OPERATIONAL AMPLIFIERS

An op-amp, short for operational amplifier, is a voltage amplifier device with two (differential) inputs and a single output. Output, i.e., amplified voltage, is usually much higher than the input. Typically, the gain is in the range of several hundred thousand (theoretically infinite).

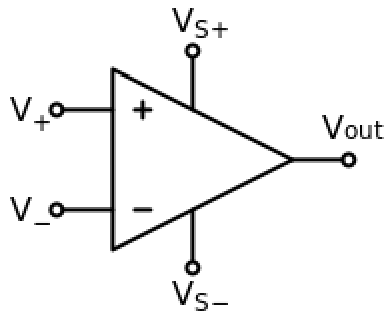


Figure 1

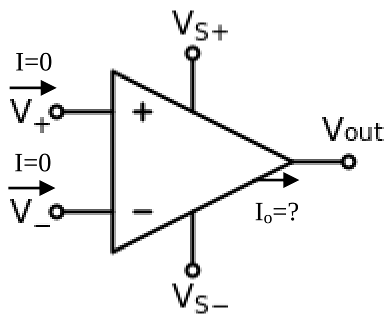
The pins of the op-amp schematic in Fig. 1 indicate:

- V_+: non-inverting input
- V_-: inverting input
- V_{out}: output
- V_{S+}: positive power supply
- V_{S-}: negative power supply

Ideal Op-Amp

For an ideal op-amp

i. The input impedance is infinite; no current may flow into the inputs of the op-amp.
ii. The output impedance is zero; any amount of current can be drawn from the output terminal.



iii. The open-loop gain is infinite. In real-life applications, this means that the gain can be controlled entirely by using negative feedback.
iv. The operation is frequency independent.
v. There is no bias; the output voltage is zero when the difference in voltage between the two inputs is zero.

The amount of voltage that can be output at the V_{out} terminal is bounded by the values of V_{S-} and V_{S+}. The V_{out} versus $V_d = V_+ - V_-$ characteristics show us the possible operating regions of an op-amp as in Fig. 2.

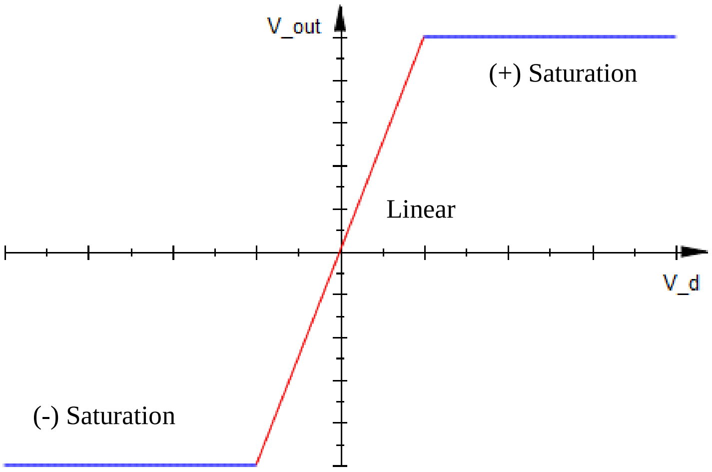


Figure 2: V_{out} vs V_{in} characteristics of a non-ideal op-amp

Note that, since for the ideal op-amp the open-loop gain is assumed infinite, the slope of the linear region is infinite. In other words, a finite difference between the input terminals produce an infinitely large output. The V_{out} vs V_{in} characteristics of an ideal op-amp is illustrated in Fig. 3.

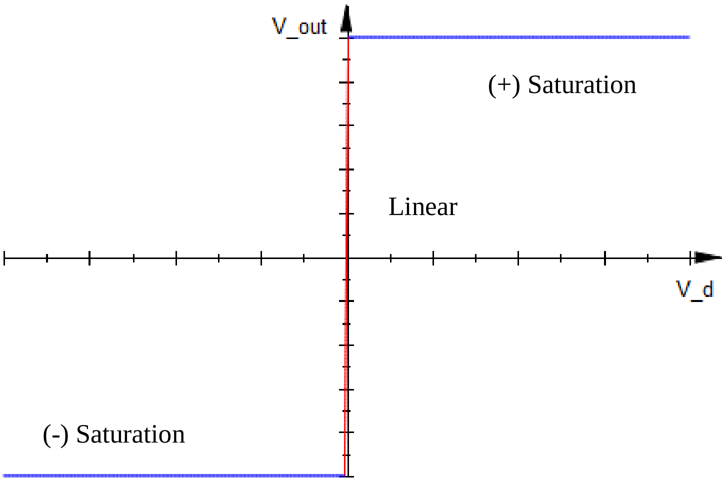


Figure 3: V_{out} vs V_{in} characteristics of an ideal op-amp

In terms of mathematical expressions, these regions can be described by the following (in)equalities:

- Linear mode: $V_+ = V_-$ and $V_{S-} < V_{out} < V_{S+}$
- (+) Saturation: $V_+ > V_-$ and $V_{out} = V_{S+}$
- (-) Saturation: $V_+ < V_-$ and $V_{out} = V_{S-}$

Analysis of Circuits with Op-Amps

A sample analysis of the op-amp circuit in Fig. 4 is done below:

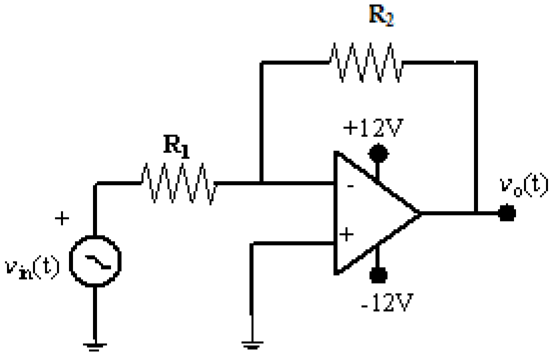


Figure 3

First, let us assume that the op-amp is in linear mode:

$$\boldsymbol{V_+} = \boldsymbol{V_-} = 0;\ I_+ = I_- = 0$$

Kirchhoff's Current Law on the $\boldsymbol{V_-}$ node gives us

$$\frac{\boldsymbol{V_{out}} - 0}{R_2} + \frac{\boldsymbol{V_{in}} - 0}{R_1} = 0$$

Therefore,

$$\boldsymbol{V_{out}} = -\frac{R_2}{R_1}\boldsymbol{V_{in}}.$$

But this is only correct if the linear mode assumption is correct, i.e. as long as $\boldsymbol{V_{out}}$ satisfies

$$\boldsymbol{V_{S-}} < \boldsymbol{V_{out}} < \boldsymbol{V_{S+}}$$

Or

$$-\frac{R_1}{R_2}\boldsymbol{V_{S+}} < \boldsymbol{V_{in}} < -\frac{R_1}{R_2}\boldsymbol{V_{S-}}.$$

If $\boldsymbol{V_{in}} \geq -\frac{R_1}{R_2}\boldsymbol{V_{S-}}$, the op-amp enters the (-) saturation region, with $\boldsymbol{V_{out}} = \boldsymbol{V_{S-}}$. In that case,

$$\frac{\boldsymbol{V_{out}} - \boldsymbol{V_-}}{R_2} + \frac{\boldsymbol{V_{in}} - \boldsymbol{V_-}}{R_1} = 0$$

$$\boldsymbol{V_-} = \frac{R_2\boldsymbol{V_{in}} + R_1\boldsymbol{V_{S-}}}{R_1 + R_2} \geq 0\ if\ \ \boldsymbol{V_{in}} \geq -\frac{R_1}{R_2}\boldsymbol{V_{S-}},$$

Then the $\boldsymbol{V_+} < \boldsymbol{V_-}$ constraint of (-) saturation mode is satisfied.

A similar analysis for the (+) saturation region is left as an exercise.

References:

- Wikipedia page on op-amps
  http://en.wikipedia.org/wiki/Operational_amplifier
- Lecture slides of Prof. Greg Kovacs, Stanford University
  http://web.stanford.edu/class/ee122/Handouts/2-Op-Amp_Concepts.pdf
- EE 201 lecture notes of Assoc. Prof. Çağatay Candan, as transcribed by N.Merve Gürel
  http://www.eee.metu.edu.tr/~ccandan/EE201/EE201_Fall201112/lecture_notes/EE201_Nezihe_Merve_Gurel_Fall20010-11.pdf