# ECE 100: Linear Electronic Systems

Professor: Drew Hall

# Lab 5:
# Nyquist Plots of the op-amp circuits and the design of the Wien-Bridge Oscillator

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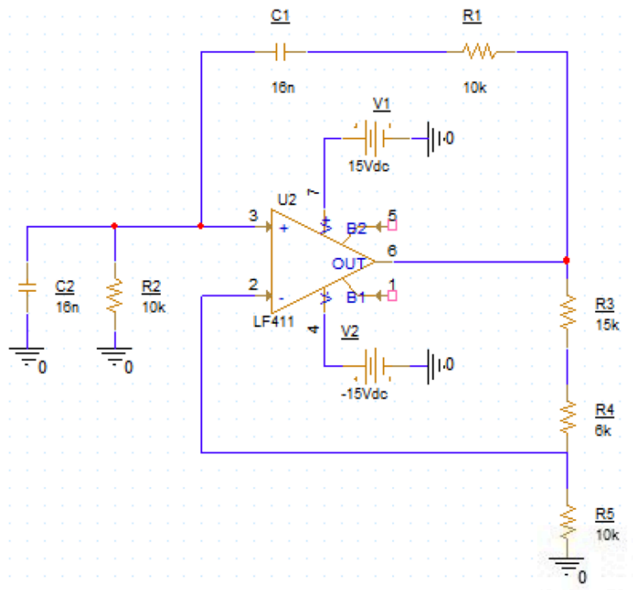
# Abstract

In this lab project we will generate the Nyquist plots for the loop gain of the voltage follower and differentiator circuits by hand. Using MATLAB and will find the phase margins in these circuits as well as ensure our calculations match. We will also simulate and build a Wein-Bridge Oscillator circuit. Our goal is to be able to manipulate the frequency and amplitude without having any signal input! This circuit gets started with the natural static noise within the components that get amplified by our LM411 op-amp.

# Experimental Procedure

## Tools:

- LM411 Op-Amp
- Pspice (or any) Circuit Simulation Software
- Circuit Components (Capacitors and Resistors)
- DC Power Supply
- Oscilloscope




Schematic: Wein-Bridge Oscillator Circuit

The basic oscillator is sketched above. It is based on an amplifier with a voltage gain K = 3, here shown implemented as a follower with gain. The feedback is through the RC network shown in the circuit diagram, where the two resistors R and the two capacitors C are the same.

## Section 1: Nyquist Plots of the Op-Amp Circuits

**Note:**

In MATLAB, use the `nyquistplot` function to draw the Nyquist plot of the loop gain. Right-click on the plot, select ”Characteristics,” and then select ”All Stability Margins.” This will draw a circle with a radius of 1 centered at the origin. It can be used to show whether the Nyquist plot encircles the -1 point. You will need to zoom in on the graph to see the circle. Click on the intersection of the unit circle and the Nyquist plot to see the phase margin. Include the original Nyquist plot and the zoomed-in version (with the phase margin data tip added to the figure) in your report.

## 1) Unloaded Voltage Follower

Draw the circuit schematic of the voltage follower circuit (Lab project 3). Use the op-amp open-loop gain equation, $A(s) = \frac{A_0}{1+s\tau_A}$, in which $A_0 = 10^5$ and $\tau_A = 0.1$. Assuming that the closed-loop DC gain is $10\frac{V}{V}$, write the equation of the loop gain. Draw the magnitude and phase Bode plots and the Nyquist plot of the loop gain by hand. Then, use MATLAB to draw the Bode and Nyquist plots of the loop gain. Read the Notes included in this document to learn more about how to do this.

## 2) Voltage follower circuit with a capacitive load

Draw the circuit schematic of the unity gain voltage follower circuit with a capacitive load (Lab project 3). Assume $R_0 = 50\ \Omega$ and $C = 200\ nF$. Using the op-amp open-loop gain equation, $a(s) = \frac{a_0}{1+s\tau_A}$, in which $a_0 = 10^5$ and $\tau_A = 0.1$, write the equation of the loop gain. Draw the magnitude and phase Bode plots and the Nyquist plot of the loop gain by hand. Then, use MATLAB to draw the Bode and Nyquist plots of the loop gain. Include the original Nyquist plot and the zoomed-in version (with the phase margin data tip added to the figure) in your report.

## 3) Voltage follower circuit with a capacitive load and a compensation resistor

Draw the circuit schematic of the unity gain voltage follower circuit with a capacitive load and a compensation resistor, $R_C$. Write the equation of the loop gain in this circuit. Find the value of $R_C$ such that the zero of the compensated loop gain is at the cross-over frequency (unity-gain frequency) of the uncompensated loop gain. Assume $R_0 = 50\ \Omega$ and $C = 200\ nF$ and $A(s) = \frac{A_0}{1+s\tau_A}$, in which $A_0 = 10^5$ and $\tau_A = 0.1$. Draw the magnitude and phase Bode plots and the Nyquist plot of the loop gain by hand. Then, use MATLAB to draw the Bode and Nyquist plots of the loop gain. Include the original Nyquist plot and the zoomed-in version with the phase margin data tip in your report.

## 4) Differentiator circuit with no compensation

Draw the circuit schematic of the differentiator circuit (Lab project 4). Write the equation of the loop gain using the op-amp open-loop gain equation, $a(s) = \frac{a_0}{1+s\tau_A}$, in which $a_0 = 10^5$ and $\tau_A = 0.1$. Use $R = 100\ k\Omega$ and $C = 5\ nF$ in your equation. Draw the magnitude and phase

Bode plots and the Nyquist plot of the loop gain by hand. Then, use MATLAB to draw the Bode and Nyquist plots of the loop gain. Include the original Nyquist plot and the zoomed-in version (with the phase margin data tip added to the figure) in your report.

## 5) Differentiator circuit with compensation resistor

Draw the circuit schematic of the differentiator circuit compensated with a resistor, $R_C$, in series with the input capacitor (Lab project 4). Write the equation of the loop gain using the op-amp open-loop gain equation, $a(s) = \frac{a_0}{1+s\tau_A}$, in which $a_0 = 10^5$ and $\tau_A = 0.1$. Use $R = 100\ k\Omega$ and $C = 5\ nF$. Find the value of $R_C$ such that the zero of the compensated loop gain is at the cross-over frequency (unity-gain frequency) of the uncompensated loop gain. Draw the magnitude and phase Bode plots and the Nyquist plot of the loop gain by hand. Then, use MATLAB to draw the Bode and Nyquist plots of the loop gain. Include the original Nyquist plot and the zoomed-in version (with the phase margin data tip added to the figure) in your report.

# Part 2: Design of the Wien-Bridge Oscillator

We have given a good deal of thought to preventing circuits from oscillating; but, of course, there are times when you want the circuit to oscillate. Such a circuit is the “Wien-Bridge Oscillator.” It has been a popular oscillator in the audio frequency range, and it is of historical interest because it was the first product developed and sold by the Hewlett-Packard company!

Oscillators work in two steps:

**a. Gain Stage:** Noise is amplified by a gain factor K, determined by resistors connected to the output signal and the negative terminal of the op-amp.

**b. Filter:** The amplified noise gets filtered to allow only certain frequencies to pass, and the new signal gets fed back into the amplifier.

The basic oscillator is sketched above. It is based on an amplifier with a voltage gain K = 3, here shown implemented as a follower with gain. The feedback is through the RC network shown in the circuit diagram, where the two resistors R and the two capacitors C are the same.

# Section A: System Level Design

## (a)

Show analytically that the feedback factor is $B(s) = \frac{sRC}{1 + 3sRC + (sRC)^2}$. The loop gain will be $T(s) = - KB(s)$. Using MATLAB, plot the Nyquist plot for this loop gain. You will see a circular trace that goes right through the -1 point on the real axis twice, meaning there are two poles on the jω axis. Include this Nyquist plot in your report. If K > 3, the poles are in the RHP (Right Hand Plane); if K < 3, the poles are in the LHP (Left Hand Plane). The resonant frequency of the oscillator is $\omega_0 = \frac{1}{RC}$. To make a real oscillator, we need to consider two values of K: first, K has to be slightly greater than 3 so that the instability starts up the oscillating sinusoidal wave from noise; secondly, when the sinusoidal signal reaches the desired amplitude, we need to decrease K until it is exactly equal to 3 to prevent any further unstable growth of the sine wave.

## (b)

Simulate the oscillator in Simulink with a gain block of 3.1 and a feedback transfer function of $\frac{s}{1 + 3s + s^2}$. Include a saturation element and set the upper limit at +13V and the lower limit at -13V. To get the oscillation to start in Simulink, add a small step of amplitude 0.1V to the amplifier input. Plot the output on the scope. Include screenshots of your block diagram and the scope graph in your report. Read the Notes included in this document to learn more about how to do this.

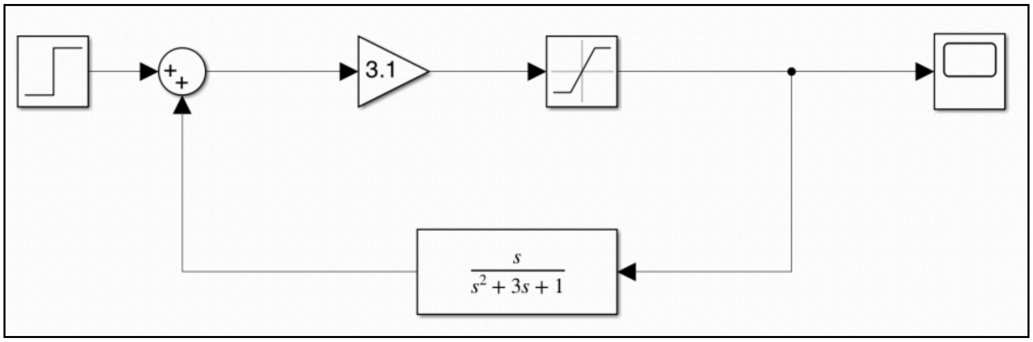


Figure A.2.1: Simulink Block Diagram Model

# Section B: Circuit Level Simulation

## (a)

A nonlinearity can reduce the effective gain of the amplifier. For example, we can let the amplifier clip at the power-supply voltages. This will limit the output amplitude to about ±13 V, and there will be noticeable clipping as the output is “flat” at points where we expect to see maxima and minima, as you will observe when you perform the following analysis in PSpice. To observe the amplifier clipping the output, use the LF411 op-amp. Notice the resistors of the gain stage are a 15 kΩ and a 6 kΩ in series. This will give you K = 3.1, with poles in the RHP and thus unstable oscillation. For the filter components, choose R = 10 kΩ and C = 16 nF. This will give you a resonant frequency of 1 kHz. You will need to run the transient simulation long enough that the oscillation builds up and saturates at the final amplitude.

- To get the oscillation started, in the time domain analysis settings in Pspice, select ”Skip the initial transient bias point calculation.” In LTspice, select ”Skip the solution of the initial operating bias point.”
- Sometimes Pspice and LTspice do not sample the waveform as finely as you would like. You can adjust the ”Maximum Step Size” in the transient options. A max step size of 10us works well in this case.
- In Pspice simulations, you need to give the amplifier input voltage at the non-inverting input terminal a nonzero initial condition (say a few mV). To do so, you can specify the non-zero initial condition (voltage) on the capacitor connected from the input to ground by double-clicking on the capacitor and adjusting its properties. This step is not required for LTspice simulation.
- Run the transient response for about 100 ms. The oscillation should start from nothing and grow to full amplitude in about 30-40 ms.

Include pictures of your circuit diagram and the simulated growing oscillation in your report. Focus on a few cycles of the full amplitude oscillation and expand it to show the wave shape. You will see that it looks a bit flat on top. Clipping the wave this way prevents the oscillation from unstable growth but gives a distorted waveform. Include a picture of the expanded clipped waveform in your report.

## (b)

The performance of oscillators is traditionally judged by the frequency domain analysis. That is, we do a Fourier transform and compare the power in the fundamental frequency with the power in the harmonics. This can be done in PSpice using the Fourier option in the Trace tab or by clicking the FFT option in the menu bar. Modify the simulation profile to save the simulation data after 60 ms, then simulate the circuit again and select the FFT option. Next, set the y-axis of the FFT plot to log scale. Measure and record the amplitude of the 1 kHz spike and the amplitude of the 3 kHz spike; clearly mark these points on your FFT plot. Include a picture of your FFT plot in your report. The ratio of those (in dB) is an important measure of performance. Find the performance of this oscillator using:

$$P = 20log\left(\frac{V_{out} @ 1kHz}{V_{out} @ 3kHz}\right)$$

## (c)

Allowing the amplifier to saturate at the power supply voltage has a couple of disadvantages. It means that the amplitude depends on the power supply level, which also means that it is quite large. We would often prefer a smaller amplitude output to avoid slew rate limiting at high frequencies. We can obtain a smaller amplitude by clipping the voltage across the 6 kΩ resistor with parallel diodes. Use the 1N4148 diode. Put one in parallel with the resistor in one polarity and the other in parallel but with the opposite polarity. This will prevent the voltage across the resistor from exceeding about 0.7 V and thus limit the signal amplitude. What amplitude do you get with this modification? Expand a couple of cycles. Can you see any sign of clipping? Make a copy of your circuit diagram and of the simulated growing oscillation for your report.
Re-measure and re-record the power ratio of the 1 kHz and 3 kHz harmonics (in dB). How much has it changed?

In fact, the original HP oscillator used a softer nonlinearity and obtained significantly lower distortion. They used a lamp filament which increases resistance as it is heated. Diodes have a much harder limiting characteristic.

## (d)

Try increasing the frequency by a factor of 10. Take a screenshot and ensure the frequency is clearly displayed for the report. Can you increase frequency by another factor of 10? You should not reduce the resistor R below 1 kΩ because it will draw too much current from the op-amp. However, you can change the capacitance C to compensate. What is the highest frequency you can reach? What seems to limit the maximum frequency?

# Section C: Measurement

## (a)

Build your oscillator and give it a test. It will start by itself because the circuit noise will be sufficient. Take a screenshot of the output waveform (or save the oscilloscope display) for your report. Include a picture of your circuit setup in your report.

## (b)

Add two parallel diodes across the 6 kΩ resistor. How does the output waveform change? Take a screenshot of the output waveform (or save the oscilloscope display) for your report. Include a picture of your circuit setup in your report.

## (c)

What happens if you put the two parallel diodes across the 15 kΩ resistor instead of the 6 kΩ resistor? Take a screenshot of the output waveform (or save the oscilloscope display) for your report.

## (d)

Connect the diodes across the 6 kΩ resistor and try increasing the frequency by a factor of 10. Take a screenshot (or save the oscilloscope display) and make sure the frequency is clearly displayed for the report. Can you increase frequency by another factor of 10? Note, you should not reduce the resistor R below 1 kΩ because it will draw too much current from the op-amp. However, you can change the capacitance C to compensate. What is the highest frequency you are able to reach? Ensure the error in the expected frequency compared to the actual frequency is within 10%. What seems to limit the maximum frequency? What about lower frequencies? Can you get it down to 1 Hz?

# Results

## Section 1: Nyquist Plots of the Op-Amp Circuits

For the following section, we will be drawing the Bode and Nyquist Plots for each of the circuits. We will use the following equations to find the loop gain:

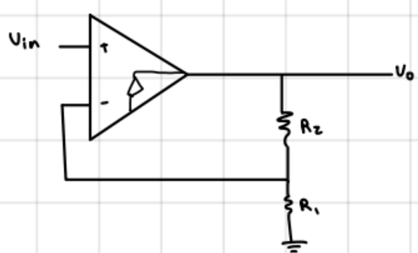
$$A(s) = \frac{A_0}{1+s\tau_A},\ a(s) = \frac{a_0}{1+s\tau_A},\ A_0 = a_0 = 10^5,\ \tau_A = 0.1$$

### 1) Unloaded Voltage Follower

We want to find the loop gain assuming that the closed-loop DC gain is 10V/V.

Lab 1

1a. Unloaded Voltage Follower




$a(s) = \underbrace{\frac{A_0}{1+s\tau_A}}_{\text{open loop gain}}$, $\tau_A = 0.1$, $A_0 = 10^5$ , $A_{cl} = 10 = \frac{1}{B} \rightarrow B = 0.1$

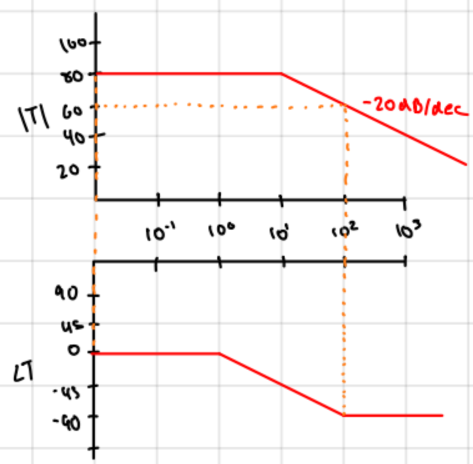
$T = a(s)B$ closed loop gain

$T = \frac{A_0}{1+s\tau_A}(B) = \frac{10^5}{1+s(0.1)}(0.1) = \frac{10^4}{1+(0.1)s}$

pole at $S = -10$

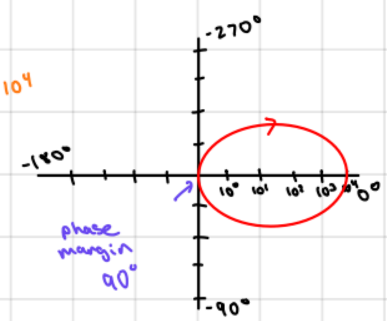
$T(0) = \frac{10^4}{1} = 10^4$

$20\log(10^4) = 20(4) = 80dB$




$0° = 80dB = 20\log(80) = 10^4$

Assymptote at -90°



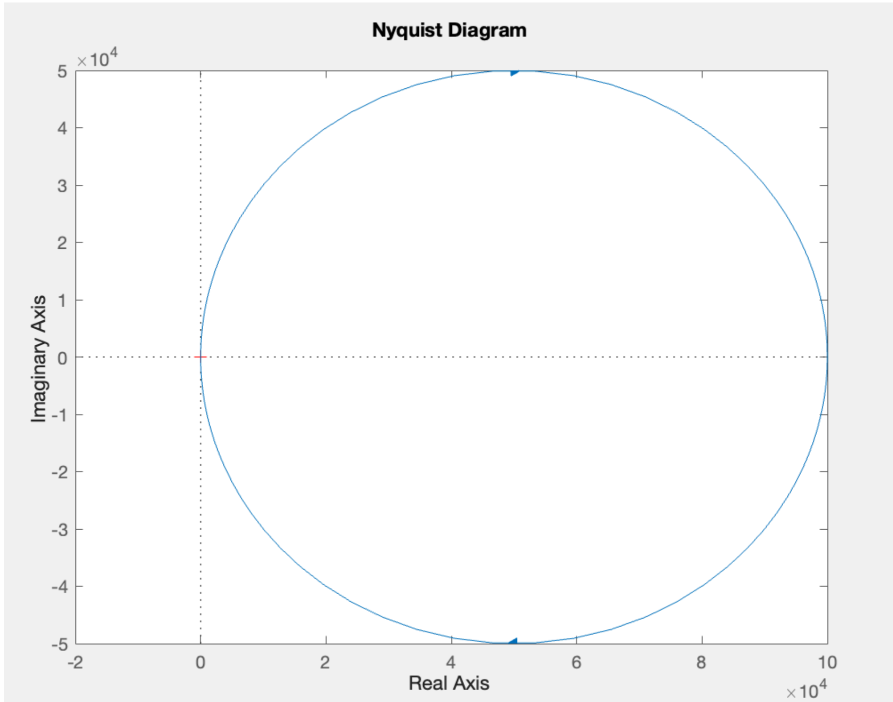


Figure 1.1.1: Simulated Nyquist Plot for Unloaded Voltage Follower

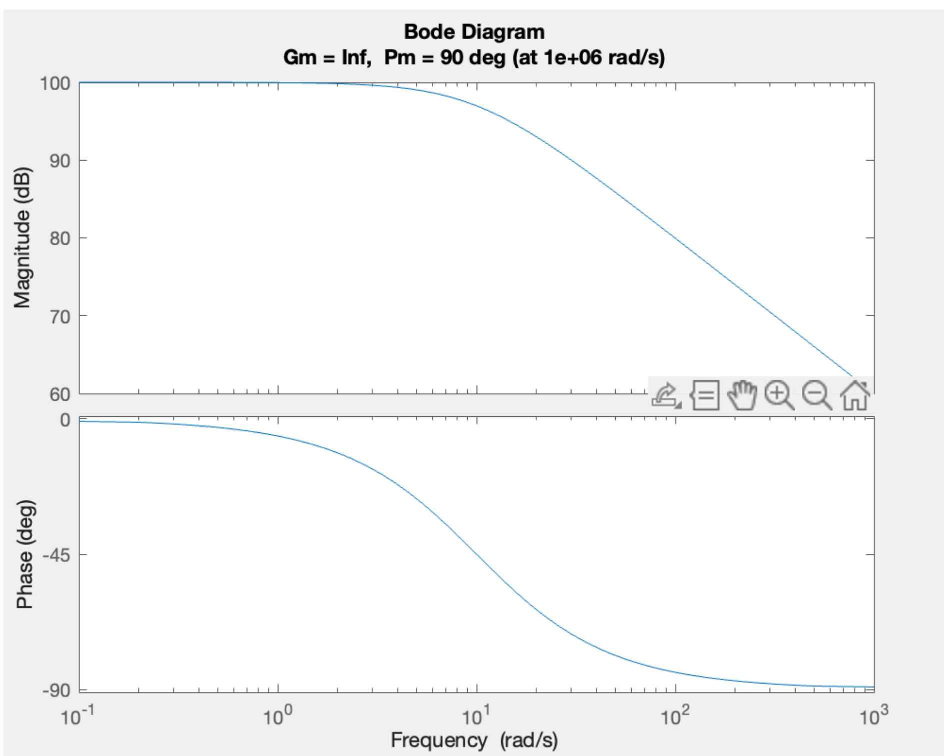


Figure 1.1.2: Simulated Bode Plot for Unloaded Voltage Follower

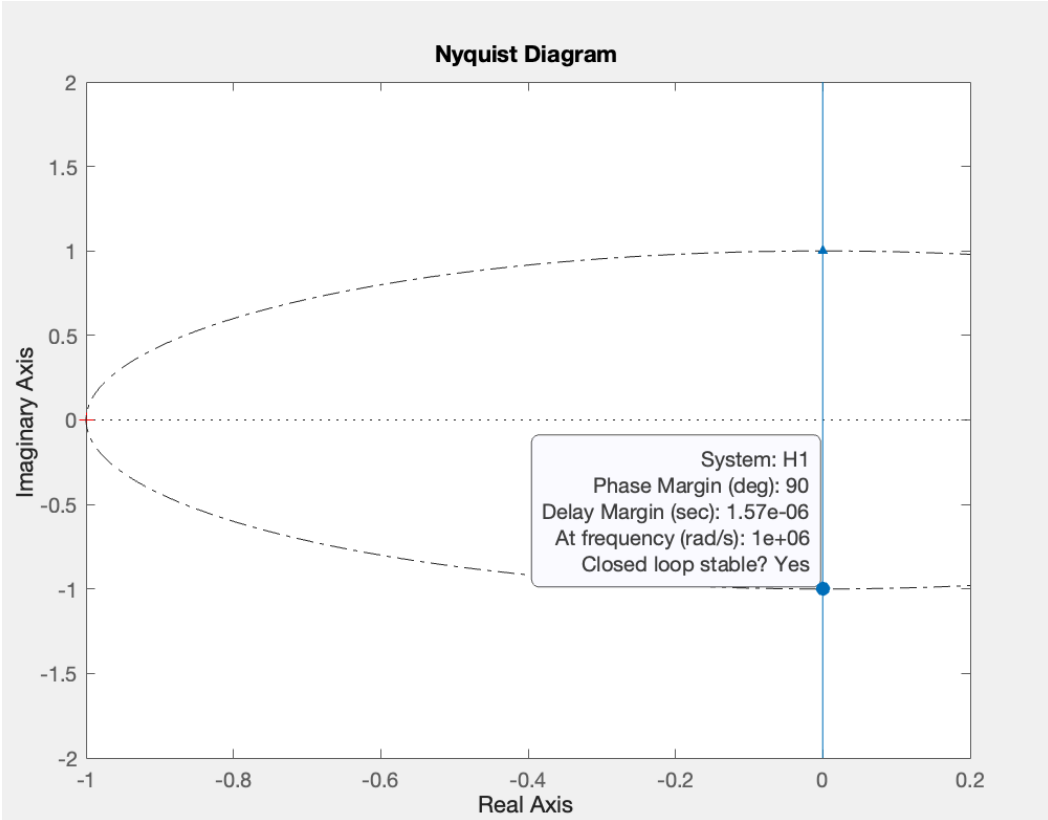



Figure 1.1.3: Simulated Nyquist Plot (zoomed in) for Unloaded Voltage Follower

Phase Margin: 90 deg

```
%1a
H1 = tf(10e4, [0.1, 1]);
s = tf('s');
figure(1)
nyquistplot(H1);
figure(2)
T1 = 10e4 / (1+(s*0.1));
bode(T1,{100, 1e6});
margin(T1);
```

Provided above is the MATLAB code to plot the graphs.

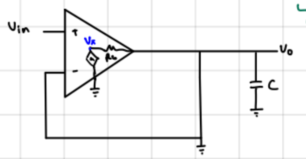
## 2) Voltage follower circuit with a capacitive load

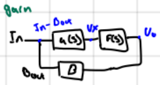
We want to find the loop gain assuming $R_0 = 50$ and C = 200nF

1b. Voltage Follower with Capacitive load

$C = 200nF$, $R_o = 60\Omega$

$a(s) = \underbrace{\dfrac{a_o}{1 + s\tau_A}}_{\text{open loop gain}}$, $\tau_A = 0.1$, $a_o = 10^3$




$V_x = a(S) V_i$

$V_o = V_x F(S)$

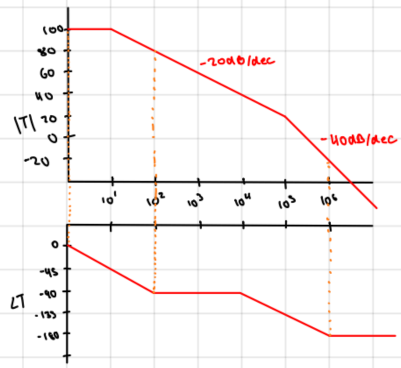
$V_o = a(S) V_i F(S) \rightarrow \dfrac{V_o}{V_i} = a(s) F(s) = T$ Loop gain

$F(s) = \dfrac{\frac{1}{sC}}{\frac{1}{sC} + R_o} = \dfrac{1}{1 + sR_oC} = B$

$T = aB = a(s)F(s) = \dfrac{a_o}{1 + s\tau_A}\left(\dfrac{1}{1 + sR_oC}\right) = \dfrac{a_o}{1 + sR_oC + s\tau_A + s^2 R_oC\tau_A} = \dfrac{10^5}{1 + s(50)(200n) + s^2(50)(200n)(0.1)}$

$T = \dfrac{10^5}{1 + 0.1001s + 10^{-6}s^2}$

pole at $s = 10$, $s = 10^5$




$0° = 100dB = 10^5$

$-90° = 80dB = 10^4$

$-180° = 0$

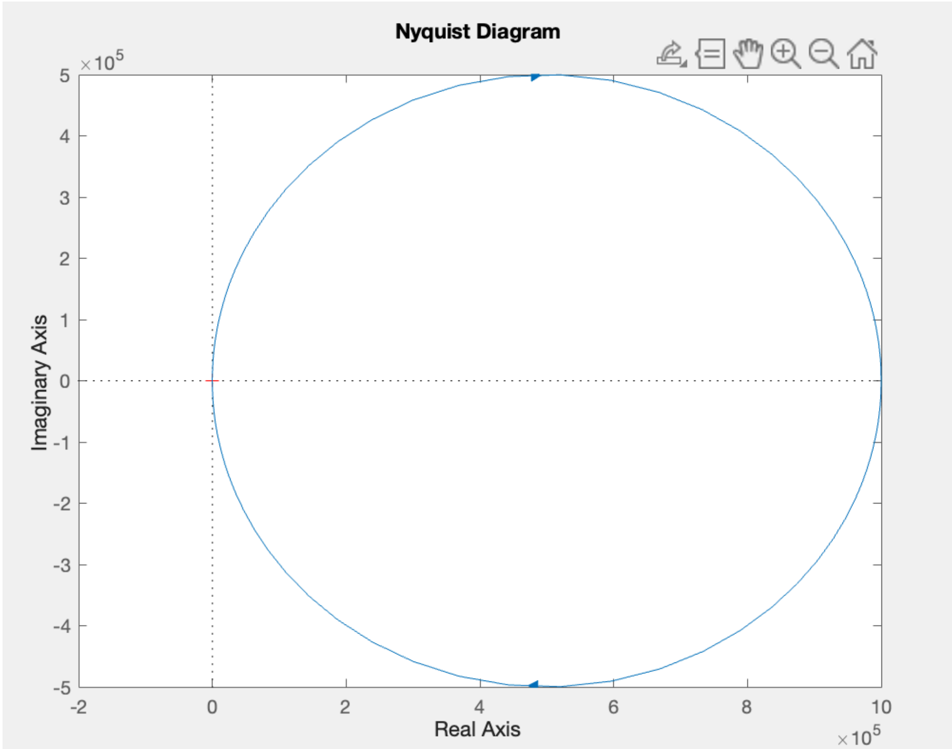



Figure 1.2.1: Simulated Nyquist Plot for Voltage Follower with Capacitive Load

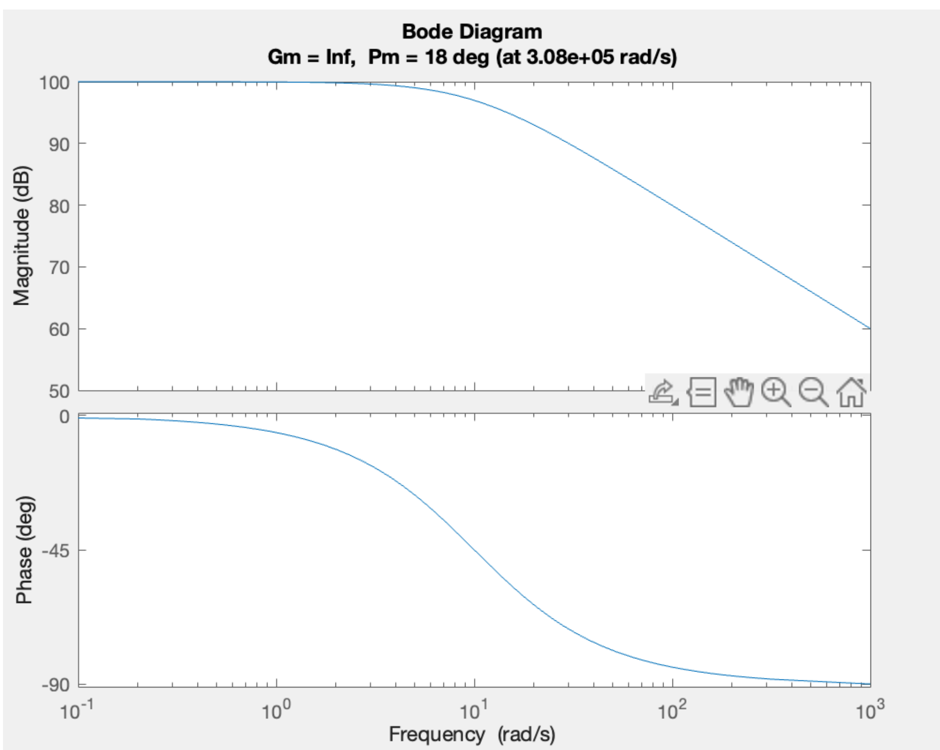



Figure 1.2.2: Simulated Nyquist Plot for Voltage Follower with Capacitive Load

Phase Margin: 18 deg

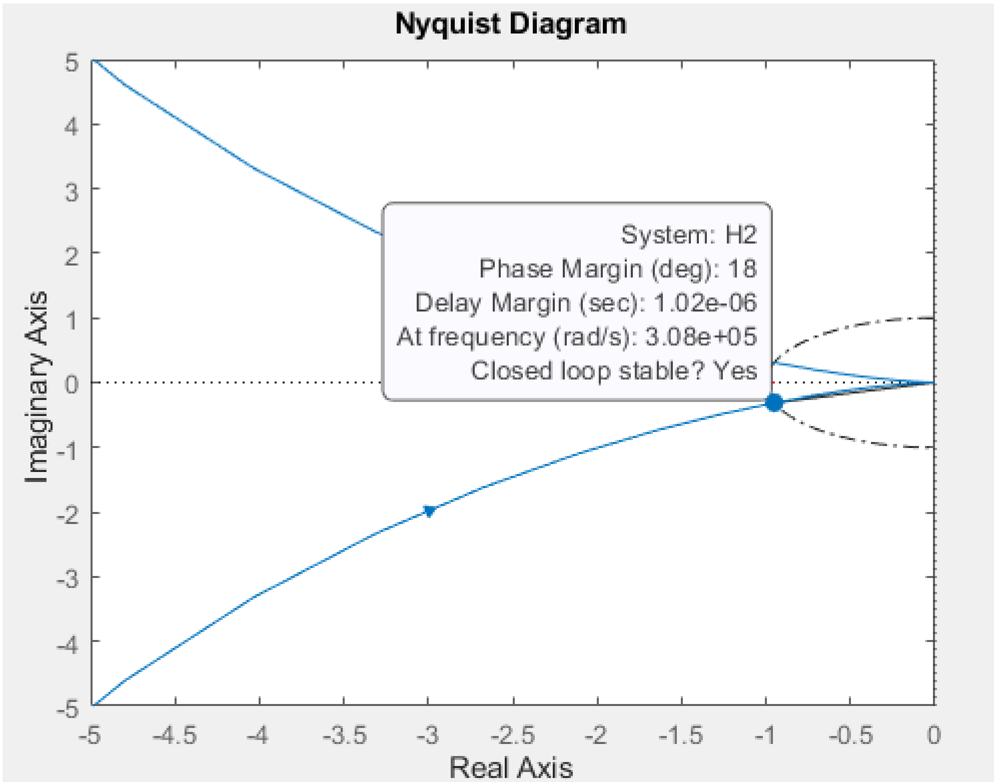


Figure 1.2.3: Simulated Nyquist Plot (Zoomed in) for Voltage Follower with Capacitive Load

Phase Margin: 18 deg

System is stable.

```
%1b
figure(3)
H2 = tf(10e5,[0.000001 .10001, 1]);
nyquistplot(H2)
figure (4)
s = tf('s');
T2= (10^5) / (1 + .10001*s + 10^-6*s^2);
bode(T2,{0, 1E6})
margin(T2)
```

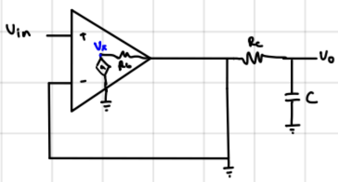
Provided above is the MATLAB code to plot the graphs.

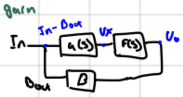
## 3) Voltage follower circuit with a capacitive load and a compensation resistor

We want to calculate the loop gain assuming $R_0 = 50$ and C = 200nF and also draw the unity gain voltage follower circuit.

1c. Voltage Follower with Capacitive load and Compensation Resistor

$\underbrace{a(s) = \frac{a_o}{1+s\tau_a}}_{\text{open loop gain}}$, $\tau_a = 0.1$, $C = 200nF$, $a_o = 10^3$, $R_o = 60\Omega$




$V_x = a(s)V_i$

$V_o = V_x B$

$V_o = a(s)V_i B \rightarrow \frac{V_o}{V_i} = a(s)B = T$ Loop gain

$$\beta = \frac{R_c + \frac{1}{sC}}{R_c + \frac{1}{sC} + R_o} = \frac{sCR_c + 1}{sCR_c + 1 + sR_oR_c}$$

$$T = aB = a(s)F(s) = \frac{a_o}{1+s\tau_a}\left(\frac{sCR_c+1}{sCR_c+1+sR_oR_c}\right) = \frac{10^3}{1+0.1s}\cdot\frac{10^{-5}s+1}{1+10\cdot10^{-5}}$$

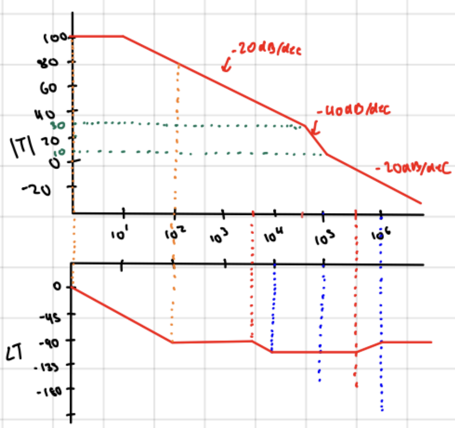
$$T = \frac{10^3(1+0.00001s)}{1+0.1s+0.000025+s^2(0.000002)}$$

zero at $s = 10^5$

pole at $s = 10$, $s = 5\times10^4$

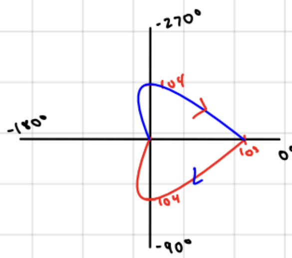
$10^x = 5\times10^4$

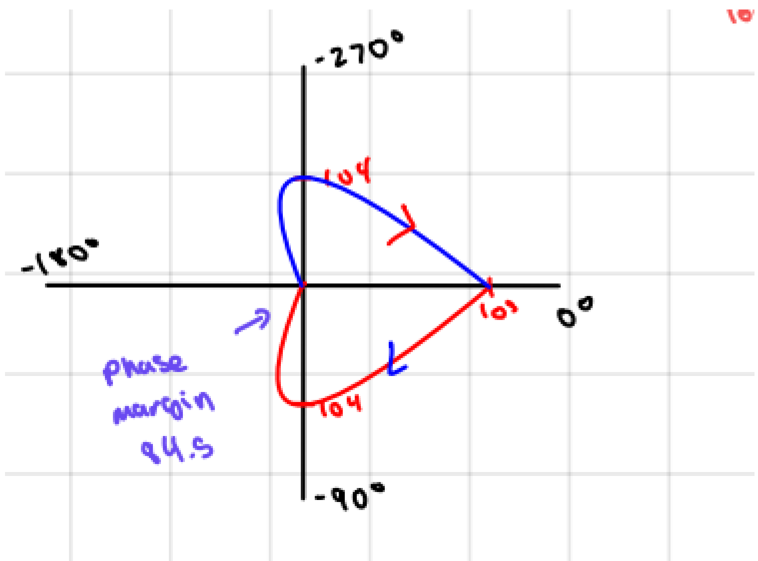
$\log(10^x) = \log(5\times10^4) \rightarrow x = 4.7 \rightarrow 10^{4.7}$




0°: 100dB = $10^2$

-90°: 80dB : $10^4$



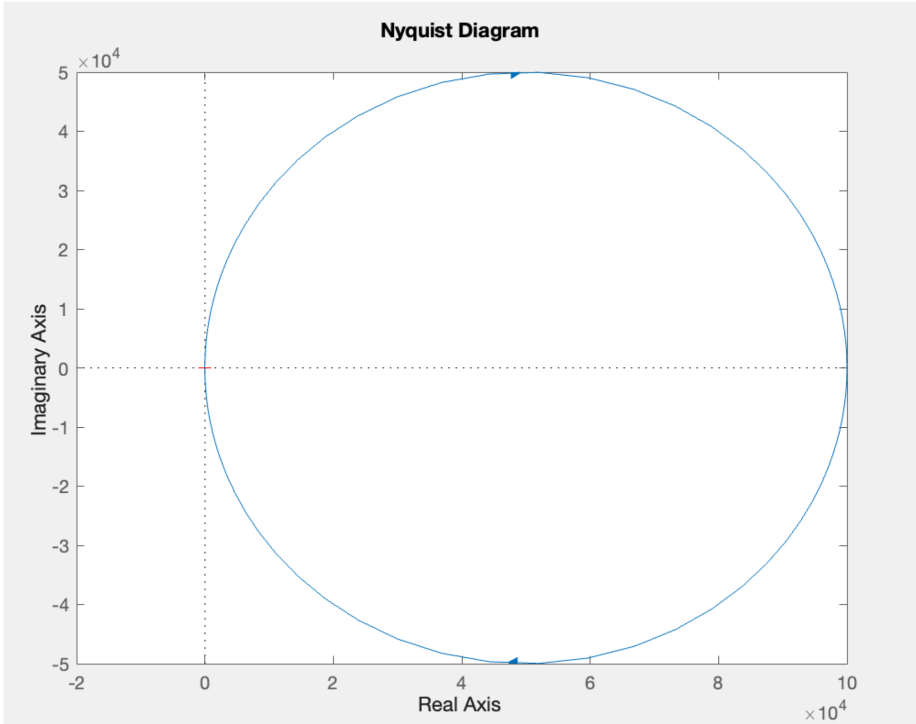



Figure 1.3.1: Simulated Nyquist Plot for Voltage Follower with Capacitive Load and Compensation Resistor

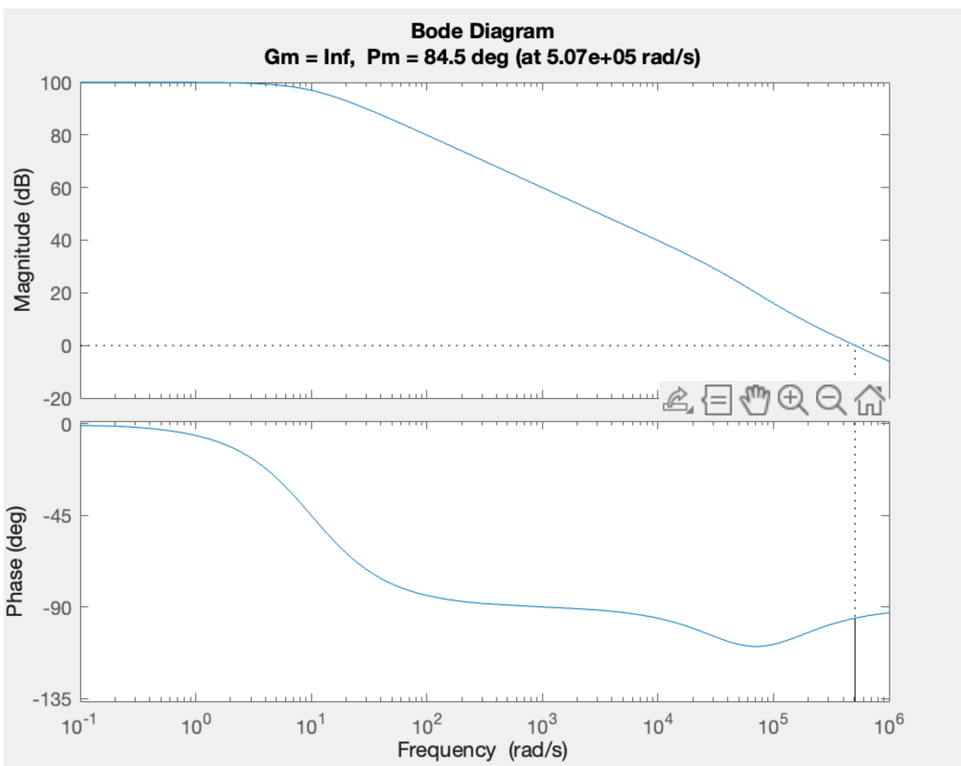



Figure 1.3.2: Simulated Bode Plot for Voltage Follower with Capacitive Load and Compensation Resistor

Phase Margin: 84.5 deg

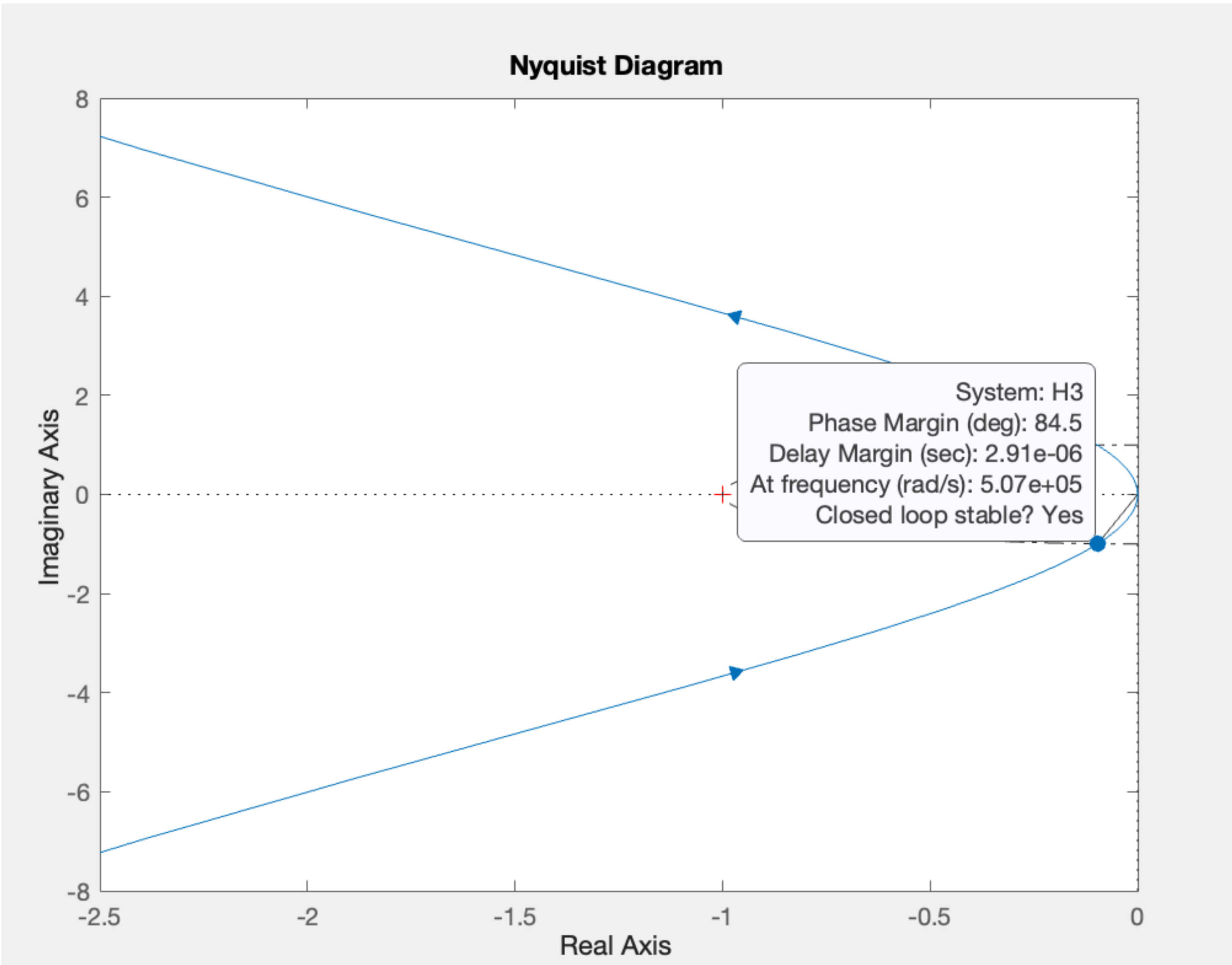



Figure 1.3.3: Simulated Nyquist Plot (Zoomed in) for Voltage Follower with Capacitive Load and Compensation Resistor

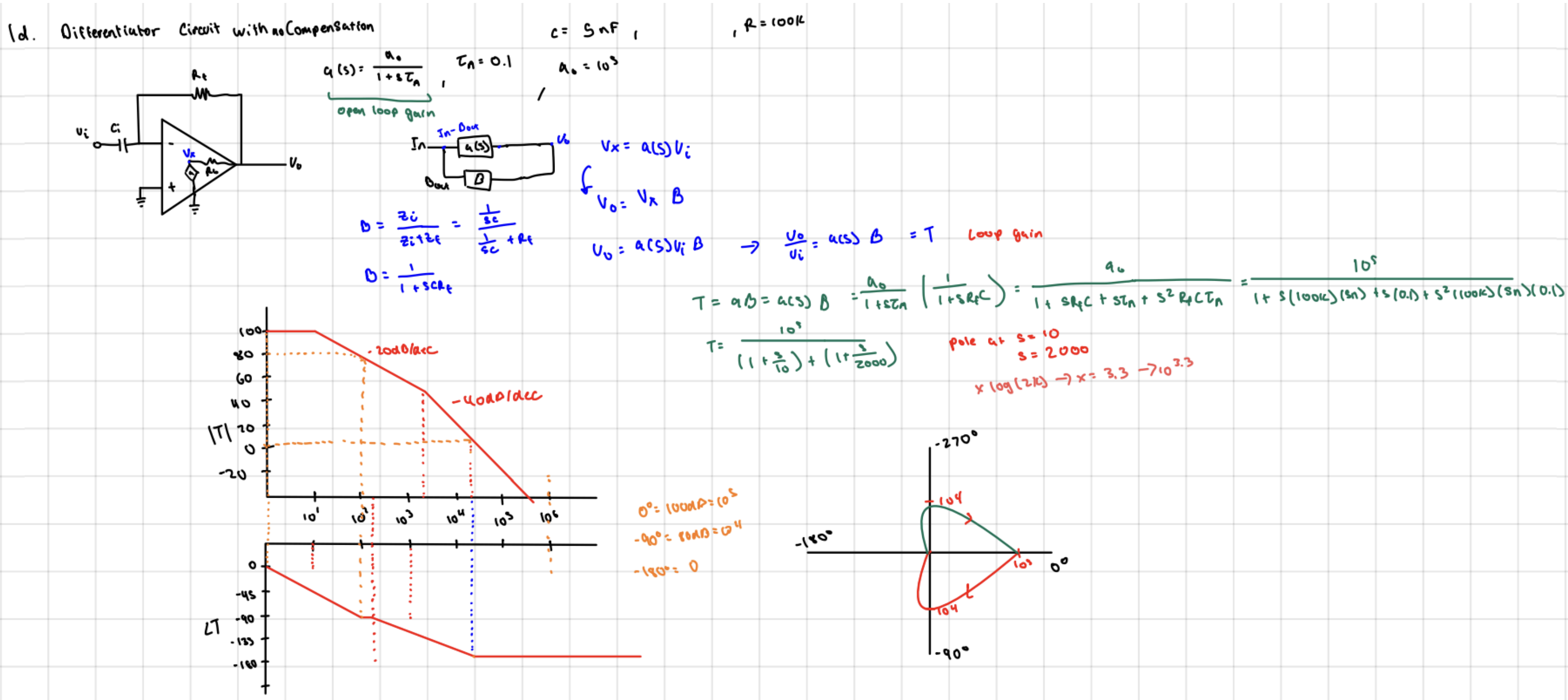
Phase Margin: 84.5 deg

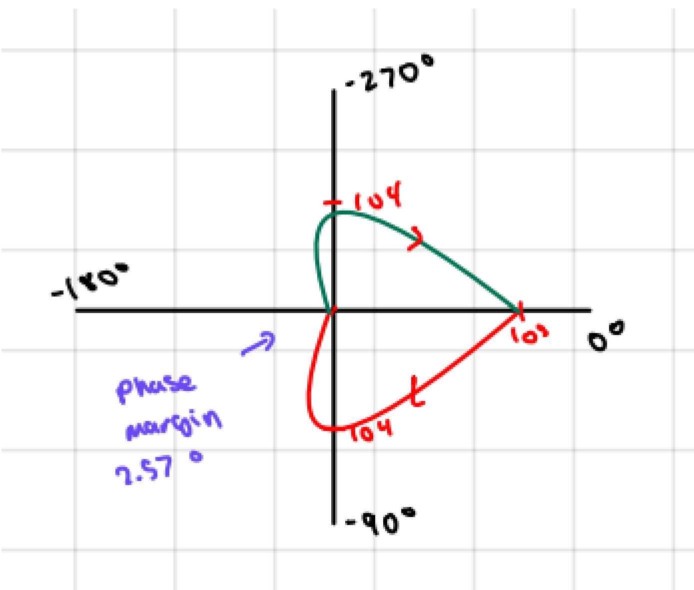
```
%1c
figure(5)
H3 = tf([1, 10^5],[0.000002, .10002, 1]);
nyquistplot(H3)
figure (6)
bode(H3)
margin(H3)
```

Provided above is the MATLAB code to plot the graphs.

# 4) Differentiator circuit with no compensation

We want to find the loop gain assuming $R = 100k\Omega$ and C = 5nF





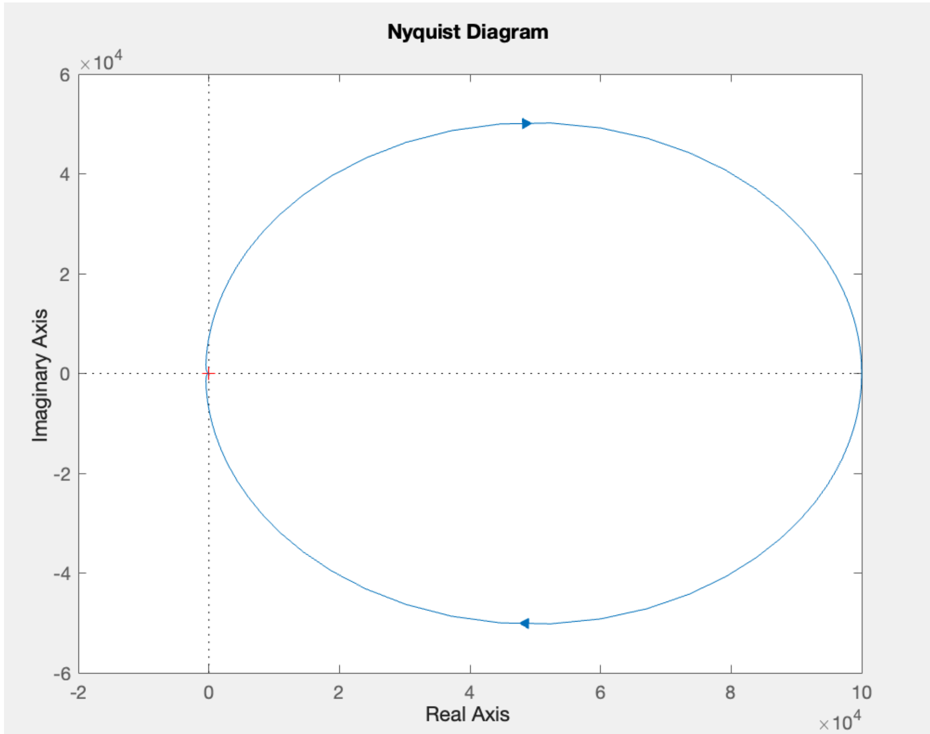



Figure 1.4.1: Simulated Nyquist Plot (Zoomed in) for Differentiator Circuit with No Compensation

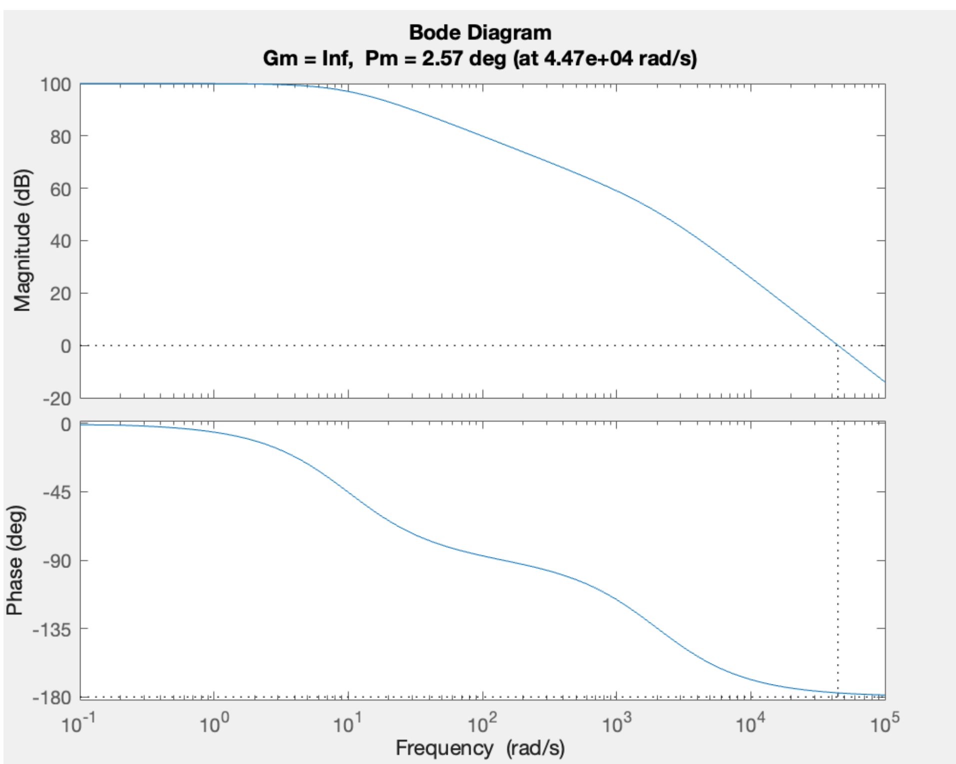



Figure 1.4.2: Simulated Bode Plot for Differentiator Circuit with No Compensation

Phase Margin: 2.57 deg

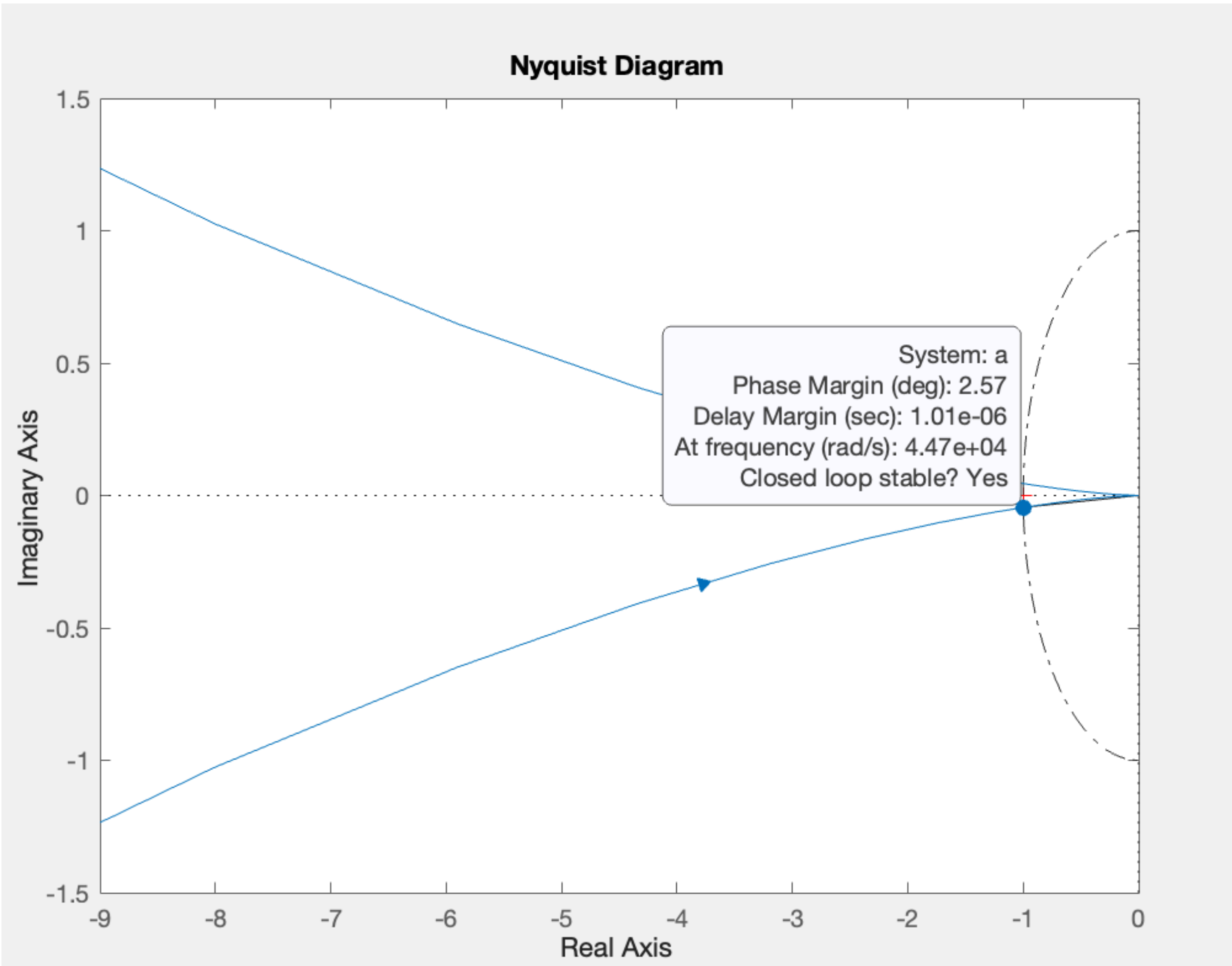


Figure 1.4.3: Simulated Nyquist Plot (Zoomed in) for Differentiator Circuit with No Compensation

Phase Margin: 2.57 deg

This shows relative instability of an uncompensated differentiator.

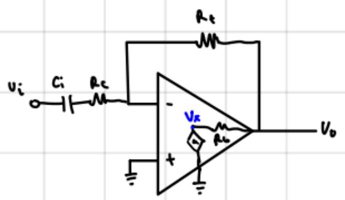
```
%1d
s = tf('s');
figure(7)
a1 = 10^5 / ((1+s*(0.1))*(1+s*100000*5e-9));
nyquistplot(a1)
figure (8)
bode(a1)
margin(a1)
```

Provided above is the MATLAB code to plot the graphs.

# 5) Differentiator circuit with compensation resistor

We want to find the loop gain assuming $R = 100k\Omega$ and C = 5nF

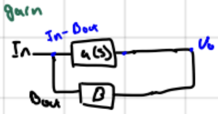
1e. Differentiator Circuit with Compensation Resistor  $c = 5nF$, $R_f = 100k$




$a(s) = \frac{a_0}{1+s\tau_A}$ open loop gain, $\tau_A = 0.1$, $a_0 = 10^3$

$\omega_0 = R_c C \to R_c = \frac{\omega_0}{C} = \frac{4.47\times10^4}{5\times10^{-8}} = 4.47k\Omega$

$R_c = 4.47k\Omega$




$V_x = a(s)V_i$

$V_o = V_x B$

$B = \frac{Z_i}{Z_i+Z_f} = \frac{R_c + \frac{1}{sC}}{R_c+R_f+\frac{1}{sC}}$

$B = \frac{sR_cC+1}{sR_cC+R_f sC+1}$

$V_o = a(s)V_i B \to \frac{V_o}{V_i} = a(s)B = T$ Loop gain

$T = aB = a(s)B = \frac{a_0}{1+s\tau_A}\left(\frac{sR_cC+1}{sR_cC+R_f sC+1}\right) = \frac{10^3}{1+0.1s}\left(\frac{s(2000)(5n)+1}{sR_cC+R_f sC+1}\right)$

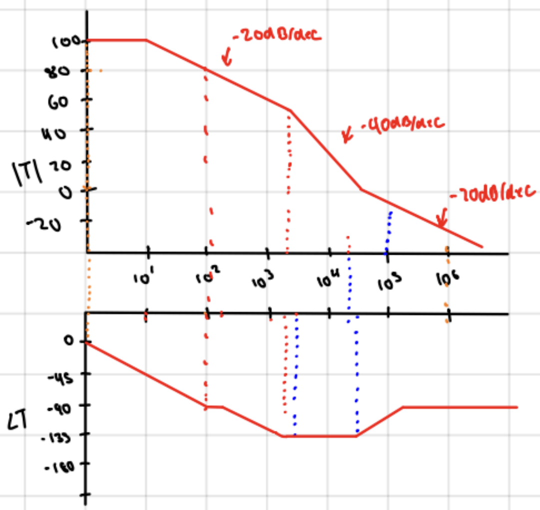
$T = \frac{10^3(1+22\times10^{-6}s)}{1+0.1006s+51\times10^{-6}s^2}$

zero at $s = 4.5\times10^4 = 10^{4.6}$

pole at $s = 10$

$s = 2000$

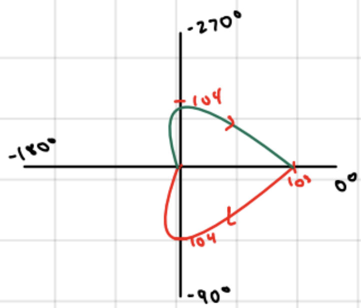
$x \log(2k) \to x = 3.3 \to 10^{3.3}$




0° = 100dB = $10^5$

-90° = 80dB = $10^4$

-180° = 0



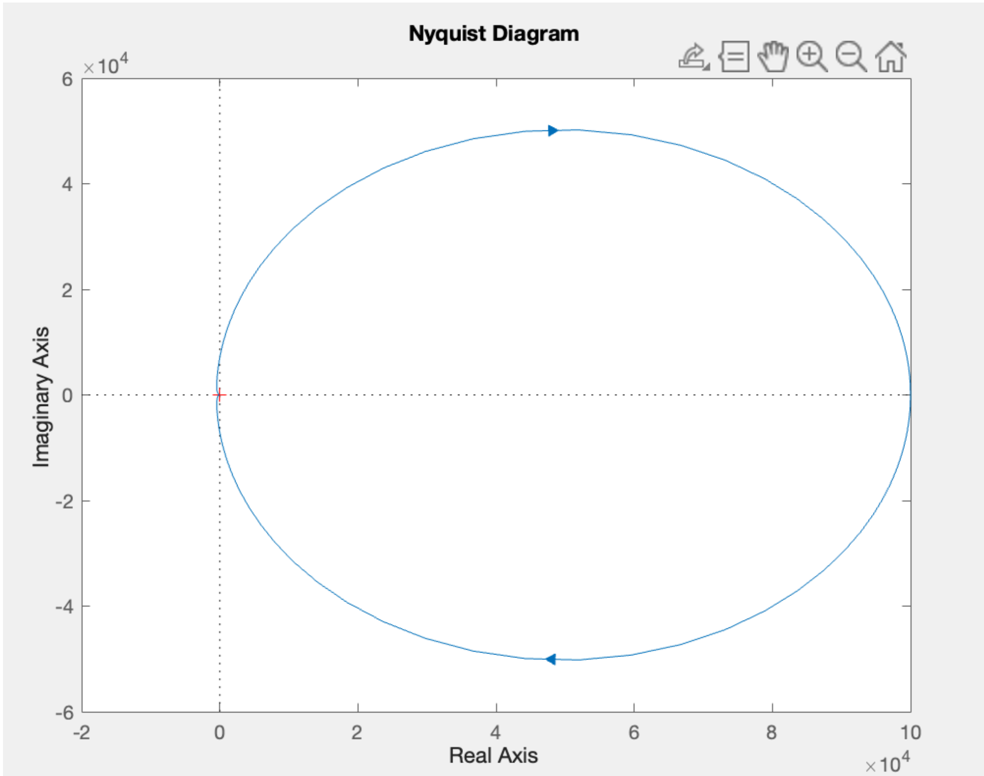




Figure 1.5.1: Simulated Nyquist Plot (Zoomed in) for Differentiator Circuit with Compensation Resistor

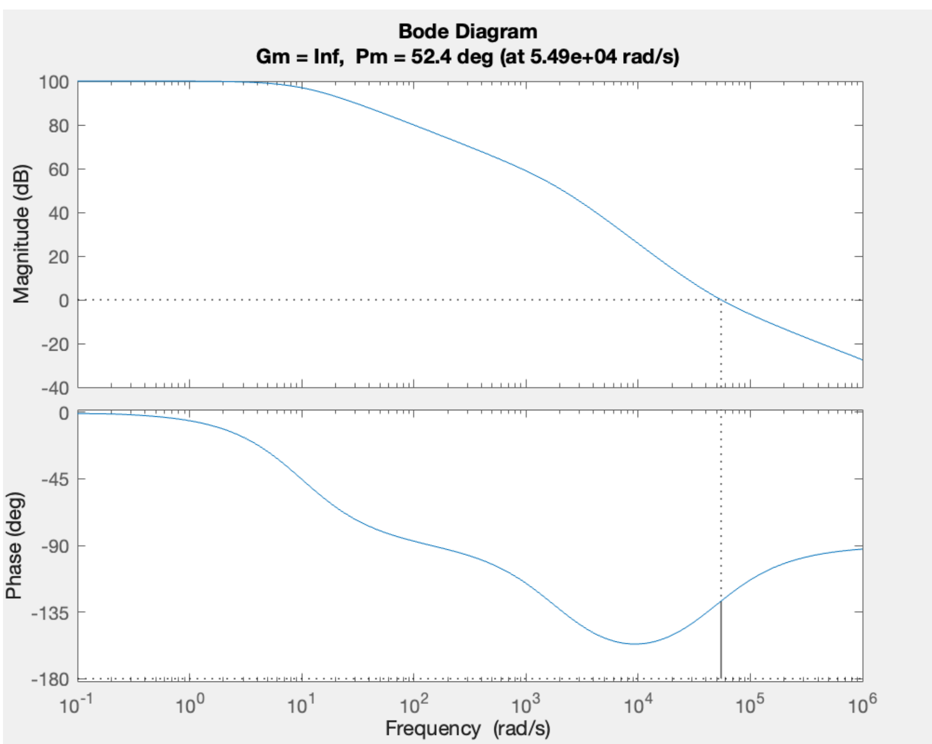



Figure 1.5.2: Simulated Bode Plot for Differentiator Circuit with Compensation Resistor

Phase Margin: 52.4 deg

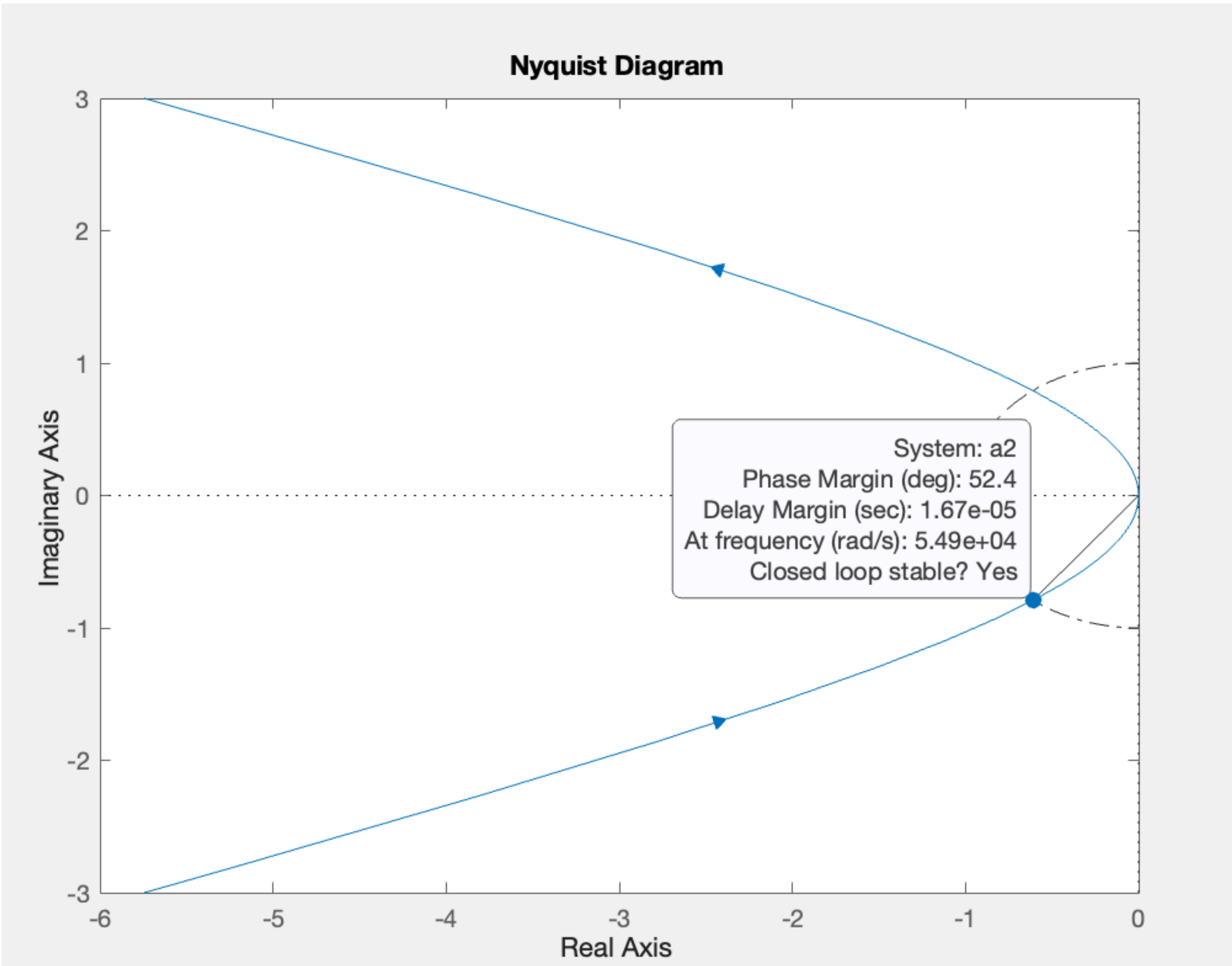



Figure 1.5.3: Simulated Nyquist Plot (Zoomed in) for Differentiator Circuit with Compensation Resistor

Phase Margin: 52.4 deg

This increases stability and decreases distortion due to ringing.

```
%1e
a2 = (10^5 * (1 + 0.000022*s)) / (1 + .10052*s + 0.000052*s^2);
figure(9)
nyquistplot(a2)
figure(10)
bode(a2)
margin(a2)
```

Provided above is the MATLAB code to plot the graphs.

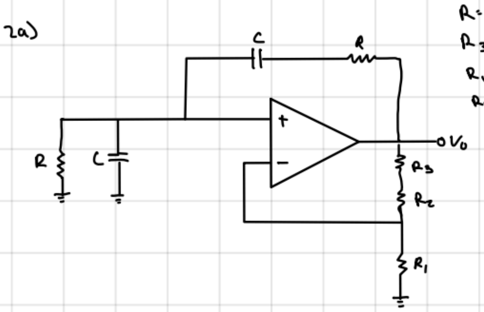
# Part 2: Design of the Wien-Bridge Oscillator

## Section A: System Level Design

### (a)

Show analytically that the feedback factor is $B(s) = \frac{sRC}{1 + 3sRC + (sRC)^2}$.

2a)

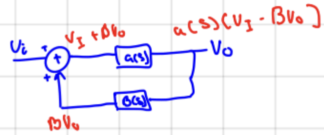


$R = 10k\Omega$
$R_3 = 15K$
$R_1 = 10K$
$R_2 = 6K$

a) Show analytically that the feedback factor is $\frac{SRC}{1+3SRC+(SRC)^2} = B$, loop gain $T(s) = -KB(s)$

$V_{tb}^- = V_o \cdot \frac{R_1}{R_1+R_2}$

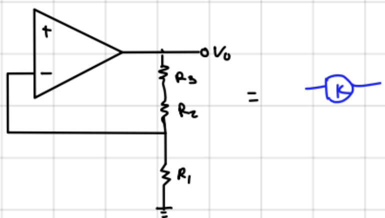
as long as the frequency at $V_o$ is not above $\omega_p$, it will have constant gain. (K)



$a(s)V_I + a(s)\beta V_o = V_o$

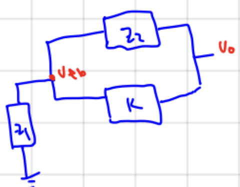
$V_o(1 - a(s)B) = a(s)V_I$

$\frac{V_o}{V_I} = \frac{a(s)}{1 - a(s)\beta}$ positive feedback



$K = \frac{R_1+R_2+R_3}{R_1} = \frac{6K+10K+15K}{10K}$

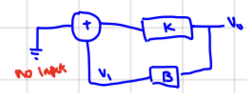
$K = 3.1$



$V_{tb} = \frac{Z_2}{Z_1+Z_2} V_o$

$Z_2 = \frac{1}{sC} + R$, $Z_1 = \frac{1}{sC} \| R = \frac{\frac{R}{sC}}{\frac{1}{sC}+R} = \frac{R}{1+RSC}$

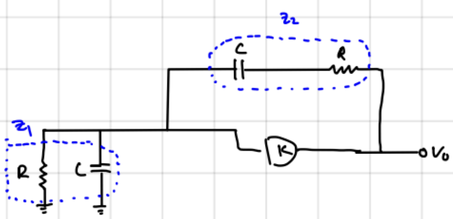
$\beta = \frac{V_{tb}}{V_o} = \frac{Z_1}{Z_1+Z_2}$



$B(s) = \frac{\frac{R}{1+SRC}}{\frac{R}{1+SRC} + \frac{1}{sC} + R}$

$= \frac{R}{R + \frac{1+SRC}{SC} + R + SR^2C} = \frac{RSC}{RSC + 1 + SRC + SCR + S^2R^2C^2}$

$B(s) = \frac{SRC}{1 + 3SRC + s^2(RC)^2}$ ✓



$T(s) = -K\,B(s) = \frac{-3.1SRC}{1+3SRC+(SRC)^2}$

when $K<3$ : stable, all poles LHP
$K=3$ : oscillator, poles on $j\omega$
$K>3$ : unstable, poles RHP

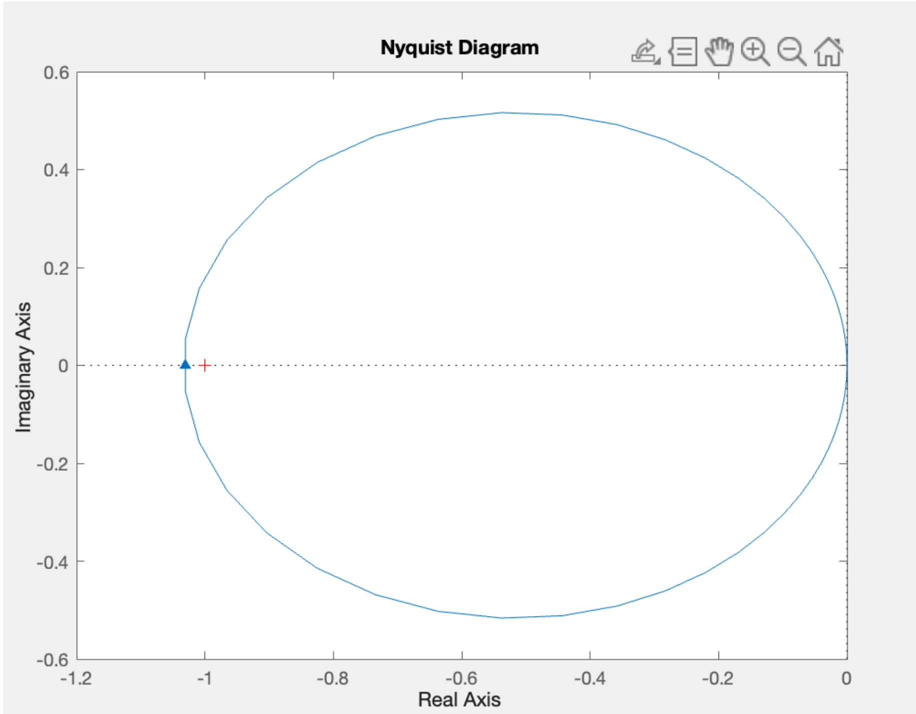



Figure A.1.1: Simulated Nyquist Plot for Wein-Bridge Oscillator Circuit

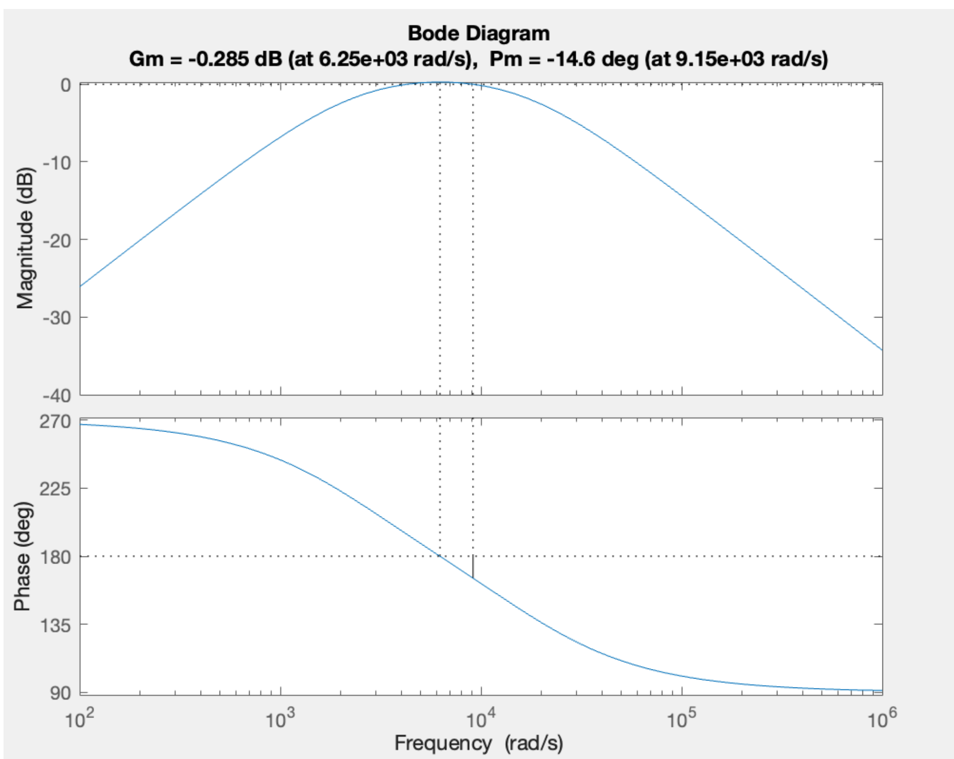



Figure A.1.2: Simulated Bode Plot for Wein-Bridge Oscillator Circuit

Phase Margin: -14.6 deg

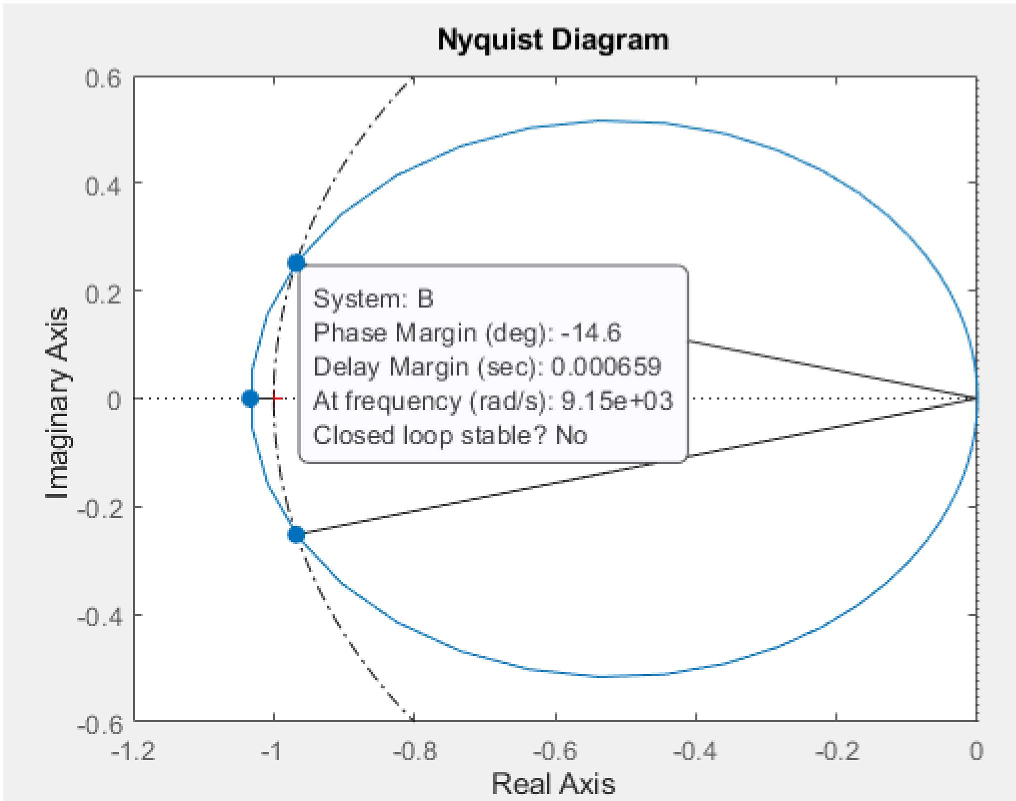



Figure A.1.3: Simulated Nyquist Plot (zoomed in) for Wein-Bridge Oscillator Circuit

Phase Margin: -14.6 deg
This system is not stable.

```
%2a
C = 16 * 10^-9;
R = 10000;
s = tf('s');
B = (-3.1*R *s * C) / (1 + (3*s*C*R)+ (s*R * C)^2);
figure(11)
nyquistplot(B)
figure(12)
bode(B)
margin(B)
```

## (b)

Simulate the oscillator in Simulink with a gain block of 3.1 and a feedback transfer function of

$$\frac{s}{1 + 3s + s^2}.$$

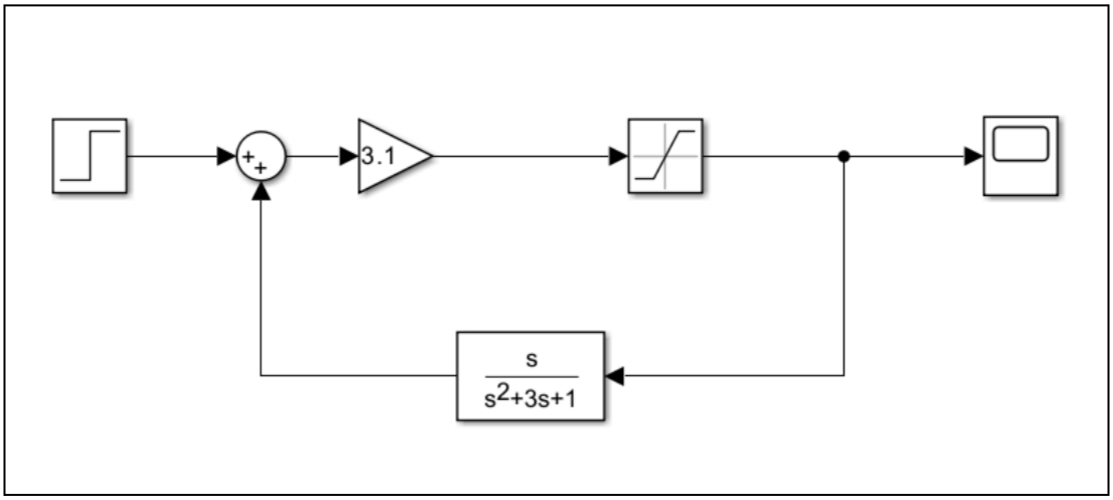



Figure A.2.2: Block Diagram for Wein-Bridge Oscillator Circuit

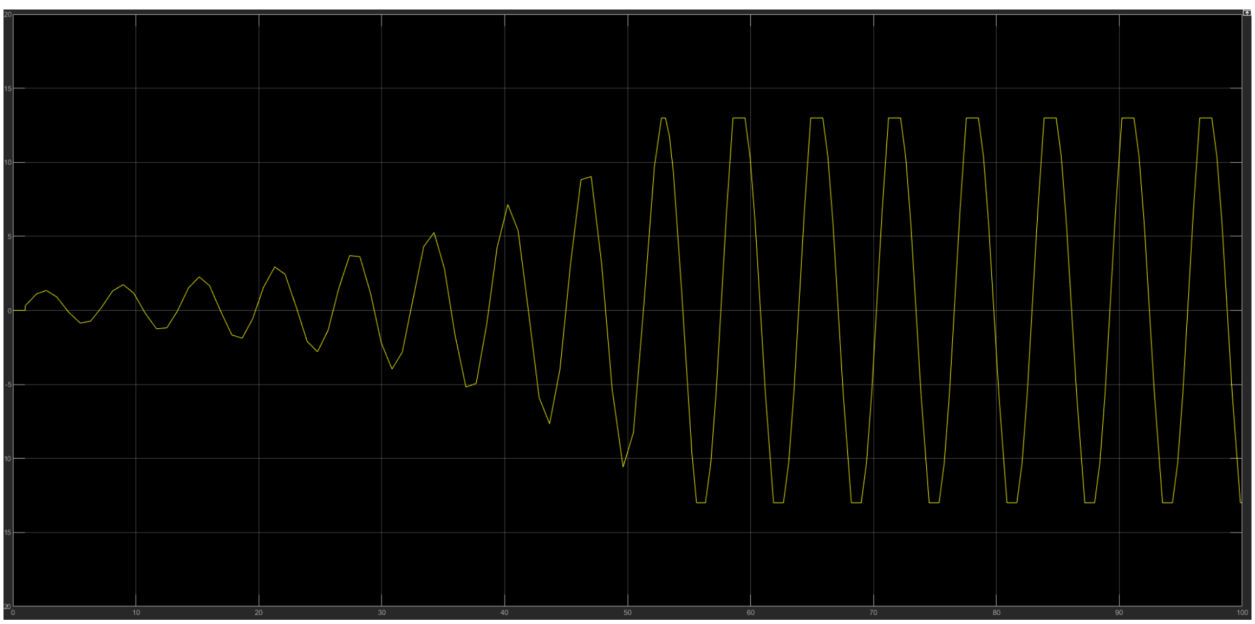


Figure A.2.3: Simulink Simulation for Wein-Bridge Oscillator Circuit

# Section B: Circuit Level Simulations

For the following parts we will use PSpice to simulate our circuits (this can be done with any circuit simulation software). We want to manipulate the circuit to either adjust the amplitude and/or the frequency by adjusting values of the circuit components.

## (a)

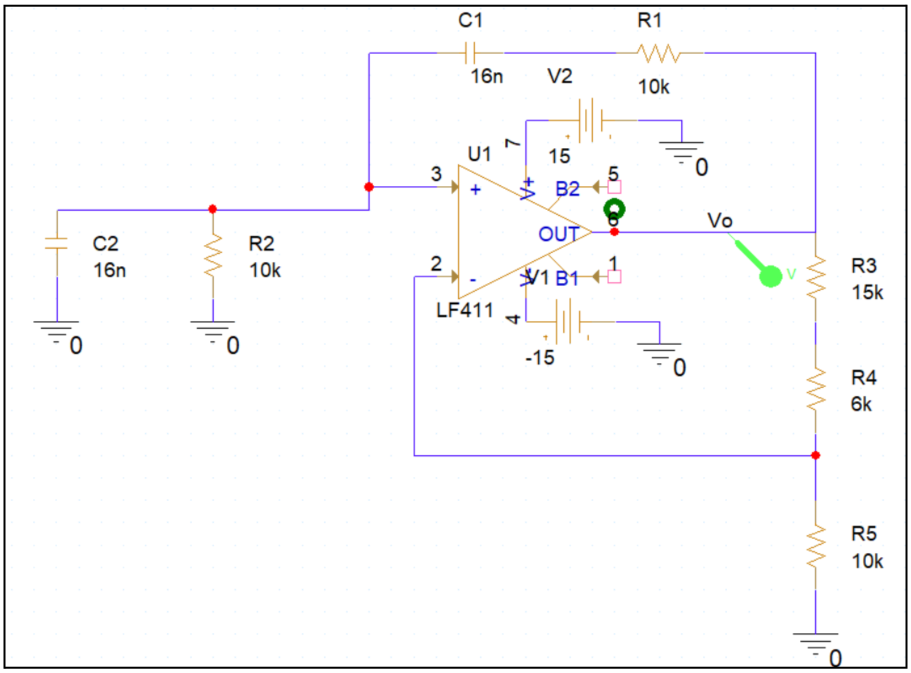



Figure B.1.1: Simulation Schematic of Wein-Bridge Oscillator without diodes, Feedback R = 1kΩ, and Feedback C = 16nF

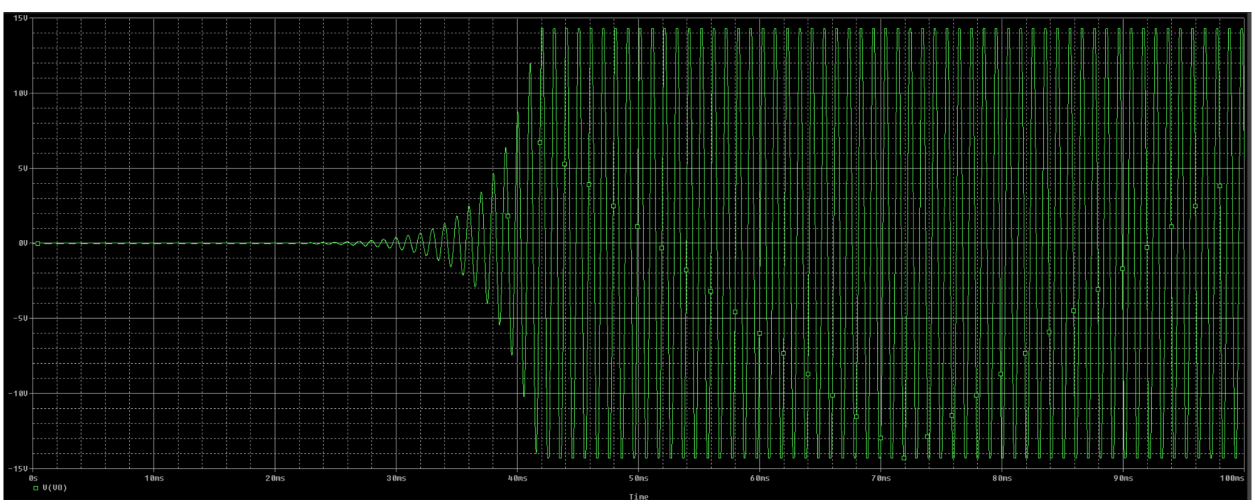
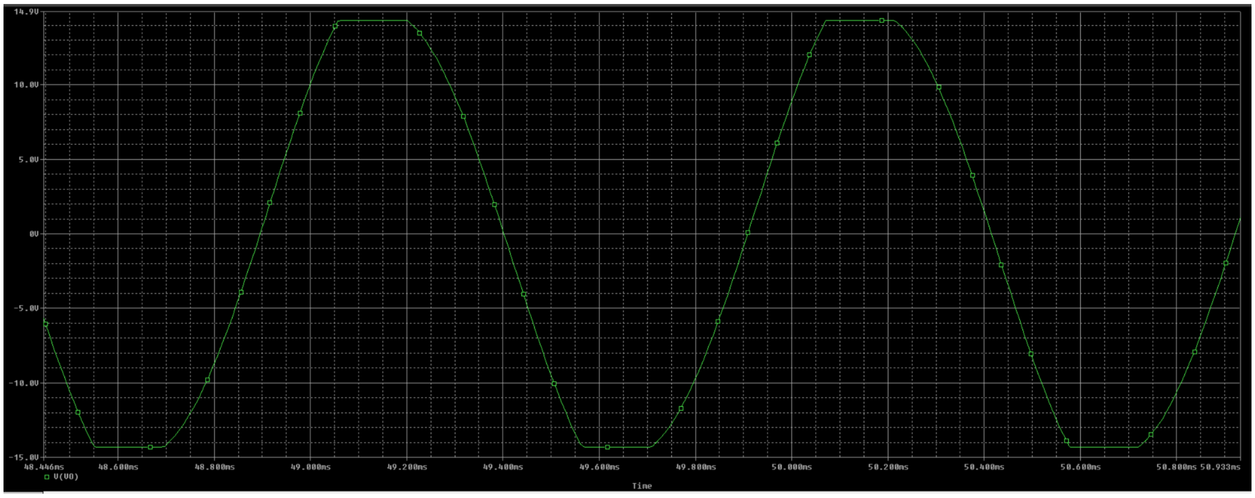


Figure B.1.2: Simulation Schematic of Wein-Bridge Oscillator without diodes, Feedback R = 1kΩ, and Feedback C = 16nF

The output starts to stabilize at 45 ms and has a 985 Hz frequency.




| Trace Color | Trace Name | Y1 | Y2 | Y1 - Y2 |
|---|---|---|---|---|
| | X Values | 49.075m | 48.446m | 629.140u |
| CURSOR 1,2 | V(VO) | 14.303 | -5.6671 | 19.970 |

Figure B.1.3: Simulation Plot and Trace of Wein-Bridge Oscillator without diodes, Feedback R = 1kΩ, and Feedback C = 16nF

It is clipping at 14.303V and -14.303 V

This structure has limited effective gain.

**(b)**

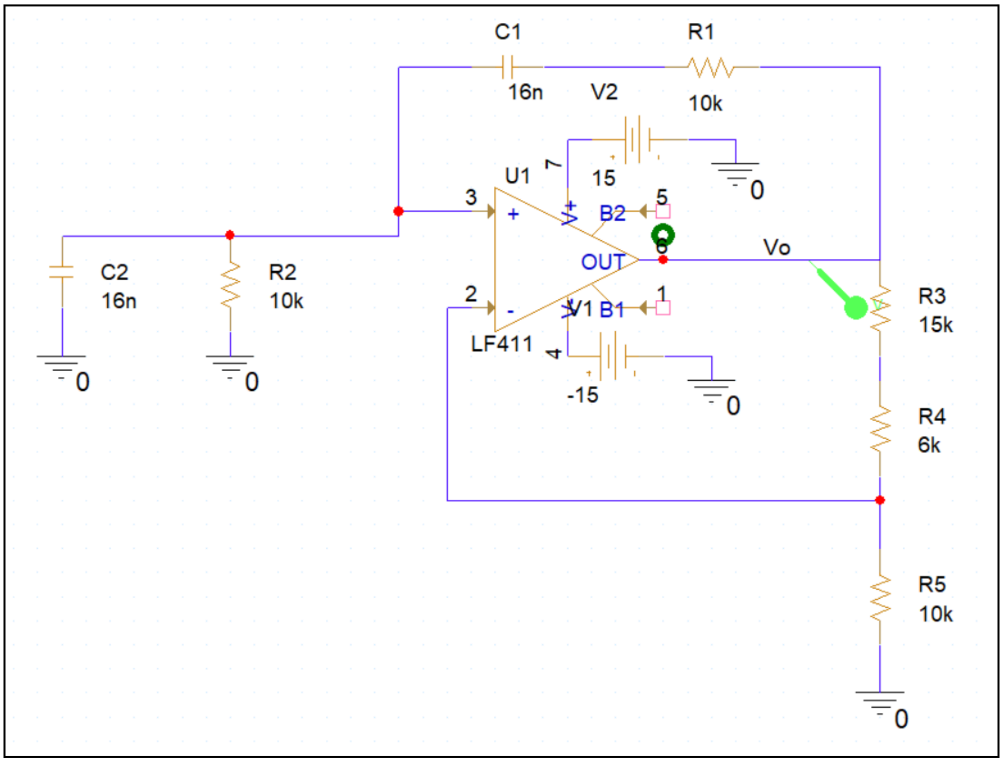



Figure B.2.1: Simulation Schematic of Wein-Bridge Oscillator

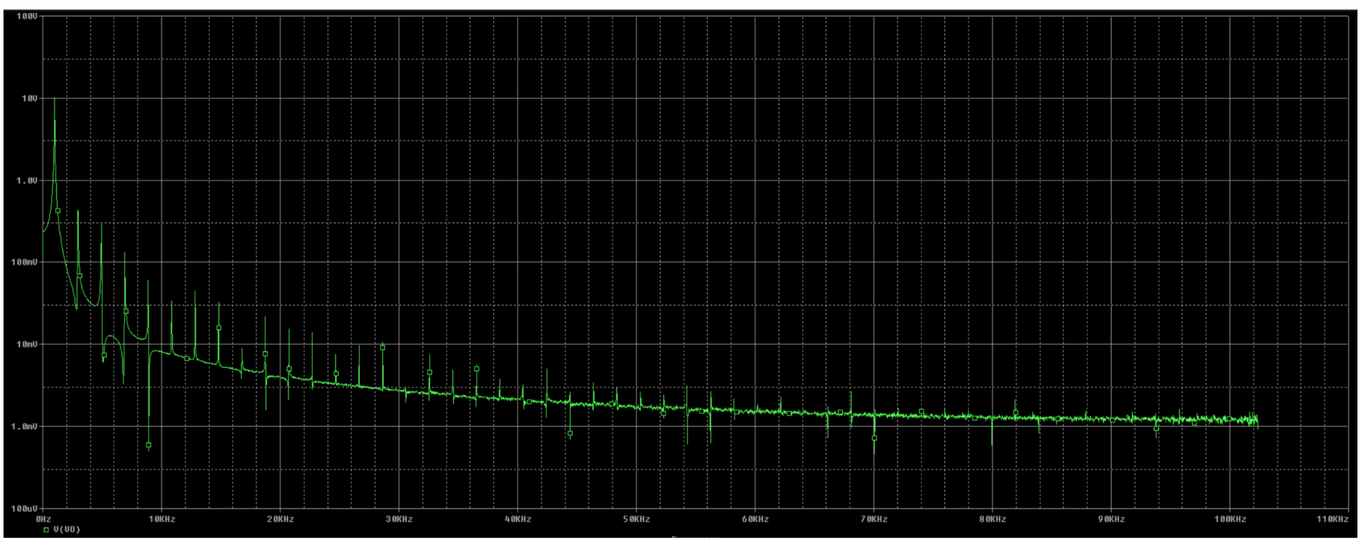
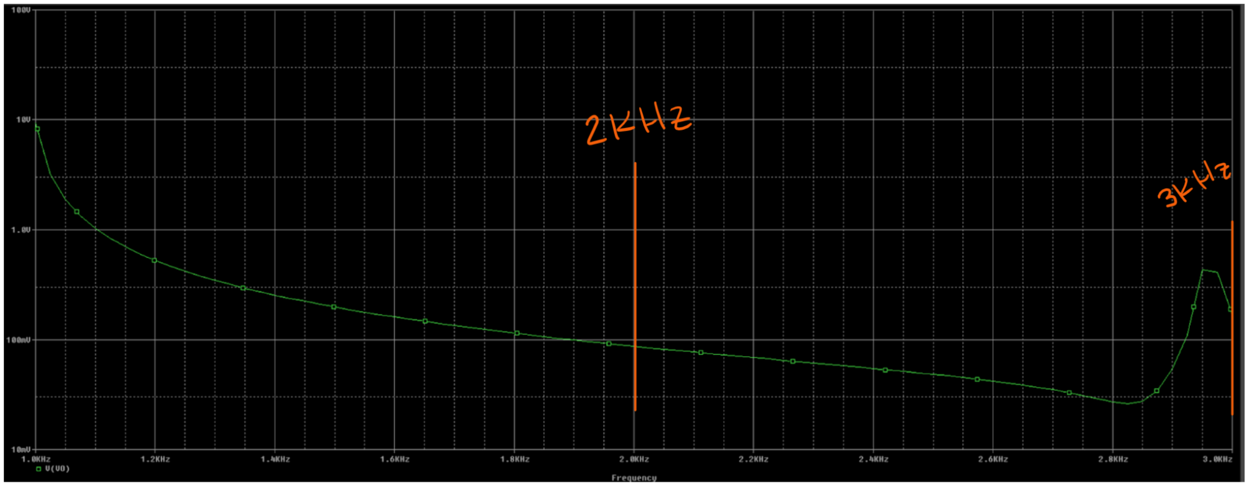



Figure B.2.2: FFT Plot of Wein-Bridge Oscillator




From 1kHz to 3kHz

| Trace Color | Trace Name | Y1 | Y2 |
|---|---|---|---|
| | X Values | 1.0000K | 3.0012K |
| CURSOR 1,2 | V(VO) | 9.3596 | 165.719m |

Figure B.2.3: FFT Plot and Trace of Wein-Bridge Oscillator

At 1k Hz= 9.3596 V

At 3kHz= 165.617m V

P = 20log(V(@1kHz)/V(@3kHz))

P = 35.04 dB

**(c)**

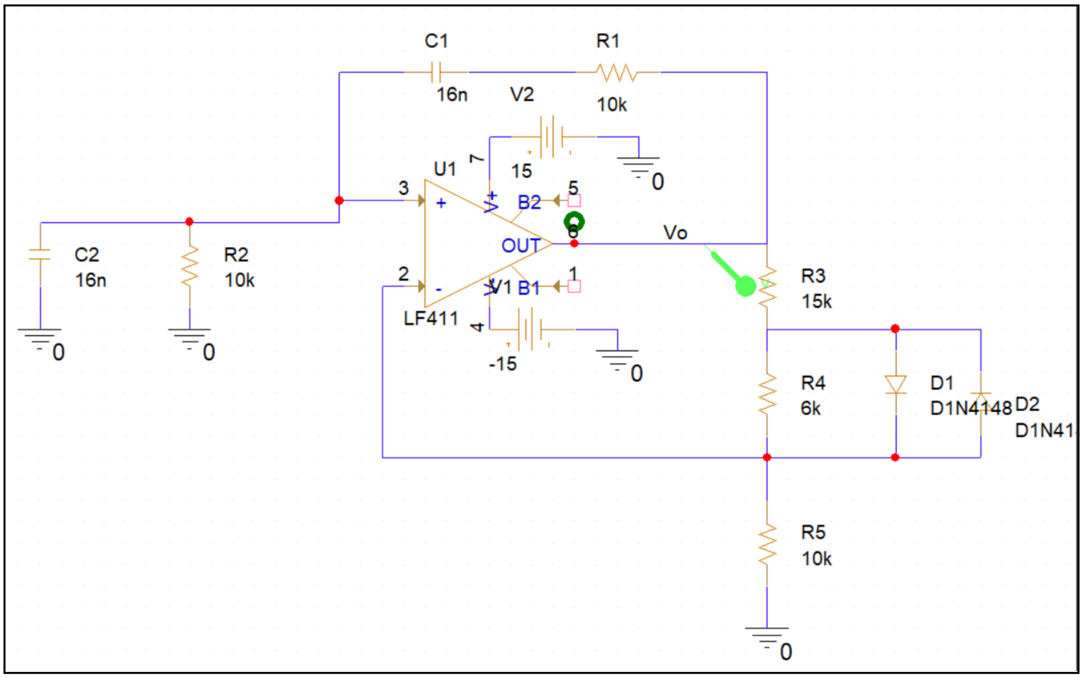



Figure B.3.1: Simulation Schematic of Wein-Bridge Oscillator w/ Diodes, Feedback R = 10kΩ, and Feedback C = 16nF

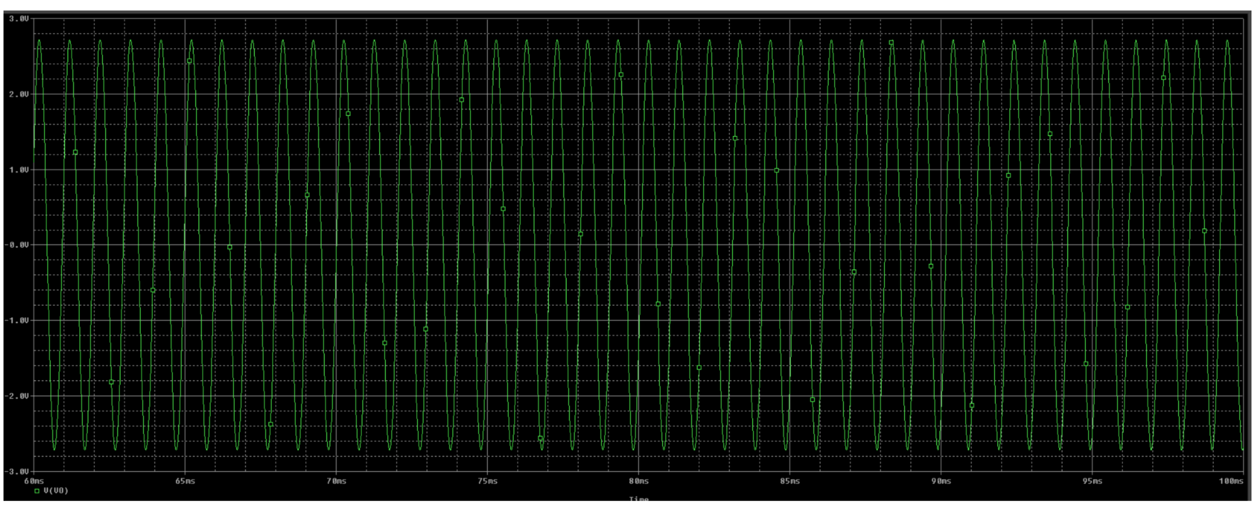
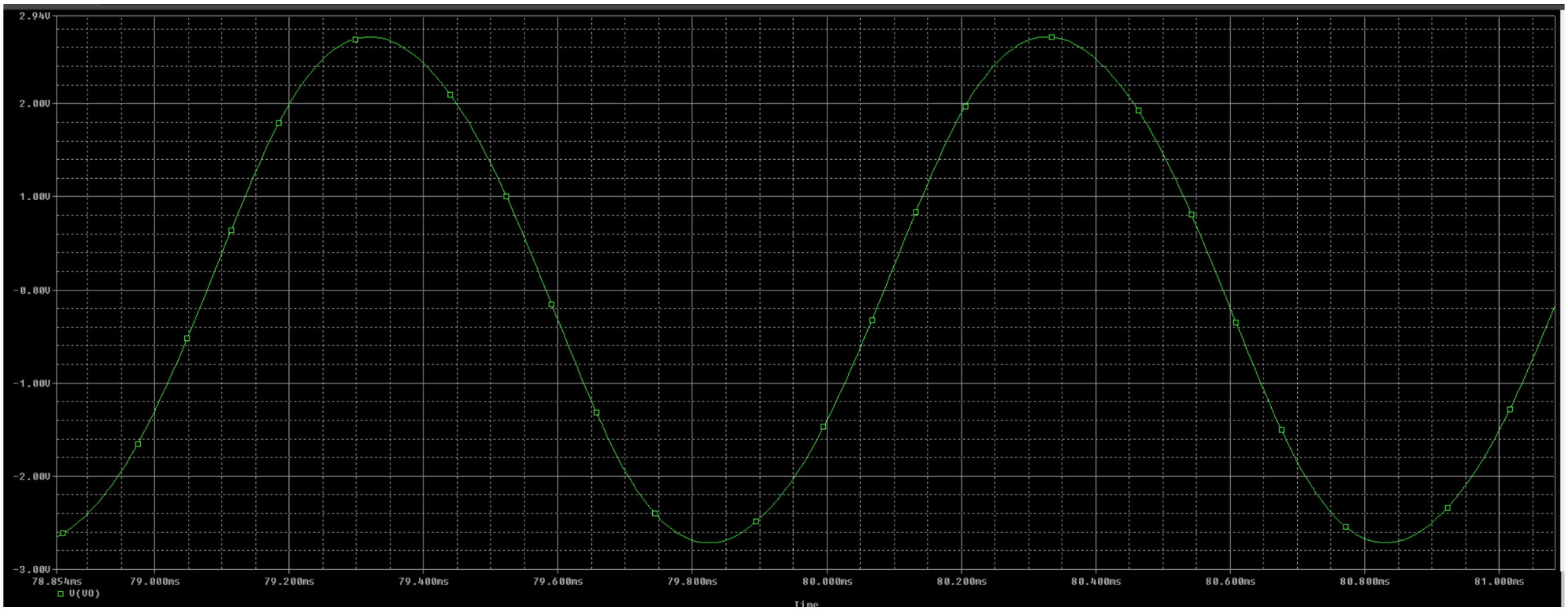
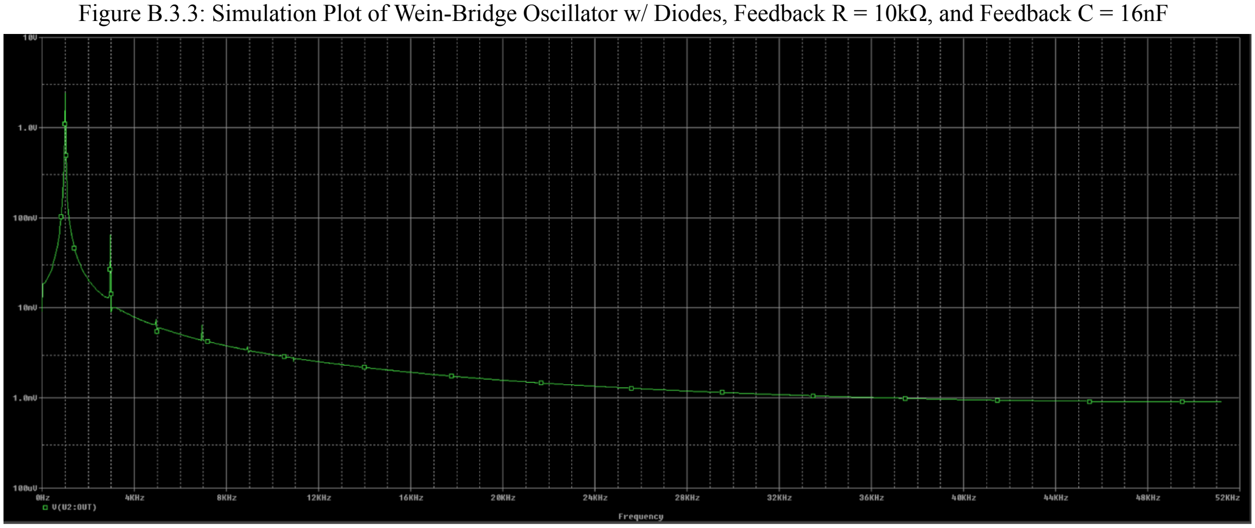


Figure B.3.2: Simulation Plot of Wein-Bridge Oscillator w/ Diodes, Feedback R = 10kΩ, and Feedback C = 16nF

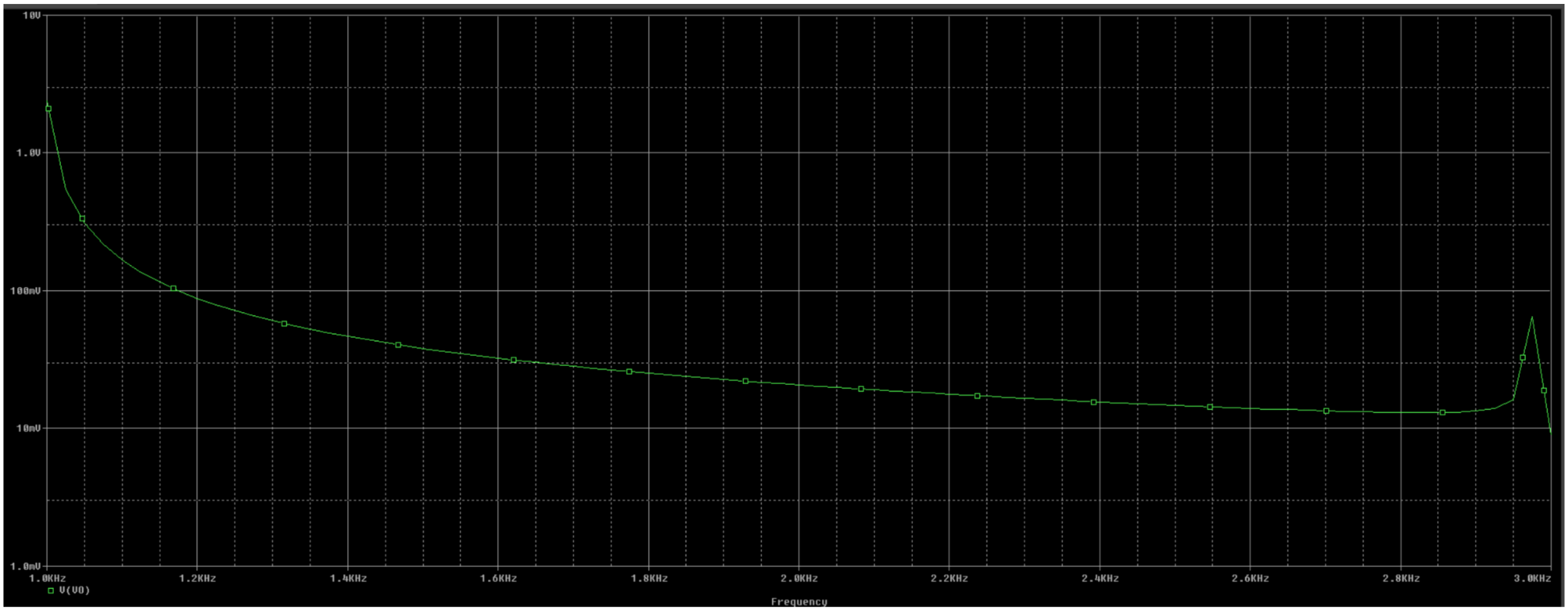



| Trace Color | Trace Name | Y1 | Y2 | Y1 - Y2 |
|---|---|---|---|---|
| | X Values | 79.332m | 79.812m | -480.870u |
| CURSOR 1,2 | V(VO) | 2.7087 | -2.7090 | 5.4177 |
| | | | | |

Figure B.3.3: Simulation Plot of Wein-Bridge Oscillator w/ Diodes, Feedback R = 10kΩ, and Feedback C = 16nF




There is no Clipping on the output signal. We achieved an Amplitude = ±2.709V




| Trace Color | Trace Name | Y1 | Y2 |
|---|---|---|---|
| | X Values | 1.0000K | 3.0010K |
| CURSOR 1,2 | V(VO) | 2.3858 | 8.9608m |

Figure B.3.4: FFT Plot of Wein-Bridge Oscillator w/ Diodes, Feedback R = 10kΩ, and Feedback C = 16nF

V(@1kHz) = 2.3858 V

V(@3kHz) = 8.9608m V

P =48.50dB

| Trace Color | Trace Name | Y1 | Y2 | Y1 - Y2 |
|---|---|---|---|---|
| | X Values | 79.319m | 78.317m | 1.0020m |
| CURSOR 1,2 | V(VO) | 2.7152 | 2.7150 | 234.702u |
| | | | | |

Frequency = 1/T

T = 1.0020 m s

F = 1k Hz

Change in performance = P = 48.50 dB -35.04 dB= P = 13.46 dB

It changed by a factor of 1.384 with the diodes thus giving a higher performance.

## (d)

We are now adjusting the Feedback Capacitors and Resistors in order to modify the oscillation frequency of the circuit.

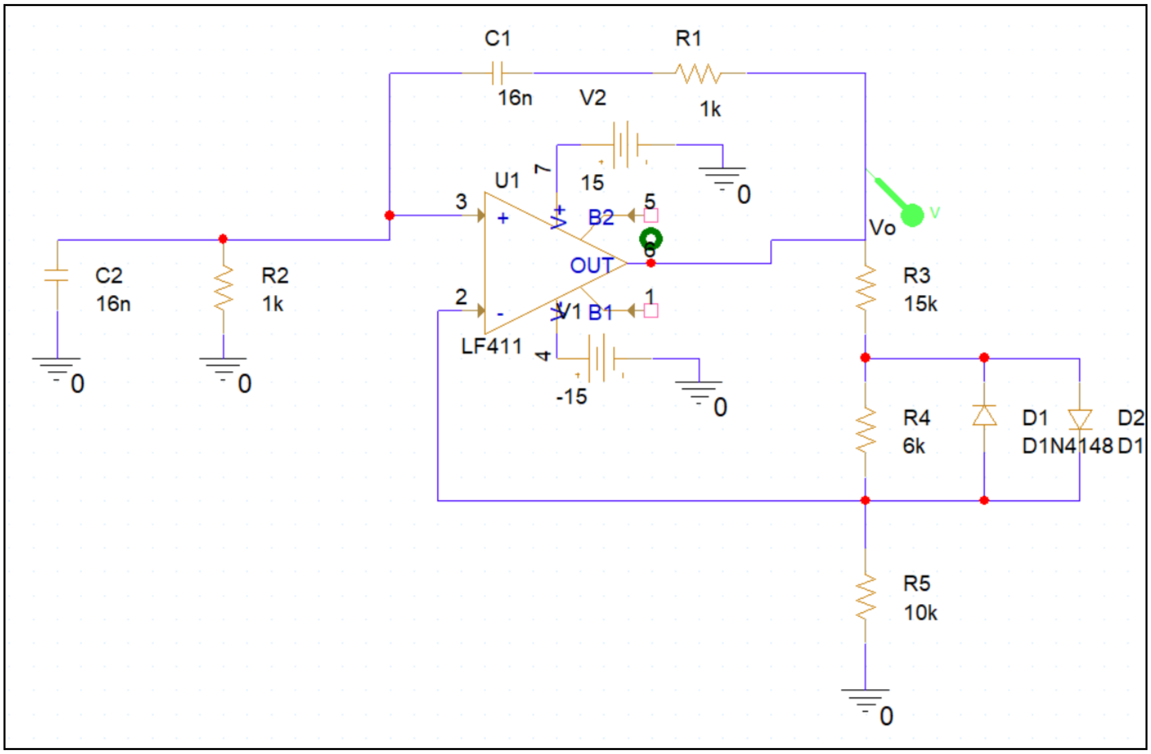



Figure B.4.1: Simulation Schematic of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 16nF

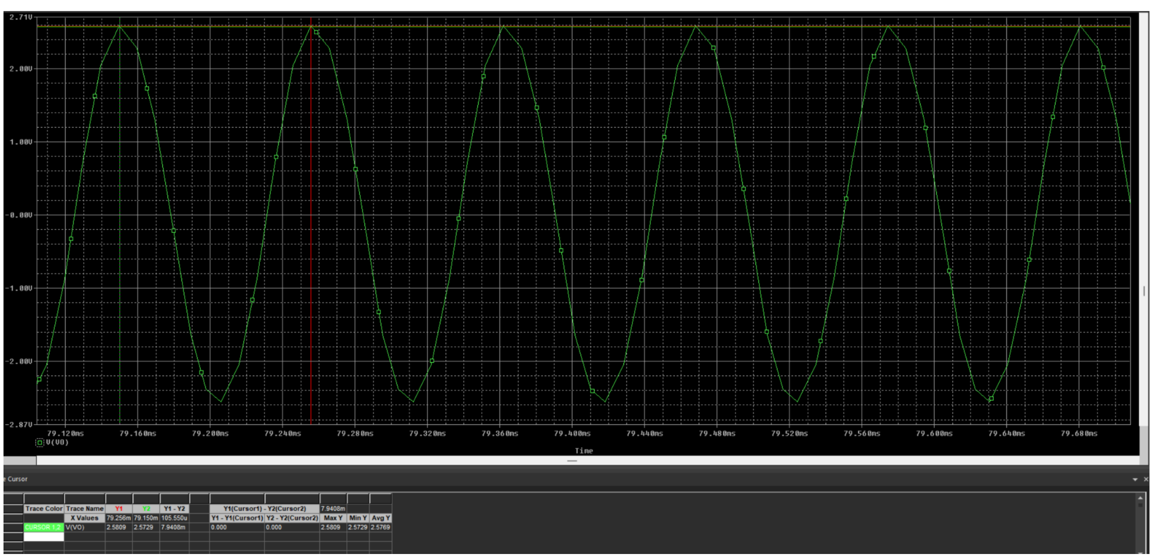


Figure B.4.2: Simulation Plot of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 16nF

T = 105.550 μs

F = 9.47k Hz

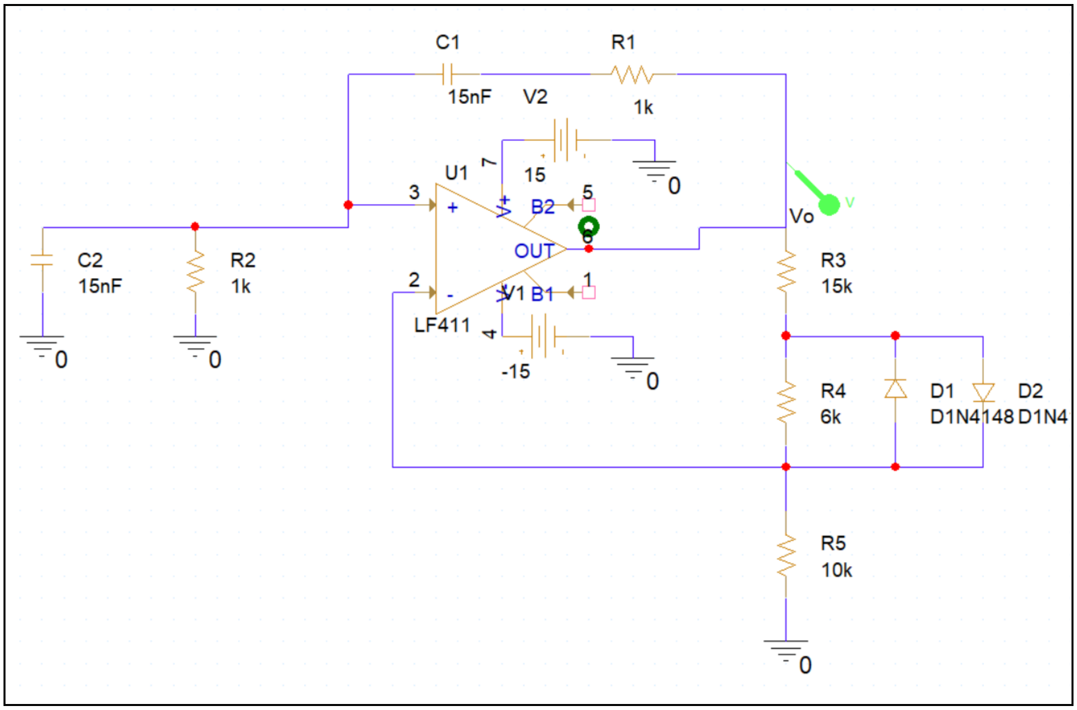



Figure B.4.3: Simulation Schematic of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 15nF

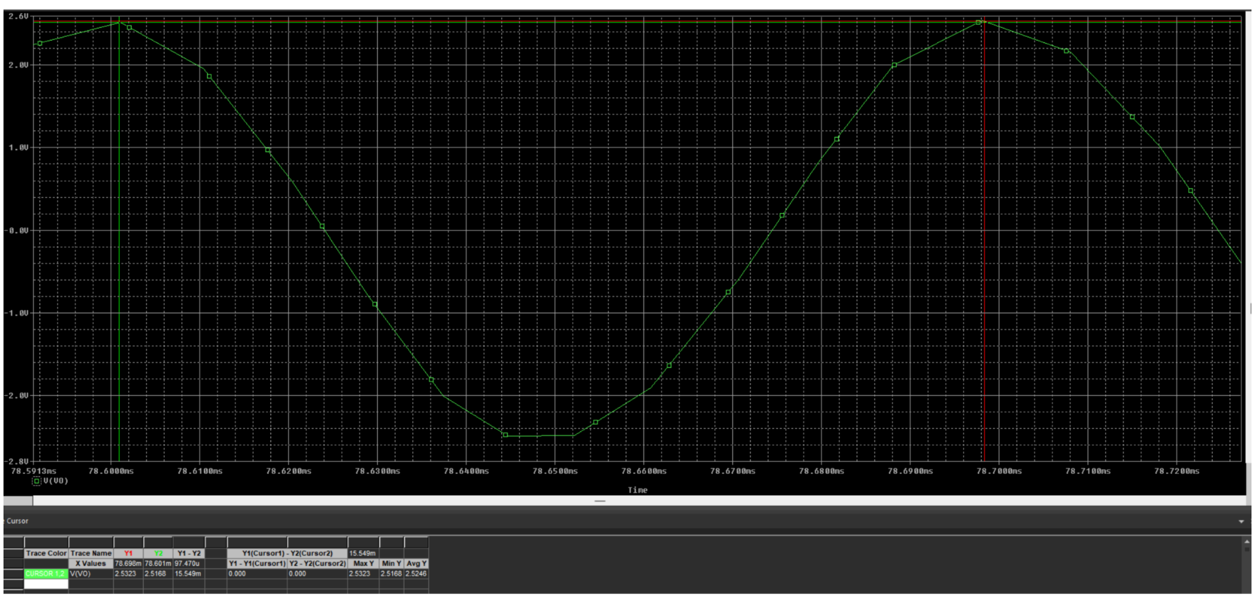


Figure B.4.4: Simulation Plot of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 15nF

T = 97.470 μs

$$\text{Frequency} = \frac{1}{T}$$

F = 10.25k Hz

This is 10 times the original

Testing for 100k (10 times this frequency)

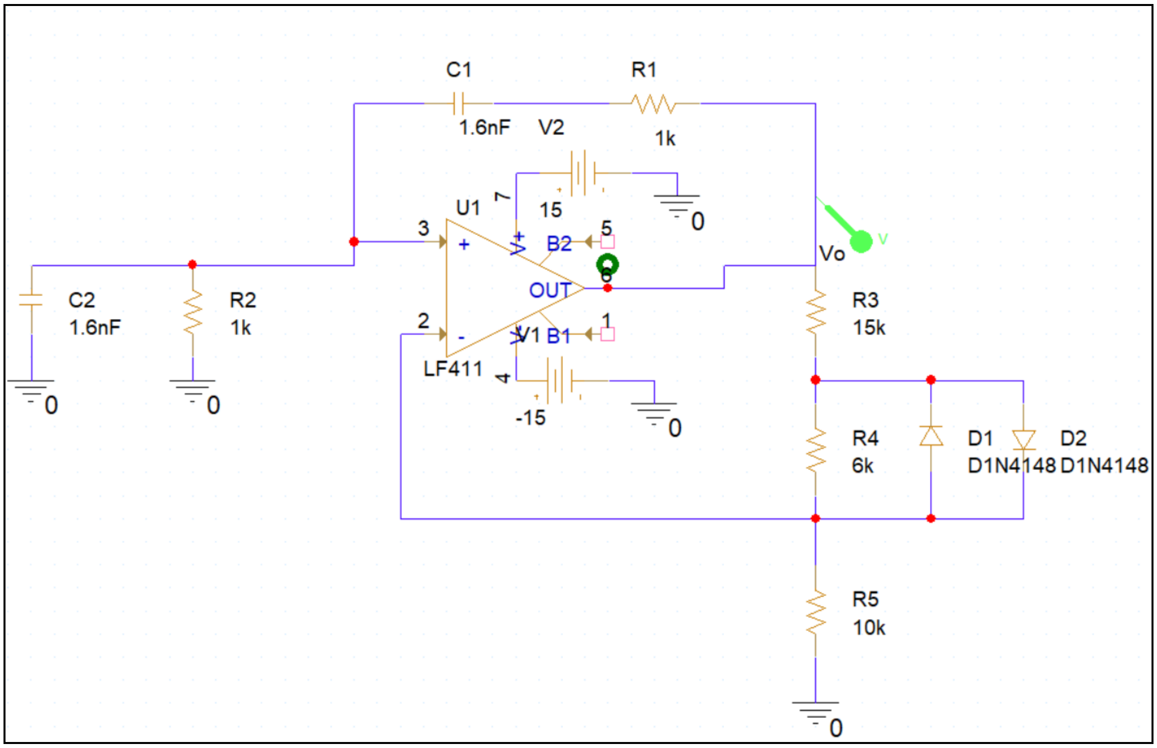



Figure B.4.5: Simulation Schematic of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 1.6nF

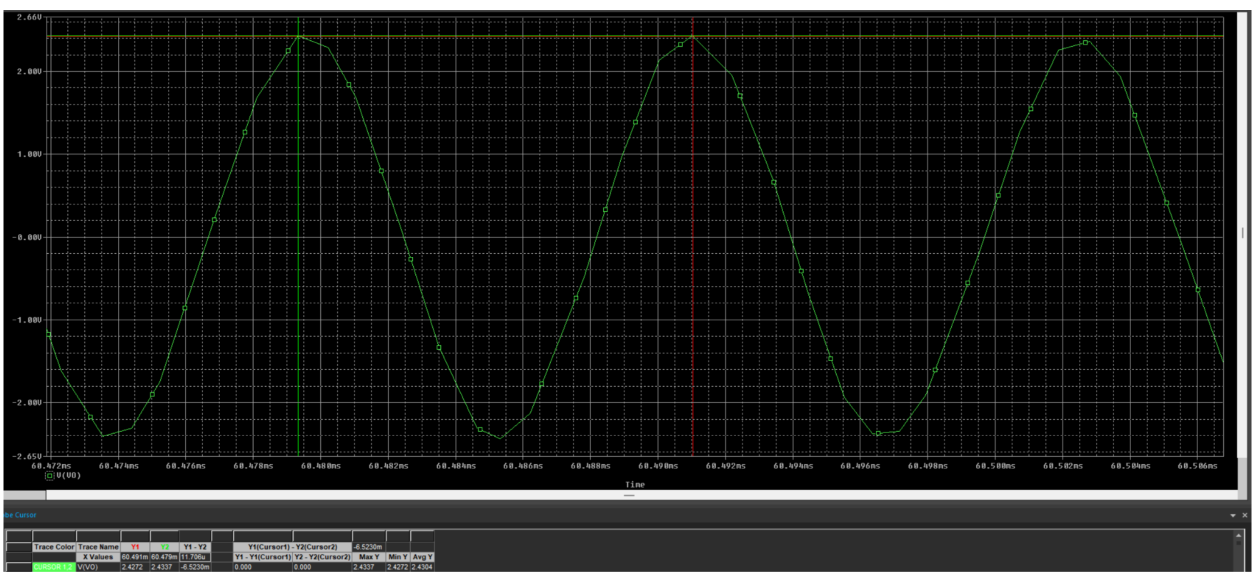


Figure B.4.6: Simulation Plot of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 1.6nF

T = 11.706 μs

F = 85.43k Hz

We expected 100 kHz but got only 85 kHz.We will try to reach 10k by changing the capacitor values.

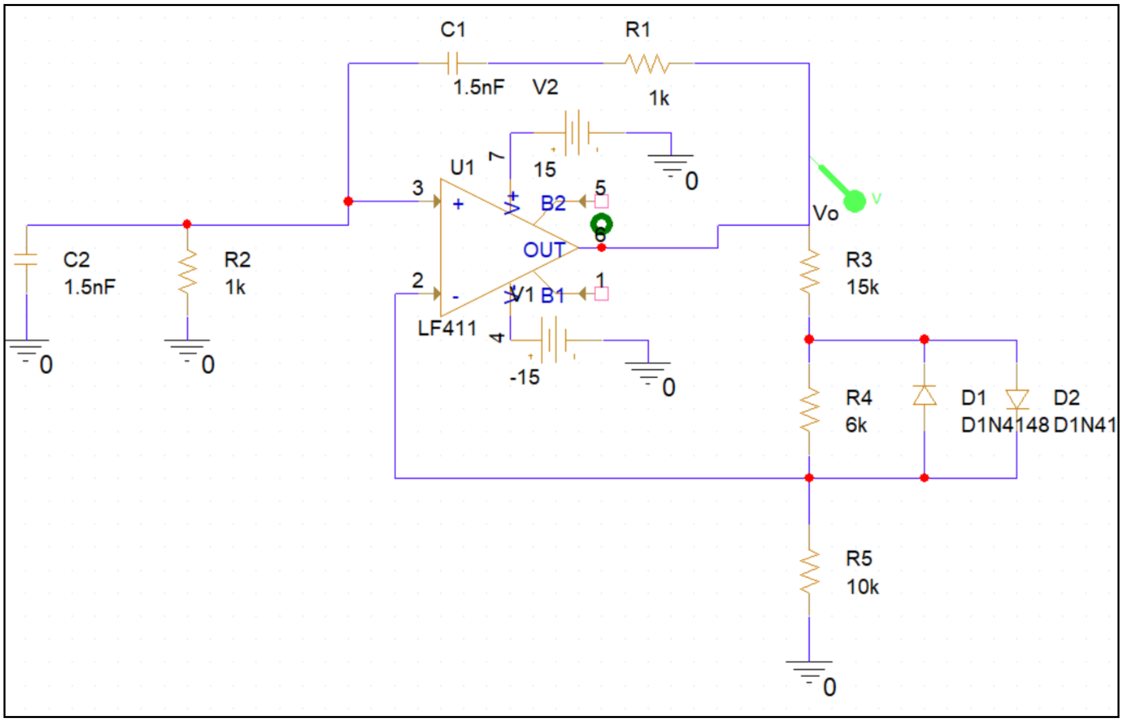



Figure B.4.7: Simulation Schematic of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 1.5nF

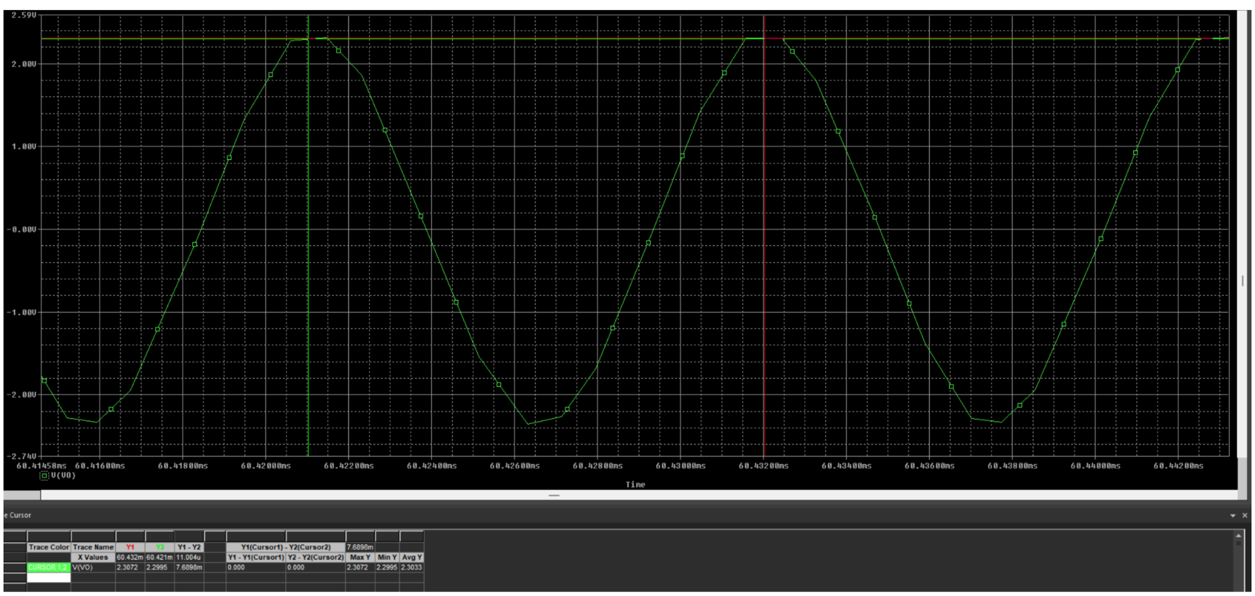


Figure B.4.8: Simulation Plot of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 1.5nF

T =11.04 µs

$$\text{Frequency} = \frac{1}{T}$$

F ≈ 100 kHz

100x Original Frequency.

Now we are going to test for the highest frequency we can reach.

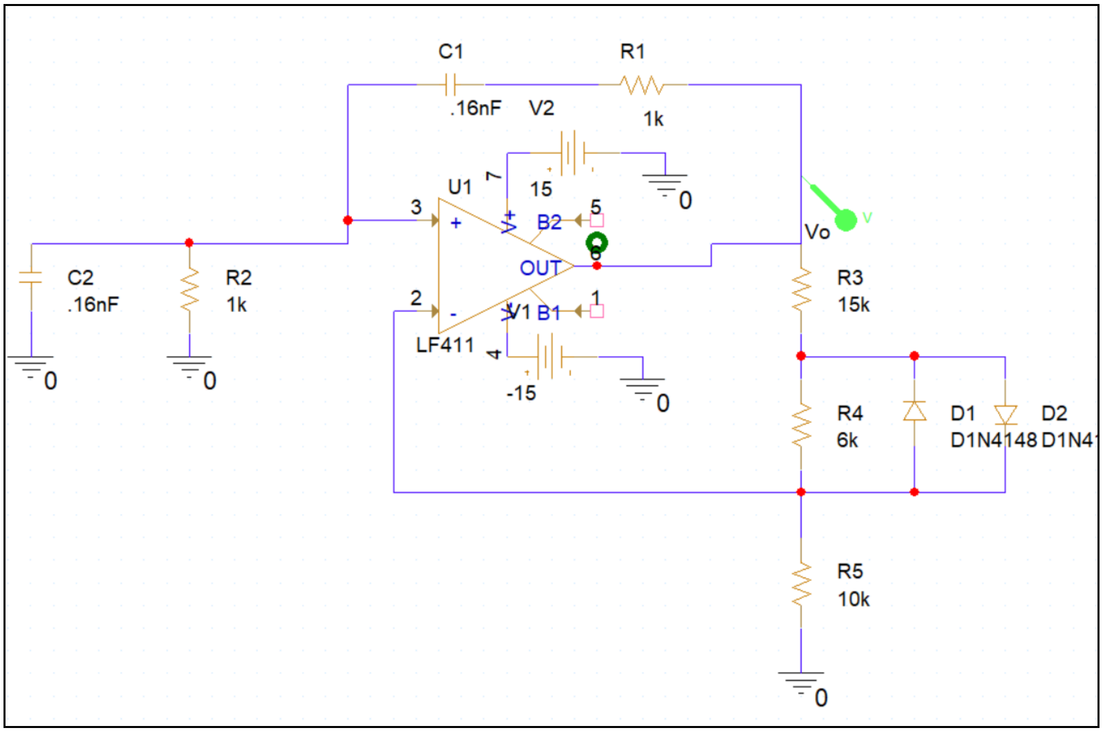


Figure B.4.9: Simulation Schematic of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 0.16nF

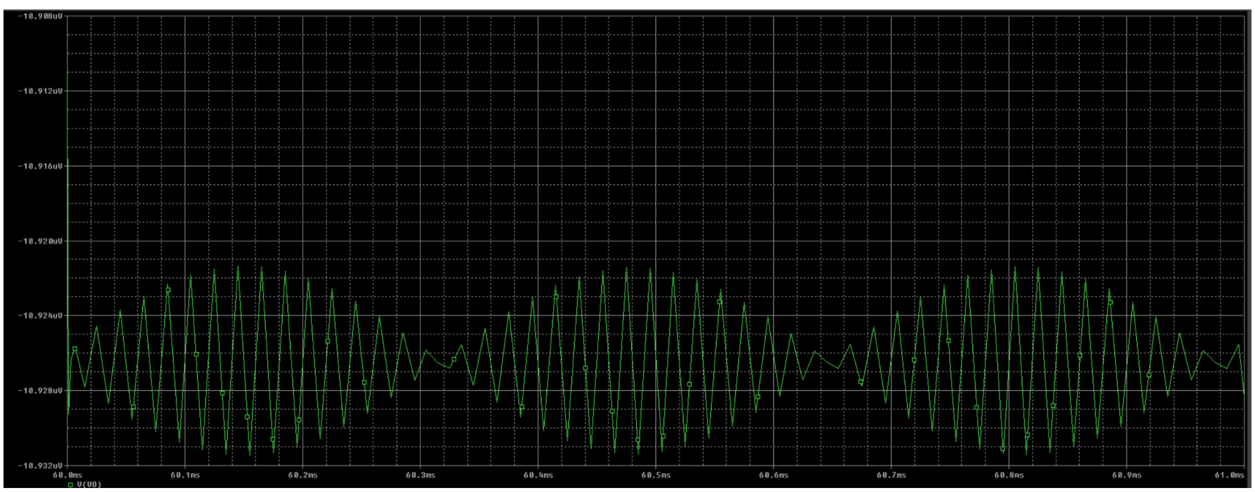


Figure B.4.10: Simulation Plot of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 0.16nF

With C = .16 we see that it is being limited. There is a large output current which causes distortion.

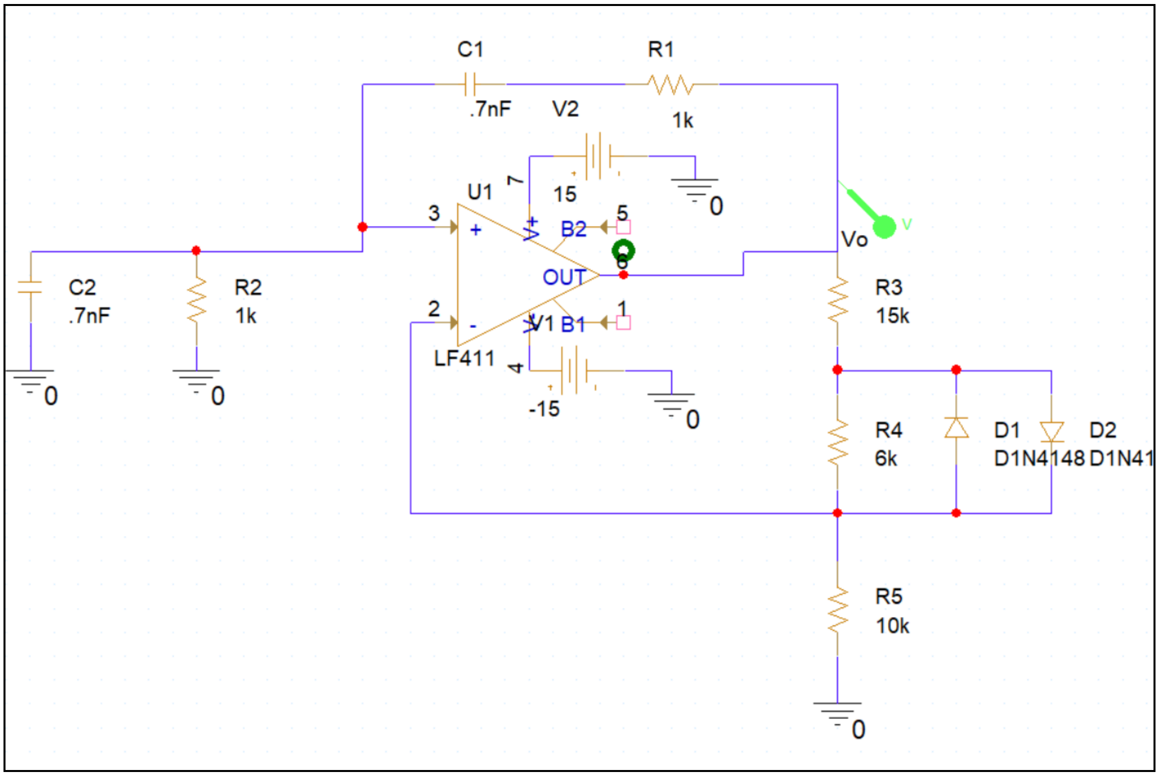



Figure B.4.11: Simulation Schematic of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 0.7nF

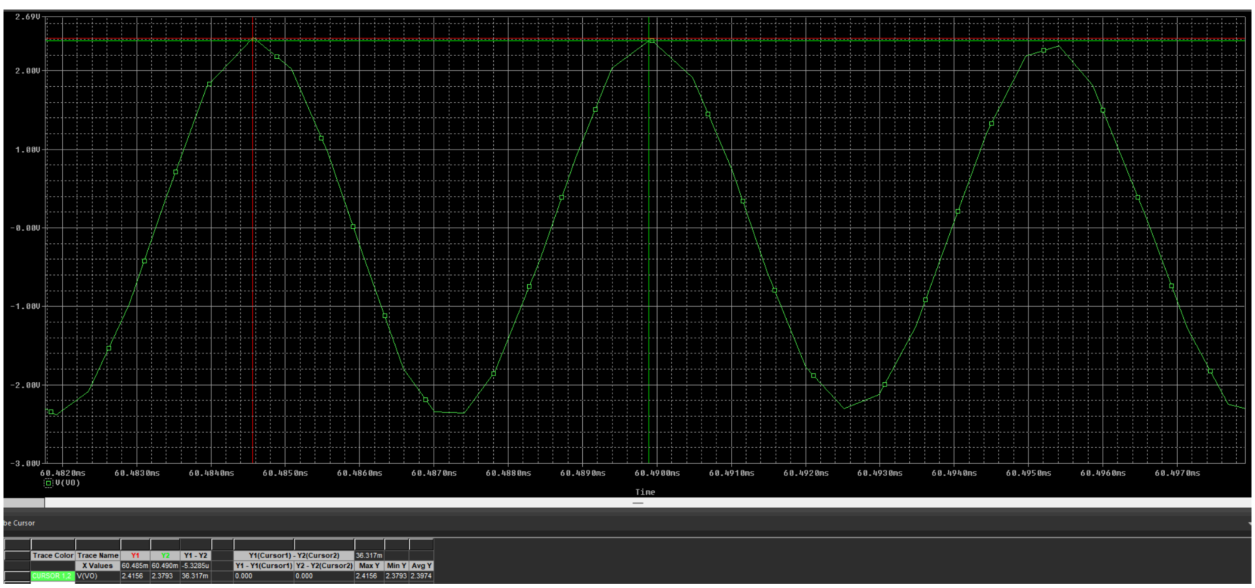


Figure B.4.12: Simulation Plot of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 0.7nF

T = 5.3285 µs

F = 187.67k Hz

We decided to raise the Capacitance and see if we could achieve a higher frequency.

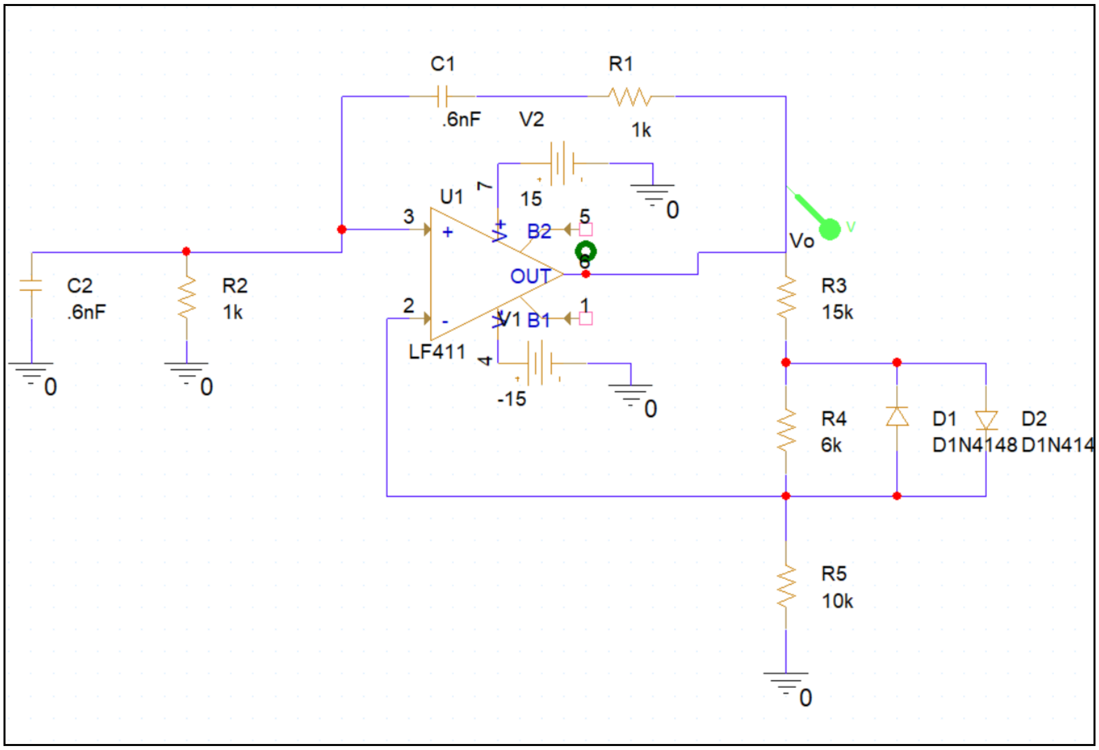


Figure B.4.13: Simulation Schematic of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 0.6nF

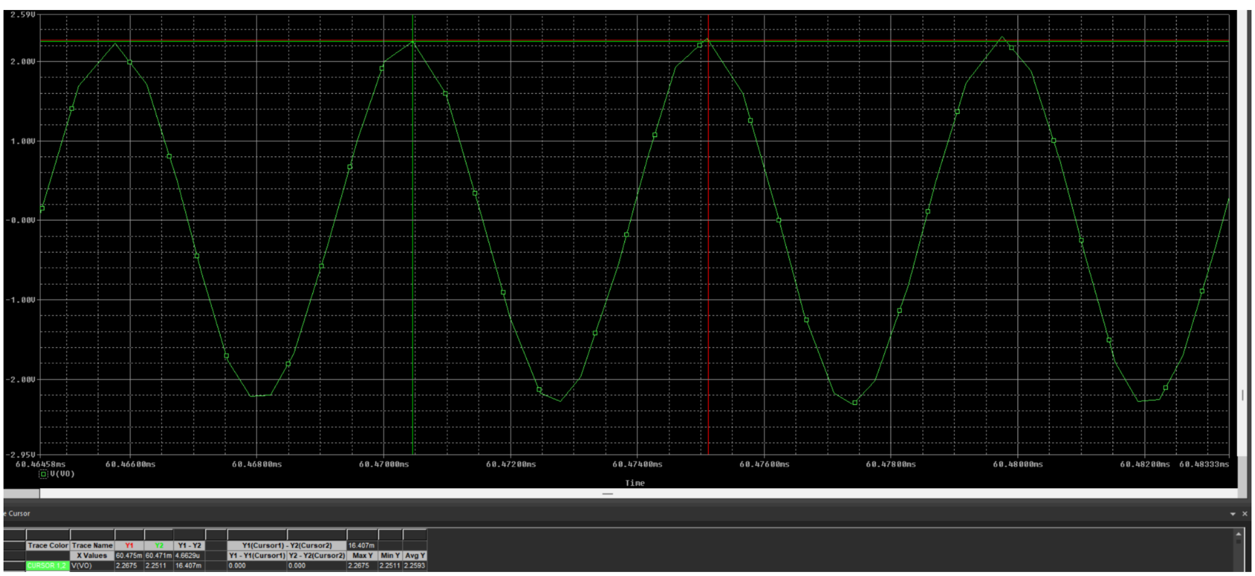


Figure B.4.14: Simulation Plot of Wein-Bridge Oscillator w/ Diodes, Feedback R = 1kΩ, and Feedback C = 0.6nF

T = 4.6629 µs

F = 214.45 kHz → MAX FREQUENCY

This is the max stable frequency that we are able to achieve before harmonic distortions.

# Section C: Circuit Measurements

## a) No Diodes

In this part, no diodes will be added to bypass the resistor.

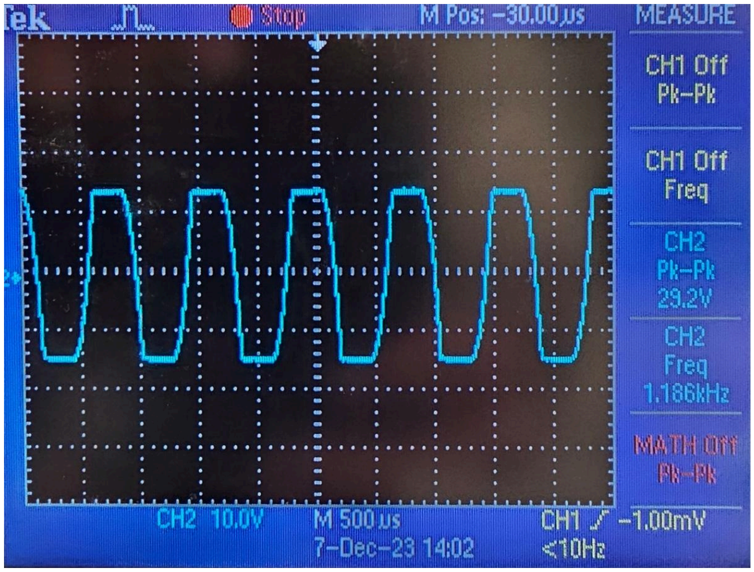



Figure C.1.1: Oscilloscope Measurement of Wein-Bridge Oscillator

The circuit wants to infinitely amplify the noise, but the op-amp limits the output. So we see clipping on the output. This structure has limited effective gain so we must limit it for this system.

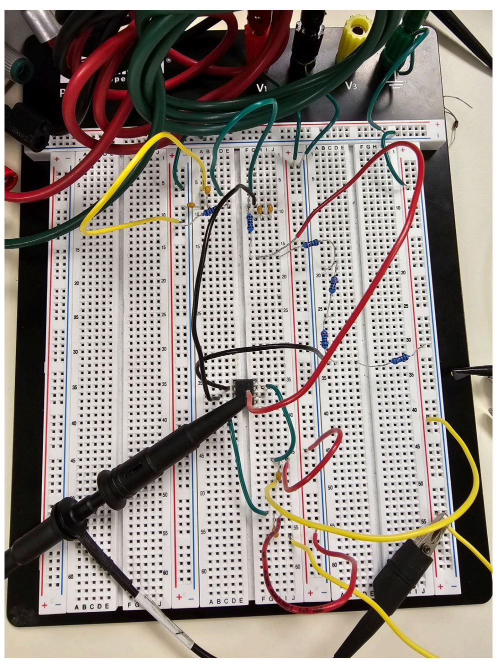


Figure C.1.2: Breadboard Circuit of Wein-Bridge Oscillator

## b) Diodes parallel to 6k Resistor

In this part, we will use the same circuit as part a, except now we place 2 diodes in parallel to the 6k resistor


Figure C.2.1: Oscilloscope Measurement of Wein-Bridge Oscillator w/ diodes across 6k Resistor

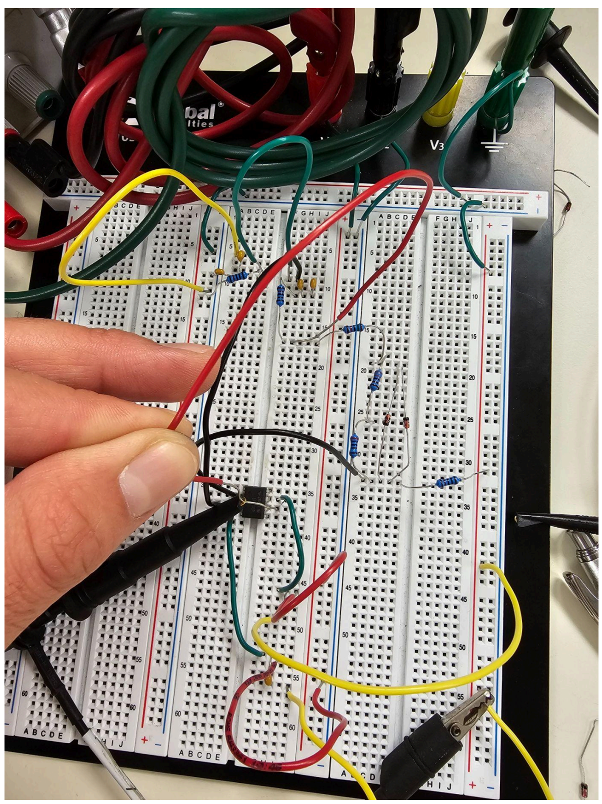


Figure C.2.2: Breadboard Circuit of Wein-Bridge Oscillator w/ diodes across 6k Resistor

The diodes pass current when the voltage across the resistor passes 0.7v. This limited the amplitude of the output waveform and removed the clipping.

## c) Diodes parallel to 15k Resistor

In this part, we will use the same circuit as part a, except now we place 2 diodes in parallel to the 15k resistor

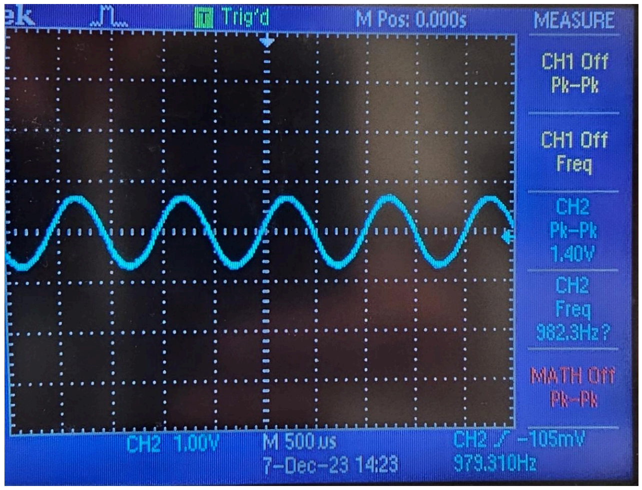



Figure C.3.1: Oscilloscope Measurement of Wein-Bridge Oscillator w/ diodes across 15k Resistor

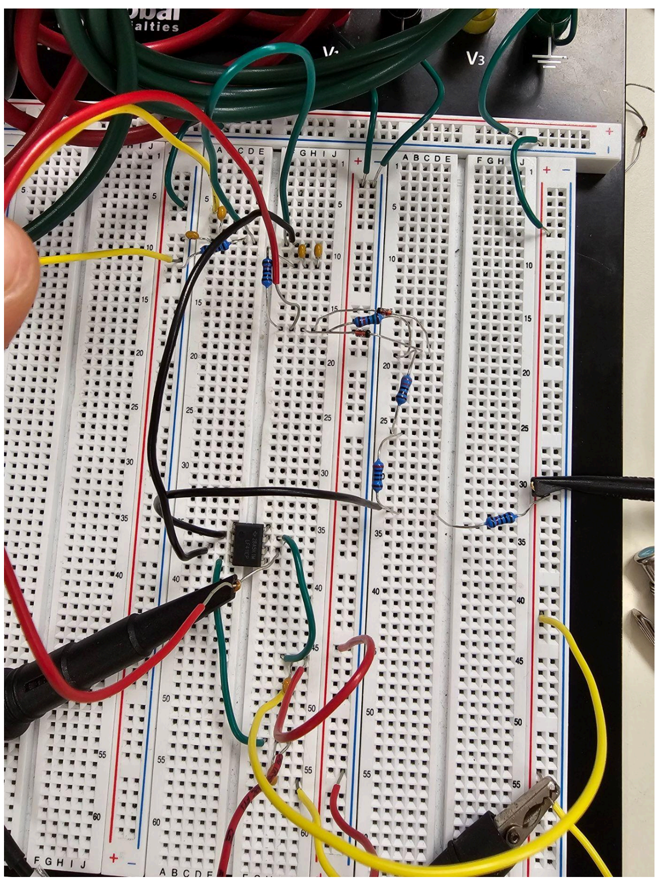


Figure C.3.2: Breadboard Circuit of Wein-Bridge Oscillator w/ diodes across 15k Resistor

When we place the diodes across the 15k resistor, the amplitude is reduced even further.

# d) Increasing frequency with diodes parallel to 6k Resistor

In this part, we will use the same circuit as part b, except now we want to manipulate the frequency to either increase or decrease by changing the values of the feedback components. Similar to the simulation steps but now in practice.

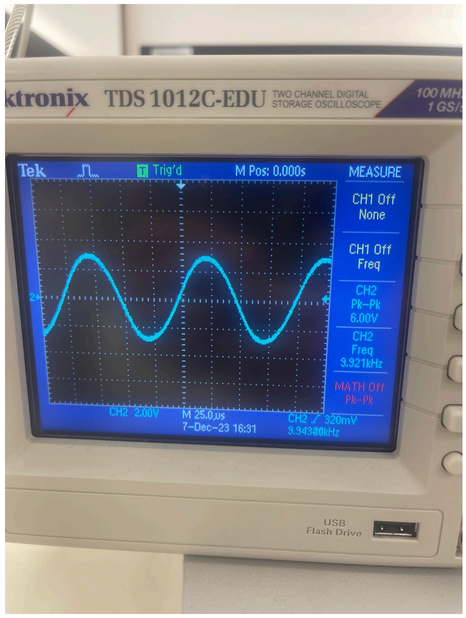



Figure C.4.1: Oscilloscope Measurement of Wein-Bridge Oscillator w/ Feedback R = 1kΩ, and Feedback C = 16nF

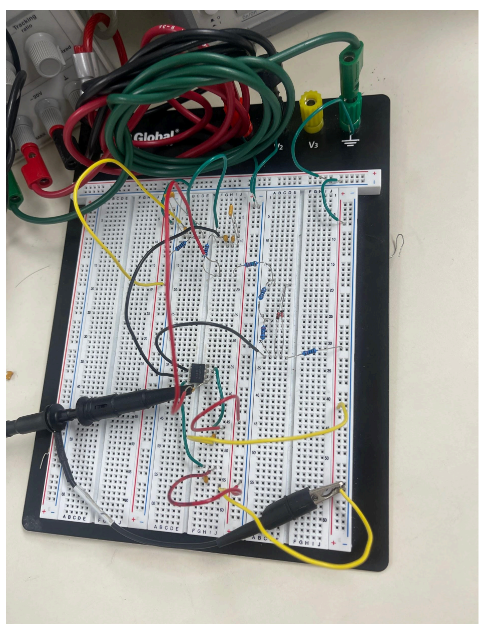


Figure C.4.2: Breadboard Circuit of Wein-Bridge Oscillator w/ Feedback R = 1kΩ, and Feedback C = 16nF

F =9.921kHz

10% Simulated (9.47k Hz) = .947k

This is within 10% error

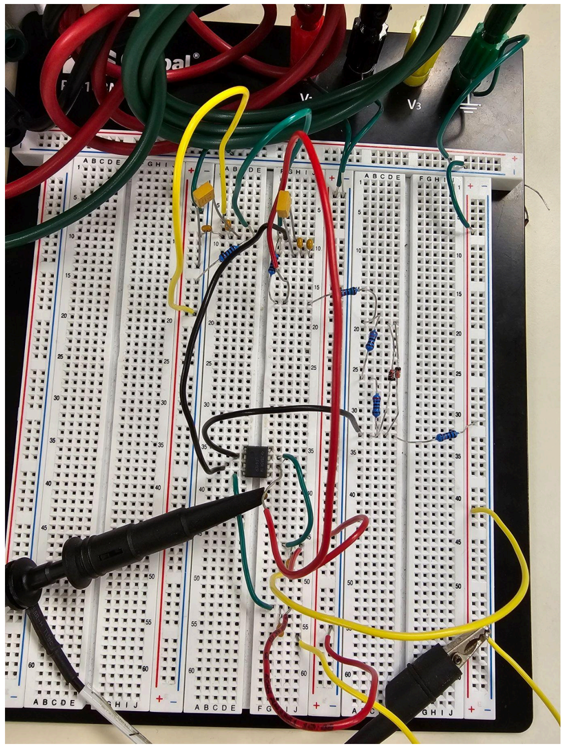


Figure C.4.3: Oscilloscope Measurement of Wein-Bridge Oscillator w/ Feedback R = 1kΩ, and Feedback C = 1.6nF

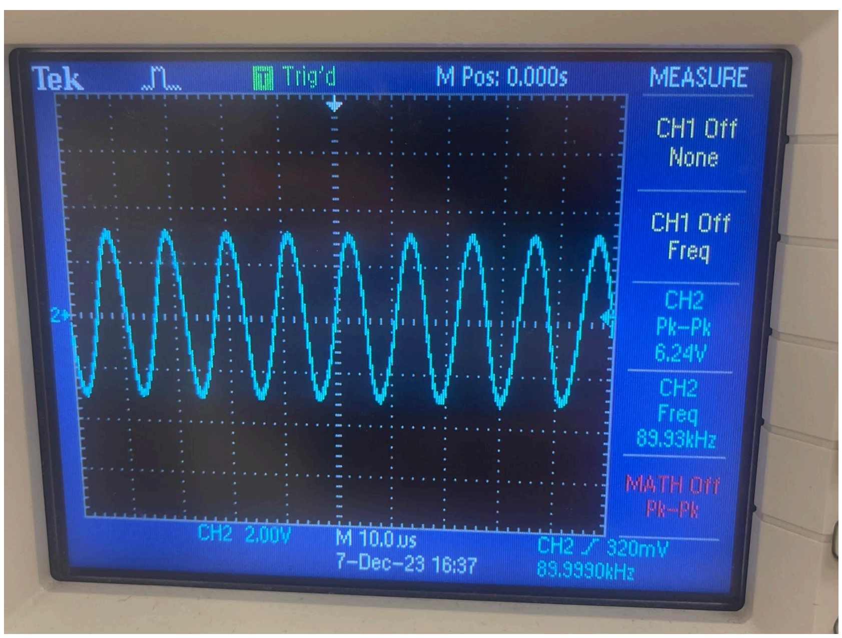



Figure C.4.4: Breadboard Circuit of Wein-Bridge Oscillator w/ Feedback R = 1kΩ, and Feedback C = 1.6nF

F =89.93 kHz

Simulated (85.43k Hz) = 8.543

By adjusting the Feedback components we see that the frequency does change.

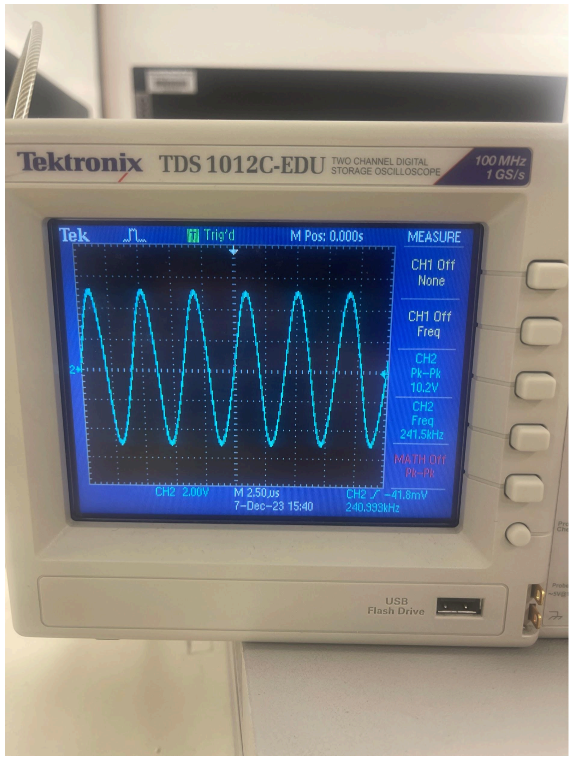



Figure C.4.5: Oscilloscope Measurement of Wein-Bridge Oscillator w/ Feedback R = 1kΩ, and Feedback C = 0.57nF

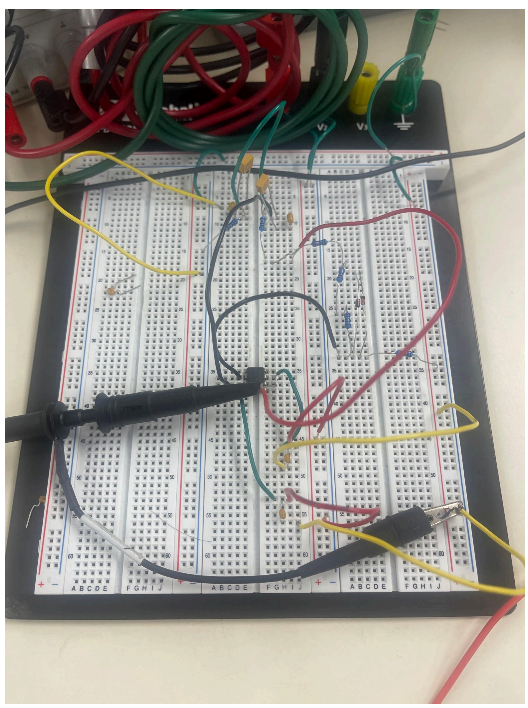


Figure C.4.6: Breadboard Circuit of Wein-Bridge Oscillator w/ Feedback R = 1kΩ, and Feedback C = 16nF

F =241.5 kHz

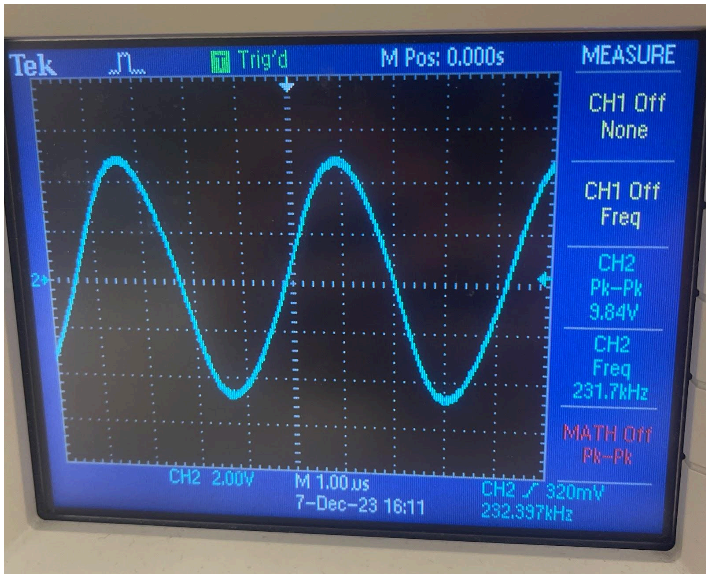



Figure C.4.7: Oscilloscope Measurement of Wein-Bridge Oscillator w/ Feedback R = 1kΩ, and Feedback C = 0.6nF

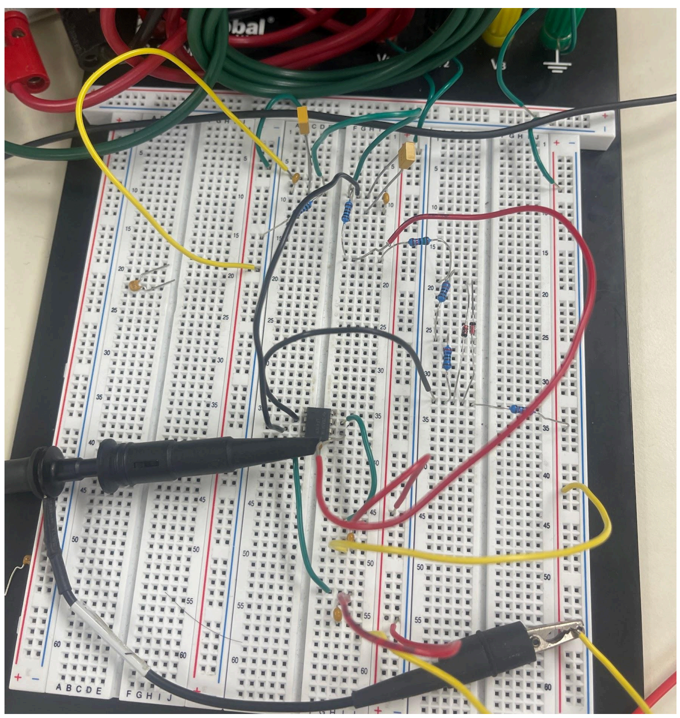


Figure C.4.8: Breadboard Circuit of Wein-Bridge Oscillator w/ Feedback R = 1kΩ, and Feedback C = 0.6nF

F =231.7kHz

10 %Simulated (215.45Hz) = 21.54 Hz

This is the maximum frequency we were able to reach, and our expected error falls within 10%.

We now want to try to achieve a 1Hz frequency by adjusting the same components.

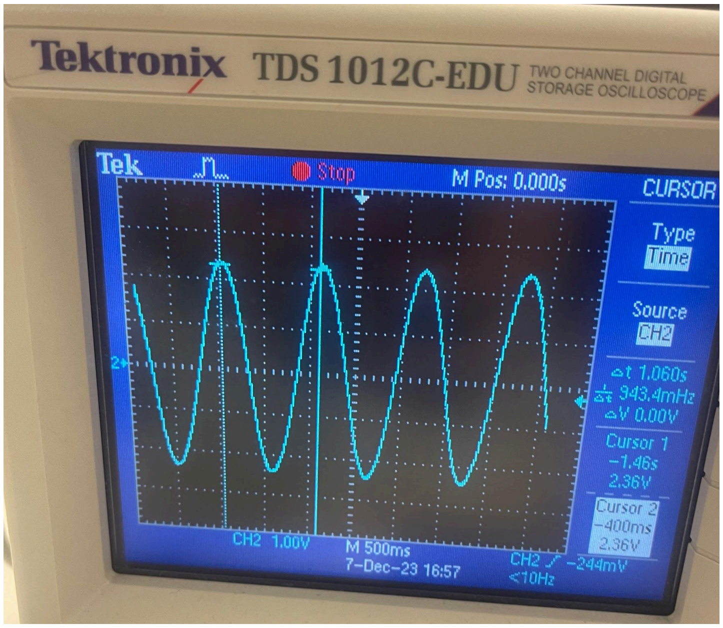



Figure C.4.9: Oscilloscope Measurement of Wein-Bridge Oscillator w/ Feedback R = 4.7kΩ, and Feedback C = 34.7pF

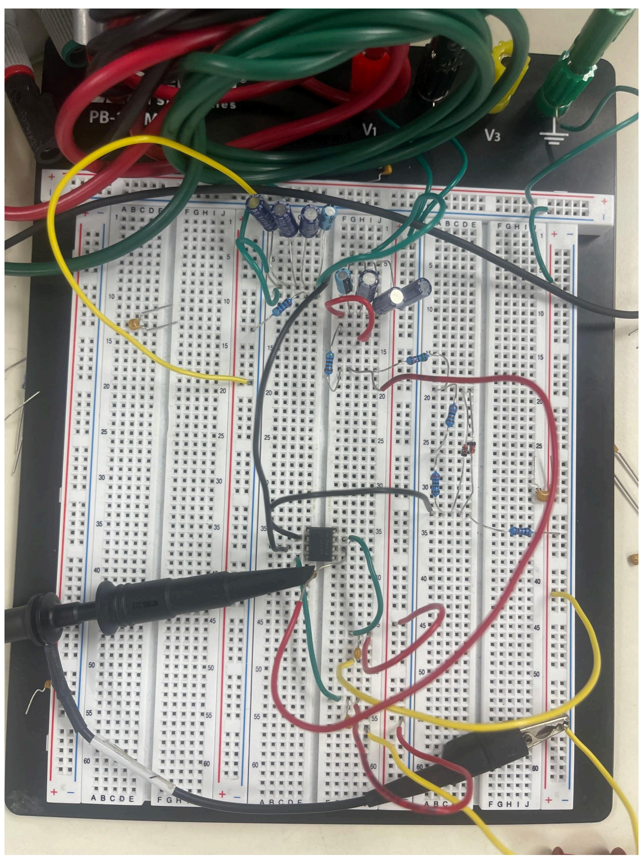



Figure C.4.10: Breadboard Circuit of Wein-Bridge Oscillator w/ Feedback R = 4.7kΩ, and Feedback C = 34.7pF

F = 943.4m Hz

# Conclusion

In summary, our exploration encompassed a thorough analysis of various circuits, integrating theoretical knowledge from our coursework with practical experiments through simulations and actual measurements. In the initial phase of our analysis, we calculated the loop gain for each circuit configuration and generated Bode plots and Nyquist diagrams for each. By examining the phase margin from the Nyquist diagram and observing the number of encirclements around the -1 point, we assessed the stability of each circuit. Although none of the configurations were inherently unstable (as indicated by the absence of -1 encirclements), those that displayed a heart-shaped pattern in the diagram (all except the unloaded follower) exhibited varying degrees of phase margin. Specifically, the two uncompensated designs showed a phase margin of less than 6 degrees, while the compensated ones were around 60 degrees. This observation underscores that, although phase margin is not the sole determinant of functionality, it serves as a significant indicator of a circuit's overall performance.

This process was applied to circuits familiar from our classroom and laboratory experiences, including the voltage follower and differentiator circuits. We then shifted our focus to the Wien-Bridge Oscillator circuit, a two-stage system comprising a gain stage that amplifies noise, and a filter stage that selectively allows certain frequencies to pass and recirculates them within the circuit. We made this circuit to oscillate autonomously by setting the K value above three. This led to self-sustained oscillation without external input. Further experimentation involved manipulating the K value to explore the circuit's maximum and minimum frequencies, employing Pspice simulations and practical circuit construction.

Our findings confirmed that the frequency could be effectively increased by a factor of 10 on two occasions, beginning at 1 kHz and culminating at about 100 kHz. The circuit's maximum frequency was identified around 215 kHz, beyond which any further K adjustment using capacitors resulted in suboptimal output behavior. Subsequent physical testing of these scenarios revealed that our measurements aligned closely with our simulated predictions, with a variance within 10%. Finally, our study culminated in proficient equation derivation and Nyquist plot drawing, alongside comprehensive analytical and manual analysis of multiple circuits, harmoniously blending simulation and physical experimentation.

# MATLAB Code

## Section 1: Nyquist Plots of the Op-Amp Circuits

**a)**

```
H1 = tf(10e4, [0.1, 1]);
s = tf('s');
figure(1)
nyquistplot(H1);
figure(2)
T1 = 10e4 / (1+(s*0.1));
bode(T1,{100, 1e6});
margin(T1);
```

**b)**

```
figure(3)
H2 = tf(10e5,[0.000001 .10001, 1]);
nyquistplot(H2)
figure (4)
s = tf('s');
T2= (10^5) / (1 + .10001*s + 10^-6*s^2);
bode(T2,{0, 1E6})
margin(T2)
```

**c)**

```
figure(5)
H3 = tf([1, 10^5],[0.000002, .10002, 1]);
nyquistplot(H3)
figure (6)
bode(H3)
margin(H3)
```

**d)**

```
s = tf('s');
figure(7)
a1 = 10^5 / ((1+s*(0.1))*(1+s*100000*5e-9));
```

```
nyquistplot(a1)
figure (8)
bode(a1)
margin(a1)
```

**e)**

```
a2 = (10^5 * (1 + 0.000022*s)) / (1 + .10052*s + 0.000052*s^2);
figure(9)
nyquistplot(a2)
figure(10)
bode(a2)
margin(a2)
```

# Part 2: Design of the Wien-Bridge Oscillator

## Section A: System Level Design

**a)**

```
C = 16 * 10^-9;
R = 10000;
s = tf('s');
B = (-3.1*R *s * C) / (1 + (3*s*C*R)+ (s*R * C)^2);
figure(11)
nyquistplot(B)
figure(12)
bode(B)
margin(B)
```