ELECENG 3EJ4

Lab Report #4

Instructor: Dr. Chen

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Part 1: Negative Feedback Amplifier

Q1. (10 Points)

(1) Based on the simulation data in Step 1.2 (Figure 1) the low frequency (100 Hz) voltage gain in dB is:

$$A_{d1} = 7.38\ dB$$

$$A_{d2} = 70.05\ dB$$

$$A_{d3} = 0\ dB$$

(2) The overall voltage gain for the differential-mode signal is

$$A_d = 7434.5\ \frac{V}{V}$$

Frequency	M(I(Q1:B))	P(I(Q1:B))	M(V(Vo1))	P(V(Vo1))	M(V(Vo2))	P(V(Vo2))	M(V(Vo))	P(V(Vo))	Ad1	Ad2	Ad3	Ad	Ad	Rin = R11
Hz	Amps	Degrees	Volts	Degrees	Volts	Degrees	Volts	Degrees	dB	dB	dB	dB	V/V	Ohm
100	2.45E-08	0.019001952	0.004677074	-0.489608015	14.8695787	179.0738634	14.86892312	179.0737932	7.38	70.05	0.00	77.42	7434.5	81757.3

Figure 1. Step 1.2 Data

(3) The non-inverting input of the op-amp is V_2 because its phase is 180 degrees which is the same as the output voltage phase (Figure 2).

Frequency	M(I(Q1:B))	P(I(Q1:B))	M(V(Vo1))	P(V(Vo1))	M(V(Vo2))	P(V(Vo2))	M(V(Vo))	P(V(Vo))
Hz	Amps	Degrees	Volts	Degrees	Volts	Degrees	Volts	Degrees
100	2.45E-08	0.019001952	0.004677074	-0.489608015	14.8695787	179.0738634	14.86892312	179.0737932

Figure 2. Step 1.2 Low Frequency

(4) The upper 3-dB frequency f_H is the frequency at which the amplitude becomes $\frac{1}{\sqrt{2}} = 0.707$ of its low frequency value, or the phase changes 45°. This gives us:

$$Phase_H = Phase_L - 45° = 135°$$
$$f_H = 6195\ Hz$$

Frequency	M(I(Q1:B))	P(I(Q1:B))	M(V(Vo1))	P(V(Vo1))	M(V(Vo2))	P(V(Vo2))	M(V(Vo))	P(V(Vo))
Hz	Amps	Degrees	Volts	Degrees	Volts	Degrees	Volts	Degrees
6195.540609	2.45E-08	1.175646	0.003657998	-19.81474959	10.51286942	134.9274319	10.51240373	134.9230843

Figure 3. Step 1.2 High Frequency

Q2. (5 Points)

Comparing the simulated differential-mode gain of Q1 Stage 1 and Lab 3 Q5 respectively…

$$A_{d1} = 7.38\ dB$$

$A_d = 70.07\ dB$

These two gains are different even though the differential amplifier is the same because Lab 4's differential amplifier uses negative feedback. Negative feedback expands the amplifier's bandwidth but causes a lower gain. This is seen by the feedback circuit-gain formula which represents both the amplifier and negative feedback circuit:

$$A_f = \frac{A}{1 + A\beta}$$

This shows us that the amplifier's gain A, decreases by a factor of $1 + A\beta$ when negative feedback is introduced.

Q3. (5 Points)

Based on the simulated results from Steps 1.2 and 1.3, the input and output resistance of the op-amp is,

$R_{in} = 81757.3\ \Omega$

$R_{out} = 460.9\ \Omega$

Rin = R11	Rout
Ohm	Ohm
81757.30322	460.8649365

Q4. (10 Points)

(1) Based on the simulated and measured results from Steps 1.6 and 1.13, the plots of the output voltage vs time characteristics at 1 kHz are included below,

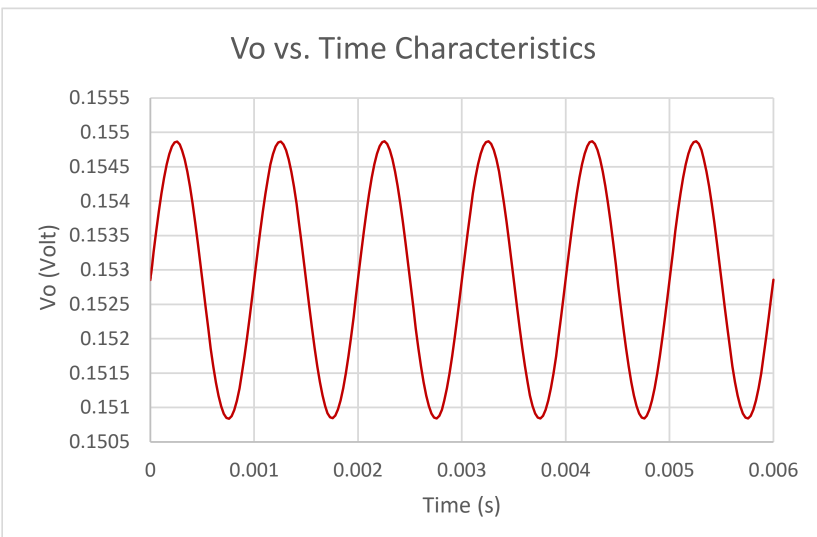


Figure 4. Step 1.6

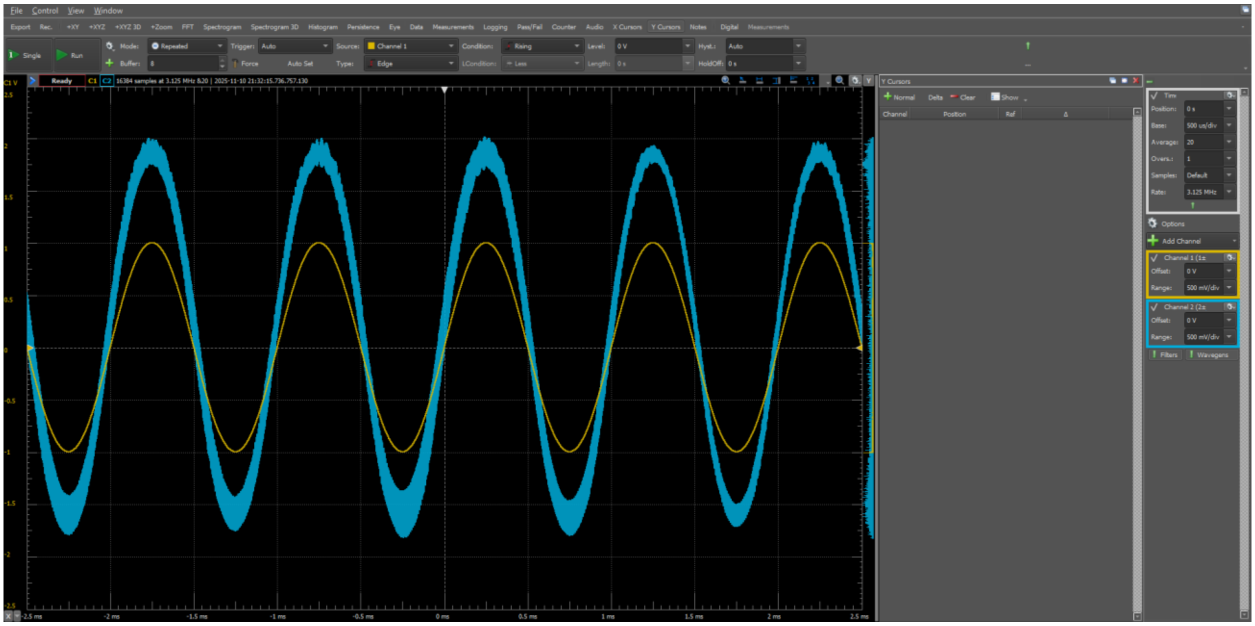


Figure 5. Step 1.13

(2) The simulated and measured peak-to-peak voltage, AC amplitude, and DC voltage of the output are,

Step 1.6	Step 1.13
$V_{pp} = 0.155 - 0.151 = 0.004\ V$	$V_{pp} = 2 - (-1.80) = 3.8\ V$
$V_p = \frac{V_{pp}}{2} = \frac{0.004}{2} = 0.002\ V$	$V_p = \frac{3.8}{2} = 1.9\ V$
$V_{dc} = V_{pp} - V_p = 0.155 - 0.002 = 0.153\ V$	$V_{dc} = 2.5 - 2 = 0.5\ V$

These results differ due to the different input AC amplitudes in Step 1.13 (1 V) and Step 1.6 (1 mV).

Q5. (10 Points)

(1) Based on the simulated and measured results from Steps 1.7 and 1.14, the plots of voltage gain magnitude and phase vs. frequency characteristics are included below,

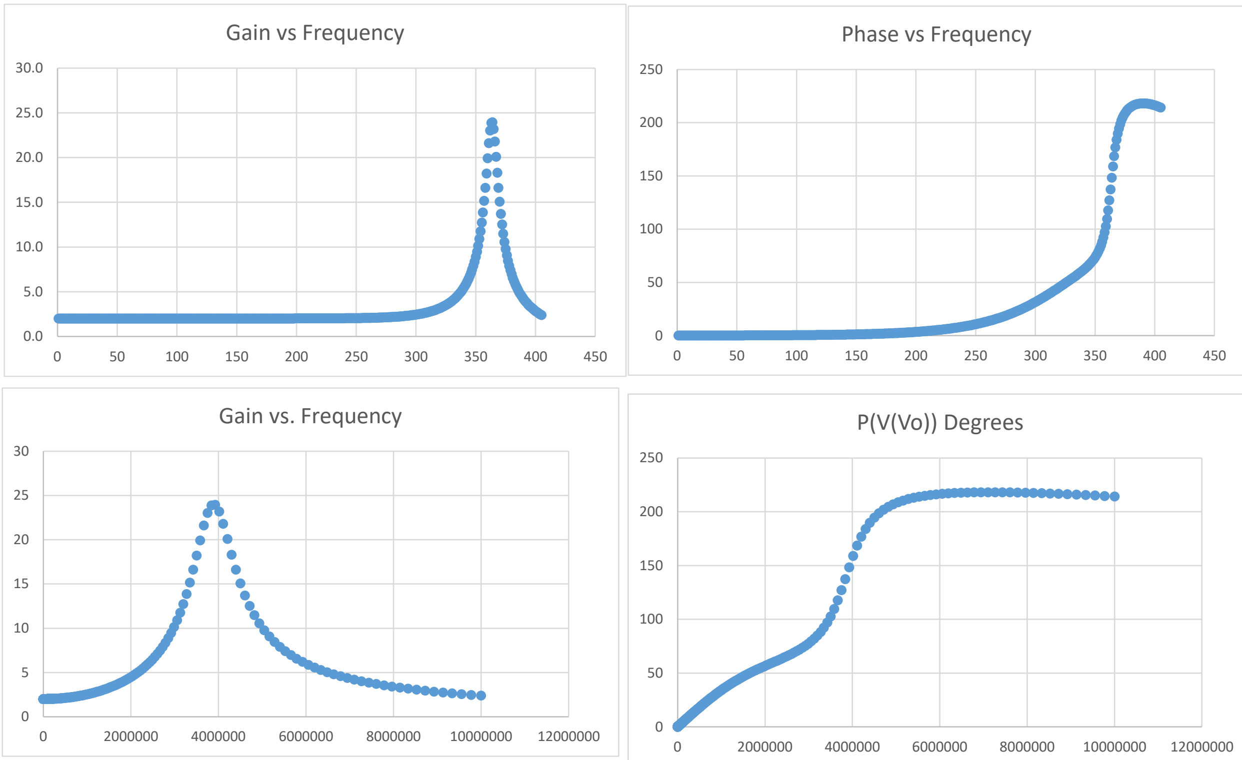


Figure 6. Step 1.7

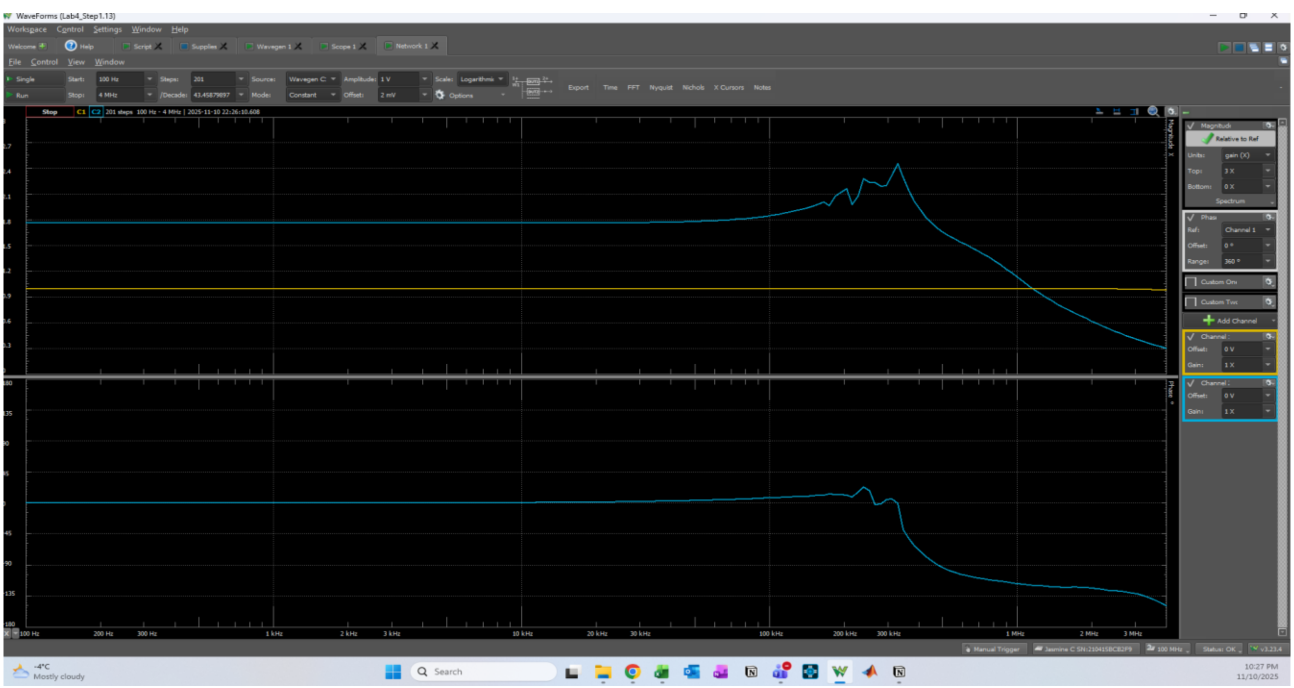


Figure 7. Step 1.14

The low-frequency gain of this amplifier is

$$A_L = 2\, V/V \ @\ f_L = \ 1000\ Hz \text{ (simulation)}$$

$$A_L = 1.77\, V/V \ @\ f_L = \ 100\ Hz \text{ (physical)}$$

Frequency	M(V(Vo))	P(V(Vo))	Av	Av
Hz	Volts	Degrees	V/V	dB
1000	0.002000074	0.036707517	2.0	6.0

Figure 8. Step 1.7 Gain

Frequency (Hz)	Channel1 (V1) Magnitude (X)	Channel2 (V2) Magnitude (X)	Channel2 (V2) Phase (°)	Av (V/V)
100	0.998363177	1.765116244	0.008656837	1.76801

Figure 9. Step 1.14 Gain

(2) To operate this amplifier, the highest operating frequency to provide a constant gain as designed can be observed as 100 kHz in Figure 7.

Q6. (5 Points)

The amplifier in Figure 2 has a series-shunt negative feedback configuration. This is because the input has no branch out, nor is it connected to a Common-base PNP BJT, which implies **Sum V_1 in <u>Series</u>** and the output probe is measuring the output voltage from the Load resistance to the ground, thus it is **Sense V_o in <u>Shunt</u>.** This can be seen in the figure 10 below:

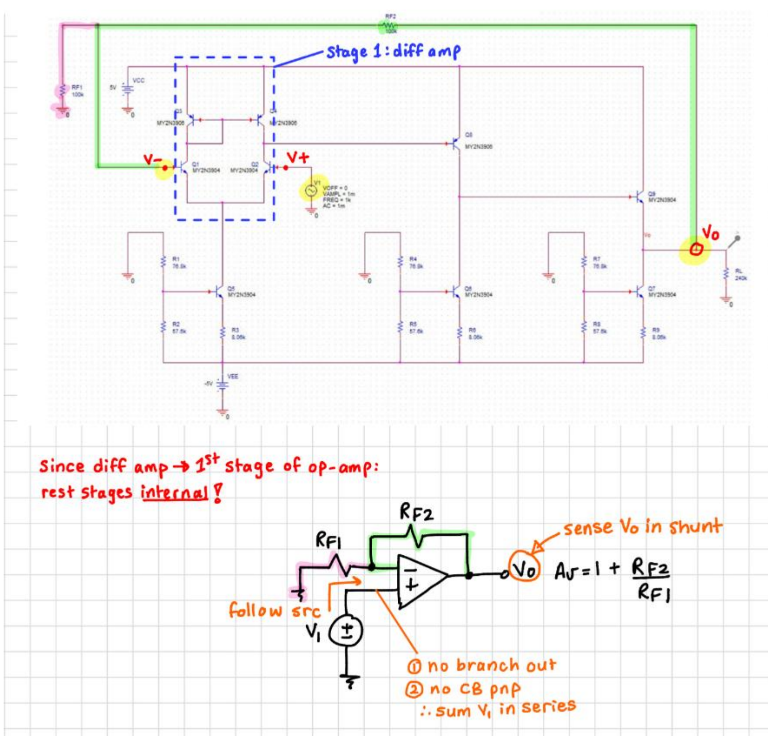


Figure 10. Multistage Op-amp Representation

Q7. (10 Points)

To find the Beta network, we must first separate the amplifier and the Beta network using the technique mentioned in class…

- For the **Sum V1 in <u>Series</u>** connection, we must cut the wire connected to the input feedback node, this represents port 1 of the Beta network.
- For the **Sense Vo in <u>Shunt</u>** connection, we must cut the feedback wire connected to the output node, this represents port 2 of the Beta network.

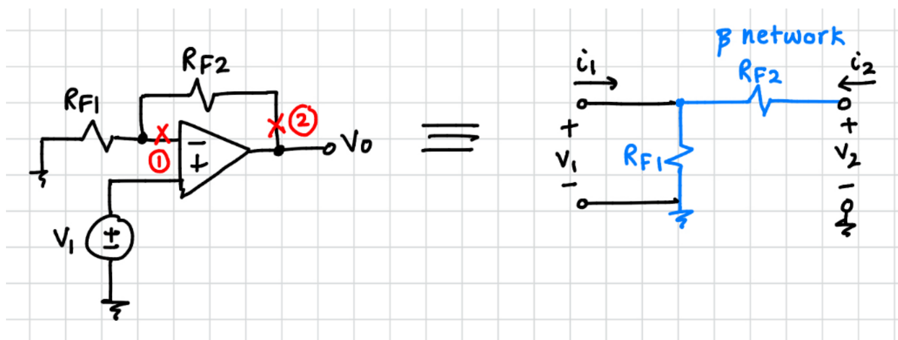


Figure 11. Separating Beta Network and Amplifier

In question 6 we determined that this is a series-shunt configuration, thus **series** implies there is a current excitation i_1 at port 1, and **shunt** implies a voltage excitation v_2 at port 2. This means the Beta network corresponds to the h-parameters:

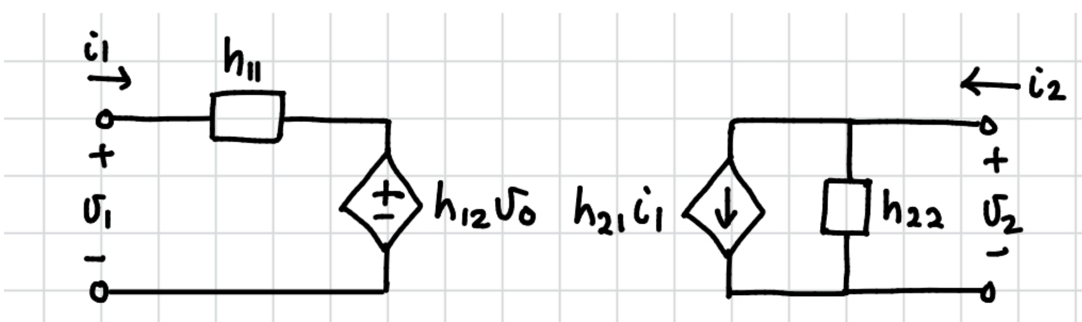


Figure 12. Two-Port Network h-parameter model

$$v_1 = h_{11}i_1 + h_{12}v_2$$

$$i_2 = h_{21}i_1 + h_{22}v_2$$

Using this information, we can find β, R_{11}, and R_{22} by replacing the beta network with the two port network model:

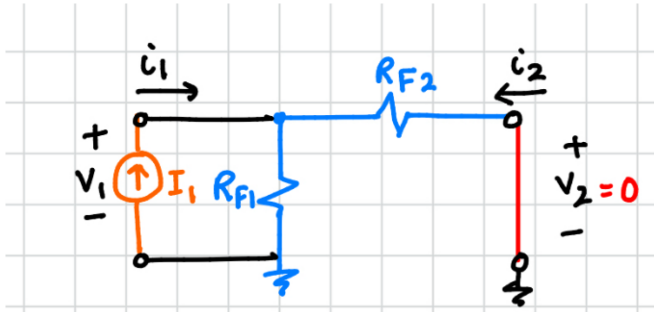


Figure 13. Circuit to find h11

$$h_{11} = \left.\frac{v_1}{i_1}\right|_{v_2=0} = R_{11}$$

$$v_1 = i_1(R_{F1} \| R_{F2})$$

$$\frac{v_1}{i_1} = R_{F1} \| R_{F2}$$

$$\therefore R_{11} = R_{F1} \| R_{F2} = 100k \| 100k = 50k$$

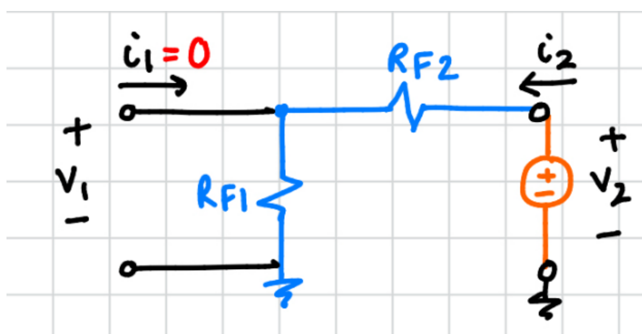


Figure 14. Circuit to find h12 and h22

$$h_{12} = \left.\frac{v_1}{v_2}\right|_{i_1=0} = \beta$$

$$v_1 = \frac{R_{F1}}{R_{F1} + R_{F2}} v_2$$

$$\frac{v_1}{v_2} = \frac{R_{F1}}{R_{F1} + R_{F2}}$$

$$\therefore \beta = \frac{R_{F1}}{R_{F1} + R_{F2}} = \frac{100k}{100k + 100k} = 0.5$$

$$h_{22} = \left.\frac{i_1}{v_2}\right|_{i_1=0} = \frac{1}{R_{22}}$$

$$i_2 = \frac{v_2}{R_{F1} + R_{F2}}$$

$$\frac{v_2}{i_2} = R_{F1} + R_{F2}$$

$$\therefore R_{22} = R_{F1} + R_{F2} = 100k + 100k = 200k$$

Q8. (15 Points)

We can determine the amplifier's voltage gain, input resistance and output resistance by using the amplifier's three parameter model, where h_{21} is negligible, R_{11} and R_{22} are disconnected from the Beta network and attached to the new amplifier circuit A';

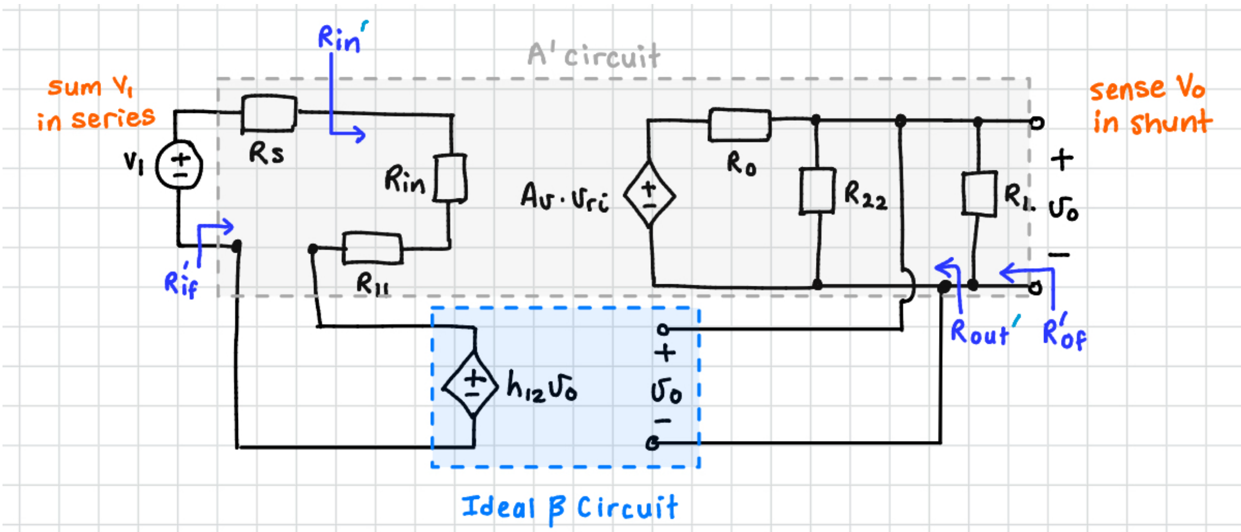


Figure 14. Three Parameter Model

The Simulated values are **bolded**:

1) $A'_{vf} = \frac{A'_v}{1+A'_v\beta} \approx \frac{1}{\beta} = \frac{1}{0.5} = 2\frac{V}{V}$

2) $A'_v = \frac{v_o}{v_1} = \frac{v_o}{v_{ri}} \times \frac{v_{ri}}{v_1}$ $\quad v_{ri} = \left(\frac{R_{in}}{R_{in}+R_{11}+R_s}\right)v_1$ $\quad v_o = \left(\frac{R_{22}\|R_L}{R_o+R_{22}\|R_L}\right)A_v v_{ri}$

$$A'_v = \boldsymbol{A_v}\left(\frac{R_{22}\|R_L}{\boldsymbol{R_o} + R_{22}\|R_L}\right) \times \left(\frac{\boldsymbol{R_{in}}}{\boldsymbol{R_{in}} + R_{11} + R_s}\right)$$

$$= \mathbf{7434.5}\left(\frac{200k\|240k}{\mathbf{0.4609k} + 200k\|240k}\right) \times \left(\frac{\mathbf{81.7573k}}{\mathbf{81.7573k} + 50k + 0}\right)$$

$$= 4595.6$$

3) $R'_{in} = \boldsymbol{R_{in}} + R_{11} + R_s = (\mathbf{81.7573k\Omega} + 50k + 0) = 131.7573k\Omega$

4) $R'_{inf} = (1 + A'_v\beta)R'_{in} = \big(1 + (4595.6\,)(0.5)\big)(131.7573k) = 302.9M\Omega$

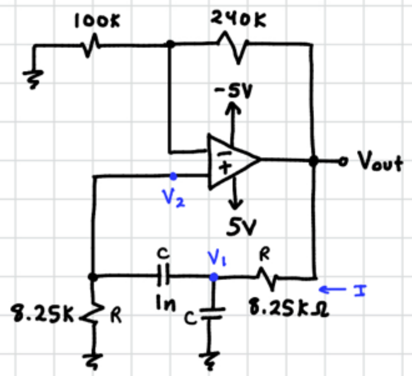
5) $R'_o = \boldsymbol{R_o}\|R_{22}\|R_L = \mathbf{460.9}\|200k\|240k = 458.9\Omega$

6) $R'_{of} = \frac{R_o'}{1+A'_v\beta} = \frac{458.9}{(1+(4595.6\,)(0.5))} = 0.2\ \Omega$

Part 2: Positive Feedback Circuit – Oscillator

Q9. (15 Points)

For the oscillator circuit, its Loop Gain, frequency for the zero-loop phase, and R_2/R_1 for oscillation are derived below,



$R_3 = R_4 = R = 8.25k\Omega$

$C_1 = C_2 = C = 1nF$

$L(s) = \left(1 + \frac{R_2}{R_1}\right)\frac{V_2}{V_o}$

① $V_o - IR = V_1$ ② $V_1 = V_2 + \frac{V_2}{R}\left(\frac{1}{sCR}\right) = V_2\left(1 + \frac{1}{sCR}\right)$

③ $I = \frac{V_2}{R} + V_2\left(1 + \frac{1}{sCR}\right)sC$

$$\therefore V_o = V_2\left(1 + \frac{1}{sCR}\right) + V_2 R\left[\frac{1}{R} + sC\left(1 + \frac{1}{sCR}\right)\right]$$

$$V_o = V_2\left(1 + \frac{1}{sCR}\right) + V_2(2 + sCR)$$

$$\frac{V_2}{V_o} = \frac{s/CR}{s^2 + s\left(\frac{3}{CR}\right) + \left(\frac{1}{CR}\right)^2}$$

$$\boxed{L(s) = \left(1 + \frac{R_2}{R_1}\right)\frac{s/CR}{s^2 + s\left(\frac{3}{CR}\right) + \left(\frac{1}{CR}\right)^2}}$$

④ Zero Loop Phase: $\omega_o = \frac{1}{CR} = \frac{1}{1nF \times 8.25K}$

$$\boxed{\omega_o = 121.2kHz}$$

⑤ $L(j\omega) = \left(1 + \frac{R_2}{R_1}\right)\frac{j\omega/CR}{-\omega^2 + j\omega\left(\frac{3}{CR}\right) + \left(\frac{1}{CR}\right)^2} \geq 1$ $\frac{1}{(CR)^2} - \omega^2 = 0$

$$\therefore L(j\omega) = \left(1 + \frac{R_2}{R_1}\right)\frac{\cancel{j\omega}/\cancel{CR}}{\cancel{j\omega}\left(\frac{3}{\cancel{CR}}\right)} \geq 1$$

$$L(j\omega) = \frac{1}{3}\left(1 + \frac{R_2}{R_1}\right) \geq 1$$

$$\therefore \boxed{\frac{R_2}{R_1} \geq 2}$$

Q10. (5 Points)

Based on the simulated results in Step 2.4, the settling times for $R_2 = 220\ k\Omega, 240\ k\Omega$, and $280\ k\Omega$ are,

$$R_2 = 220\ k\Omega \rightarrow 1.77 \text{ ms}$$
$$R_2 = 240\ k\Omega \rightarrow 0.921 \text{ ms}$$
$$R_2 = 280\ k\Omega \rightarrow 0.480 \text{ ms}$$

R2 = 220 kΩ	R2 = 240 kΩ	R2 = 280 kΩ
Settling Time (ms)	Settling Time (ms)	Settling Time (ms)
1.7701	0.921001	0.480497

Figure 13. Step 2.4 Data

The observed trend is that resistance and settling time are inversely proportional. As the resistance increases from 220 to 280 $k\Omega$, the settling time decreases from 1.77 to 0.48 ms. This relationship can be explained by the equation derived in question 10:

$$L(s) = \left(1 + \frac{R_2}{R_1}\right) \frac{s/CR}{s^2 + s\left(\frac{3}{CR}\right) + \left(\frac{1}{CR}\right)^2}$$

It is clear that L(s) is proportional to R2. If R2 increases, so will L(s). A higher loop-gain shifts the dominant pole of the circuit to a higher frequency, which reduces the settling time.

Q11. (10 Points)

(1) Based on the setup in Steps 2.3, 2.5, 2.8, and 2.9, the plots of the simulated and measured output voltages are included below,

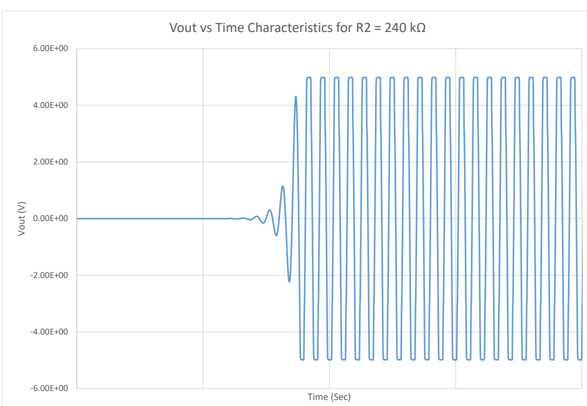


Figure 14. Step 2.3

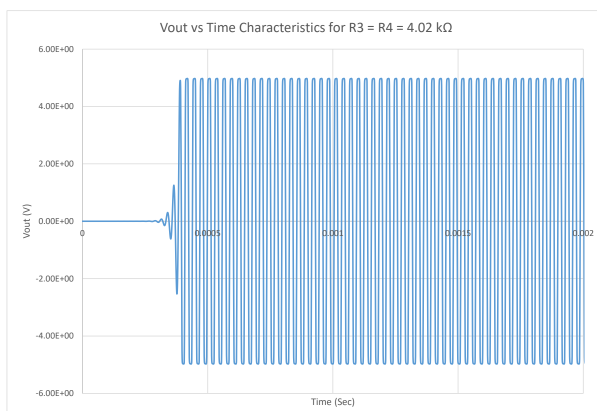


Figure 15. Step 2.5

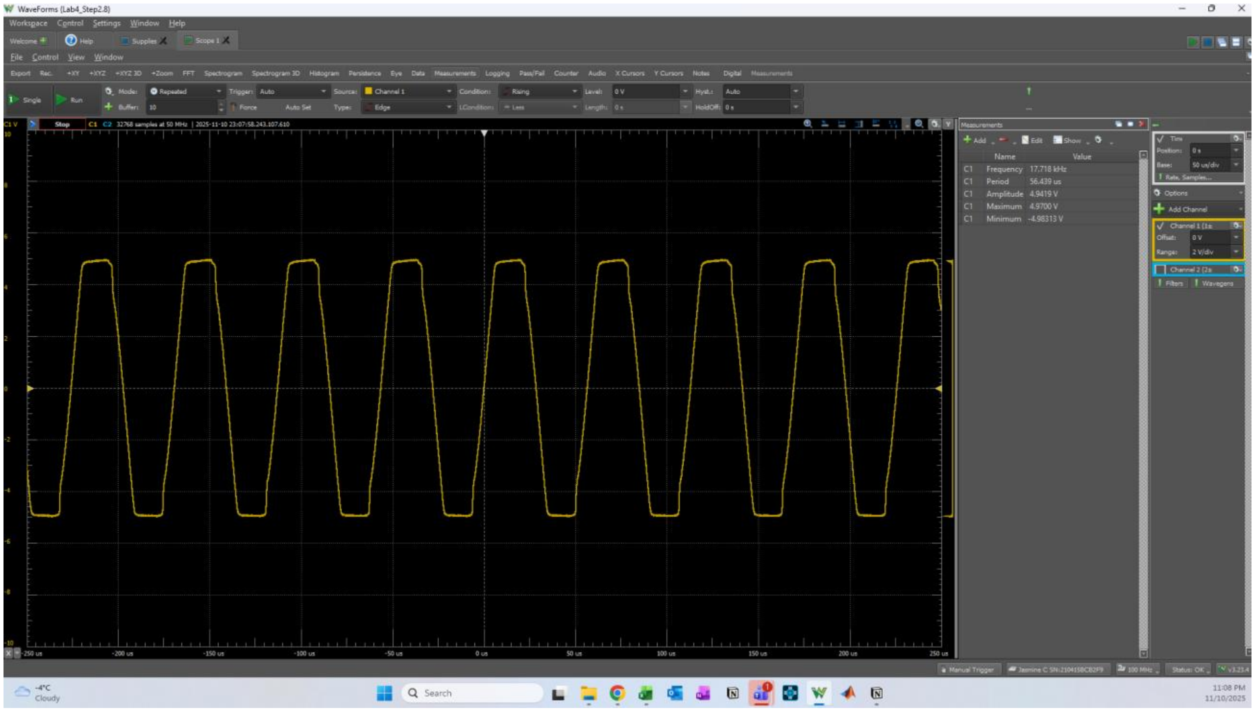


Figure 13. Step 2.8

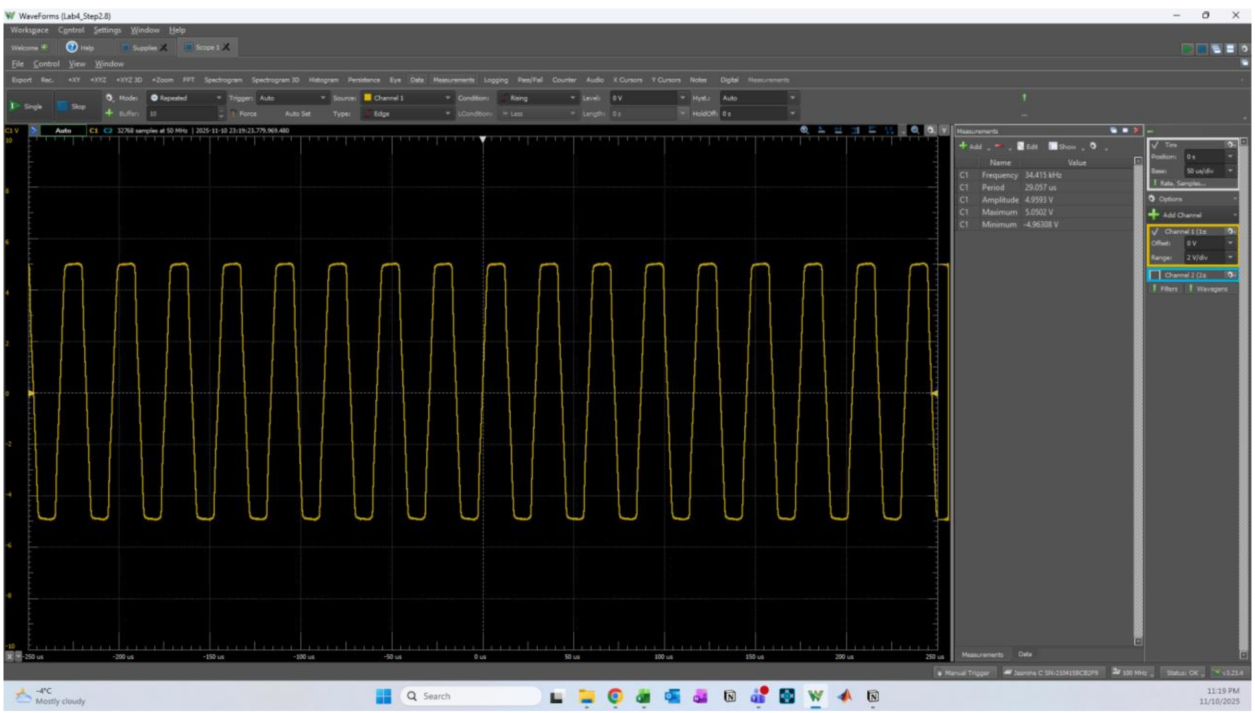


Figure 14. Step 2.9

(2) Step 2.3: $f = \frac{1}{T} = 18\ k\text{Hz}$

Step 2.5: $f = \frac{1}{T} = 34\ k\text{Hz}$

Step 2.8: $17.718\ k$Hz

Step 2.9: $34.415\ k$Hz

The measured values above are similar to the simulated values. From Question 9, we know that $\omega = 1/CR$, showing that frequency and resistance are inversely proportional. Decreasing $R_3 = R_4 = 8.25\ k\Omega$ to $4.02\ k\Omega$, we approximately half the resistance, and as seen above, we nearly double the frequency from 18 to 34 kHz.