Reverse Classroom: Op Amps Quiz 4

REV 0; August 18, 2019

1 Using an Op Amp to Undo the Dog

Just a reminder:

Perfect Op Amp Design Rules

1. No current flows into or out of the inputs (V_- and V_+) of an op amp.
2. If there is negative feedback, the op amp keeps the negative input at the same voltage as the positive input, so you can assume that $V_- = V_+$.
3. The inputs of an op amp should always be kept between V_{CC} and V_{EE} (i.e., $V_{EE} \leq V_-, V_+ \leq V_{CC}$).
4. The output of an op amp cannot be greater than V_{CC} or less than V_{EE}.

1.1 Design

Assume you have the following circuit:

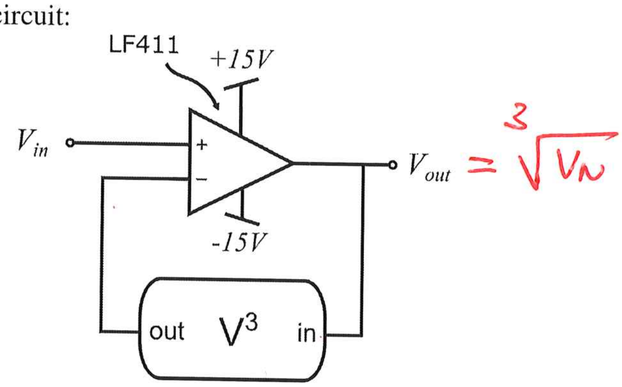

Figure 1: An Operational Amplifier Circuit

The block in the feedback loop takes the input voltage ("in") and cubes it (so the voltage marked "out" is the output voltage of the op amp cubed).

Use the op amp design rules to determine V_{out} as a function of V_{in}. neg feedback ✓ yes

$V_+ = V_-$ $V_+ = V_{IN}$

$V_- = V_{OUT}^3$ $V_{IN} = V_{OUT}^3$

$V_{OUT} = \sqrt[3]{V_{IN}}$

1.2 Contemplation

What does this problem have to do with "Undoing the dog?"

in the non inverting configuration the op amp "undoes" whatever the feedback does

1.3 More Contemplation

Why do you think I chose V^3 for the feedback function rather than V^2?

V^3 maintains polarity so works w/ $V_{in} < \phi$

Now complete the rest of Lab 6. Note that the second half of part 6L.9 requires and analog scope so if you plan to do this experiment let us know so we can set you up with one.

Bipolar Transistor and Op Amp Rules

REV 0; February 12, 2019

NPN Bipolar Junction Transistor ("BJT") Design Rules

1. Ground rules – proper "biasing." If ...
   (a) We set things up so that base to emitter is "forward biased," i.e.,
      i. The base to emitter acts like a diode in the direction of the arrow
      ii. We arrange things so that V_{BE} can be large enough to allow current to flow from base to emitter ($\approx 0.6V$)

   (b) and we set things up so that $V_{CE} \geq 0.2V$
2. ... then the result is the *Simple Transistor Model* and
   (a) The emitter current is about the same as the collector current ($I_C \approx I_E$)
   (b) The base to emitter voltage looks like a forward biased diode ($V_{BE} \approx 0.6V$)
   (c) The base current is a small fraction of the collector current[1]
      i. $I_C \approx 100 * I_B$ for small signal NPN transistors (like the 2N3904)
      ii. $I_C \approx 40 * I_B$ for power NPN transistors (like the MJE3055)

PNP Bipolar Junction Transistor Design Rules[2]

1. Ground rules – proper biasing. If ...
   (a) We set things up so that the BJT is 'forward biased, i.e. V_B is about $0.6V$ lower than V_E,
      i. The base to emitter acts like a diode *in the direction of the arrow*
      ii. We make sure that V_{BE} can be large enough to allow current to flow from emitter to base ($\approx -0.6V$)

   (b) and we set things up so that $V_{CE} \leq -0.2V$ (i.e, V_C is $0.2V$ or more negative than V_E)
2. ... then the result is the *Simple Transistor Model* and
   (a) The emitter current is about the same as the collector current ($I_C \approx I_E$)
   (b) The base to emitter voltage looks like a forward biased diode ($V_{BE} \approx -0.6V$)
   (c) The base current is a small fraction of the collector current[3]
      i. $I_C \approx 100 * I_B$ for small signal PNP transistors (like the 2N3906)
      ii. $I_C \approx 40 * I_B$ for power PNP transistors (like the MJE2955)

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[1] The ratio $\frac{I_C}{I_B}$ is shown as the parameter β or h_{fe} on the transistor data sheet.

[2] Note that I_B, I_C and I_E flow in the opposite direction compared to a NPN transistor. I_B and I_C flow out of a PNP BJT while I_E flows into the transistor. That is why we draw the PNP upside down compared to the NPN, so that voltages still are more positive at the top and current flows from top to bottom.

[3] The ratio $\frac{I_C}{I_B}$ is shown as the parameter β or h_{fe} on the transistor data sheet.

Ebers Moll BJT Model

If the emitter of a BJT is connected directly to ground (or any other voltage source) the simple BJT model above does not allows us to figure out what the emitter current will be. We need a more complicated model to estimate the emitter current. The Ebers Moll model adds a small resistance, "little r_e', in the emitter lead of the BJT that accounts for the change in emitter current with changes in V_{BE}. This resistance is also present in the simple model but can usually be ignored for reasonably large values of the external emitter resistor.

To estimate the value of r_e:

1. Figure out the approximate collector current in mA
2. Divide 25Ω by the collector current *in mA* to get r_e
3. Add r_e to the external emitter resistor R_E to get total emitter resistance.

[Perfect] Op Amp Design Rules

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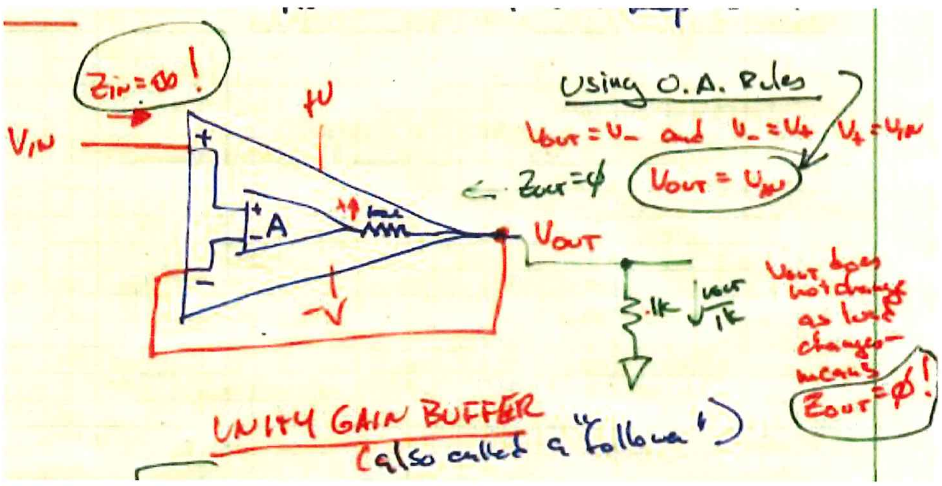
4. The output of an op amp cannot be greater than V_{CC} or less than V_{EE}.

The Effect of Feedback on Op Amp Output Impedance

In class today we noted that the input impedance of an op amp unity gain follower was very high and I tried to convince you by the op amp rules that its output impedance was very low. Here is an exact analysis of why the latter is true.

Consider an operational amplifier with an open loop gain of A and a Thevenin output impedance of R_{out} (here shown as 100Ω) connected as a unity gain follower (i.e., the output is connected to the V₋ input):



First assume no load on the circuit ($R_L = \infty$).

$V_{out} = (V_+ - V_-) * A$ so

$V_{out} = (V_{in} - V_{out}) * A$, solving for V_{out}:

$V_{out} = \frac{A}{A+1} * V_{in}$ If A is large (on the order of 10^5), $V_{out} = V_{in}$ to a few thousandths of a percent.

Now suppose we pull 1mA of current from the output. This causes a voltage drop of $1mA * R_{out}$ across the output impedance of the op amp. Now:

$V_{out} = (V_+ - V_-) * A - 1mA * R_{out}$ or

$V_{out} = (V_{in} - V_{out}) * A - 1mA * R_{out}$, solving for V_{out}:

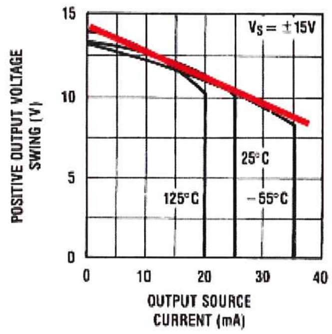
$V_{out} = \frac{A}{A+1} * V_{in} - \frac{R_{out}}{1+A} * 1mA$

So a 1mA load causes an output change of $\frac{R_{out}}{1+A}$. We can calculate the effective output impedance with feedback by Ohm's law:

$R_{out(fb)} = \frac{\Delta V}{\Delta I} = \frac{\frac{R_{out}}{1+A} * 1mA}{1mA} = \frac{R_{out}}{1+A}$

So feedback reduces the natural Thevenin output impedance of the op amp by a factor of $A + 1$.

Looking at the LF411 op amp data sheet at http://www.ti.com/lit/ds/symlink/lf411-n.pdf, Figure 6 implies an open loop output impedance of about 140Ω (red line and text added to show slope):



ΔV/ΔI ~= 13V-8V/35mA = 140 Ohm

Figure 6. Positive Current Limit

The data sheet shows the Large Signal Voltage Gain (A_{VOL}) is a minimum of 25,000 (typically 200,000), so the follow would have a minimum output impedance of about:

$$\frac{143}{25{,}001} \cong 6m\Omega$$

and a typical output impedance of less than a milliohm.

This is not likely to be an issue into most loads (as long as we don't hit the op amp current limit)! For the most part, we will consider the output impedance of a op amp circuit that meets the golden rules as zero ohms.

Note that as the closed loop gain of the op amp circuit increases, the excess open loop gain available to reduce the output impedance decreases. That means that if you build a non-inverting amplifier with a gain of 10, the output impedance will increase to about $60m\Omega$, or about ten time greater than the unity gain follower.

Also, the open loop gain of an op amp decreases with frequency, so the output impedance will be higher for a higher frequency input signal.