ELEC 301: Electronic Circuits

Mini Project 4: Active Filters, Oscillators, and Feedback Amplifiers

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1. Introduction

This final project report outlines the process of wiring up and testing a 2nd order active filter, a phase-shift oscillator, and a feedback circuit, using a simulator. We strengthen our understanding of the fundamental principles involved in the designs of these circuits, as given in the ELEC 301 course. Part A introduces an active filter, with which a 2nd order Butterworth filter is created. Different gain values are tested to measure the oscillation frequency. In Part B, we wire a phase shift oscillator and explain its functioning. We calculate its oscillating frequency using given equations taught in class. Finally, Part C consists in testing and simulating a feedback circuit. A two-stage cascaded transistor amplifier, a common-emitter amplifier in cascade with a common-collector amplifier, is used as the basic amplifier, with a resistive network used as the feedback network.

2. Objective

The objective of this mini project is to strengthen our understanding of the basic operation of active filters and oscillators. The characteristics of feedback amplifiers are also explored through computer based circuit simulation tools.

3. Project

3.1 Part A: An Active Filter

This part consists in building an active filter using a UA741 as the op-amp and a 15V power supply as shown in Figure 1.1.

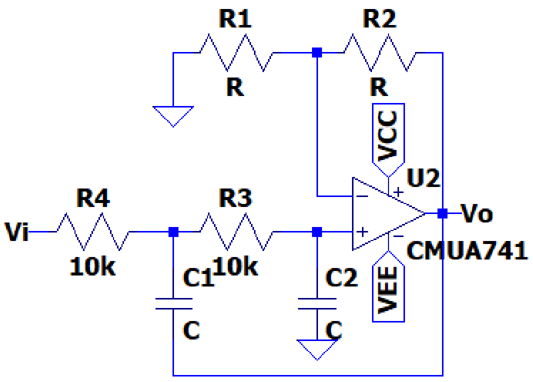

Figure 1.1: Active Filter

The filter's transfer function is given as $H(s) = A_M \frac{1/(RC)^2}{s^2+s\frac{3-A_M}{RC}+\frac{1}{(RC)^2}}$ where A_M is the pass-band gain given by $A_M = 1 + R_2/R_1$. This transfer function has two poles.

1. Creating a 2nd Order Butterworth filter

By varying A_M, the damping ratio can be controlled to make the poles complex. By placing the poles at specific locations, a 2nd order Butterworth filter can be created. The denominator of the transfer function can be represented in the form of $s^2 + 2\zeta\omega_n s + \omega_n^2$ where $\zeta = \frac{3-A_M}{2}$ is the damping constant, and $\omega_n = \frac{1}{RC}$ is the system's undamped natural frequency. As the filter's desired 3dB frequency is 10 kHz, we use $10kH = \frac{1}{RC}$ where R = $10\ k\Omega$ to solve for $C = 1.6\ nF$. To create a 2nd order Butterworth filter. the poles must be 45 degrees apart from the negative imaginary axis as shown in Figure 1.2.

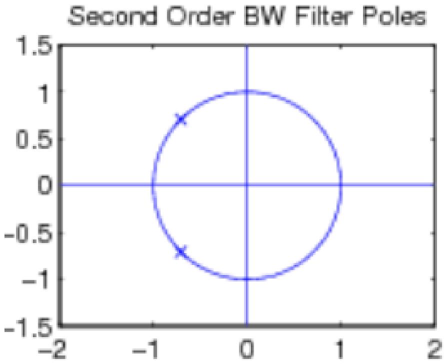

Figure 1.2: 2nd Order Butterworth Filter Poles

Therefore, the Butterworth polynomials corresponding to a 2nd order filter are $s^2 + \sqrt{2}s + 1$. Using $\sqrt{2} = \frac{3-A_M}{2}$, we can solve for $A_M = 1.586$. The corresponding resistors are found using $A_M = 1 + R_2/R_1$ and $R_1 + R_2 = 10\ k\Omega$, as $R_1 = 3.868\ k\Omega$ and $R_2 = 6.132\ k\Omega$. A magnitude and phase bode plot can be plotted using these values as shown in Figure 1.3.

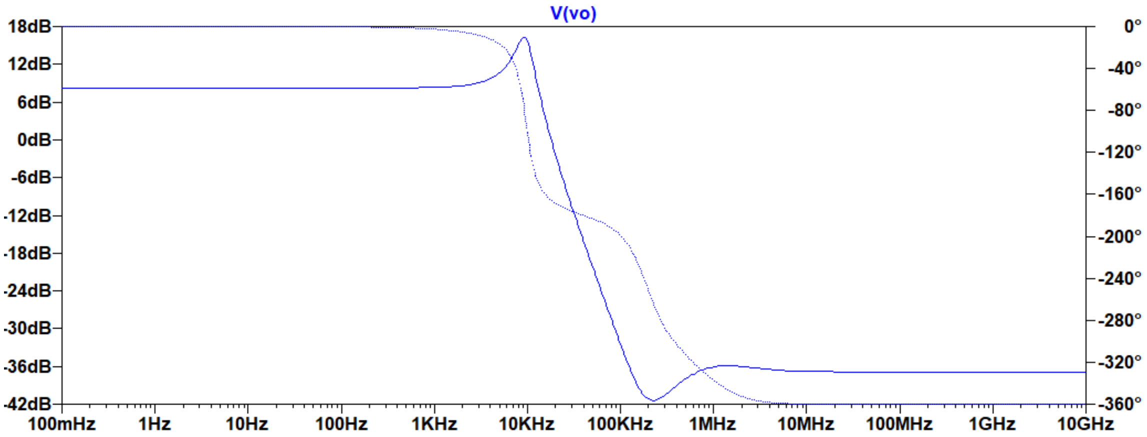

Figure 1.3: Magnitude and Phase Bode plot of 2nd order BW Filter

On the s-plane, the two poles are placed at 45 degrees from the negative real axis with a radius calculated from the cut-off frequency of $\omega_c = \frac{1}{RC} = \frac{1}{10k*1.6n} = 62.5\ krad/s$. The Root Locus and pole locations are shown in Figure 1.4.

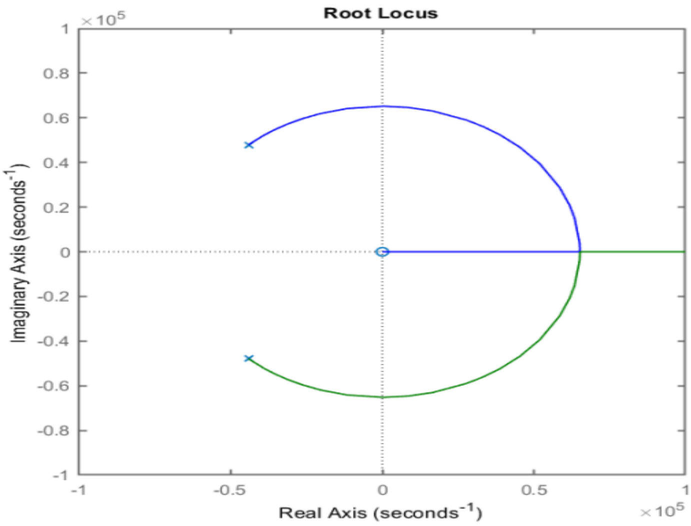

Figure 1.4: Root Locus of 2nd order BW Filter

2. Circuit Oscillation and Gain

While keeping $R_1 + R_2 = 10\ k\Omega$, the two resistors are slowly changed in order to increase the gain and observe when the circuit begins to oscillate. Since $\zeta = \frac{3-A_M}{2}$, the first order term of the transfer function's denominator becomes 0 when $A_M = 3$. At this gain value, the root locus poles shown in Figure 1.5 are located on the imaginary axis, indicating that the circuit is marginally stable.

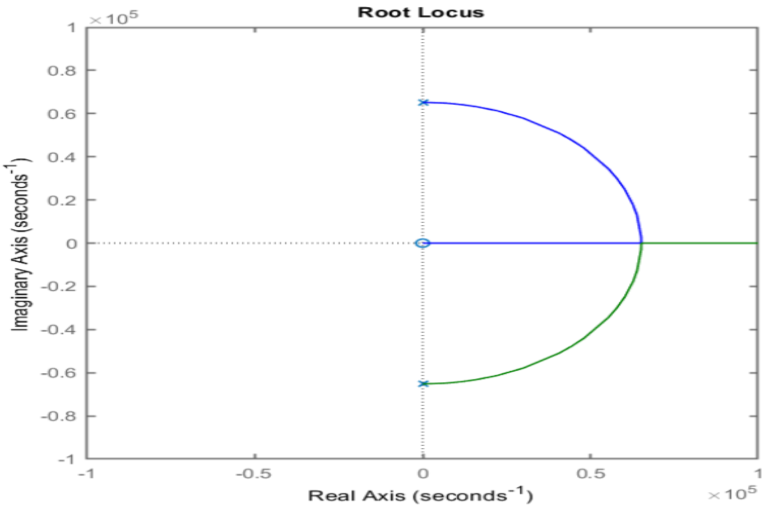

Figure 1.5: Marginally Stable Root Locus of 2nd Order BW filter

At this gain value, we find that $R_1 = 3.333\ k\Omega$ and $R_2 = 6.667\ k\Omega$ using the previous equations. The circuit oscillates at a frequency of 9.5 kHz as shown by the circuit's oscillating output in Figure 1.6.

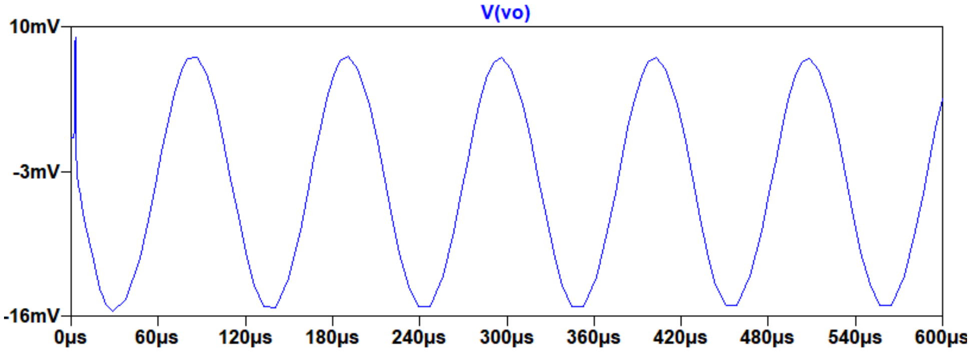

Figure 1.6: BW Filter Circuit Oscillating Output

Discussion

As the gain increases, the root locus poles will continue to move to the right until they reach the imaginary axis, indicating that the circuit is marginally stable. Increasing the gain any further will result in an unstable circuit, as the root locus poles will continue to move to the right.

3.2 Part B: A Phase Shift Oscillator

This section consists in creating a Phase Shift Oscillator circuit using a UA741 shown in Figure 2.1. Once an adequate value for the 29R resistor is found, R and C are increased and decreased in order to observe and plot their oscillating frequencies.

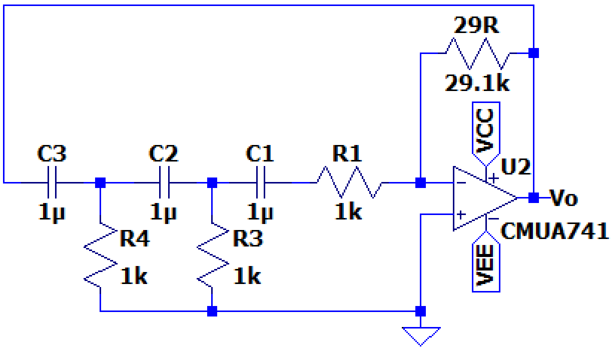

Figure 2.1: Phase Shift Oscillator

An oscillator is a circuit that can produce a finite output signal without an input. The denominator of an oscillator's transfer function consists of two complex poles on the imaginary axis, to form a marginally stable circuit. The initial value of the 29R resistor is 29 $k\Omega$ This feedback resistor value results in an oscillation. We adjust this resistor value and increase it to 29.1 $k\Omega$ such that the signal stabilizes and does not decay, as shown in Figure 2.2.

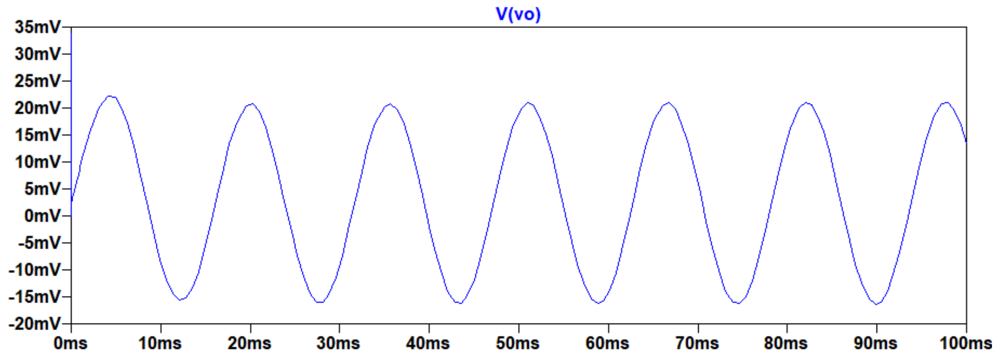

Figure 2.2: Phase Shift Oscillator Output

Next we increase R and C by factors of 2, before decreasing them by factors of 2. The corresponding values can be seen in Table 2.1.

	R	C	Calculated Freq	Measured Freq	% Error
Initial	$1\ k\Omega$	$1\ \mu F$	64.7 Hz	64.68 Hz	0.03 %
Decreased	$0.5\ k\Omega$	$0.5\ \mu F$	259 Hz	230 Hz	11.1 %
Increased	$2\ k\Omega$	$2\ \mu F$	16.2 Hz	18.45 Hz	13.8%

Table 2.1: Adjusted Resistor and Capacitor Values and Resulting Frequencies

The oscillating circuit outputs can be observed in Figure 2.3 for decreased and increased values of R and C.

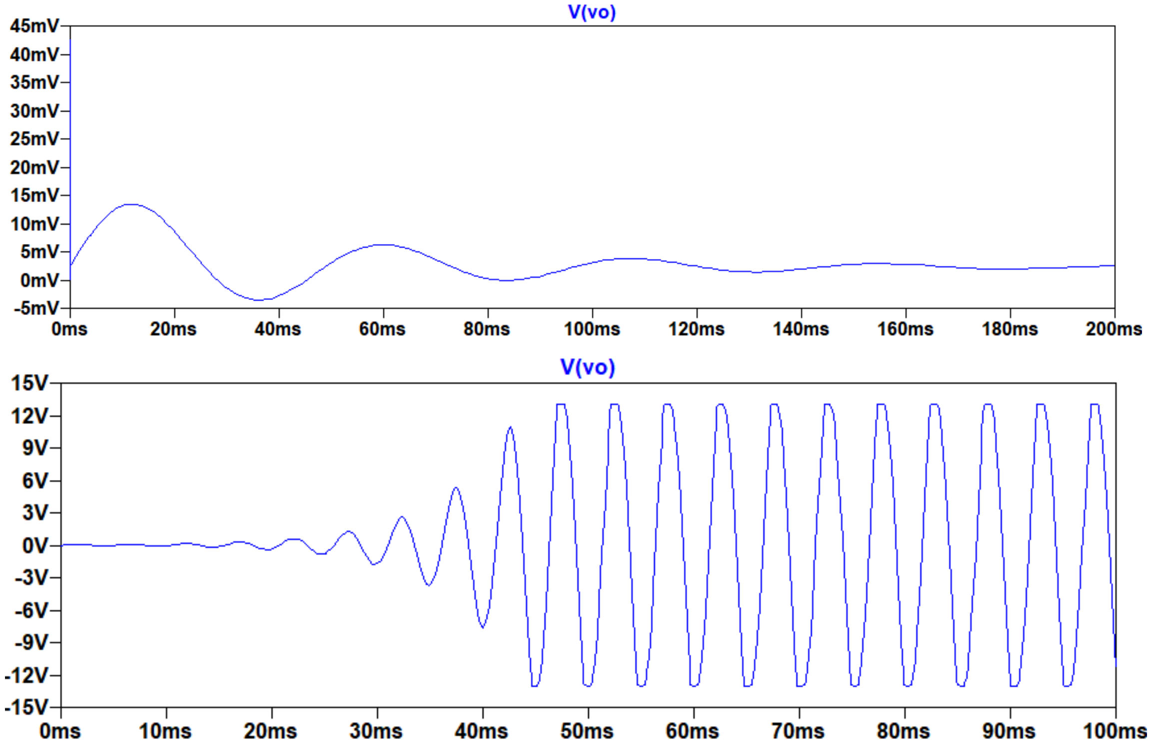

Figure 2.3: Oscillating Output from Decreased (Top) and Increased (Bottom) R and C values

To obtain the output signal's frequency by calculations, we use the following equations: $\omega = \frac{1}{\sqrt{6}RC}$ and $f = \frac{1}{2\pi\sqrt{6}RC}$. The resulting frequency from the R and C values at initial, decreased by a factor of 2, and increased by a factor of 2, are shown in Table 2.1. As this equation is dependent on R and C, the resulting frequency after increasing the values by a factor of 2 is expected to be approximately 4 times less than that of its original frequency. Similarly when R and C values are decreased by a factor of 2, the frequency is expected to be around 4 times that of its original frequency.

Discussion

While the measured and calculated output frequency values are very similar with R and C at their initial values, increasing and decreasing the R and C values resulted in a higher error margin when measuring and calculating the output frequency. The margin of error is mostly insignificant, and may be due to human error when measuring frequencies, or due to inaccuracies related to real amplifiers being non-ideal components.

3.3 Part C: A Feedback Circuit

This section consists in wiring and testing the Feedback Amplifier circuit shown in Figure 3.1, built from two 2N3904 BJTs. We must first find the variable resistor R_{B2} by adjusting the DC bias of the amplifier to obtain the largest open-loop gain at 1kHz. By doing a parameter sweep on the resistor as shown in Figure 3.1, it is found that an R_{B2} value of approximately $20\ k\Omega$ yields the largest gain value.

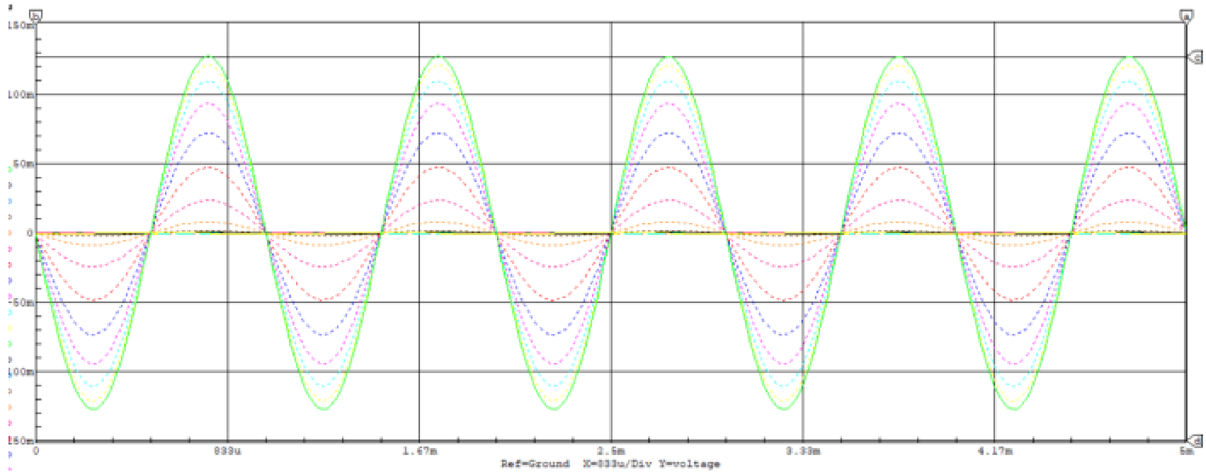

Figure 3.1 Parameter Sweep with RB2 Variable Resistance

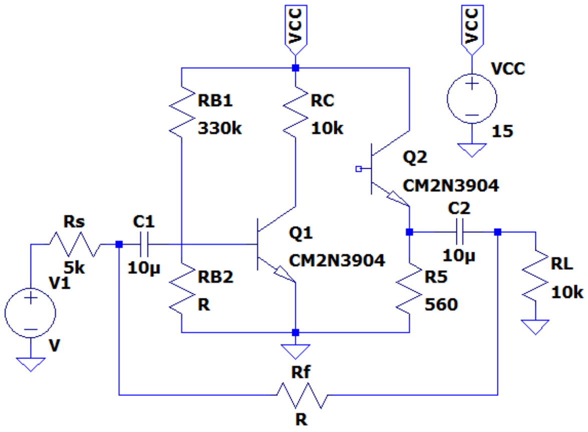

Figure 3.2: Feedback Amplifier Circuit

1. DC Biasing and Operating Point

Using the LTSPICE model designed in Figure 3.2, we measure the DC bias circuit for both transistors as shown in Table 3.1.

	VC	**VB**	**VE**	**IC**	**IB**	**IE**
Q1	1.9 V	654 mV	0 V	1.295 mA	10.77 uA	1.305 mA
Q2	15 V	1.9 V	1.235 V	2.19 mA	15.39 uA	2.205 mA

Table 3.1: DC Operating Points of Feedback Amplifier Circuit

Using the following equations, the transistor parameters can be determined as shown in Table 3.2. $h_{fe} = \beta = \frac{IC}{IB}$, $g_m = \frac{IC}{VT}$, $r_\pi = \frac{hfe}{gm}$

	β	g_m	r_π
Q1	120	0.052	2.321 $k\Omega$
Q2	142	0.088	1.624 $k\Omega$

Table 3.2: Feedback Amplifier Transistor Parameters

2. Open-Loop Frequency Response

Next, we measure the open-loop frequency response, A(ω) with $R_f = \infty$, from 10 mHz to 100 MHz to find the 3dB frequencies. The amplitude and phase Bode plot are shown in Figure 3.3.

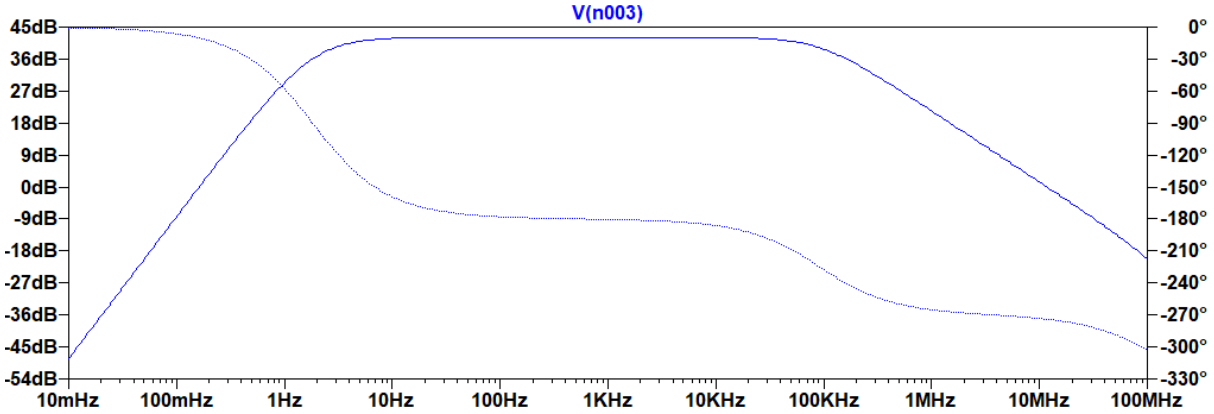

Figure 3.3: Magnitude and Phase Bode Plot of Open-Loop Response

By measurement, it is observed that the 3dB frequencies are $\omega_{L3dB} = 2.623\ Hz$ and $\omega_{H3dB} = 91.25\ kHz$. We find that the midband gain is 41.7 dB, or 121.8 V/V. However as this is an inverting amplifier, the voltage gain is 0121.8 V/V. The input and output resistance of the amplifier at 1kHz are calculated as follows. $R_{in} = \frac{V_{test}}{I_{test}} = 3.585\ k\Omega$, and $R_{out} = \frac{V_{test}}{I_{test}} = 59.27\ \Omega$.

Using the measured open-loop frequency response, the closed-loop frequency response is calculated as well as the input and output resistances at 1 kHz and $R_f = 100\ k\Omega$. As the feedback network is a shunt-shunt topology, we use y-parameters to represent the feedback network: $I_1 = y_{11}V_1 + y_{12}V_2$ and $I_2 = y_{21}V_1 + y_{22}V_2$.

A the forward gain of y_{21} is small, the gain is neglected. At $R_f = 100\ k\Omega$, the feedback gain can be found $\beta = y_{12} = \frac{-1}{Rf} =- 10\mu S$.

With an open loop gain of -121.75 V/V, we write the gain in terms of $\frac{Vout}{i_i} = \frac{Vout/Vi}{Rs} = R_s(\frac{Vout}{Vi})$. At $R_s = 5\ k\Omega$, the open-loop gain $A =- 608.75\ kV/A$. The closed loop gain can now be calculated as $A_f = \frac{A}{1+A\beta} = 85.890\ kV/A$. The corresponding voltage gain is found to be -17.178 V/V.

Next we can find the closed-loop frequencies by dividing the open-loop frequencies by the bandwidth extension factor: $\omega_{L3dBf} = \frac{\omega L3dB}{1+A\beta} = 0.37\ Hz$ and $\omega_{H3dBf} = \omega_{H3dB}(1 + A\beta) = 708.75\ kHz$.

Finally, the closed-loop input and output impedances are calculated. Due to the shunt-shunt topology, the impedance is divided by the bandwidth extension factor as well.

$R_{if} = \frac{R_i}{1+A\beta} = 344.8\ \Omega$ and $R_{of} = \frac{R_o}{1+A\beta} = 6.97\ \Omega$.

The simulated magnitude and phase bode plot for the feedback amplifier with $R_f = 100\ k\Omega$ is shown in Figure 3.4.

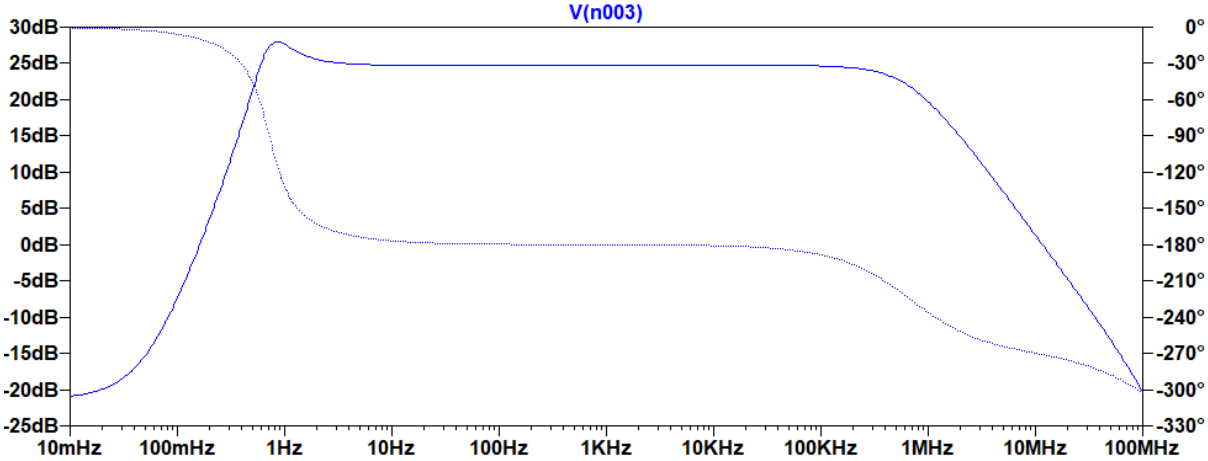

Figure 3.4: Magnitude and Phase Bode Plot of Feedback Amplifier at $R_f = 100\ k\Omega$

The 3dB frequencies are measured to be $\omega_{L3dB} = 482.1\ mHz$ and $\omega_{H3dB} = 703.62\ kHz$. The calculated and measured 3dB frequencies both have very minimal error.
Finally the input and output impedance of the feedback circuit are calculated using a test source at the input and output. The test current is measured, yielding input and output impedance values of $R_{if} = 245.63\ \Omega$ and $R_{of} = 6.789\ \Omega$. While the margin of error is higher for the input impedance, the output impedance is very close to the resistance value.

3. Closed-Loop Frequency Response

The feedback amplifier's frequency response over 10 mHz to 100MHz was measured and plotted for $R_f = 1k\Omega, 10k\Omega,\ 100k\Omega,\ 1M\Omega,\ 10M\Omega$ as shown in Figure 3.5 and Figure 3.6.

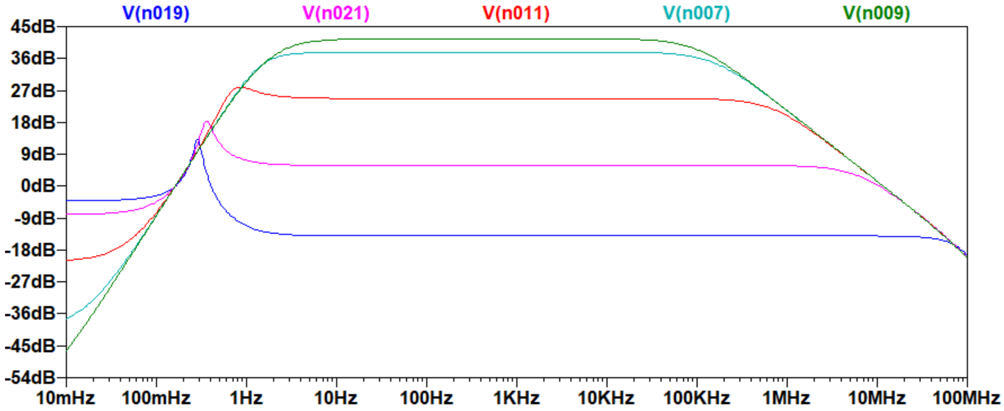

Figure 3.5: Magnitude Bode Plot With Varying R_f

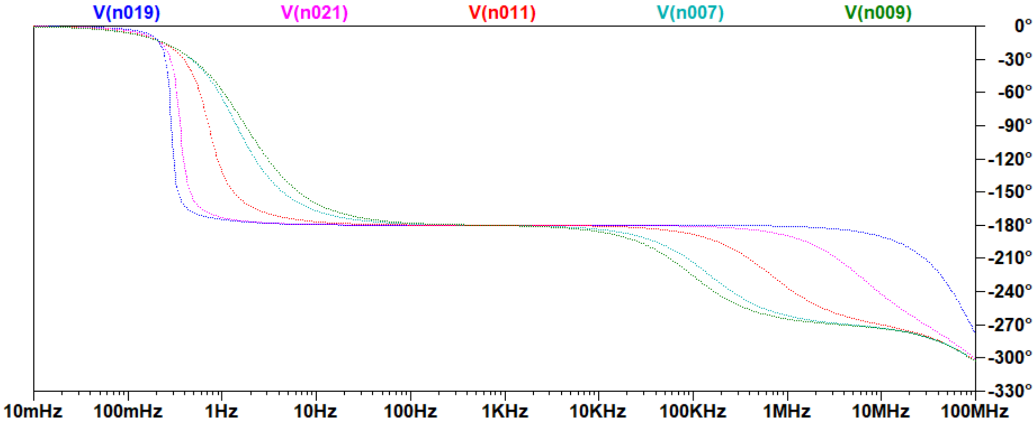

Figure 3.6: Phase Bode Plot With Varying R_f

The feedback gain β can be computed by using the midband gain and the open-loop gain previously calculated. From Figure 3.5, we can find the midband gain in dB, then convert it to V/A units. It is known that $A_f = \frac{A}{1+A\beta}$ and $\beta = -\frac{1}{Rf}$. Using these equations the theoretical feedback factors for each of the R_f values above are calculated and compared in Table 3.3.

$R_f(\Omega)$	$V_{gain}(dB)$	$V_{gain}(V/V)$	$A_f(V/A)$	β	β_{calc}
1k	-14.7	-0.2	-989.2	-1E-3	-1E-3
10k	5.8	-2.01	-9745	-1E-4	-1E-4
100k	24.6	-16.99	-85893	-9.9E-6	-1E-5
1M	35.74	-75.83	-384210	-9.6E-7	-1E-6
10M	41.3	-116.76	-589541	-5.4E-8	-1E-7

Table 3.3: Theoretical Feedback Factors for Varying R_f

At lower values of R_f, the feedback factors remain the same, however as the value increases, the error margin also increases, although the values remain approximately in the same order of magnitude.

4. Input and Output Impedance

The input and output resistance of the amplifier at 1 kHz are calculated for $R_f = 10\ k\Omega,\ 100\ k\Omega,\ 1\ M\Omega$. Similarly to the last sections, the input and output impedances are measured as shown in Table 3.4.

R_f	R_{if}	R_{of}
10 $k\Omega$	26.5 Ω	0.885 Ω
100 $k\Omega$	240.96 Ω	6.12 Ω
1 $M\Omega$	1.314 $k\Omega$	29.324 Ω

Table 3.4: Input and Output Impedances at Varying R_f

Then, we can determine the feedback gain β using the following: $R_{if} = \frac{Ri}{1+A\beta}$ and $R_{of} = \frac{Ro}{1+A\beta}$. The feedback gain corresponding to each R_f value is shown in Table 3.5.

R_f	R_{if}	R_{of}	β_i	β_o
10 $k\Omega$	26.5 Ω	0.885 Ω	-1.581E-4	-9E-5
100 $k\Omega$	240.96 Ω	6.12 Ω	-1.594E-5	-1.06E-5
1 $M\Omega$	1.314 $k\Omega$	29.324 Ω	-1.589E-6	-1.09E-6

Table 3.5: Feedback Gain at Varying R_f

It is noticed that the feedback gain calculated from the input impedance is less accurate than the gain calculated from the output impedance.

5. Desensitivity Factor

With $R_f = \infty,\ 100\ k\Omega$, the simulation is run for $R_c = 9.9\ k\Omega,\ 10\ k\Omega,\ and\ 10.1\ k\Omega$. At 1 kHz, the de-sensitivity factor of the amplifier is calculated and compared with previous sections.

The desensitivity factor is is given by $1 + \beta A$. At $R_f = \infty$, $\beta = 0$ and the desensitivity factor is 1. The voltage gain of the open-loop circuit with varying R_C is given in Table 3.6.

R_C	V_{gain} (V/V)
9.9 $k\Omega$	-126.85
10 $k\Omega$	-127.31
10.1 $k\Omega$	-127.96

Table 3.6: Feedback Amplifier Gain at $R_f = \infty$ With Varying R_C

At $R_f = 100\ k\Omega$, the voltage gain of the open-loop circuit with varying R_C is given in Table 3.7.

R_C	V_{gain} (V/V)
9.9 $k\Omega$	-17.02
10 $k\Omega$	-17.11
10.1 $k\Omega$	-17.2

Table 3.7: Feedback Amplifier Gain at $R_f = 100\ k\Omega$ With Varying R_C

From gain found in Table 3.7, we find $\beta =- 1.01$. Therefore, the desensitivity factor is $1 + A\beta = 1 + 6.447 = 7.447$. This value is consistent with the measured values of A and β in Part 2 and 3.

Discussion

In this (very long) section, a feedback amplifier was created, then biased to find its parameters and DC operating point. The open-loop was measured and used to predict the closed-loop frequency response. The closed-loop frequency response was then measured at varying resistances then compared with its calculated values. The input and output resistance of the amplifier at various resistances were calculated before estimating the amount of feedback for each. Finally, the desensitivity factor of the amplifier was observed, showing that the gain is desensitized by the feedback network.

5. Conclusion

This project consisted in wiring up and testing three types of amplifiers. A 2nd order active filter, a phase-shift oscillator, and a feedback circuit. All three circuits were simulated with their frequency response plotted. In Part A, we reported the capacitance and gain values that would turn the filter into a 2nd order Butterworth filter, and located the poles in the s-plane. In Part B we explained the functioning of a phase-shift oscillator, and the use of the 29R resistor. Lastly, Part C tested and simulated a feedback circuit, measuring open-loop and closed-loop frequency responses over a range of frequencies, and determining the input and output impedances of the circuit and various values of R_f.

6. References

1. ELEC 301 Course Notes.
2. 2. A. Sedra and K. Smith, "Microelectronic Circuits," 5 th Ed., Oxford University Press, New York.
3. LTSpice™ User’s Manual.