Lab 4

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ELECENG 3EJ4

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Part 1: Negative Feedback Amplifier

Q1.
At 100 Hz, the voltage gains in dB are:
$A_{d1} = 7.38$, $A_{d2} = 70.05$, $A_{d3} = 0$
The overall voltage gain of the differential-mode signal is 77.43 dB or 7434.5 V/V.

	A	J	K	L	M	N
1	Frequency	Ad1	Ad2	Ad3	Ad	Ad
2	Hz	dB	dB	dB	dB	V/V
3	100	7.38	70.05	0.00	77.43	7434.5

Figure 1: Gain values obtained in Step 1.2 at 100 Hz

The non-inverting input of the opamp is V_2. This is because when V_2 is positive, current flows from V_{o1} to AC ground through the current mirror load, meaning V_{o1} is positive, and when V_2 is negative, current flows from AC ground to V_{o1} through the current mirror load, meaning V_{o1} is negative.

The upper 3-dB frequency is 6195.54 Hz.

	A	J	K	L	M	N
1	Frequency	Ad1	Ad2	Ad3	Ad	Ad
2	Hz	dB	dB	dB	dB	V/V
184	6195.540609	5.24	69.17	0.00	74.41	5256.2

Figure 2: Upper 3-dB frequency of the amplifier

Q2.
The simulated differential-mode gain A_{d1} is 7.38 dB and the simulated gain A_d from the same differential amplifier in Lab 3 is 70.07 dB. The gain is significantly lower when the same amplifier is placed in a multistage configuration because the output impedance of the differential amplifier is much higher than the input impedance of the common-emitter amplifier at the next stage. This voltage division causes the output of the differential amplifier at the first stage to lose its gain.

Q3.
The input resistance R_{in} is 81.7573 kOhms and the output resistance R_o is 460.9 Ohms.

Rin = R11	Rout
Ohm	Ohm
81757.3	460.9

Figure 3: Input and output resistance measured and calculated in Steps 1.2 and 1.3

Q4.

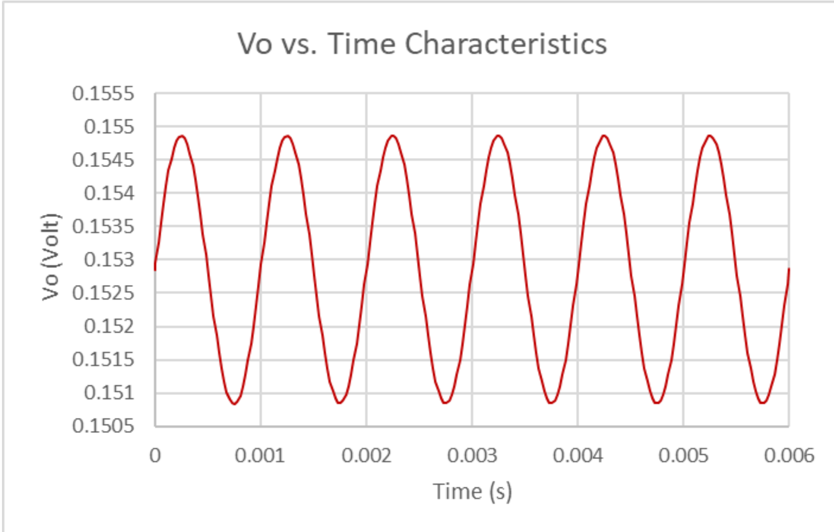


Figure 4: Simulated plot for V_o vs. time characteristics at 1 kHz

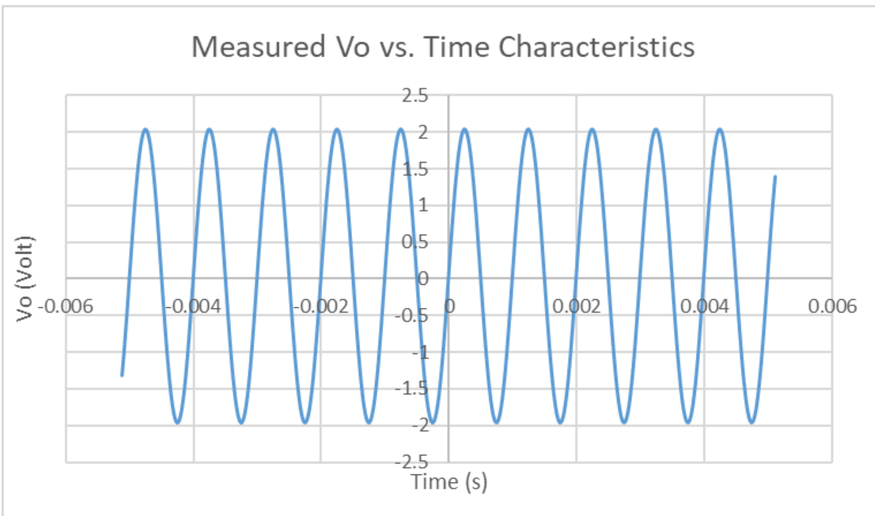


Figure 5: Measured plot for V_o vs. time characteristics at 1 kHz

The following figures show the peak-to-peak voltage V_{pp}, the AC amplitude V_p and the dc voltage V_{dc}, calculated using functions in excel. V_{pp} = max - min, $V_p = V_{pp} / 2$ and V_{dc} = (max + min) / 2.

Max	Min	Vpp	Vp	Vdc
0.15487	0.150837	0.004033	0.002017	0.152854

Figure 6: Simulated V_{pp}, V_p and V_{dc} values. All values are in volts.

Max	Min	Vpp	Vp	Vdc
2.04065	-1.96832	4.00897	2.00449	0.03617

Figure 7: Measured V_{pp}, V_p and V_{dc} values. All values are in volts.

The peak to peak voltage of the simulated circuit is 4mV and of the measured circuit is 4V. The AC amplitude V_p of the simulated circuit is 2mV and of the measured circuit is 2V. These numbers make sense and show that both the simulated and measured circuit behave similarly. This is because the simulated circuit had an input AC amplitude of 1mV and the measured circuit had an input AC amplitude of 1V. Both the simulated and measured circuits have a gain of 2V/V. Where the simulated and measured circuits differ is in the dc voltage V_{dc}. The measured circuit had a dc voltage of 0.03617V, close enough to zero to allow the output AC signal to swing both positive and negative. The simulated circuit had a dc voltage of 152.854 mV, and with V_p being 2mV, the output signal does not swing both positive and negative. The output signal of the simulated circuit swings from 150.837 mV to 154.87 mV. This is because in practical conditions, Vout is not zero when both inputs are zero due to a mismatch in the differential amplifier. The DC offset was adjusted in the measurement but was not adjusted in the simulation.

Q5.

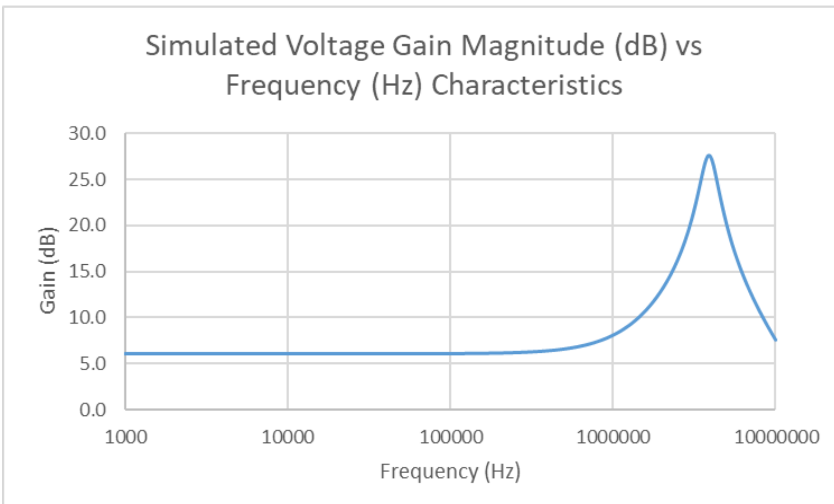


Figure 8: Simulated gain magnitude vs frequency characteristics from Step 1.7

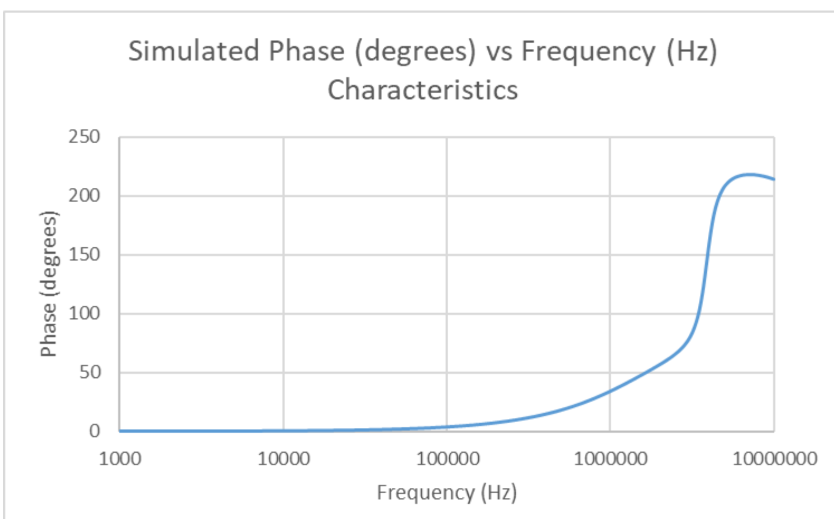


Figure 9: Simulated phase vs frequency characteristics from Step 1.7

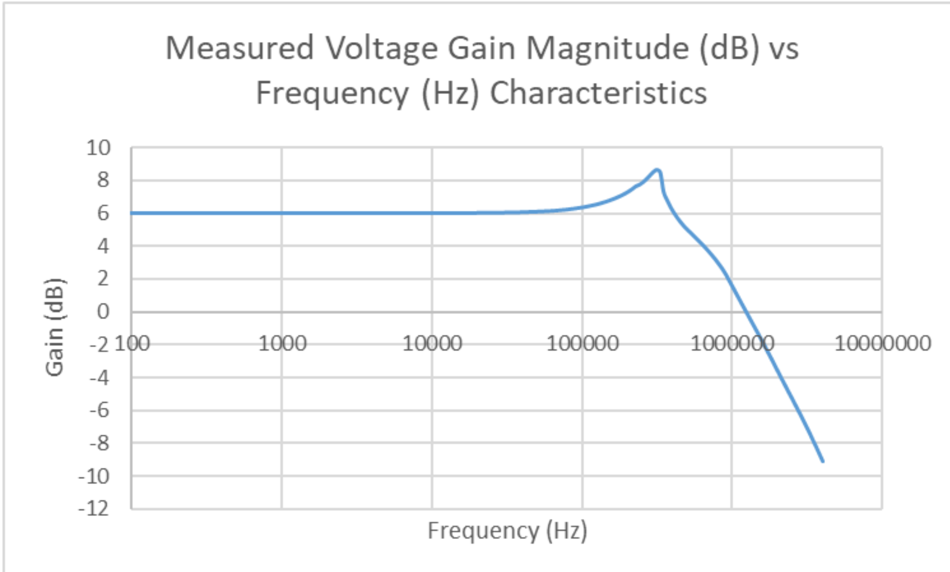


Figure 10: Measured gain magnitude vs frequency characteristics from Step 1.14

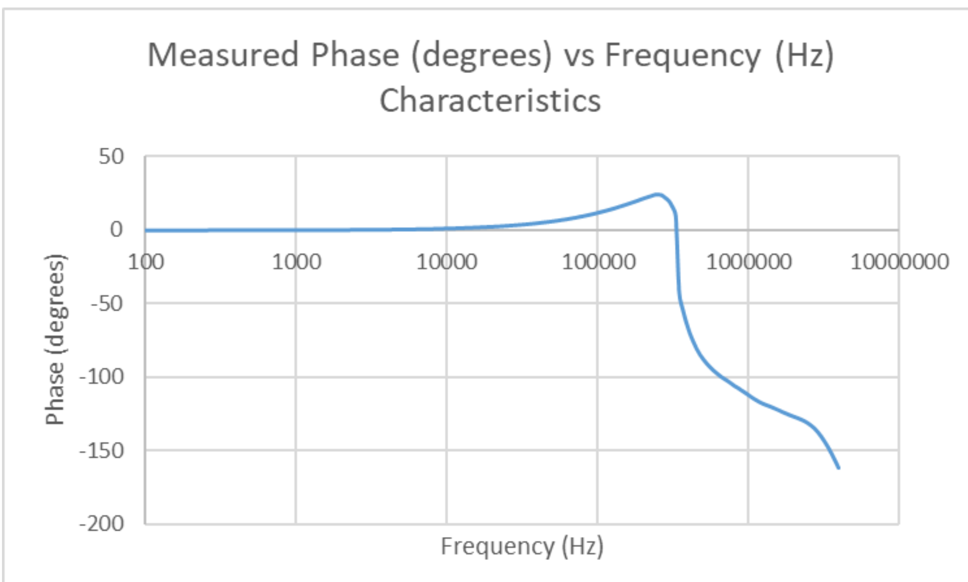


Figure 11: Measured phase vs frequency characteristics from Step 1.14

The low-frequency gain of this amplifier, consistent in both the simulation and measurement, is 2 V/V or 6 dB. To provide a constant gain of 2 V/V or 6 dB, the highest operating frequency is around 100kHz for the simulation and 40kHz for the measurement.

1	Frequency	M(V(Vo))	P(V(Vo))	Av	Av
209	109547.8757	0.002005897	4.017841469	2.0	6.0
210	112074.0201	0.002006169	4.110329692	2.0	6.0
211	114658.4168	0.002006454	4.204939154	2.0	6.0
212	117302.4089	0.002006752	4.301717984	2.0	6.0
213	120007.3707	0.002007064	4.400715278	2.0	6.1
214	122774.7083	0.00200739	4.50198127	2.0	6.1
215	125605.8599	0.002007732	4.60556729	2.0	6.1

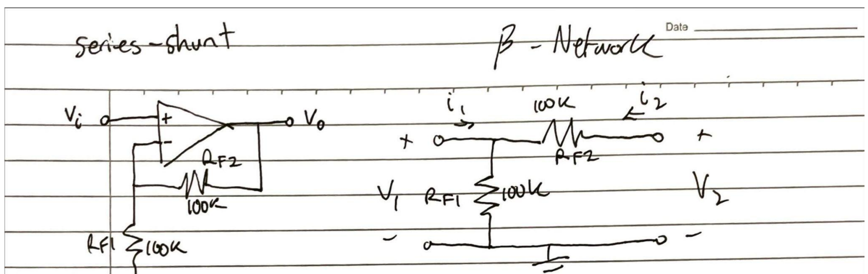
Figure 12: Highest operating frequency to provide a constant gain (simulation)

	A	B	C	D	E	F
1	Frequency (Hz)	Channel 1 Magnitude (X)	Channel 2 Magnitude (X)	Channel 2 Phase (°)	Av (V/V)	Av (dB)
111	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
112	33972.92929	1.006123833	2.007404354	4.145639149	2.007404	6.052697
113	35821.46103	1.005902037	2.008419578	4.369648516	2.00842	6.057089
114	37770.57489	1.005620983	2.009700558	4.603879836	2.009701	6.062627
115	39825.74376	1.006526583	2.011186693	4.849357043	2.011187	6.069048
116	41992.73826	1.006939008	2.012562179	5.12621954	2.012562	6.074986
117	44277.64307	1.007079921	2.014507148	5.403561278	2.014507	6.083376
118	46686.87389	1.007338121	2.015933654	5.702112704	2.015934	6.089525
119	49227.19555	1.007414787	2.018534242	5.963288228	2.018534	6.100722

Figure 13: Highest operating frequency to provide a constant gain (measurement)

Q6.
The amplifier in Fig. 2 has a series-shunt feedback configuration. This is because at the input, it sums voltages (voltage sources in series add up), and at the output, it senses voltage (like how a voltmeter connects in shunt to measure voltage).

Q7.
For the beta network, R_{11} is 50k Ohms, R_{22} is 200k Ohms, and beta is 0.5. Work is shown in the photo below.



Series input : i_1 excitation variable

Shunt output : V_2 excitation variable

∴ Use h-parameter

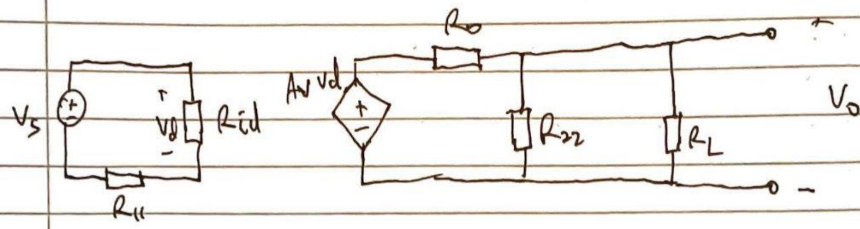
$R_{11} = h_{11} = \frac{V_1}{i_1}\Big|_{V_2=0} = R_{F1} // R_{F2} = 100k // 100k = \boxed{50K\Omega}$

$R_{22} = \frac{1}{h_{22}} = \frac{V_2}{\cancel{V}i_2}\Big|_{i_1=0} = R_{F1} + R_{F2} = 100k + 100k = \boxed{200k\Omega}$

$\beta = h_{12} = \frac{V_1}{V_2}\Big|_{i_1=0} = \frac{R_{F1}}{R_{F1}+R_{F2}} = \frac{100k}{100k+100k} = \boxed{0.5}$

Q8.
The input resistance is 302.8 MegOhms, output resistance is 0.1997 Ohms, and the amplifier's voltage gain is 2V/V. Work is shown in the photo below.

Sum V in series sense V in shunt



$$A_v' = \frac{V_o}{V_s}$$

$$V_o = \frac{R_{22} // R_L}{R_{22}//R_L + R_o} \times A_v V_d$$

$$V_d = \frac{R_{id}}{R_{id} + R_{11}} \times V_s$$

$$V_o = \frac{R_{22}//R_L}{R_{22}//R_L + R_o} \times A_v \times \frac{R_{id}}{R_{id} + R_{11}} \times V_s$$

$R_o' = R_o // R_{22} // R_L$

$= 460.9 // 200k // 240k$

$= 458.96$

$$R_{of}' = \frac{R_o'}{(1 + A_v'\beta)} = \frac{458.96}{1 + 4593.8 \times 0.5}$$

$= 0.1997\,\Omega$

$R_{of}' = R_{out} // R_L = R_{out}$ (Because $R_L >> R_{out}$)

$\boxed{R_{out} = 0.1997\,\Omega}$

$$A_v' = \frac{V_o}{V_s} = A_v \times \frac{R_{22}//R_L}{R_{22}/R_L + R_o} \times \frac{R_{id}}{R_{id} + R_{11}}$$

$$= 7434.5 \times \frac{200k // 240k}{200k // 240k + 460.9} \times \frac{81757.3}{81757.3 + 50k}$$

$= 4593.8$ V/V

$$A_{vf}' = \frac{A_v'}{1 + A_v'\beta} \approx \frac{A_v'}{A_v'\beta} = \frac{1}{\beta} = \frac{1}{0.5} = \boxed{2}$$

(Because $A_v'\beta >> 1$)

$R_i' = R_{id} + R_{11} \rightarrow R_{if} = R_i'(1 + A_v'\beta) = (R_{id} + R_{11})(1 + A_v'\beta)$

$= (81757.3 + 50k)(1 + 4593.8 \times 0.5)$

$= \boxed{302.8\ M\Omega}$

<u>Part 2</u>: Positive Feedback Circuit – Oscillator

Q9.

$$L(s) = A \cdot \beta \qquad A = \left(1 + \frac{R_2}{R_1}\right)$$

$$\beta = \frac{V_f}{V_o}$$

$$= \frac{\left(R + \frac{1}{sC}\right) // \frac{1}{sC}}{\left(R + \frac{1}{sC}\right) // \frac{1}{sC} + R} \times \frac{R}{R + \frac{1}{sC}}$$

$$= \frac{\cancel{R + \frac{1}{sC}}}{\cancel{R} + \frac{1}{sC\cancel{R}} + sR^{\cancel{2}}C + 2\cancel{R}} \times \frac{\cancel{R}}{\cancel{R + \frac{1}{sC}}}$$

$$= \frac{1}{sRC + \frac{1}{sRC} + 3}$$

$$L(s) = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{1}{sRC + \frac{1}{sRC} + 3}\right)$$

Zero phase shift occur at $w = w_0 = \frac{1}{CR}$:

$$|L(jw)| = \frac{1}{3}\left(1 + \frac{R_2}{R_1}\right)$$

For oscillations to begin:

$$\frac{1}{3}\left(1 + \frac{R_2}{R_1}\right) \geq 1$$

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

Q10.
The settling times for R2 = 220k Ohms, 240k Ohms, and 280k Ohms are 1.83ms, 0.92ms and 0.49ms, respectively.

	A	B	C
1	R2 = 220 kΩ	R2 = 240 kΩ	R2 = 280 kΩ
2	Settling Time (ms)	Settling Time (ms)	Settling Time (ms)
3	1.826150126	0.92379358	0.488883088

Figure 14: Settling times from Step 2.4

It can be noticed that as R2 increases, the settling time decreases. This is because as R2 increases, the loop gain increases, causing V_{out} to reach the saturation voltage faster, decreasing the settling time.

Q11.

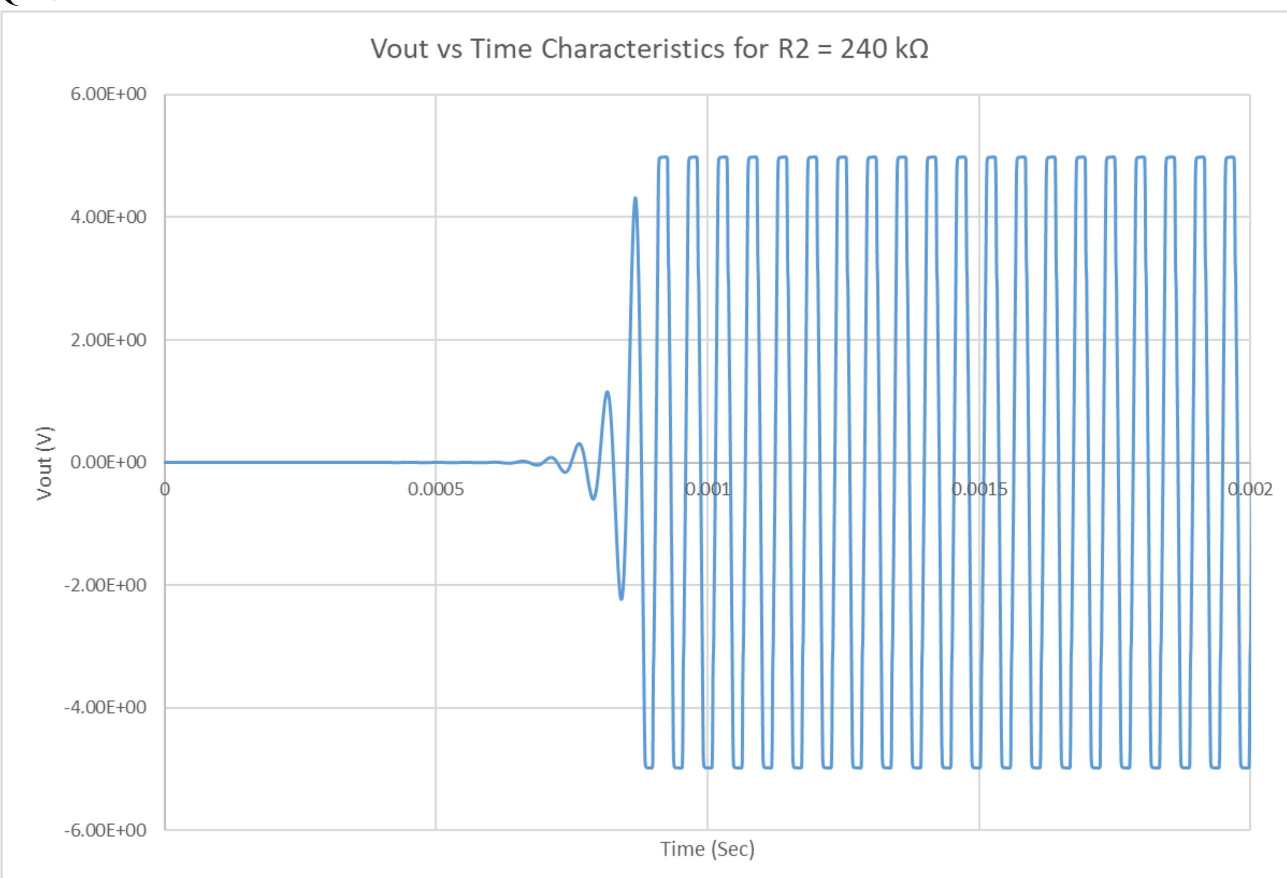


Figure 15: Simulated plot of Vout vs Time from Step 2.3, R3=R4=8.25k

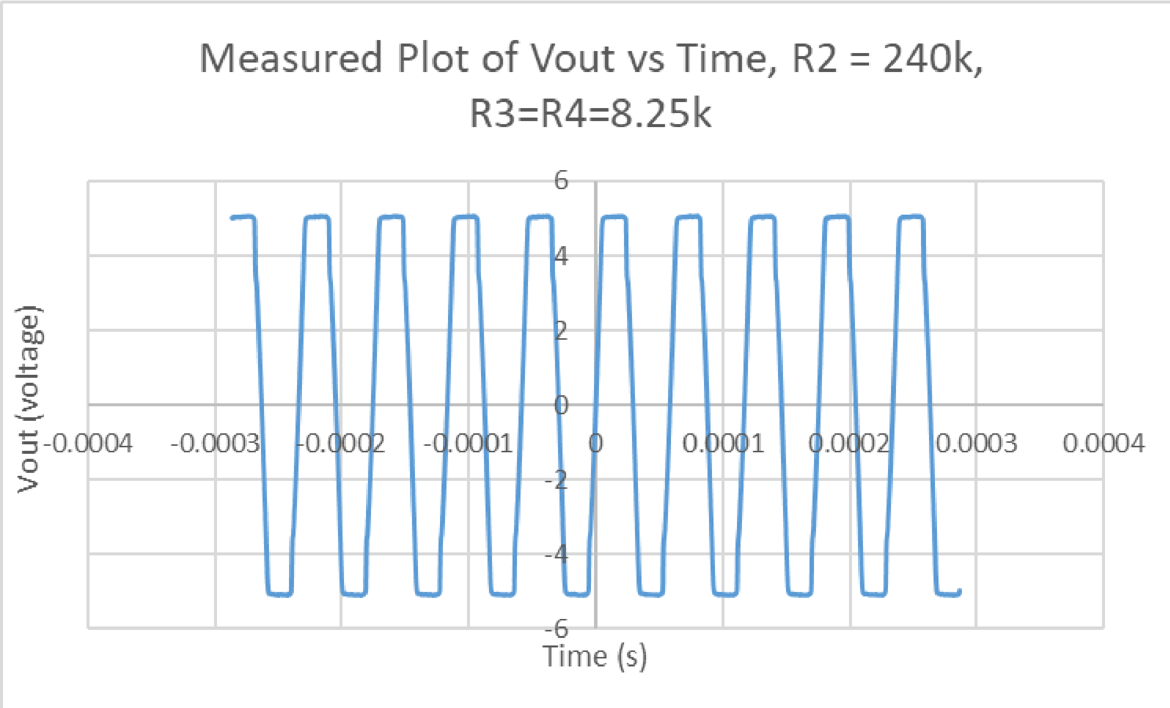


Figure 16: Measured plot of Vout vs Time from Step 2.8

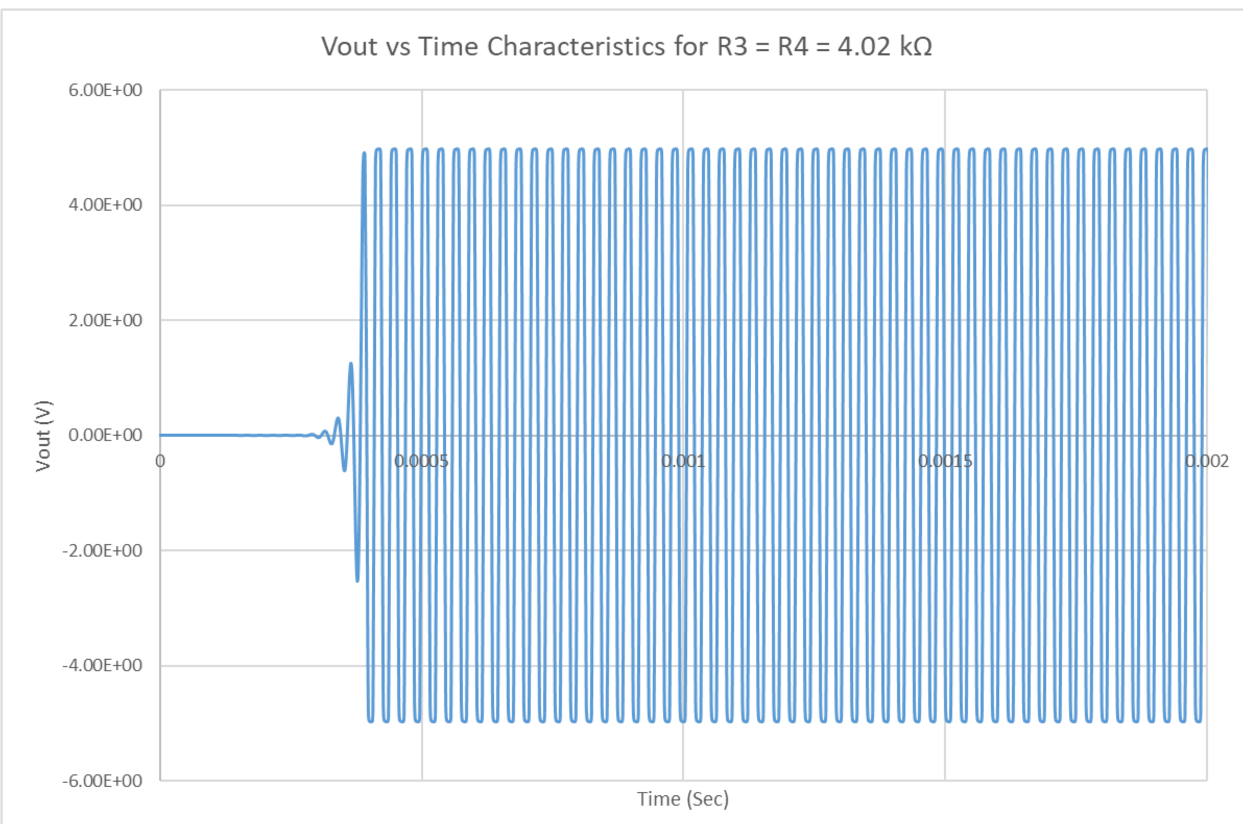


Figure 17: Simulated plot of Vout vs Time from Step 2.5, R2=240k

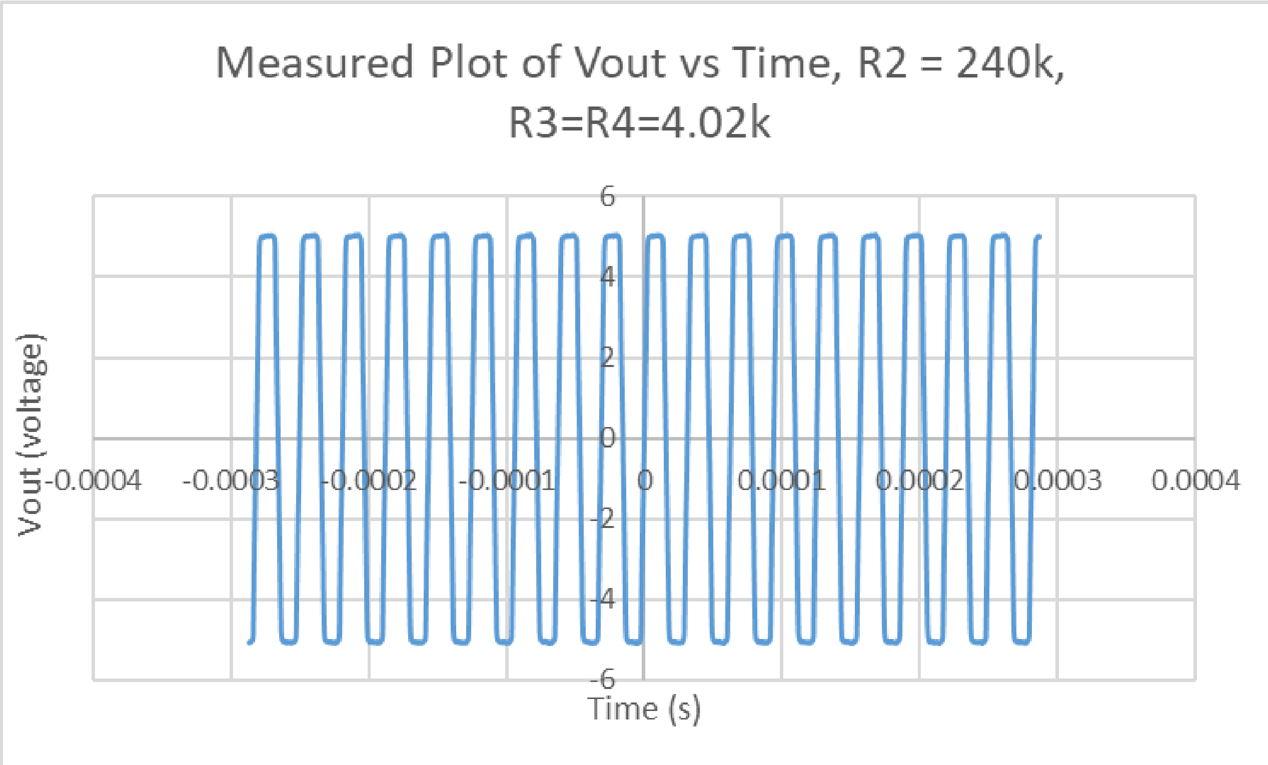


Figure 18: Measured plot of Vout vs Time from Step 2.9

Time for 1 period	Frequency
5.43862E-05	18387.02

Figure 19: Frequency of simulated plot from Step 2.3

Frequency	17.087 kHz
Period	58.523 us

Figure 20: Frequency of measured plot from Step 2.8

Time for 1 period	Frequency
2.981E-05	33545.84

Figure 21: Frequency of simulated plot from Step 2.5

Frequency	31.979 kHz
Period	31.271 us

Figure 22: Frequency of measured plot from Step 2.9

The frequencies from the measurement were calculated in Waveforms and the frequencies from the simulation were calculated by examining the data points to find the period of the wave, then taking 1/T to obtain the frequency.

The frequencies from the measurements and simulation align almost perfectly. With R=8.25k, the simulation had a frequency of 18.4 kHz and the measurement had a frequency of 17.1 kHz. With R=4.02k, the simulation had a frequency of 33.5 kHz and the measurement had a frequency of 32.0 kHz.

The operating frequency of an amplifier with R3=R4=R=8.25k Ohms and C=1nF is:
$w_o = 1/(CR)$
$f = w_o / (2*pi) = 1/(CR*2*pi) = 19.3$ kHz

The operating frequency of an amplifier with R3=R4=R=4.02k Ohms and C=1nF is:
$f = 1/(CR*2*pi) = 39.6$ kHz

Both the simulation and measurement produced frequencies very similar to the theoretical frequencies.