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Mini Project 4

University of British Columbia

Electrical and Computer Engineering

ELEC 301

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0 Introduction

For this project, we will be using Multisim to simulate active filters and oscillators.

1 Part A

1.0.1 Part 1

For this part, we will be designing a 2nd order Butterworth low pass active filter using the UA741 operational amplifier. Here is the circuit that we will be using for this part:

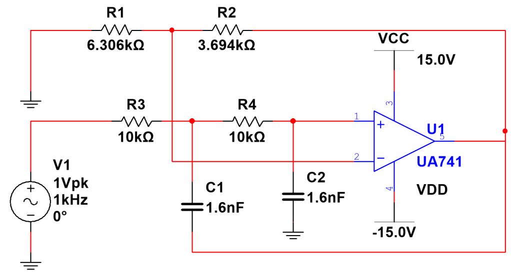

Figure 1: Second Order Butterworth Filter

The calculations to find the resistance R_1,R_2 and capacitance C, we will be using the formulas from the class notes [1]. The formulas can also be found from no. 1 in the Appendix. From the formulas, we can see that

$$\boxed{R_1 = 6.306k\Omega, R_2 = 3.694k\Omega, C = 1.6nF, A_m = 1.59\frac{V}{V}}$$

Below is the phase and magnitude plot for our filter:

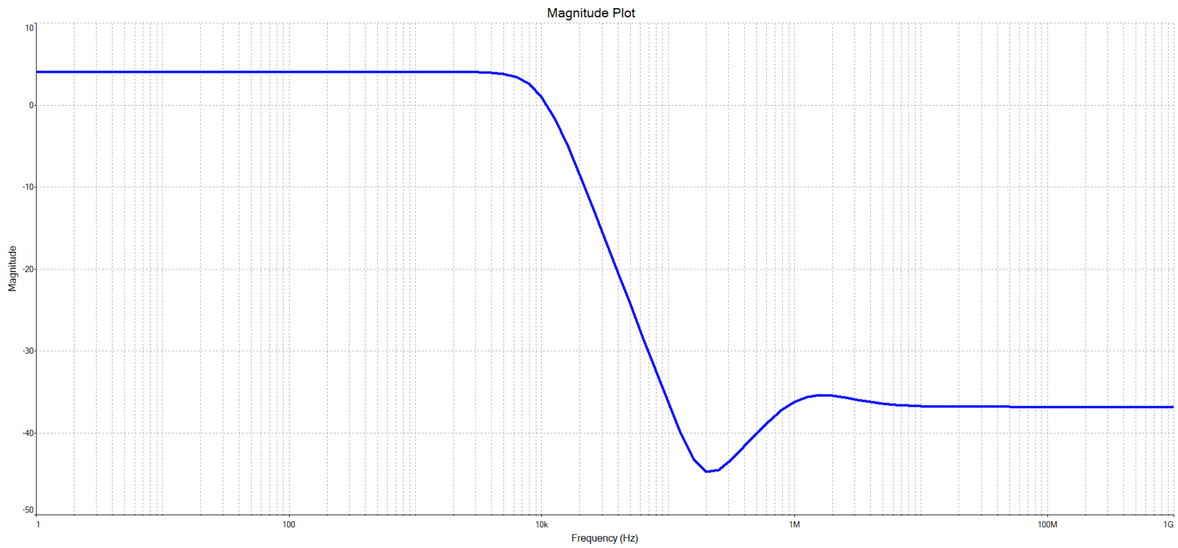

Figure 2: Bode Magnitude Plot

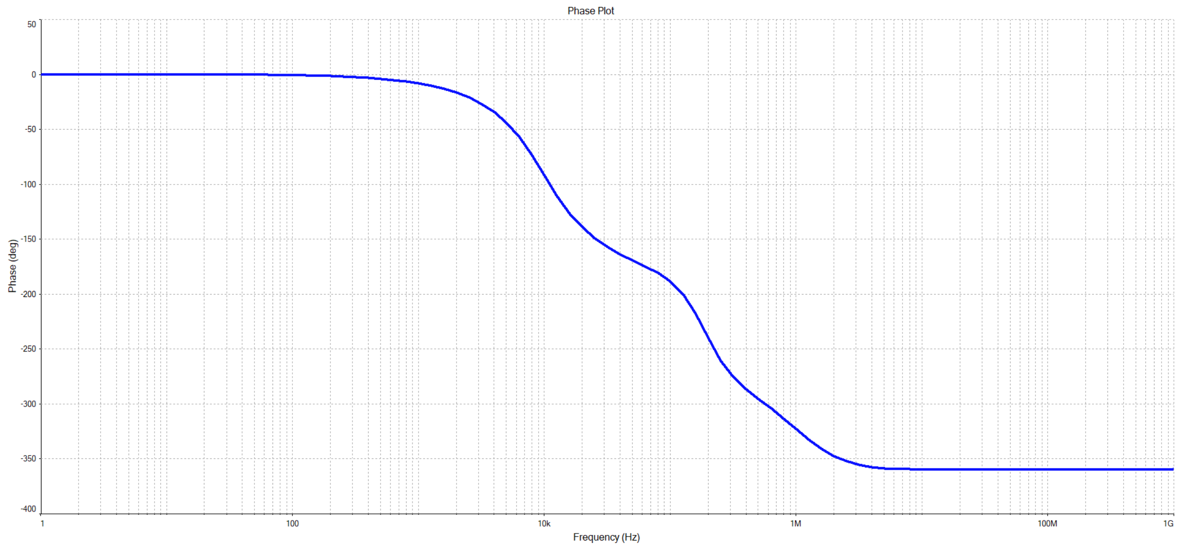

Figure 3: Bode Phase Plot

1.0.2 Part 2

For this part, we will be grounding the input, and measuring the output of the OpAmp. To determine the value of A_m when the circuit begins to oscillate, we need the transfer fucntion. The function is shown below, where R = $10k\Omega$ and C is the value found previously:

$$H(s) = A_M \frac{\frac{1}{(RC)^2}}{s^2 + s\frac{3-A_M}{RC} + \frac{1}{(RC)^2}}$$

Changing the values of the resistances, we find that the oscillations occour when the resistor values are around$R_1 = 3k\Omega$ and $R_2 = 7k\Omega$. The oscillation is shown below:

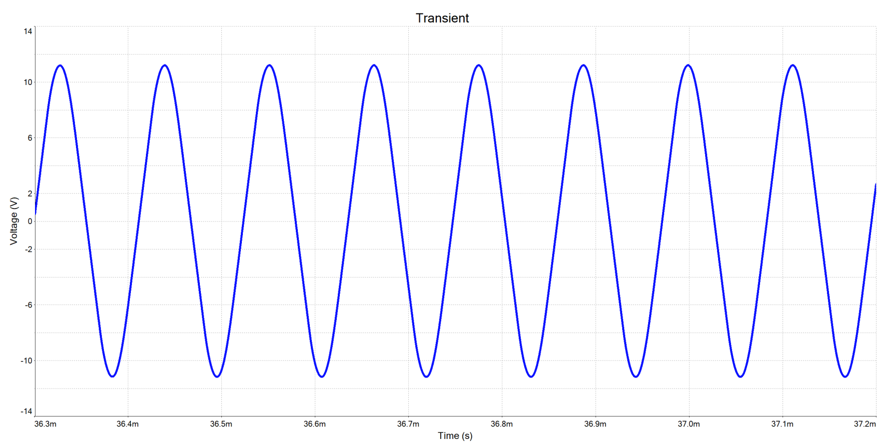

Figure 4: Oscillating Output

Using the cursors and measuring the differences between the crests of the plot, we find that the oscillating frequency is $\boxed{f_o = 8.93kHz}$. Below is the root locus plot:

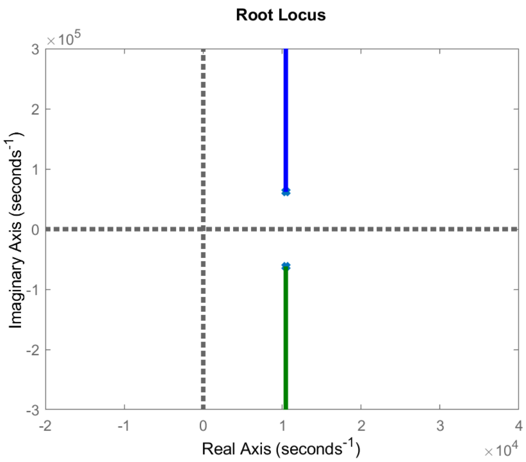

Figure 5: Unstable Root Locus Plot

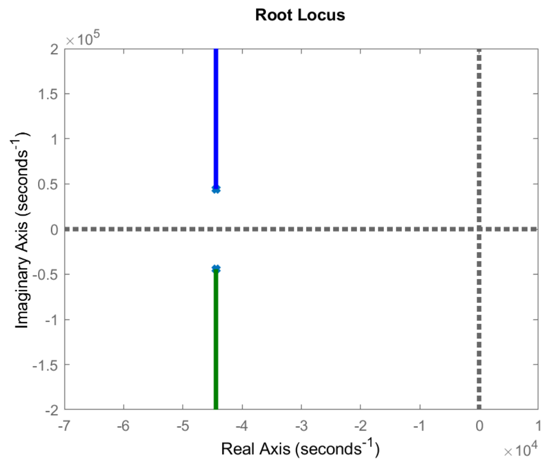

Figure 6: Stable Root Locus Plot

The root locus plot where $A_M > 3$ and $A_M < 3$ is Figure **??** and Figure **??** respectively. We can see from the plot that when the oscillations occour, A_M is greater than 3. This would then cause the system to be unstable as shown in Figure **??**, since the poles are on the right side on the jw axis. When the poles are on the other side of the jw axis, the system is stable, and doesn't cause the output to oscillate. This happens when $A_M < 3$. The reason why it has to be less than 3 for the system to be stable is because of the characteristic equation in the transfer function. If A_M is equal or greater than 3, it causes one of the coefficients in the characteristic equation to be negative, causing instability in the system and thus, the oscillations occour.

2 Part B

Below is our phase shift oscillator circuit:

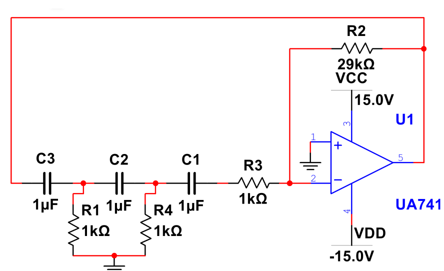

Figure 7: Phase Shift Oscillator Circuit

To find the proper value of the 29R resistor, we will simulate the output response for a very large amount of time (in this case, 1000 seconds was used). Simulating with just $29k\Omega$ we find that the output amplitude eventually decays to zero. Increasing the resistor to $29.1k\Omega$ makes the output amplitude to be sustained indefinitely.

Plotting the output of the circuit with the values given in the project document [2] and the increased 29R resistor , we find that the output oscillates as shown:

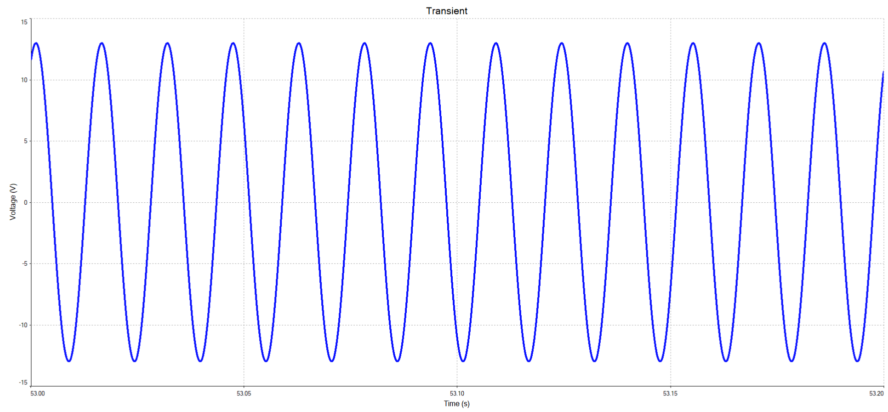

Figure 8: Circuit Output With Unchanged Circuit Elements

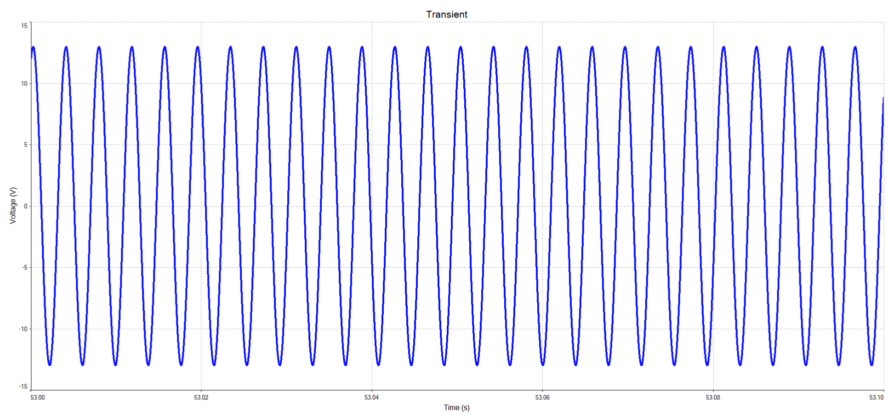

Figure 9: Circuit Output With Half Circuit Elements

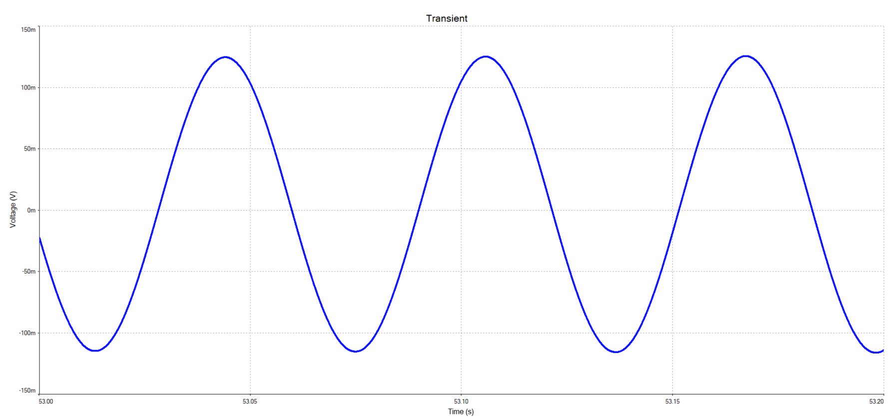

Figure 10: Circuit Output With Double Circuit Elements

From class notes[1], we can calculate the output frequency with:

$$f = \frac{1}{2\pi RC\sqrt{6}}$$

Comparing the calculated and measured frequencies for each modified circuit:

R and C Multiplier	0.5x	1x	2x
Calculated $f_o(Hz)$	259.899	64.975	16.244
Measured $f_o(Hz)$	259.067	64.872	16.221
% Error	0.32	0.15	0.14

Table 1: Calculated and Measured Frequencies

We can observe that the calculated and measured values are very close to each other.

3 Part C

Below is our Feedback Circuit:

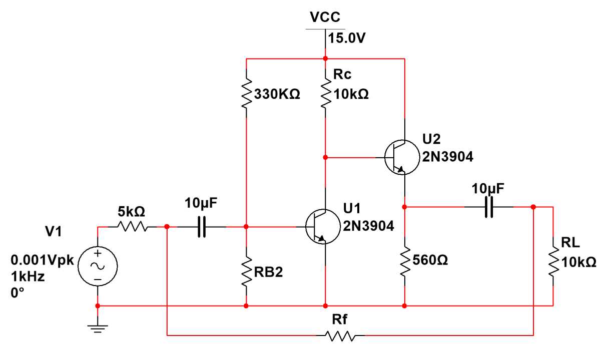

Figure 11: Feedback Circuit

Since we want to find the value of R_{B2} that creates the largest open-loop gain at 1kHz, we will be setting our input voltage at 1kHz at 1mV. To find the value, we will be doing a parameter sweep with a transient response to find which resistance value results in the largest gain. We find that after doing the parameter sweep, the value R_{B2} to be around $\boxed{20k\Omega}$. Resistance values above $20k\Omega$, we find that the output amplitude decreases. The paramater sweep is shown below:

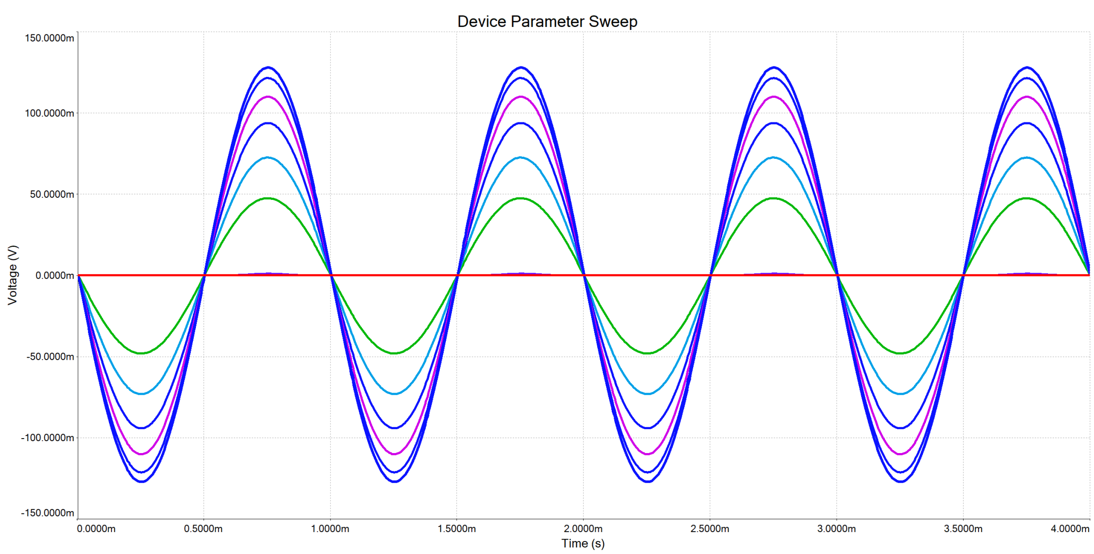

Figure 12: Parameter Sweep with R_{B2} and Transient Response

3.1 Part 1

To measure the DC Operating points, we will be using the DC Circuit below:

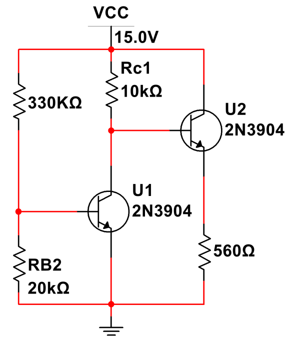

Figure 13: Feedback DC Circuit

For this project, we will be assuming that V_T= 0.025V. We can use these formulas to calculate our transistor parameters:

$$r_\pi = \frac{V_T}{I_B}, \beta = \frac{I_C}{I_B} \text{ and } g_m = \frac{\beta}{r_\pi}$$

Here are the DC Operating points, with our measured r_π, g_m, and h_{FE}:

	I_C	I_B	I_E	V_C	V_B	V_E	g_m	r_π	h_{FE}
Q1	1.29mA	10.8uA	1.31mA	1.90V	0.654V	0V	0.05	2.315kΩ	119
Q2	2.19mA	15.4uA	2.21mA	15V	1.90V	1.23V	0.09	1.623kΩ	142

Table 2: DC Operating Points

3.2 Part 2

3.2.1 Finding Measured Open Loop Frequency Responce and I/O Impedance

Here is the open loop frequency response plot:

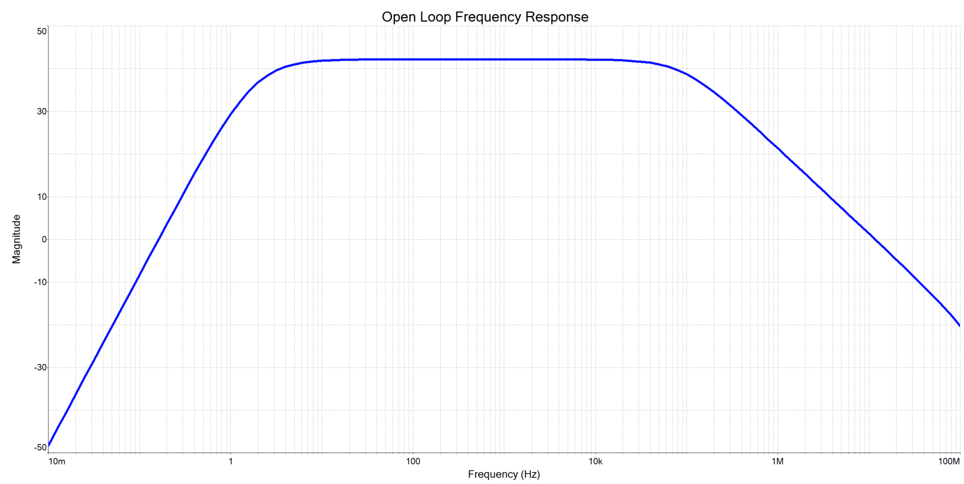

Figure 14: Open Loop Frequency Response

Measuring with the cursors in our simulation software, we find that the 3dB points are:

$$\boxed{w_{L3dB} = 2.9219 * 2\pi[\frac{rad}{s}], w_{H3dB} = 91.3083 * 2\pi * 10^3[\frac{rad}{s}]}$$

We can also find our mid-band gain $\boxed{A_m = 127.557\frac{V}{V}}$. In order to find the input and output resistance at 1kHz, we will be measuring the voltage and current at the input, and we will be adding a test source at the output and grounding the input for the output impedance measurements. After measuring, we find:

$$R_{in} = \frac{240\mu V}{93.4nA} = \boxed{2.569k\Omega}, \ R_{out} = \frac{707\mu V}{11.4\mu A} = \boxed{62.017\Omega}$$

3.2.2 Predicted Closed Loop Frequency Response

For this section, we will need to calculate our circuit parameters and input and output resistance at 1kHz with $R_f = 100k\Omega$. To do this, we need to know our circuit's topology. Since the output is sampled by R_f and mixes the current from the output into the input, we can determine that our feedback circuit uses shunt-shunt topology. Due to this, we will be using y-parameters to perform our calculations. Below is the y-parameter matrix we will be using:

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix}$$

In this case, we only need our β value from our y-parameters, therefore we can just solve for that value

3.2.3 Gain Calculations

Since our circuit is in shunt-shunt topology, our open-loop will be $\frac{V_{out}}{I_{in}}$. Therefore, we need to convert our input to the amplifier from a voltage source to a current source. To do this, we will be transforming our source from a voltage source in series with our source resistance to a current source in parallel to our source resistance. Doing this, our resulting input current is $\boxed{I_{in} = \frac{V_s}{5k\Omega}}$. So we find our open loop gain to be:

$$A' = \frac{V_{out}}{I_{in}} = \frac{V_{out}}{\frac{V_s}{5k\Omega}} = \frac{V_{out}}{V_s}(5k\Omega) = 127.557\frac{V}{V} * (5k\Omega) = \boxed{637.786k\frac{V}{A}}$$

Now, we are able to find our gain with feedback. The formula used can be found in the class notes[1]. It is found as:

$$A_f = \frac{A'}{1 + \beta A'} = 86.446k\frac{V}{A}$$

Since the units we need is $\frac{V}{V}$ we convert our input to a voltage source, and this can be done by dividing A_f by $5k\Omega$. After doing this, we find $\boxed{A_f = 17.289\frac{V}{V}}$. Which is our closed loop gain.

3.2.4 3dB Calculations

To calculate the w_{3dBf} (3dB frequencies with feedback), we can use the following formulas from the class notes[1]. The frequencies are found to be:

$$w_{Hf3dB} = (w_{H3dB})(1 + A^{'}\beta) = (91.308k * 2\pi)(1 + \frac{1}{100k\Omega}637.786k\frac{V}{A}) = \boxed{4233.189k\frac{rad}{s}}$$

$$w_{Lf3dB} = \frac{w_{L3dB}}{1 + A'\beta} = \frac{2.9219 * 2\pi}{1 + \frac{1}{100k\Omega}(637.786k\frac{V}{A})} = \boxed{2.488\frac{rad}{s}}$$

3.2.5 Input and Output Resistance Calculations

To calculate our input and output resitance values with feedback, we can use our open loop resistance values and formulas[1] to calculate the values we eventually find:

$$R_{if} = \frac{R_{in}}{1 + A'\beta} = \frac{2.569k\Omega}{1 + \frac{1}{100k\Omega}(637.786k\frac{V}{A})} = \boxed{348.204\Omega}$$

$$R_{of} = \frac{R_{out}}{1 + A'\beta} = \frac{62.017\Omega}{1 + \frac{1}{100k\Omega}(637.786k\frac{V}{A})} = \boxed{8.406\Omega}$$

Here is our closed loop frequency response curve:

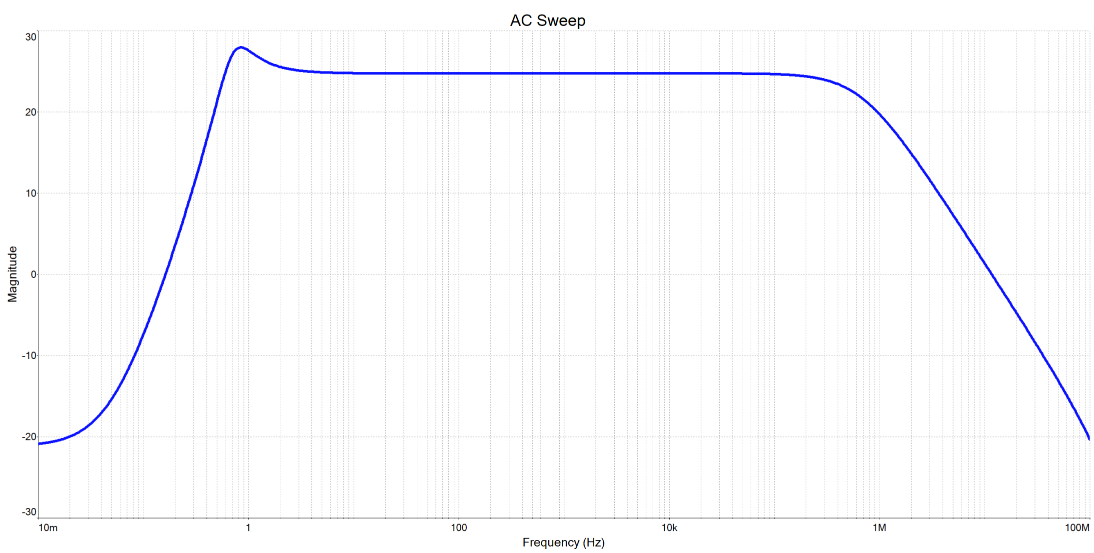

Figure 15: Closed Loop Frequency Response

From this, we can measure the following values:

	w_{L3dB}	w_{H3dB}	R_{in}	R_{out}	A_M
Measured	3.221$[\frac{rad}{s}]$	4257.361k$[\frac{rad}{s}]$	240.7Ω	8.456Ω	17.248$\frac{V}{V}$

Table 3: Measured Feedback Values

Comparing the measured values and the calculated values, we can see that the calculated values are accurate to the measured values.

3.3 Part 3

From the bottom most trace, the values of R_f are increasing for each increasing curve. Here is all of the different bode plots of various R_f values:

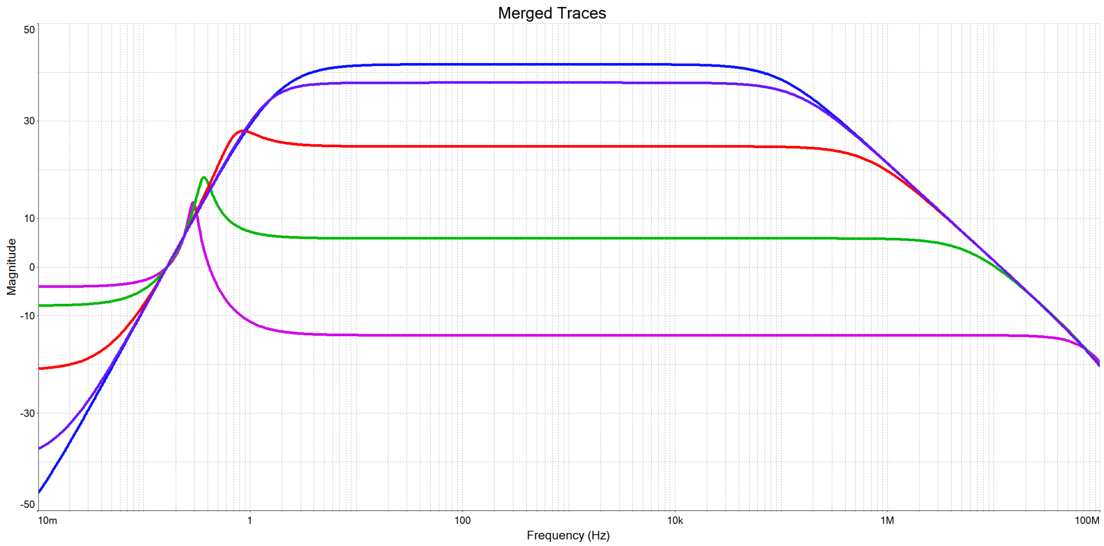

Figure 16: Closed Loop Frequency Response with Different R_f Values

Comparing the values as shown in the previous part, all of the estimates are close to the measured values.

3.3.1 Part 4

4 Appendix

$$k = 3 - \sqrt{2} \tag{1}$$

$$\tag{2}$$

5 References

1. ELEC 301 Class notes
2. Mini Project 4 Document
3. Standard Resistor and Capacitor Values (Canvas)
4. Circuit Maker SPICE Model