

Lab 5: CE Amplifier Gain with Emitter Degeneration

Proper calculation for base width modulation

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Introduction

This lab summarizes my own investigation of the voltage gain v_{out}/v_{in} for the Common Emitter amplifier with a finite Early voltage. This research sprung from my attempt to solve question 4 of Homework 6 when accounting for base width modulation.

I knew that r_o inclusion was not required but I wanted to solve for the gain anyway. Even despite the warning from Sedra and Smith who advise to ignore r_o in the small-signal model: “[...] note that we have not included r_o , because it would complicate the analysis significantly, which is not worth the trouble, given that r_o has little effect on the performance of discrete-circuit amplifiers.” (p. 467, 8th ed.)

A search for the gain found only this equation for the voltage gain,

$$\frac{v_{out}}{v_{in}} \approx -\frac{g_m(R_C \parallel r_o(1 + g_m R_E))}{1 + g_m R_E},$$

(see MIT Course link, slide 19 and another YouTube video with the same result) but as I’ll show this equation isn’t exactly correct. The derivation on YouTube neglects the base current’s contribution to the voltage of the emitter resistor twice, and this simplification can lead to significant errors when either $\frac{R_E}{r_\pi}$ or $\frac{R_E}{\beta r_o}$ is not negligibly small. I confirmed that adding the missing emitter voltage contribution yields the same equation that I derive in this report.

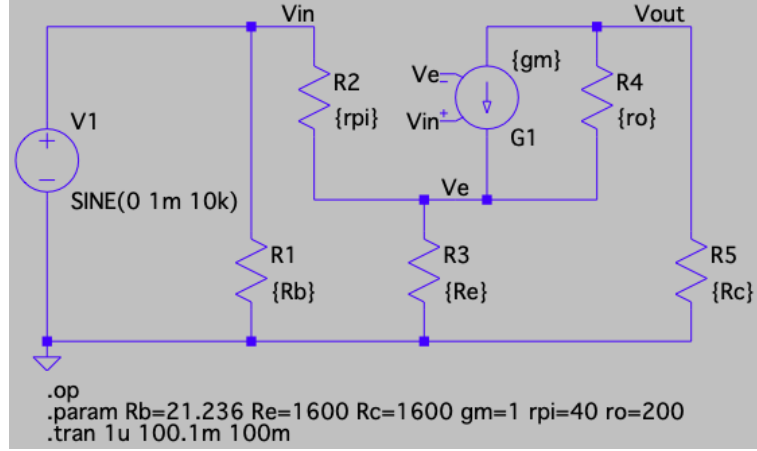
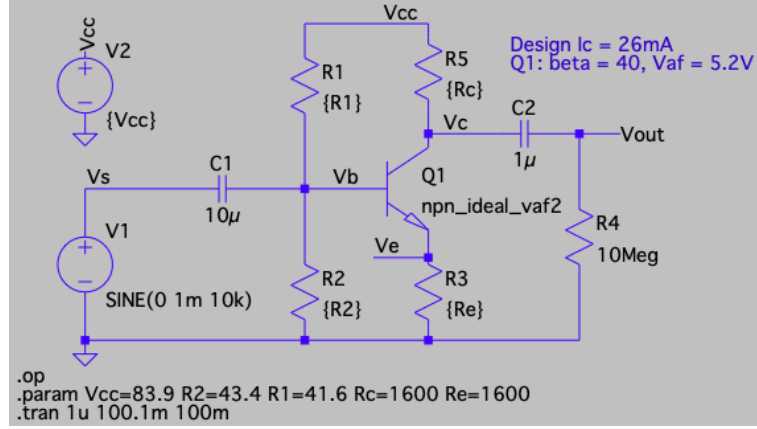
This report has three sections. In the first section, I derive A_v for a CE amplifier with emitter degeneration and base width modulation effects under a typical four resistor biasing scheme. In the second section, I present a summary for these CE amplifiers as they grow in complexity:

1. CE amplifier without R_E or base width modulation,
2. CE amplifier with base width modulation ($V_A < \infty$),
3. CE amplifier with emitter degeneration ($V_A = \infty$),
4. CE amplifier with emitter degeneration and base width modulation.

The third section presents comprehensive LTspice simulations that confirm the derivations.

Voltage gain for the CE amplifier with emitter degeneration and $V_A < \infty$

Here is a schematic of the amplifier under consideration (DC then AC):



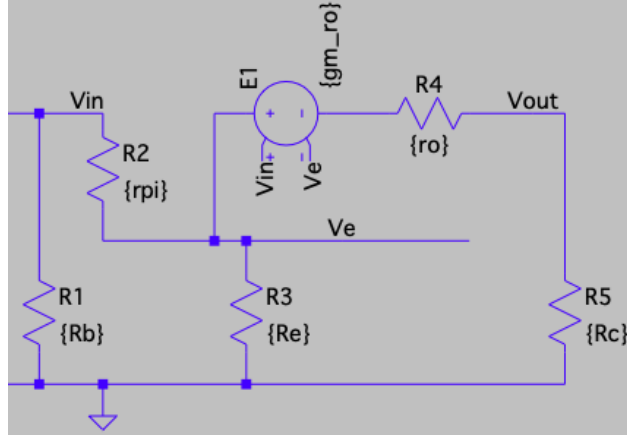
There are two important equations to derive the voltage gain. The first is KCL at the emitter node using the collector current through R_C :

$$v_{in} = v_{\pi} + \left(\frac{v_{\pi}}{r_{\pi}} - \frac{v_o}{R_C} \right) R_E$$

After a Thevenin transform of the VCCS to a VCVS (with voltage $-g_m r_o v_{\pi}$ and resistance r_o), KVL yields:

$$v_o + g_m r_o v_{\pi} = -\frac{v_o}{R_C} r_o + \left(\frac{v_{\pi}}{r_{\pi}} - \frac{v_o}{R_C} \right) R_E,$$

noting that on RHS the first term is the r_o voltage using collector current and the second term is the same R_E voltage used in the first equation. Here is a schematic of the KVL loop using the Thevenin source:



The first equation yields this substitution for v_π :

$$v_\pi = \left(v_i + \frac{R_E}{R_C} v_o \right) \frac{r_\pi}{r_\pi + R_E}$$

After substituting v_π and some reduction, the voltage gain becomes

$$\frac{v_o}{v_i} = \frac{-R_C(\beta r_o - R_E)}{r_\pi(r_o + R_C + R_E) + R_C R_E + (\beta + 1)r_o R_E}$$

Summary of CE properties

R_E	r_o	A_v
0	∞	$-\frac{\beta R_C}{r_\pi}$
R_E	∞	$-\frac{\beta R_C}{r_\pi + (\beta + 1)R_E}$
0	r_o	$-\frac{\beta R_C}{r_\pi \left(1 + \frac{R_C}{r_o}\right)}$
R_E	r_o	$-\frac{\left(\beta - \frac{R_E}{r_o}\right) R_C}{r_\pi \left(1 + \frac{R_C}{r_o}\right) + R_E \frac{r_\pi + R_C}{r_o} + (\beta + 1)R_E}$

resistance	value as function of R_E and r_o
R_{in}	$R_1 \parallel R_2 \parallel \left\{ \frac{r_\pi + (\beta + 1)R_E + \frac{1}{r_o}(r_\pi R_C + r_\pi R_E + R_C R_E)}{1 + \frac{1}{r_o}(R_C + R_E)} \right\}$
R_{out}	$R_C \parallel \left\{ r_o \frac{r_\pi + R_E + (\beta + 1)R_E}{r_\pi + R_E + R_E} + (r_\pi + R_E) \parallel R_E \right\}$

LTspice simulations

First, I simulate the DC and AC models for the following realistic test case:

- $I_C = 1.3mA$, $\beta = 80$
- $g_m = 0.05$, $r_\pi = 1600$, $I_B = 16\mu A$, $I_E = 1.316mA$
- $V_{CC} = 9V$, $V_E = 4V$ and $V_B = 4.7V$
- $V_{CE} = 0.7V$, $V_{BC} = 0V$ (limit input to $5mV$ to remain in soft saturation)
- $R_E = 4V/I_E = 3039\Omega$, $R_C = 4.3V/I_C = 3308\Omega$
- $R_1 = 4.3V/(50 I_B) = 5292\Omega$, $R_2 = 4.7/(49, I_B) = 5903\Omega$
- $I_S = 1.3mA \exp(-0.7V/V_T) = 2.639fA$
- $V_A = 5.2V$, $r_o = 4000\Omega$

Note that the transistor must be kept close to saturation in order to achieve the desired β , otherwise the small signal parameters change.

The voltage gain should be

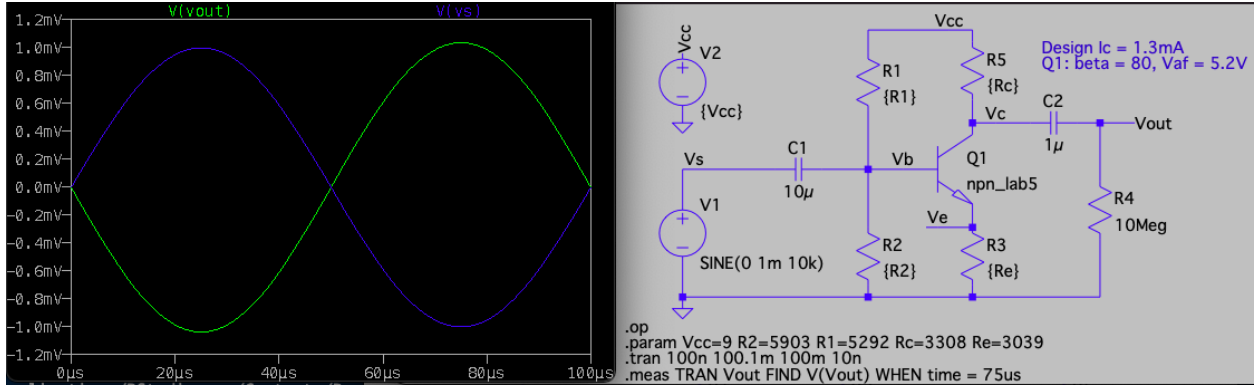
$$\frac{v_{out}}{v_{in}} = -\frac{(80 - \frac{3039}{4000})3308}{1600(1 + \frac{3308}{4000}) + 3039\frac{1600+3308}{4000} + 81 \cdot 3039} = \frac{-262126.75}{2923.20 + 3728.85 + 246159.00} = -1.03685,$$

noting that the voltage gain formula given online yields

$$\frac{v_{out}}{v_{in}} = \frac{-g_m r_o R_C}{R_C + r_o + R_E(1 + g_m r_o)} = \frac{-0.05 \cdot 4000 \cdot 3308}{3308 + 4000 + 3039(1 + 0.05 \cdot 4000)} = \frac{-661600}{618147} = -1.07030,$$

which is 3.23% higher than my calculated value. Note that larger collector currents, lower gain, or lower r_o amplify this error.

DC Simulation

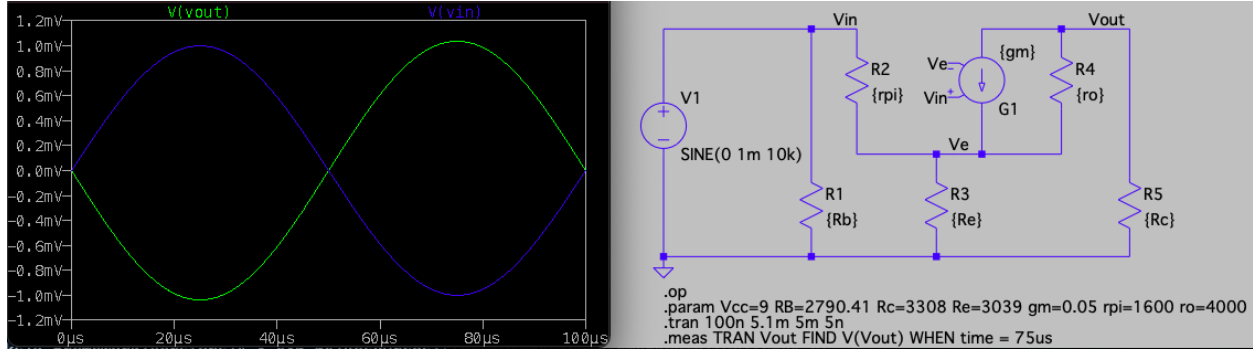


The result of the saved measurement at the V_{out} peak is:

time	V_{out}
75μs	1.03611mV

with the difference from the calculated value due to the small loss in the output RC circuit.

AC Simulation



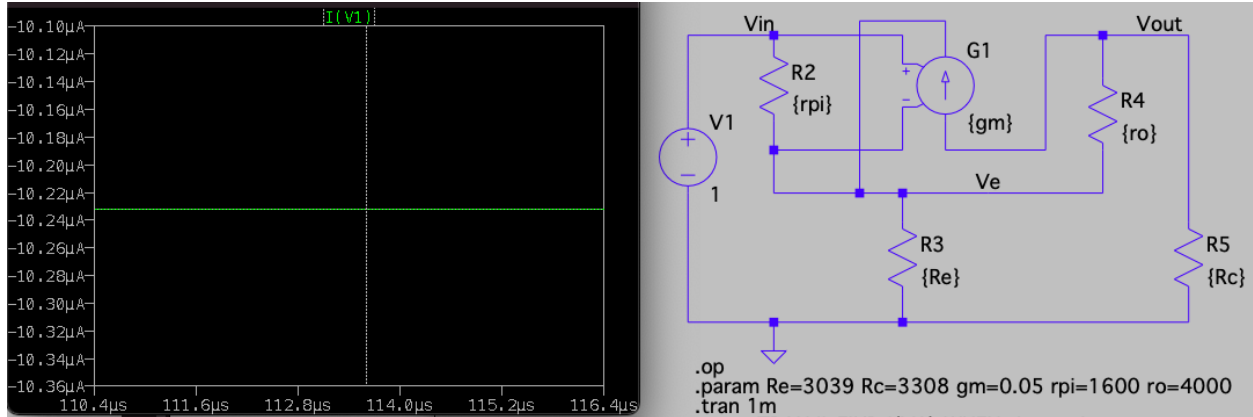
The result of the saved measurement at the V_{out} peak is:

time	V_{out}
75 μs	1.03684mV

which is essentially no difference from the calculated value.

Input resistance

We can run an input resistance test in LTspice using a 1V input.



The calculated R_{in} with my derived formula is:

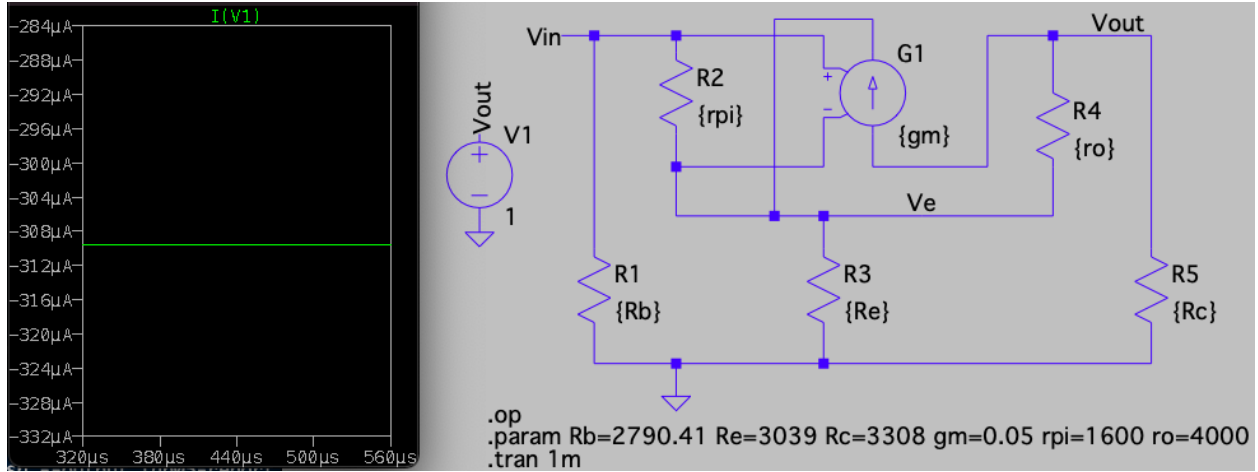
$$R_{in} = 2790.41 \parallel R_{in,b}$$

$$R_{in,b} = \frac{1600 + (81)3039 + \frac{1}{4000}(1600 \cdot 3308 + 1600 \cdot 3039 + 3308 \cdot 3039)}{1 + \frac{1}{4000}(6347)} = \frac{1600 + 246159 + 5052}{2.58675} = \frac{252811}{2.58675} = 97.733k\Omega$$

time	$I(V_1)$	$1V/I(V_1)$
1ms	10.23195 μA	97733 Ω

Output resistance

Similarly we can run an output resistance test in LTspice using a 1V input.



The calculated R_{out} with my derived formula is:

$$R_{out} = 3308 \parallel \left\{ 4000 \frac{1600 + 2790.41 + 246159}{7429.41} + (4390.41 \parallel 3039) \right\} = 3308 \parallel (134896.0 + 1795.9) = 3229.837 \Omega$$

time	$I(V_1)$	$1V/I(V_1)$
1ms	$309.613 \mu A$	3229.839Ω

Discussion

This lab is a great demonstration of how I can use LTspice to address circuit questions in the future. I successfully confirmed my derivations for all three amplifier performance characteristics (voltage gain, input resistance, and output resistance) for the complex case of a common emitter amplifier with a emitter resistance under base width modulation.

I have confirmed that if you select $R_E = \beta r_o$, albeit an unlikely condition, the CE voltage gain is zero. This guides the designer in choosing r_o and β relative to R_E in order to maximize voltage gain.