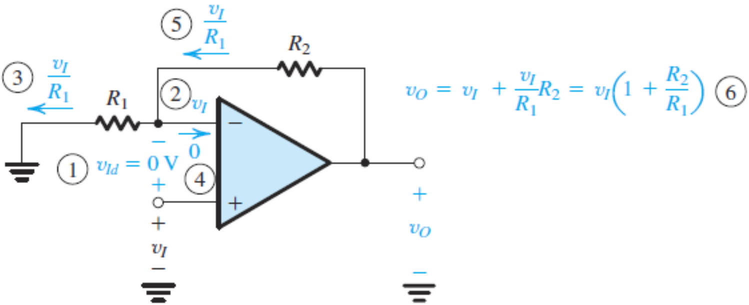
$R_1 = 5\mathrm{k}\Omega$, $R_2 = 10\mathrm{k}\Omega$, $R_a = 10\mathrm{k}\Omega$, $R_b = 10\mathrm{k}\Omega$, $R_3 = 2.5\mathrm{k}\Omega$, $R_c = 10\mathrm{k}\Omega$, $R_4 = 10\mathrm{k}\Omega$, determine v_O



Solution: $v_O = 2v_1 + v_2 - 4v_3 - v_4$

The noninverting configuration

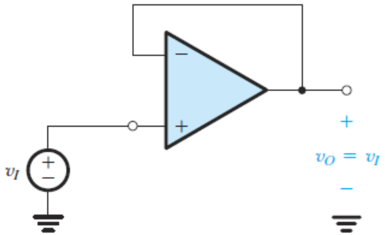
$$v_O = v_I(1 + \frac{R_2}{R_1}) \tag{11}$$



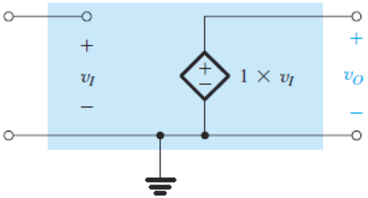
The voltage follower

A special noninverting case such that $R_1 = \infty$ and $R_2 = 0$

$$v_O = v_I \tag{12}$$



(a)

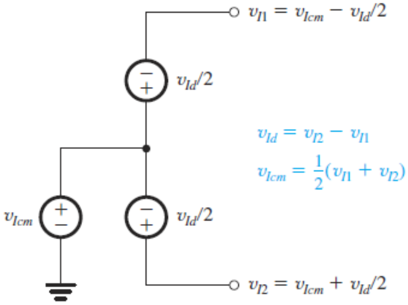


(b)

Difference Amplifiers

$$v_O = A_d v_{Id} + A_{cm} v_{Icm} \tag{13}$$

$$\mathrm{CMRR} = 20 \log \frac{|A_d|}{|A_{cm}|} \tag{14}$$

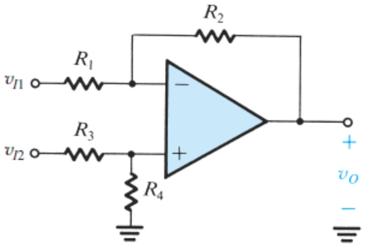


Difference Amplifier

Inverting part + noninverting part + voltage divider (superposition)

$$\frac{R_4}{R_4 + R_3}\left(1 + \frac{R_2}{R_1}\right) = \frac{R_2}{R_1} \tag{15}$$

$$\frac{R_4}{R_3} = \frac{R_2}{R_1} \tag{16}$$



Difference Amplifier

The differential gain

$$A_d = \frac{v_O}{v_{Id}} = \frac{R_2}{R_1} \tag{17}$$

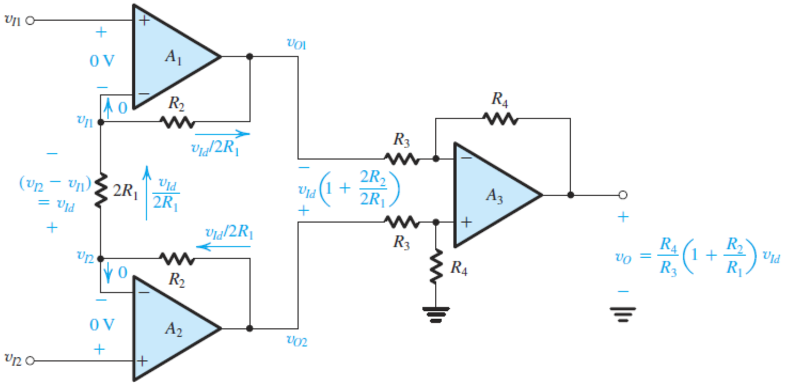
What about the common-mode gain A_{cm}?

$$A_{cm} \equiv \frac{v_O}{v_{Icm}} = \left(\frac{R_4}{R_4 + R_3}\right)\left(1 - \frac{R_2}{R_1}\frac{R_3}{R_4}\right) \tag{18}$$

The Instrumentation Amplifier

Two noninverting (A_1, A_2) + difference amplifier (A_3)

$$v_O = \frac{R_4}{R_3}\left(1 + \frac{R_2}{R_1}\right) v_{Id} \tag{19}$$



Example

Hw3 Question 3

Inverting & Noninverting (Finite gain)

Inverting:

$$G \equiv \frac{v_O}{v_I} = \frac{-R_2/R_1}{1 + (1 + R_2/R_1)/A} \tag{20}$$

Noninverting:

$$G \equiv \frac{v_O}{v_I} = \frac{1 + (R_2/R_1)}{1 + \frac{1+(R_2/R_1)}{A}} = \frac{A}{1 + A\beta} \tag{21}$$

where $\beta = \frac{R_1}{R_1+R_2}$ is called the feedback factor.

Output and input resistance

Output resistance (both inverting and noninverting):

$$R_{out} = \frac{R_o}{1 + A\beta} \| (R_1 + R_2) \tag{22}$$

Input resistance (noninverting):

$$R_{\text{in}} = R_{id}(1 + A\beta) \tag{23}$$

Input resistance (inverting):

$$R_{\text{in}} = R_1 + R_{id} \| \left(\frac{R_2}{1 + A} \right) \tag{24}$$

Example

Hw3 Question 4

Voltage follower (Finite gain)

$$v_{Id} = v_I - v_O \quad v_{Icm} = \frac{v_I + v_O}{2} \tag{25}$$

$$v_O = A_d v_{Id} + A_{cm} v_{Icm} \tag{26}$$

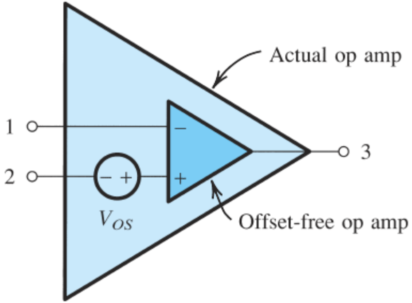
$$v_O = A_d \left[(v_I - v_O) + \frac{v_I + v_O}{2\mathrm{CMRR}} \right] \tag{27}$$

$$A_v = \frac{v_O}{v_I} = \frac{A_d \left[1 + \frac{1}{2\mathrm{CMRR}}\right]}{1 + A_d \left[1 - \frac{1}{2\mathrm{CMRR}}\right]} \tag{28}$$

Nonideal amplifier

Input offset voltage V_{OS}, usually $1mV \leq V_{OS} \leq 5mV$

Exercise: Use the model below to sketch the transfer characteristic v_O versus v_{Id}($v_O = v_3$ and $v_{Id} = v_2 - v_1$)of an op amp having an open-loop dc gain $A_0 = 10^4 V/V$, output saturation levels of $\pm 10V$, and V_{OS} of $+5$ mV.



Solution:

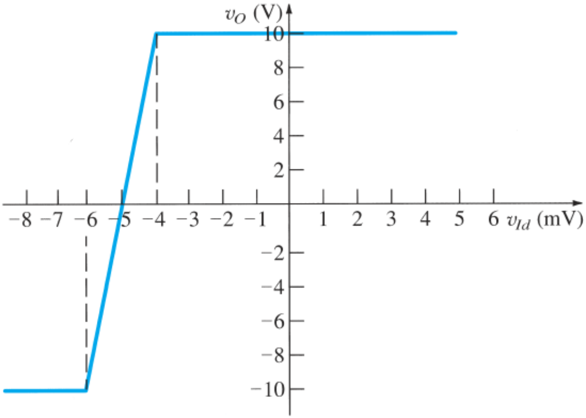
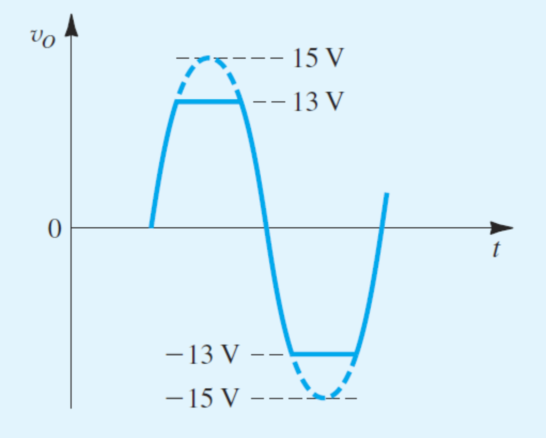


Figure E2.21 Transfer characteristic of an op amp with $V_{OS} = 5$ mV.

Output saturation

Clipping: Theoretical output voltage > Rated output voltage



Exercise

Consider an op amp connected in the inverting configuration to realize a closed-loop gain of $-100V/V$ utilizing resistors of $1k\Omega$ and $100k\Omega$. A load resistance R_L is connected from the output to ground, and a low-frequency sine-wave signal of peak amplitude V_p is applied to the input. Let the op amp be ideal except that its output voltage saturates at $\pm 10V$ and its output current is limited to the range $\pm 20mA$.

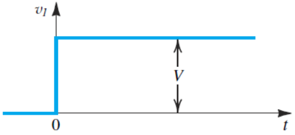
- For $R_L = 1k\Omega$, what is the maximum possible value of V_p while an undistorted output sinusoid is obtained?
- Repeat (a) for $R_L = 200k\Omega$.
- If it is desired to obtain an output sinusoid of $10 - V$ peak amplitude, what minimum value of R_L is allowed?

Slew rate

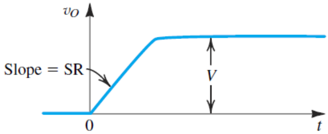
A large signal effect, "saturation in rate of change of output voltage"

$$\mathrm{SR} = \left.\frac{dv_O}{dt}\right|_{\max} \tag{29}$$

For a unity-gain voltage-follower,



Input



Output

Suggestion

- Read questions carefully (inverting&noninverting, ideal&nonideal, AC&DC...)
- Practice more to get familiar with simple models mentioned in class
- Write some important conclusions and definitions in your ctpp (e.g. voltage gain, CMRR)
- Try to decompose complex circuits to multiple simple circuits when you get stucked in exam (superposition principle)
- ...

Thank You&Good Luck