ECE 100: Linear Electronic Systems

Professor: Drew Hall

Lab 4:
Differentiator Op-Amp Circuit

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Abstract

This project aims to design a signal processing circuit that will output the time derivative of the input scaled by a desired factor. This differentiator should convert a triangle wave of 1 Vpp (peak-to-peak amplitude) at 1 kHz into a square wave of ±1 V (at 1 kHz, of course). The lab illustrates the method of adjusting R_C (Compensation Resistor) and C_C (Compensation Capacitor) to alter the output voltage. We observed that using a compensation component greatly reduced the amount of overshoot and ringing in the output waveform. This allowed for a much cleaner square wave.

Experimental Procedure

Tools:

- P-Spice Simulation Software
- Oscilloscope
- Function Generator (≥1 MHz)
- DC Power Supply
- LM411 Op-Amp
- Circuit Components (Resistors, Caps, Etc.)

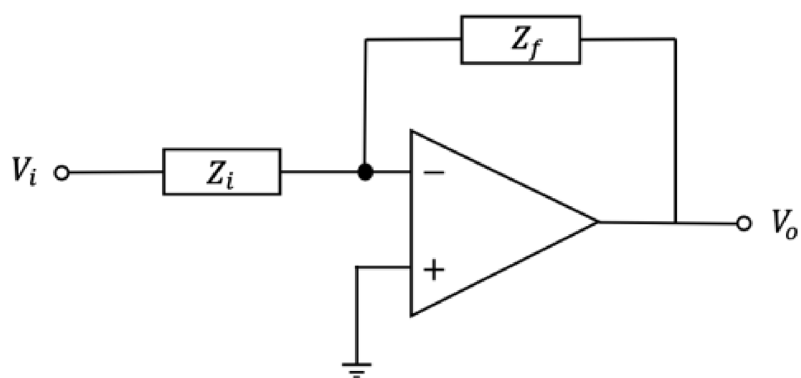


Figure 1: Schematic of Differentiator Circuit

The closed-loop gain or the transfer function for the op-amp inverter, including the frequency-dependant open-loop op-amp gain, $a(s)$, is:

$H(s) = A(s) = \frac{V_0(s)}{V_{in}(s)} = \left(-\frac{Z_F(s)}{Z_I(s)} x \frac{a(s)B(s)}{1 + a(s)B(s)}\right),$

where $T(s) = a(s)B(s) = a(s)\frac{Z_i(s)}{Z_i(s)+Z_f(s)}$ is the loop gain.

When the loop gain is large, $A(s) \rightarrow \frac{-Z_F(s)}{Z_I(s)}$, which can be called the "ideal" transfer function because it would apply if the op-amp were ideal. The factor $\frac{aB}{1 + aB}$ gives the deviation from ideal behavior. All feedback circuits have a factor like this in their transfer function. The possibility of having a zero in the term $(1 + aB)$ causes instability.

Section 1: System Level Design

Part 1)

Using $H_{ideal}(s) = \left(-\frac{Z_f(s)}{Z_i(s)}\right) = (-\ sRC)$ in an op-amp differentiator, we know that

$V_o(t) = \left(-\ RC\frac{dV_i(t)}{dt}\right)$. We need $V_o(t) = \pm 1V\ or\ 2V_{PP}$ for a 1 V_{PP} triangle wave input signal. We must choose the RC product necessary to meet the specs. A reasonable choice for the resistor is $R = 100k\Omega$. You can then find the required capacitor value.

Part 2)

Check that R and C have correctly been calculated by simulating the differentiator circuit with an ideal op-amp. Read the Notes included in this document to learn more about finding this component. Use VPulse as the input and set the parameters to provide a few cycles for a 1 V_{PP} triangle wave. Make sure that the output voltage is the desired square wave. Include these plots in your report and show your work for the calculations of the capacitor value

Part 3)

We can think of the differentiator as the product of H_{ideal}, which converts the triangle wave into the desired square wave, and a second filter $H(s) = \frac{aB}{1+aB}$ which turns out to be a second-order low-pass filter. This low pass filter will have finite bandwidth and, thus, finite rise time. We must ensure the bandwidth is broad enough that the rise time will meet the spec. Write the expression for $\frac{aB}{1+aB}$ in normalized form assuming a(s) = G0 s . You will see that it is a quadratic low-pass filter. Find expressions for ω_0 and ζ in terms of G0 and $\tau = RC$. For a second order circuit, tr (rise time) depends on both ω_0 and ζ, however for a first order circuit with transfer function $H(s) = \frac{1}{1+\frac{s}{\omega_0}}$, the rise time can be calculated as $t_r = 2.2\omega_0$. In a second-order system, with small ζ values, the rise time will be shorter than this limit. Using this limit, what is the minimum value of G (the unity gain bandwidth in Hz) needed for the circuit? Will the minimum G of the LF411 be satisfactory? Provide calculations. (Look up the datasheet for the min G value for the LF411 op-amp). The spec provided in the introduction part of the lab states the requirement on the rise time.

Part 4)

Estimate ζ using the typical value of G for the LF411. What overshoot would you expect? Use $OS\% = 100 * e^{\sqrt{\frac{-\pi\zeta}{1-\zeta^2}}}$. Clearly, this will not meet the spec. The problem is that the phase margin of the loop gain is rather small. We must increase the phase margin to at least 45◦ . Make a Bode plot of $a(s)B(s)$ using MATLAB, find the unity gain frequency, and then read off the phase margin. Use the provided MATLAB script to find the phase margin.

Part 5)

We can improve the phase margin by modifying the loop gain. Adding a zero near the unity gain frequency can be very helpful in such cases. You can do this by putting a compensation resistor R_C in series with the input C. Write the modified expression for $a(s)B(s)$. You will see that adding R_C places a zero at $\frac{1}{R_C C}$. Find the value of R_C that puts this zero at the unity gain frequency. Create the Bode plots of the compensated loop gain, $a(s)B_C(s)$, and find the new phase margin. Show that you can obtain exactly the same effect by putting C_C in parallel with R instead of R_C in series with C. Create the Bode plots of the revised loop gain.

Part 6)

We need to check the overshoot with the compensation resistor. The overshoot should be much smaller but may still be over the spec. Increase R_C until the overshoot just meets the spec. Check the phase margin with this R_C.

Section 2: Circuit Level Spice Simulation

The system-level design was done using a rather simple model for the op-amp, and it may be too simple to get the behavior exactly correct. Thus, we must simulate the circuit using a macro model for the desired op-amp. (A macro model is a simplified circuit model that captures most (though not all) the circuit's behavior using a simplified schematic.)

Part 1)

Simulate the original differentiator (with $R_C = 0\Omega$) using the specified input triangle wave and the LF411 op-amp. Plot the input and output waveforms and measure the rise time and the overshoot. Include the simulation result in your report.

Part 2)

Repeat the simulation with the calculated value of R_C. Measure the rise time and overshoot. Does it meet the spec? It should be close. If it does not meet the spec, adjust R_C until it does meet the spec. Include the simulation result in your report.

Part 3)

Find the C_C that should put a zero in exactly the same place as R_C and simulate to confirm that the rise time and overshoot are the same. C_C is the capacitor in parallel with R, instead of having R_C in series with C in the differentiator circuit. Include the simulation result in your report

Section 3: Measurement

It is essential to test real systems where stability is an issue because small variations in the circuit may be quite important. In this case, the real op-amp significantly differs from its spice model, which can impact stability. Furthermore, the actual circuit, as constructed on a breadboard, has significant "stray" capacitance at the circuit nodes, which can be important too. Before you start, check the calibration on your scope probes and adjust if necessary. Would you expect slew rate limiting to be a factor with this circuit?

Part 1)

Set up and measure the original differentiator (with $R_C = 0\Omega$) using the specified input triangle wave. Measure the rise time and the overshoot. Make a hard copy of the waveform and your measurements. Include these results and a picture of your circuit setup in your report.

Part 2)

Repeat the test with the calculated value of R_C. Measure the rise time and overshoot. Does it meet the spec? It should be close. If it does not meet the spec, adjust R_C until it does meet the spec. Make a hard copy of the waveform and your measurements.

Part 3)

Try the test with the equivalent value of C_C instead of R_C and see if the overshoot and rise time are the same in real life.

Results

Section 1: System Level Design

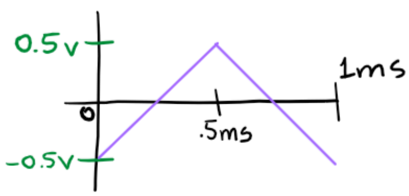
Part 1)

(a)

1) Calculate required 'C'

$$V_o(t) = -RC \underbrace{\frac{dV_i(t)}{dt}}$$

$$\Delta V_i(t) = 1\,V_{pp}.$$



$$1 \text{ period} = T = \frac{1}{f} = \frac{1}{1\text{kHz}}$$

$$T = .001\,s = \underline{1ms}$$

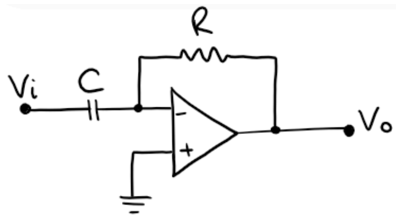
$$V_o(t) = -RC\left[\frac{-.5 - .5}{.0005\,(s)}\right]$$

$$(1_V) = -(100K)\cdot C \cdot (-2000)$$

$$C = \frac{1}{200M} = 5\times10^{-9}\,F$$

$$\boxed{C = 5nF}$$

(b)



$$H(s) = \frac{aB}{1+aB}, \quad a(s) = \frac{G'}{s}, \quad B(s) = \frac{Z_I}{Z_I + Z_f}$$

$$H(s) = \frac{\left(\frac{G'}{s}\right)B}{1+\left(\frac{G'}{s}\right)B} = \frac{G'B}{s\left(1+\frac{G'B}{s}\right)}$$

$$B(s) = \frac{Z_c}{Z_c + Z_R}$$

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

$$H(s) = \frac{G'B}{s+G'B}$$

$$H(s) = \frac{1}{1+\frac{s}{G'B}}$$

$$B(s) = \frac{1}{1+sRC}$$

$$H(s) = \frac{1}{1+\frac{s}{G'}(1+sRC)}$$

$$\boxed{H(s) = \frac{1}{1+\frac{s}{G'}+\frac{s^2RC}{G'}}}$$

Comparing to General Form

$$H(s) = \frac{1}{1+2\zeta\frac{s}{\omega_o}+\frac{s^2}{\omega_o^2}}$$

Finding ω_o

$$\frac{1}{\omega_o^2} = \frac{RC}{G'}$$

$$\boxed{\omega_o = \sqrt{\frac{G'}{RC}} = \sqrt{\frac{G'}{\tau}}}$$

Finding Zeta (ζ)

$$\frac{2\zeta}{\omega_o} = \frac{1}{G'}$$

$$\zeta = \frac{\omega_o}{2G'} = \frac{\left(\sqrt{\frac{G'}{\tau}}\right)}{G'}$$

$$\zeta = \frac{1}{2G'} \cdot \sqrt{\frac{G'}{\tau}}$$

$$= \sqrt{\frac{G'}{4(G')^2\tau}}$$

$$\boxed{\zeta = \sqrt{\frac{1}{4G'\tau}}}$$

Finding minimum value of G'

Rise time (t_r) must be $\leq 20\mu s$ (Given)

$$t_r = \frac{2.2}{\omega_0}$$

$$\therefore \frac{2.2}{\omega_0} \leq 20 \times 10^{-6}$$

$$\frac{2.2}{\left(\sqrt{\frac{G'}{\tau}}\right)} \leq 20 \times 10^{-6}$$

$$\frac{2.2}{20 \times 10^{-6}} \leq \sqrt{\frac{G'}{\tau}}$$

$$(1.21 \times 10^{10}) \leq \frac{G'}{\tau}$$

$$* \quad \tau = RC = (100k)(5nF) \quad *$$

$$\tau = 500\mu S$$

$$(1.21 \times 10^{10})(500 \times 10^{-6}) \leq G'$$

$$6.05 \times 10^{6} \left(\frac{rad}{s}\right) \leq G'$$

* unit conversion *

$$\frac{rad}{s} \longrightarrow Hz \quad \left(\frac{1}{s}\right)$$

$$\frac{G'}{2\pi}$$

$$\boxed{9.63 \times 10^{5} Hz \leq G'}$$

The minimum G' of the LF411 op-amp must be greater than the calculated G'

Which it satisfies

$$G'_{(op\text{-}amp)} = 3 \times 10^{6} > 9.63 \times 10^{5}$$

(c)

1c) Find expected overshoot

$$OS\% = e^{\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}}$$

$$\zeta = \sqrt{\frac{1}{4G'\tau}} = \sqrt{\frac{1}{4(3\times10^{6})(500\times10^{-6})}}$$

$$\zeta = 0.01291$$

$$OS\% = e^{\left(\frac{-\pi(.01291)}{\sqrt{1-(.01291)^2}}\right)} \times 100$$

$$OS\% = e^{-0.04056} \times 100$$

$$\boxed{OS\% = 96.03\%}$$

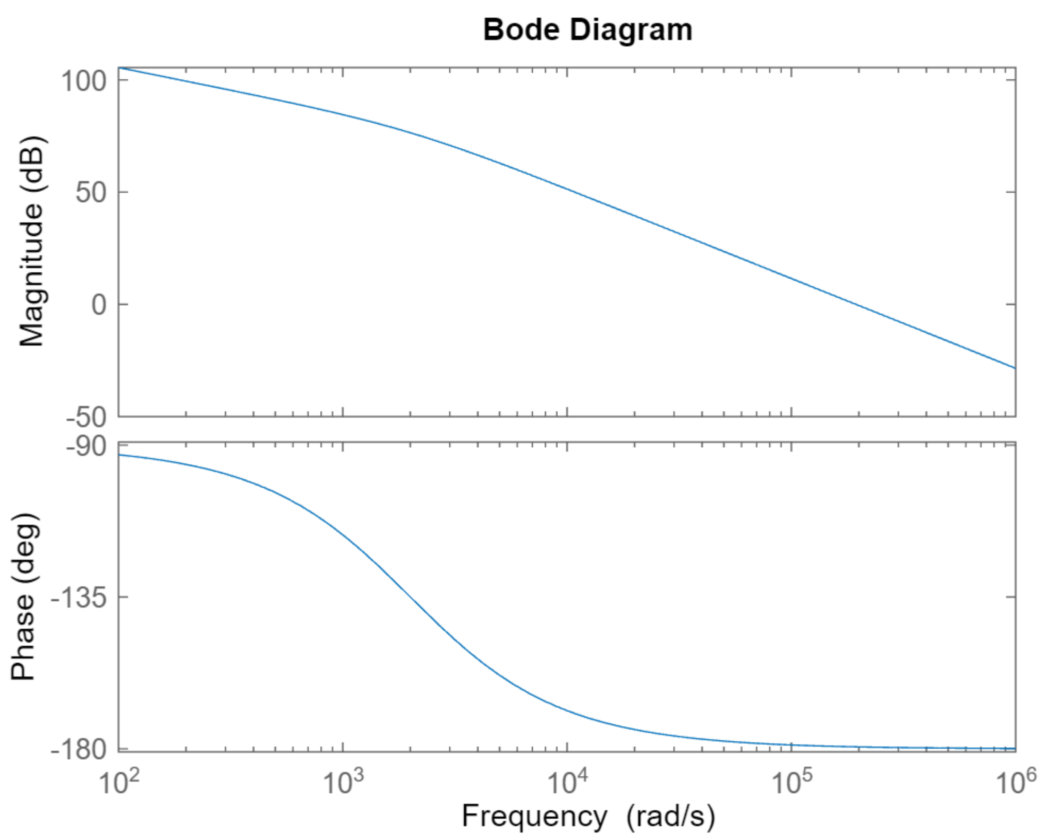


Figure 1.3.1: Bode Plot of Circuit without Compensation

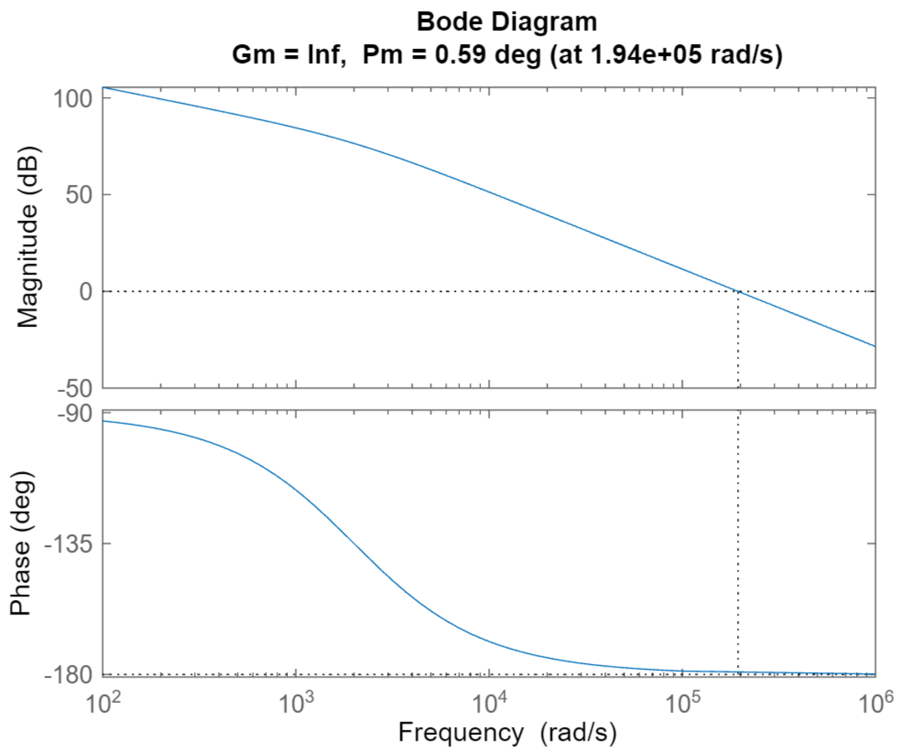


Figure 1.3.2: Bode Plot

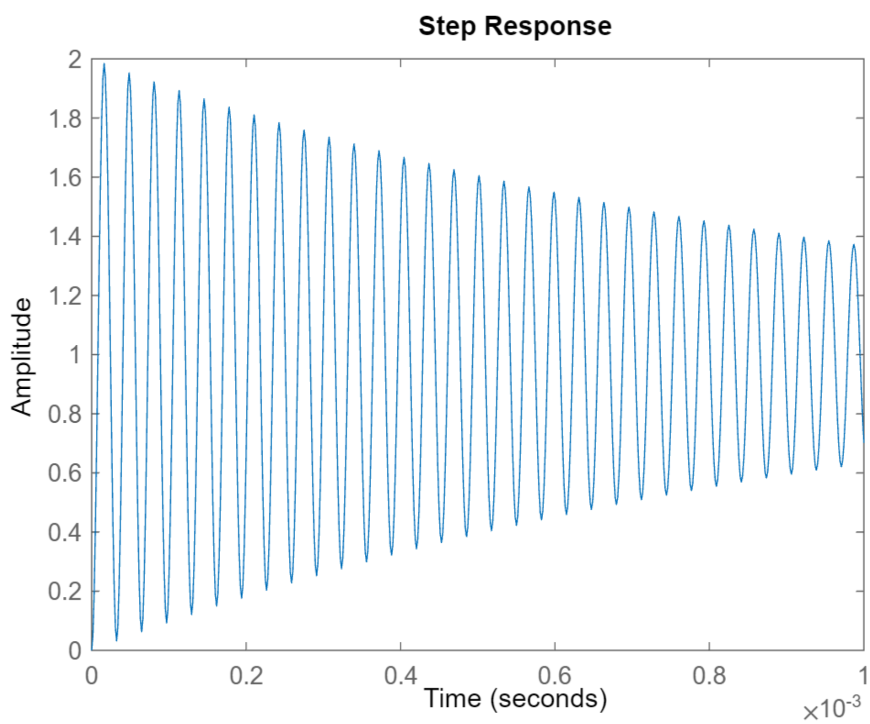
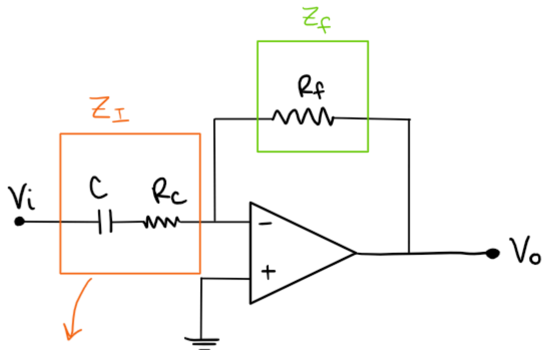


Figure 1.3.3: Step Response of Circuit without Compensation

(d)

In order to minimize the amount of overshoot, we place a Compensation Resistor in series with the input capacitor.

1d)



$$Z_I = \frac{1}{sC} + R_c = \frac{1 + sR_cC}{sC}$$

$$B(s) = \frac{Z_I}{Z_I + Z_f} = \frac{\left(\frac{1+sR_cC}{sC}\right)}{\left(\frac{1+sR_cC}{sC}\right) + R_f}$$

$$= \frac{\left(\frac{1+sR_cC}{s\cancel{C}}\right)}{\left(\frac{1+sR_cC+sR_fC}{s\cancel{C}}\right)}$$

$$B(s) = \frac{1 + sR_cC}{1 + sC(R_c + R_f)} \qquad 1$$

Find value of R_c that makes $B(s) = 0$

$$1 + sR_cC = 0$$

$$R_c = \frac{-1}{sC}$$

$$|s| = \left|\frac{-1}{R_cC}\right|$$

$$R_c = \frac{1}{sC}$$

$$R_c = \frac{1}{(1.94\times10^5)(5\times10^{-9})}$$

s = calculated from MATLAB

$|s| = 1.94\times10^5 \ \frac{rad}{s}$

$$\boxed{R_c = 1.03\,k\Omega}$$

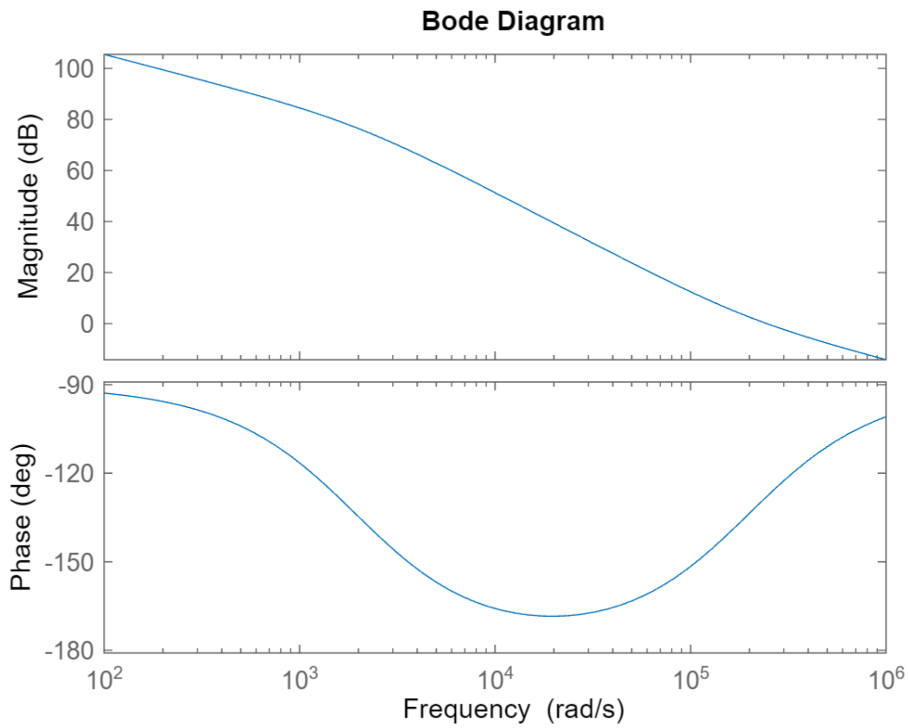


Figure 1.4.1: Bode Plot of Circuit with Compensation Resistor

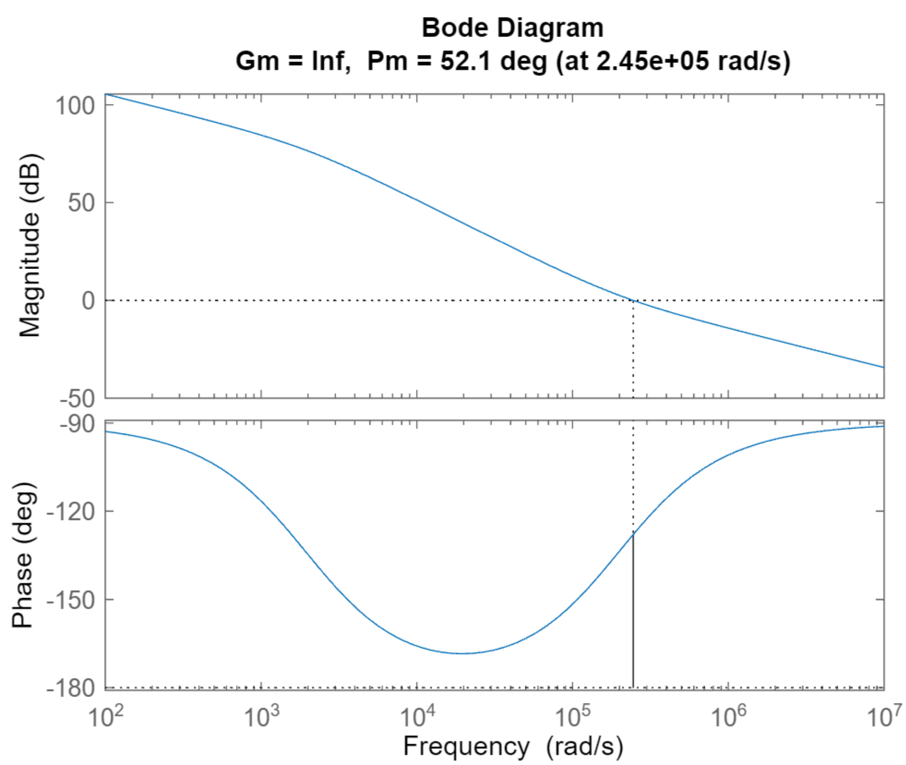


Figure 1.4.2:

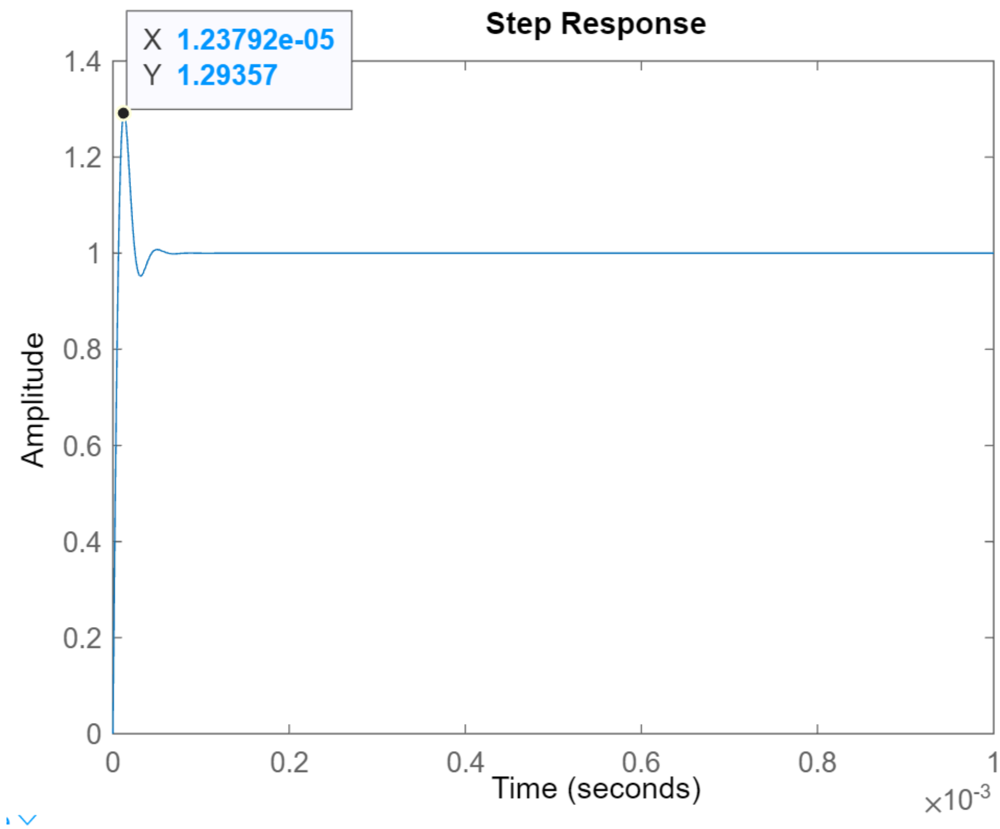
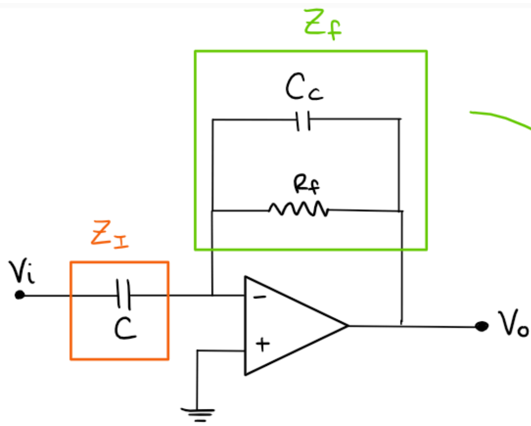


Figure 1.4.3: Step Response of Circuit with Compensation Resistor

Now we place a Compensation Capacitor in parallel with the feedback resistor and repeat the process. In the end we should get the same effects, proving the circuits function equivalently.



$$Z_f = \frac{(R_f)\left(\frac{1}{sC}\right)}{R_f + \frac{1}{sC}}$$

$$= \frac{\left(\frac{R_f}{\cancel{sC}}\right)}{\left(\frac{1 + sCR_f}{\cancel{sC}}\right)}$$

$$Z_f = \frac{R_f}{1 + sCR_f}$$

$$B(s) = \frac{Z_I}{Z_I + Z_f} = \frac{\left(\frac{1}{sC}\right)}{\left(\frac{1}{sC}\right) + \left(\frac{R_f}{1 + sC_cR_f}\right)} \cdot \left(\frac{sC_c}{sC_c}\right)$$

$$= \frac{1}{1 + \left(\frac{sCR_f}{1 + sC_cR_f}\right)}$$

$$= \frac{1}{\left(\frac{1 + sC_cR_f + sCR_f}{1 + sC_cR_f}\right)}$$

$$\boxed{B(s) = \frac{1 + sC_cR_f}{1 + sR_f(C + C_c)}}$$

Finding value of C_c that makes $B(s) = 0$

$$1 + sC_cR_f = 0$$

$$|s| = \left|\frac{-1}{C_cR_f}\right|$$

$$1.94 \times 10^5 = \frac{1}{C_cR_f}$$

$$C_c = \frac{1}{(1.94 \times 10^5)(100k)}$$

$$C_c = 5.155 \times 10^{-11}\,F$$

$$\boxed{C_c = 51.55\,pF}$$

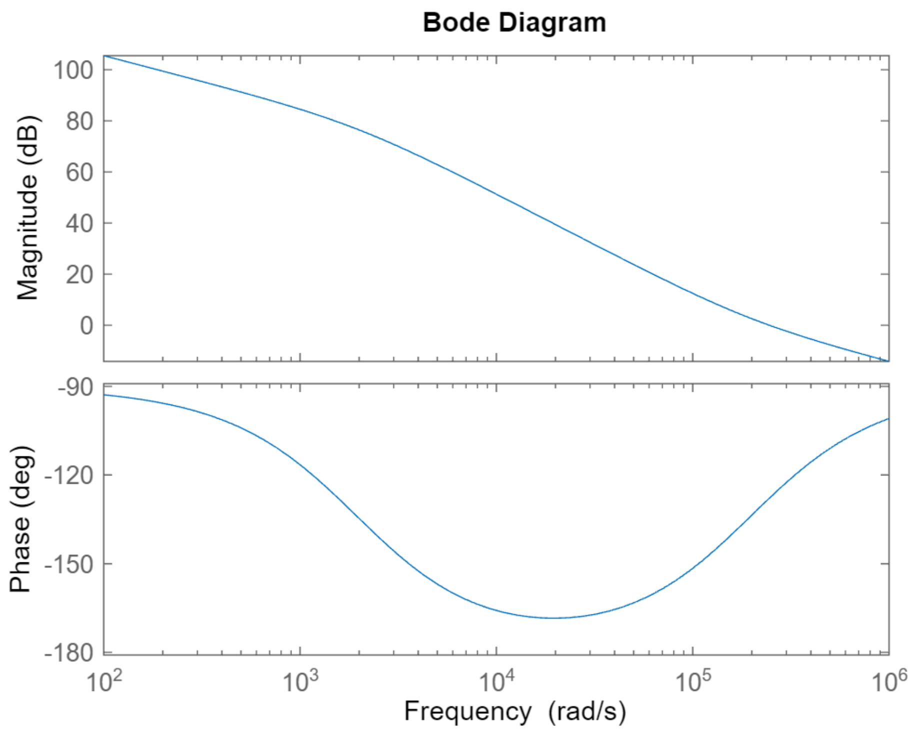


Figure 1.4.4: Bode Plot of Circuit with Compensation Capacitor

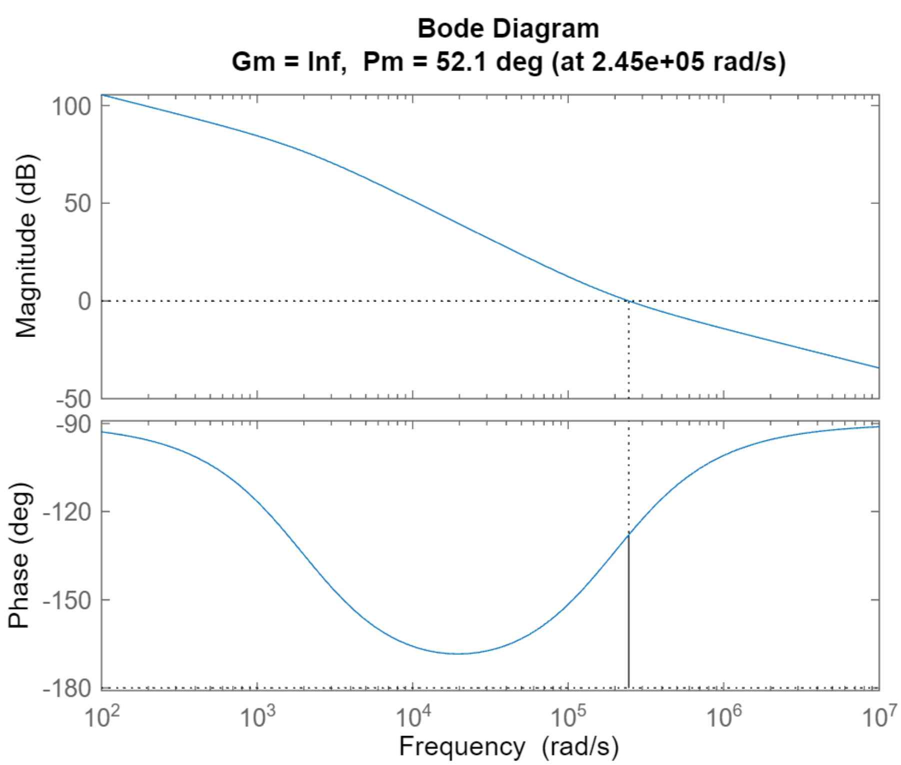


Figure 1.4.5: n Resistor

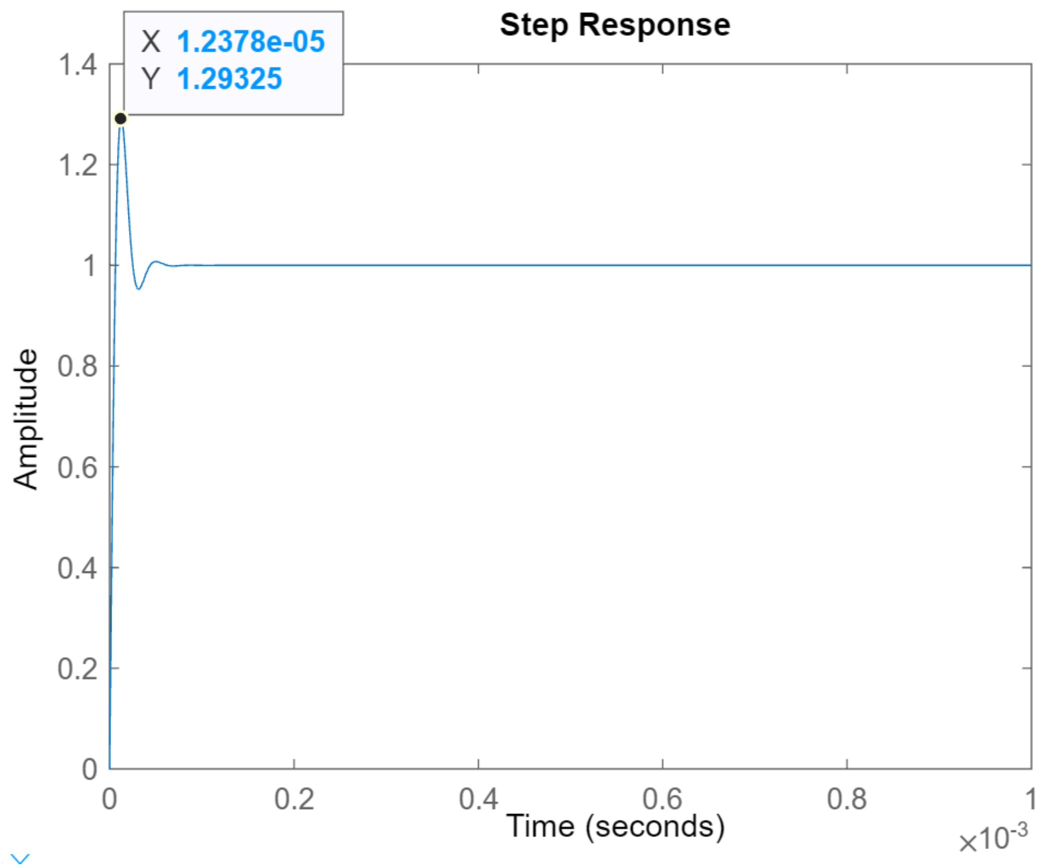


Figure 1.4.6: Step Response of Circuit with Compensation Capacitor

(e)

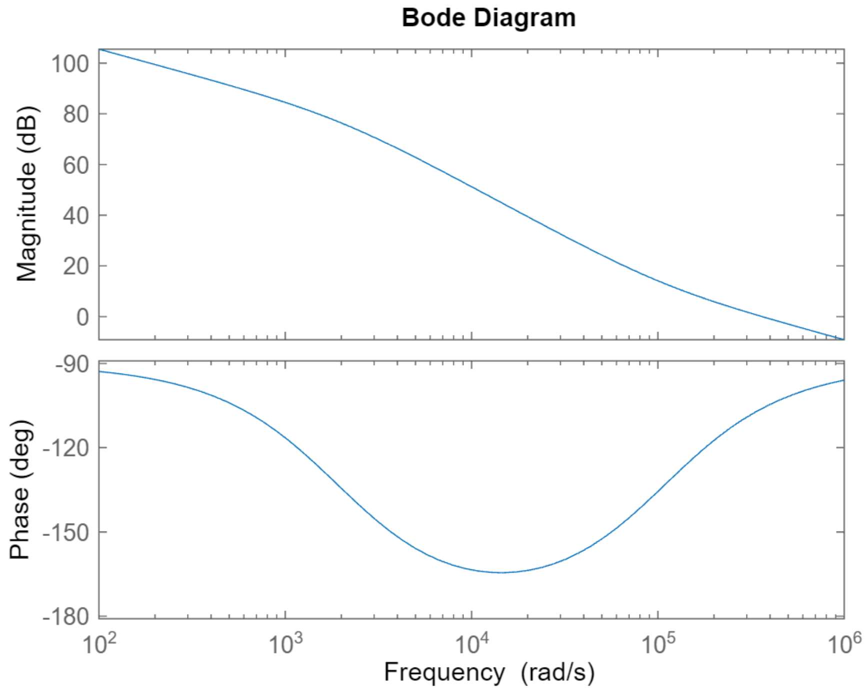


Figure 1.5.1:

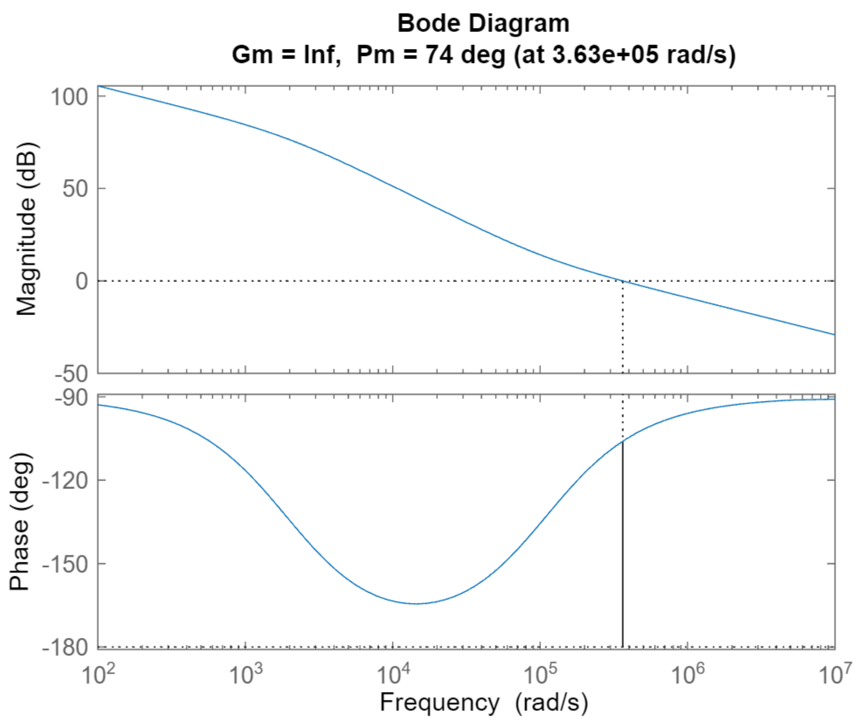


Figure 1.5.2:

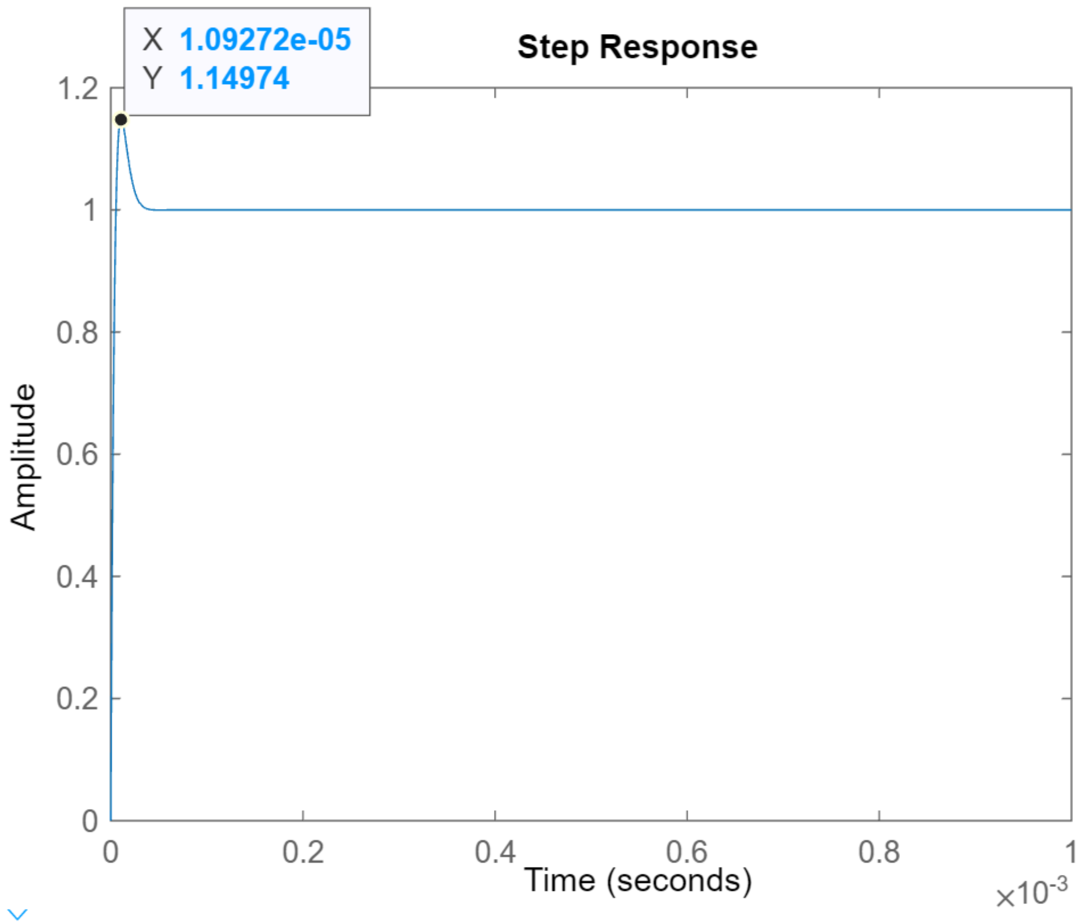

X 1.09272e-05
Y 1.14974
Step Response
1.2
1
0.8
0.6
0.4
0.2
0
Amplitude
0
0.2
0.4
0.6
0.8
1
Time (seconds)
×10^-3

Figure 1.5.3:

Section 2: Circuit Level Spice Simulation

The goal is to simulate and compare the rise time and the amount of overshoot with varying Compensation Components. To do this we must perform calculations. Our requirement for overshoot is that it must be **no greater than 15%** in order for the circuit to be considered properly compensated.

Calculating Overshoot

$$Overshoot\ \% = \left(\frac{V_O Max - V_2}{V_2 - V_1}\right) x\ 100$$

$$\text{Overshoot }\% = \left(\frac{2.64 - 1}{1 - (-1)}\right) x\ 100$$

$$V_1 = Upper\ Steady\ State\ Voltage$$

$$V_2 = Lower\ Steady\ State\ Voltage$$

Calculating Rise Time

$$V_x = V_1 + 10\% * (V_2 - V_1)$$

$$V_y = V_1 + 90\% * (V_2 - V_1)$$

$$Rise\ Time\ \left(t_r\right) = t_2 - t_1$$

Part 1)

As a control we simulated the circuit using an Ideal Op-Amp to compare to our actual circuit.

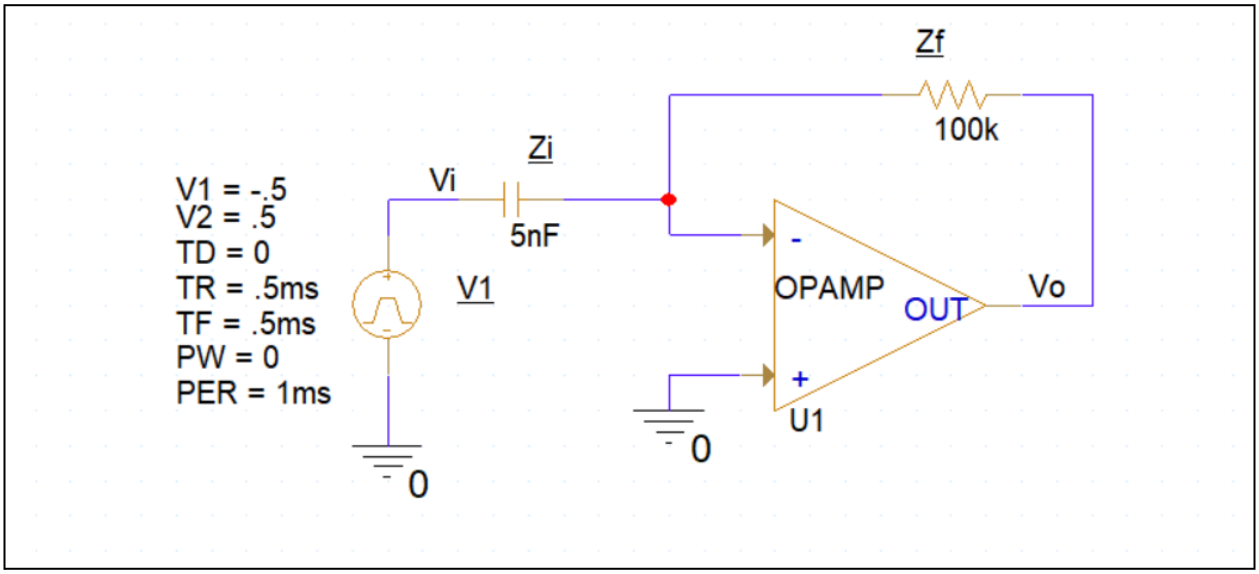


Figure 2.1.1: Schematic of Ideal Differentiator Circuit Macro Model

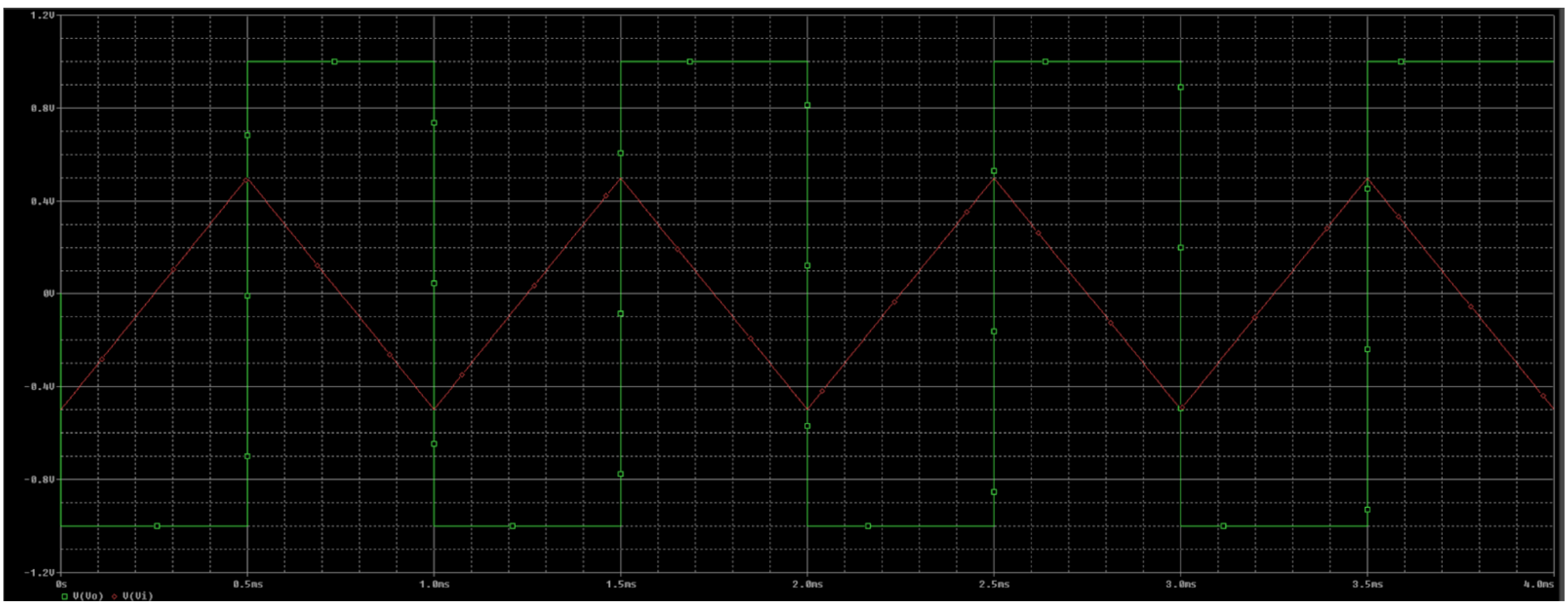


Figure 2.1.2: Simulation Plot of Ideal Differentiator Macro Model

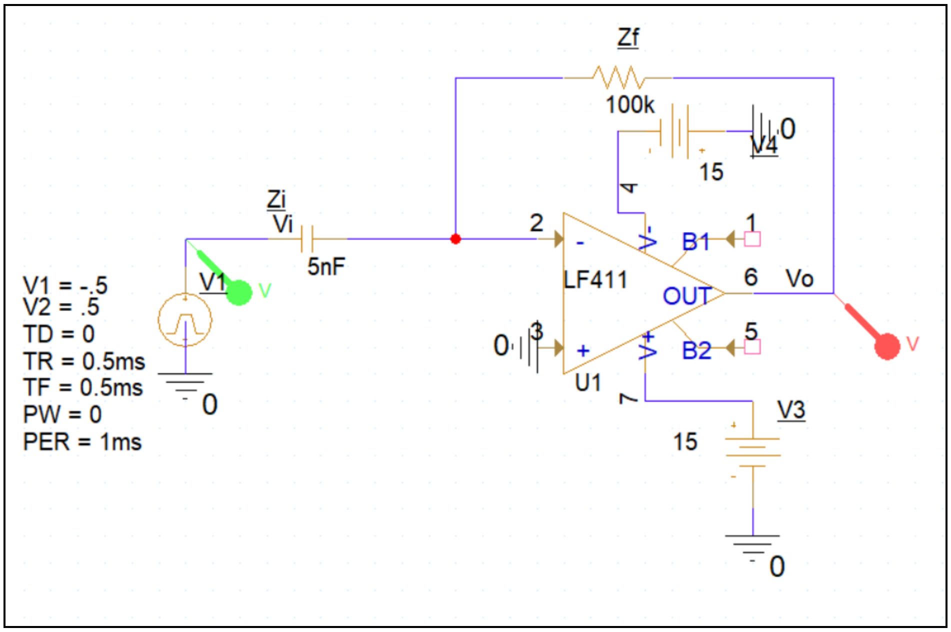


Figure 2.1.3: Schematic of Differentiator Circuit with LF411

	Trace Color	Trace Name	Y1	Y2	Y1 - Y2		Y1(Cursor1) - Y2(Cursor2)		-1.5862		
		X Values	100.502m	100.505m	-2.8991u		Y1 - Y1(Cursor1)	Y2 - Y2(Cursor2)	Max Y	Min Y	Avg Y
	CURSOR 1,2	V(Vo)	-795.549m	790.616m	-1.5862		0.000	0.000	790.616m	-795.549m	-2.4668m
		V(Vi)	495.973m	490.032m	5.9409m		1.2915	-300.584m	495.973m	490.032m	493.003m

Figure 2.1.4: Simulation Plot and Trace of Differentiator with LF411

Rise Time: -2.8991μs

Part 2)

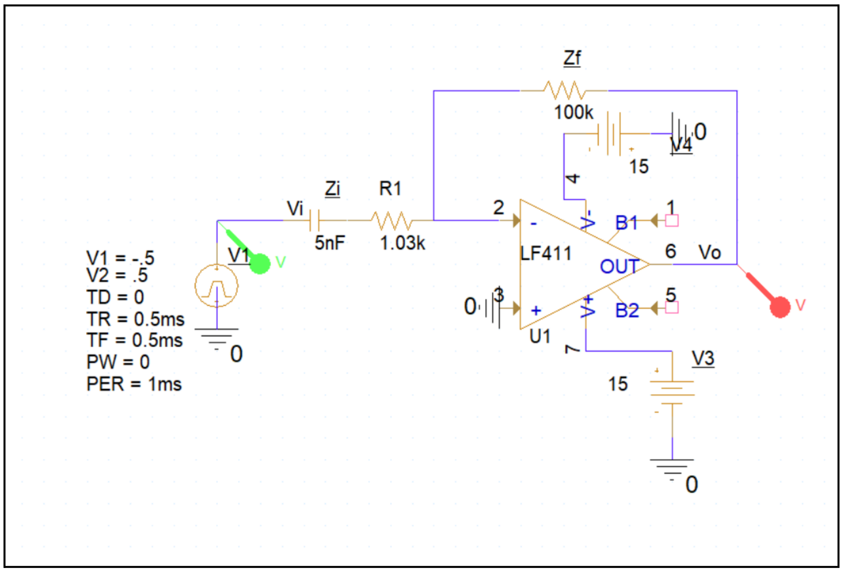


Figure 2.2.1: Schematic of Differentiator Circuit with $R_C = 1.03K\Omega$

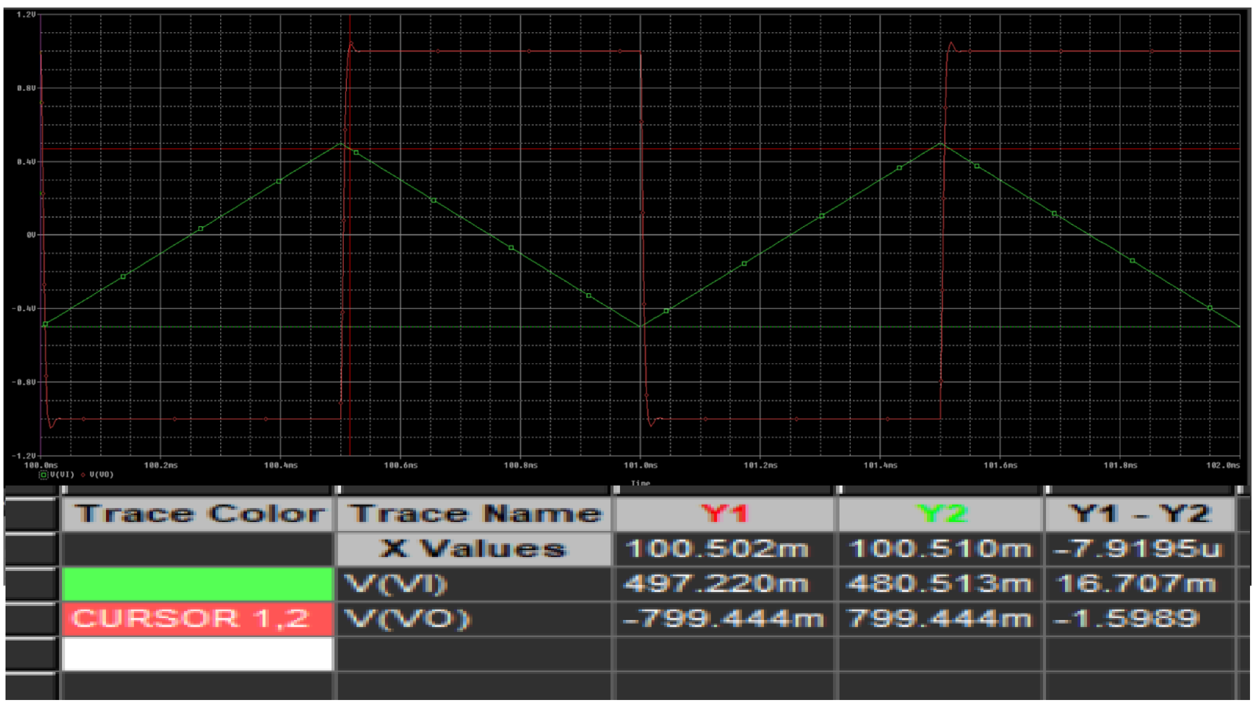


Figure 2.2.2: Simulation Plot and Trace with $R_C = 1.03K\Omega$

$$Overshoot\ \% = \left(\frac{1.0465 - 1}{1 - (-1)}\right) x\ 100 = \mathbf{2.3\%}$$

Rise Time: -7.9195µs

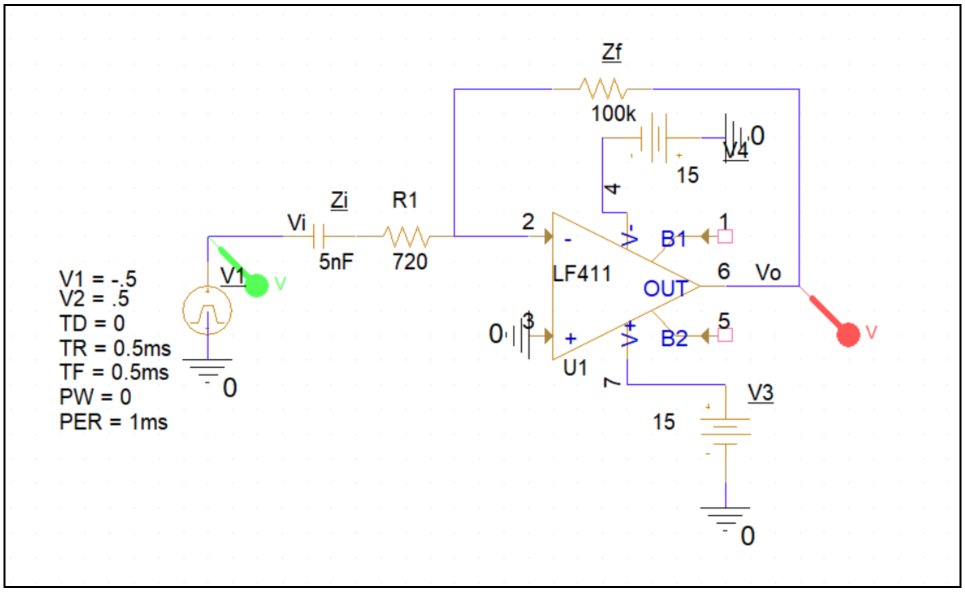
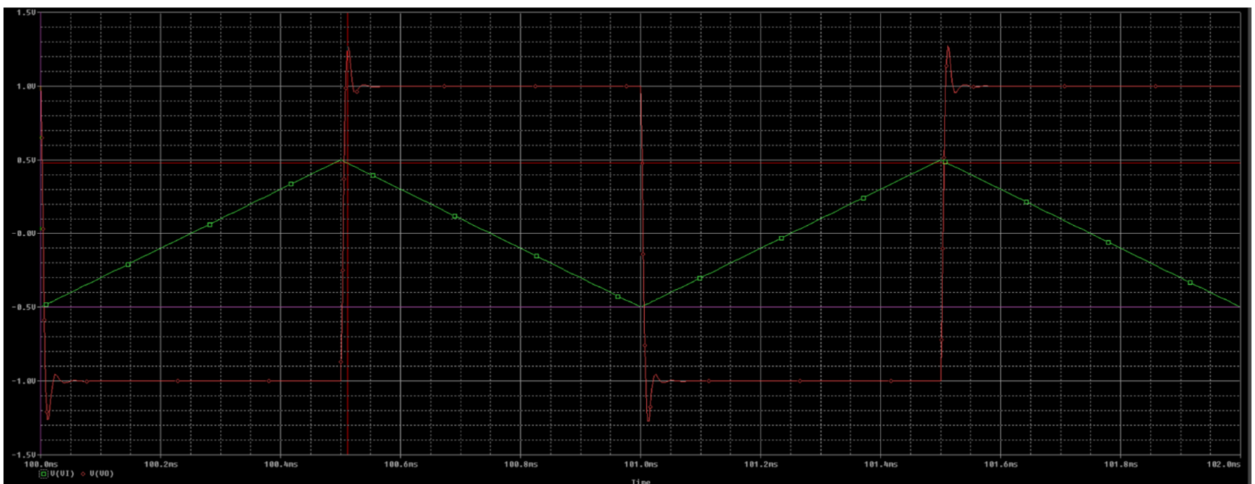


Figure 2.2.3: Schematic of Differentiator Circuit with $R_C = 720\Omega$



Trace Color	Trace Name	Y1	Y2	Y1 - Y2		Y1(Cursor1) - Y2(Cursor2)		-1.6004		
	X Values	100.502m	100.507m	-5.7939u		Y1 - Y1(Cursor1)	Y2 - Y2(Cursor2)	Max Y	Min Y	Avg Y
	V(VI)	497.234m	485.752m	11.483m		1.2963	-315.597m	497.234m	485.752m	491.493m
CURSOR 1,2	V(VO)	-799.026m	801.349m	-1.6004		0.000	0.000	801.349m	-799.026m	1.1611m

Figure 2.2.4: Simulation Plot and Trace with $R_C = 720\Omega$

$$Overshoot\ \% = \left(\frac{1.2686 - 1}{1 - (-1)}\right) x\ 100 = \mathbf{13.4\%}$$

Rise Time: -5.7939μs

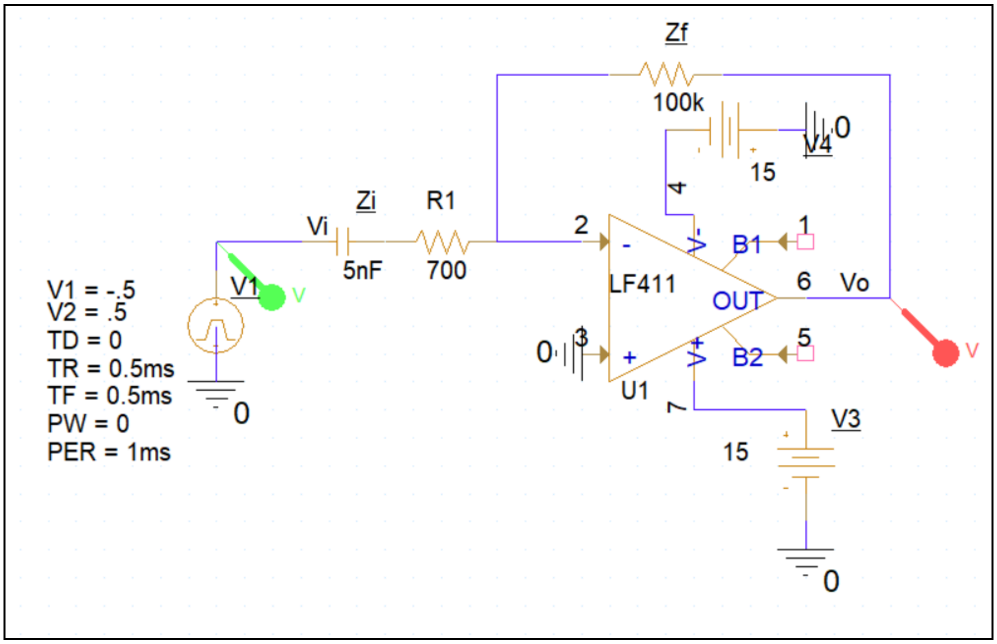


Figure 2.2.5: Schematic of Differentiator Circuit with $R_C = 700\Omega$

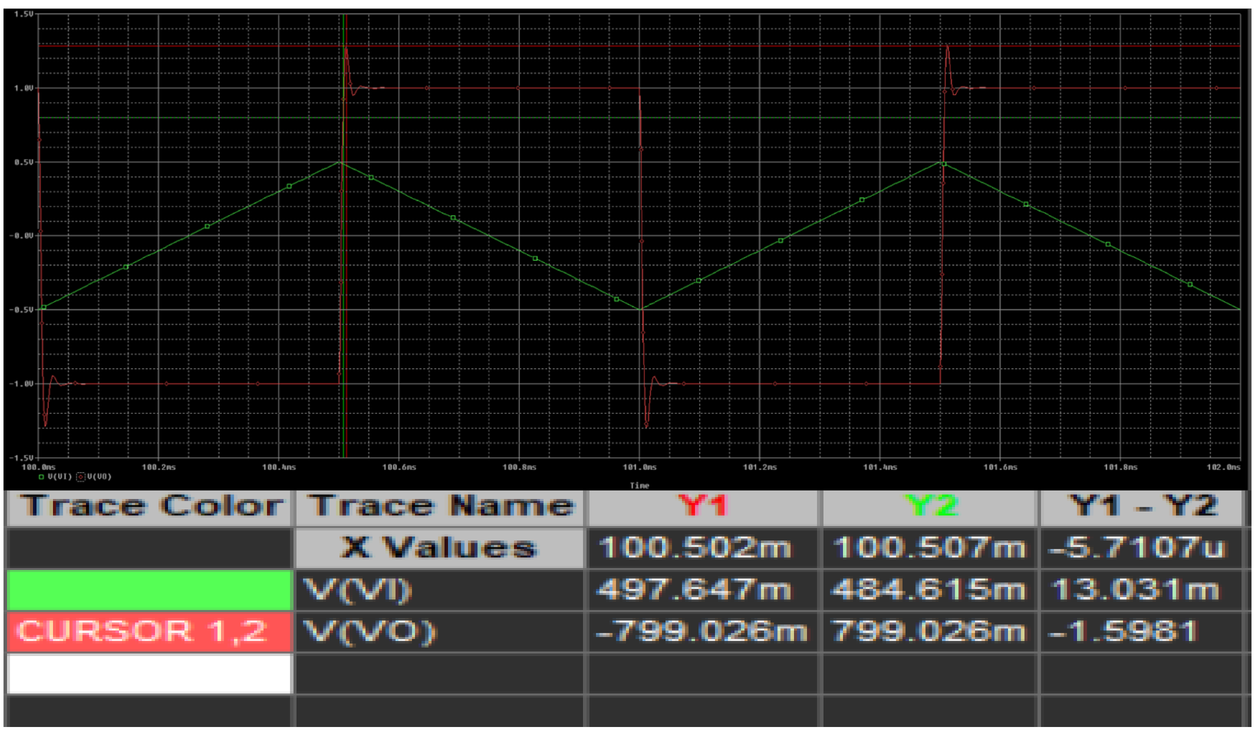


Figure 2.2.6: Simulation Plot and Trace with $R_C = 700\Omega$

$$Overshoot\ \% = \left(\frac{1.2830 - 1}{1 - (-1)}\right) x\ 100 = \mathbf{14.2\%}$$

Rise Time: 5.7107μs

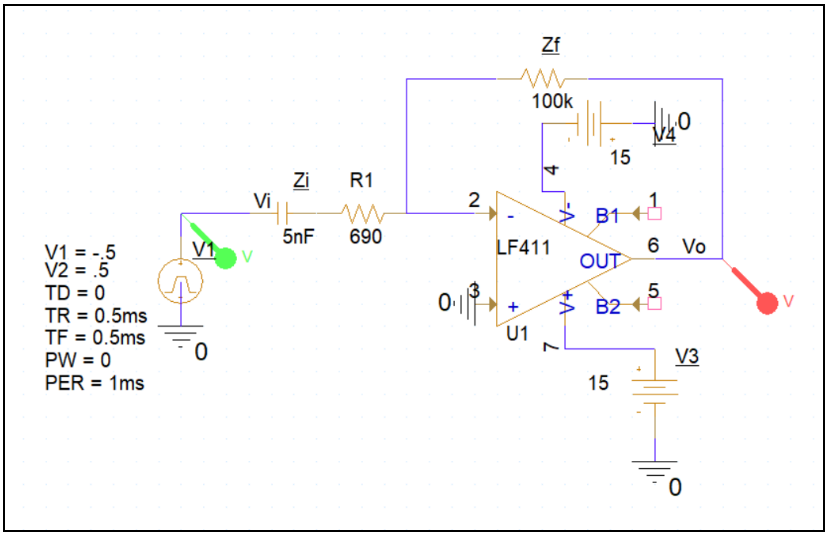
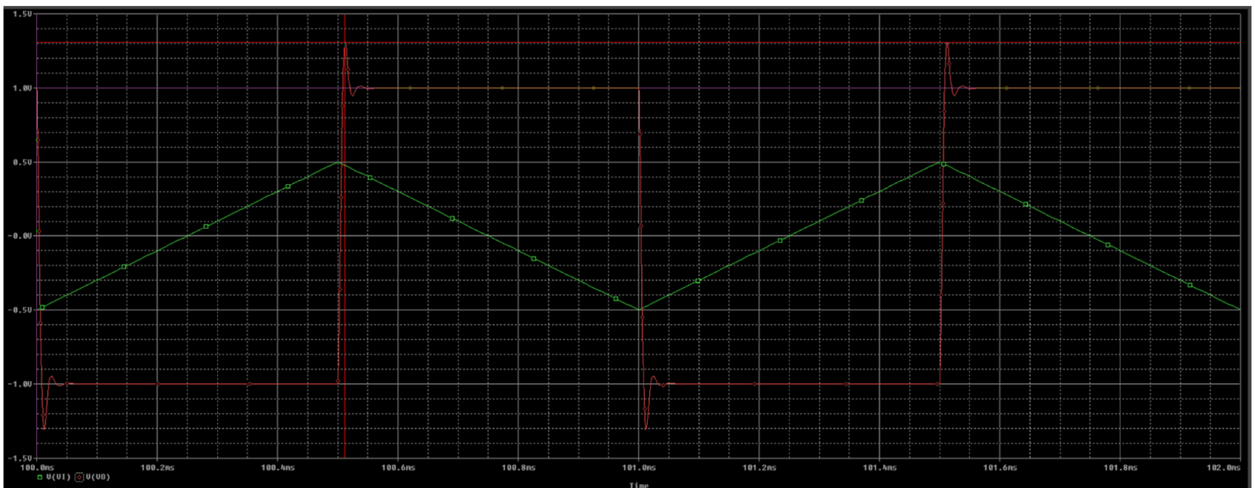


Figure 2.2.7: Schematic of Differentiator Circuit with $R_C = 690\Omega$



	Trace Color	Trace Name	Y1	Y2	Y1 - Y2
		X Values	100.502m	100.507m	-5.6662u
		V(VI)	497.099m	484.615m	12.483m
	CURSOR 1,2	V(VO)	-799.026m	799.026m	-1.5981

Figure 2.2.8: Simulation Plot and Trace with $R_C = 690\Omega$

$$Overshoot\ \% = \left(\frac{1.3081 - 1}{1 - (-1)}\right) x\ 100 = \mathbf{15.4\%}$$

Too much Overshoot

Rise Time: 5.662μs

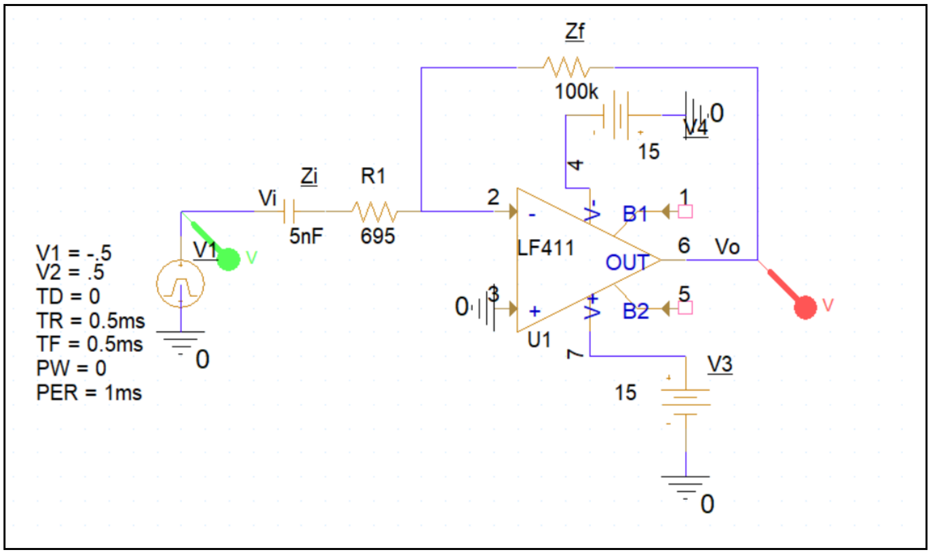
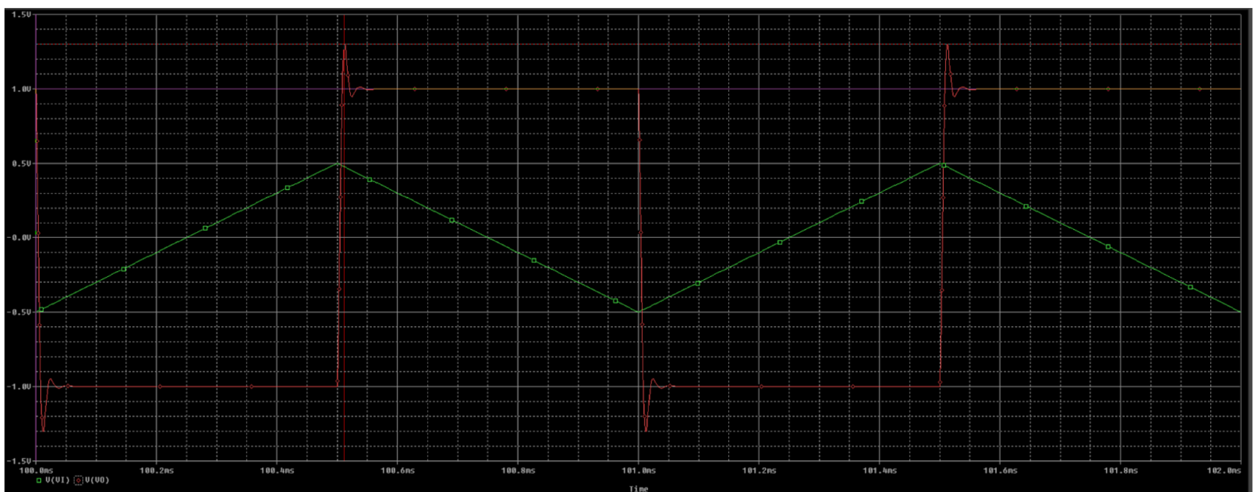


Figure 2.2.9: Schematic of Differentiator Circuit with $R_C = 695\Omega$



	Trace Color	Trace Name	Y1	Y2	Y1 - Y2
		X Values	100.502m	100.507m	-5.6749u
		V(VI)	497.025m	484.615m	12.410m
	CURSOR 1,2	V(VO)	-799.026m	799.026m	-1.5981

Figure 2.2.10: Simulation Plot and Trace with $R_C = 695\Omega$

$$Overshoot\ \% = \left(\frac{1.2997 - 1}{1 - (-1)}\right) x\ 100 = \mathbf{14.985\%}$$

<u>Barely Meets the Spec</u>

Rise Time = 5.6749us

R_C Value (Ω)	Overshoot (%)	Rise Time (μs)
1.03k	2.3%	7.9195
720	13.4	5.7939
700	14.2 %	5.7107
690	15.4%	5.6620
695	14.985%	5.6749

Figure 2.2.11: Table of Simulated Rc Values

Part 3)

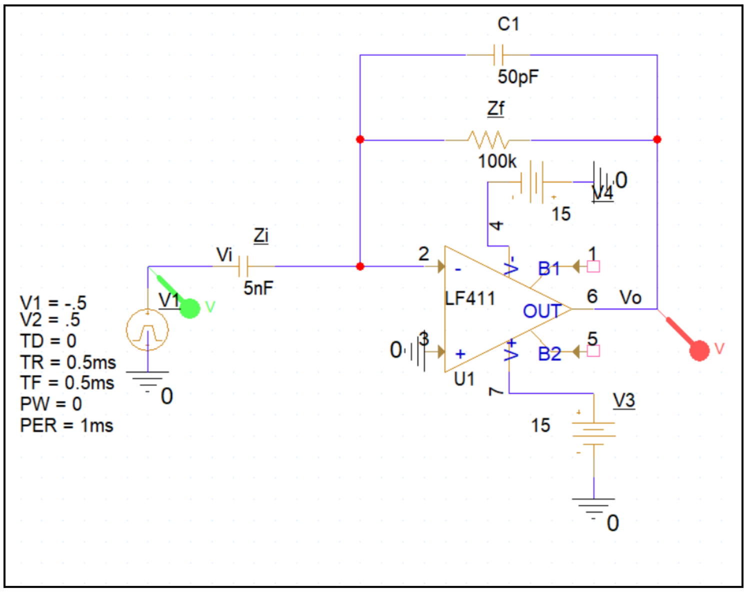
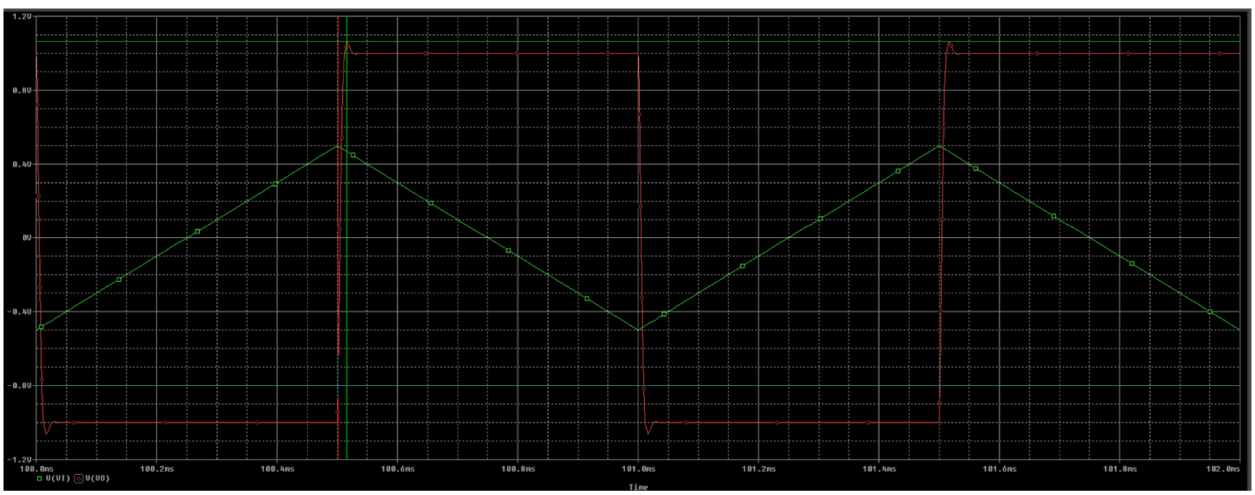


Figure 2.3.1: Schematic of Differentiator Circuit with $C_c = 50pF$



Trace Color	Trace Name	Y1	Y2	Y1 - Y2
	X Values	100.502m	100.509m	-7.4678u
	V(VI)	496.923m	482.564m	14.359m
CURSOR 1,2	V(VO)	-799.444m	799.444m	-1.5989

Figure 2.3.2: Simulation Plot and Trace with $C_c = 50pF$

$$Overshoot\ \% = \left(\frac{1.0631 - 1}{1 - (-1)}\right) x\ 100 = \mathbf{3.155\%}$$

Rise Time: 7.467µs

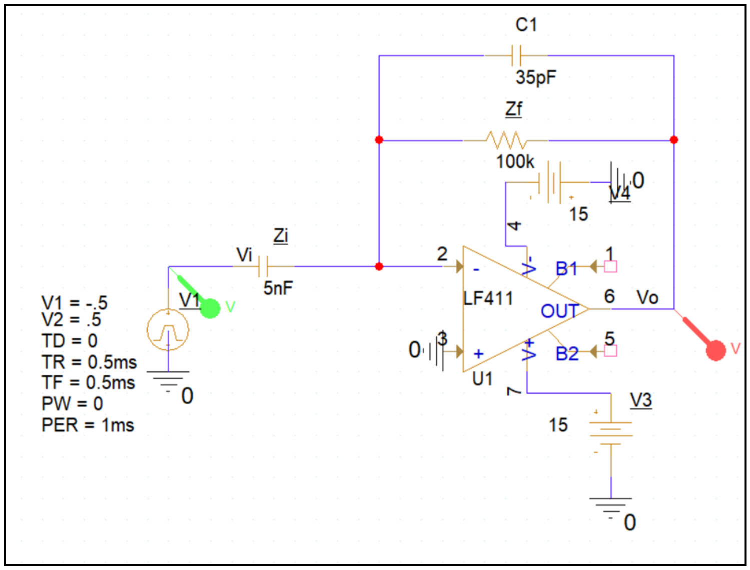
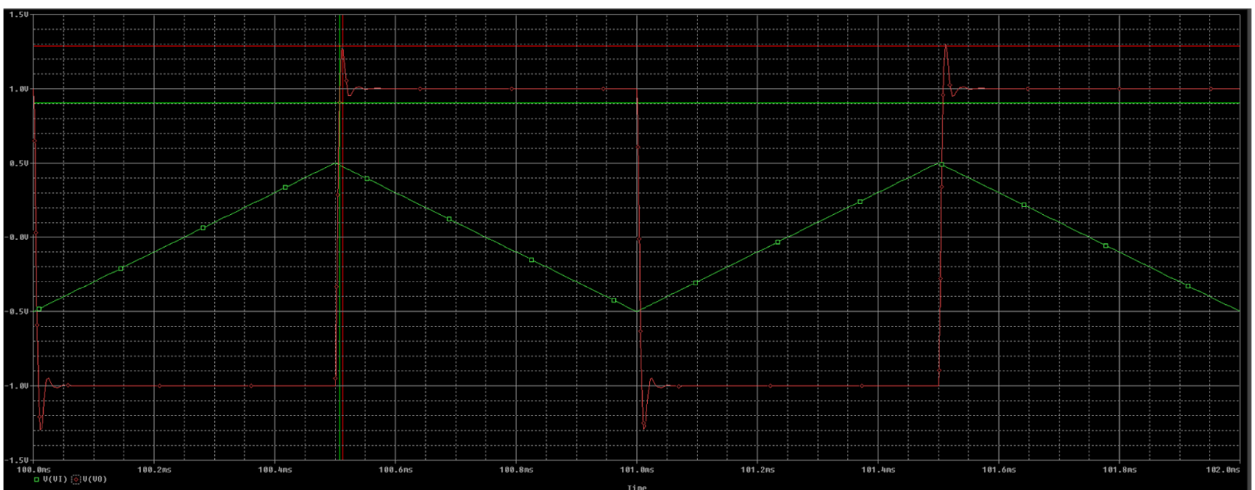


Figure 2.3.3: Schematic of Differentiator Circuit with $C_C = 35pF$



	Trace Color	Trace Name	Y1	Y2	Y1 - Y2
		X Values	100.502m	100.507m	-5.6765u
		V(VI)	498.609m	484.615m	13.994m
	CURSOR 1,2	V(VO)	-799.026m	799.026m	-1.5981

Figure 2.3.4: Simulation Plot and Trace with $C_C = 35pF$

$$Overshoot\ \% = \left(\frac{1.2872 - 1}{1 - (-1)}\right) x\ 100 = \mathbf{14.360\%}$$

Rise Time: 5.6765µs

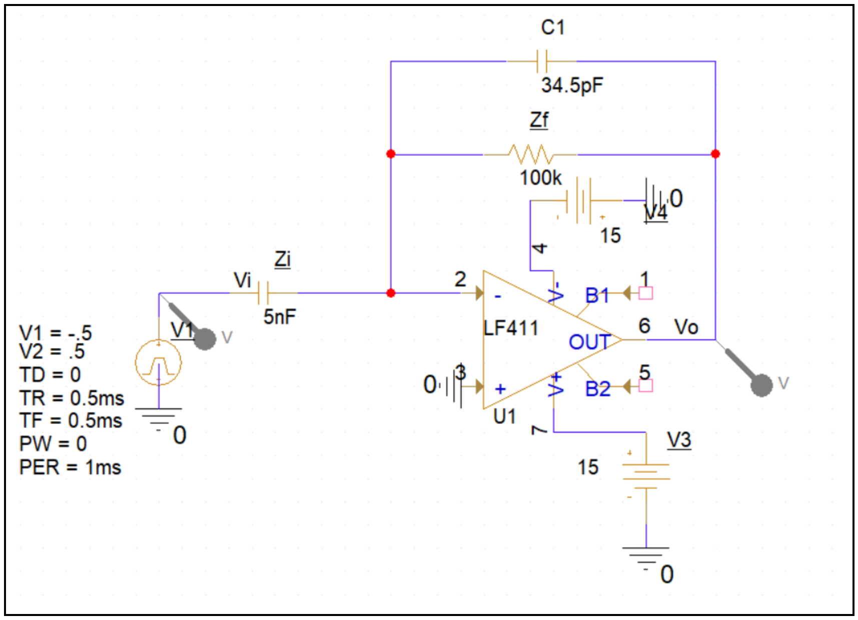
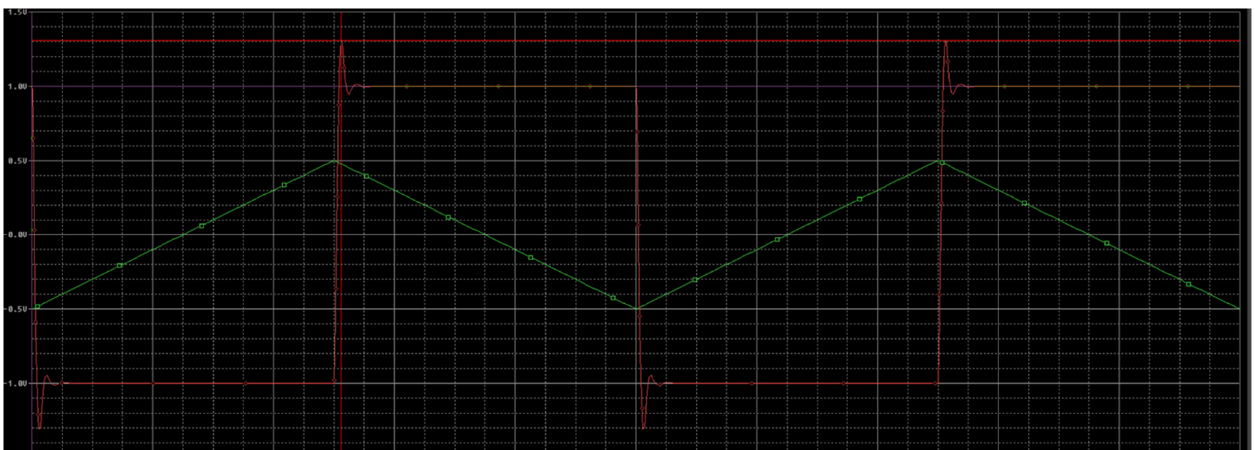


Figure 2.3.5: Schematic of Differentiator Circuit with $C_c = 34.5pF$



	Trace Color	Trace Name	Y1	Y2	Y1 - Y2
		X Values	100.502m	100.507m	-5.6662u
		V(VI)	497.099m	484.615m	12.483m
	CURSOR 1,2	V(VO)	-799.026m	799.026m	-1.5981

Figure 2.3.6: Simulation Plot and Trace with $C_c = 34.5pF$

$$Overshoot\ \% = \left(\frac{1.3081 - 1}{1 - (-1)}\right) x\ 100 = \mathbf{15.4\%}$$

Does not meet spec so 35pF is our final answer.

C_C Value (pF)	Overshoot (%)	Rise Time (μs)
50	3.155	7.467
35	14.360	5.6765
34.5	15.4	5.5735

Figure 2.3.7: Table of Simulated Cc Values

Section 3: Measurements

The LF411 has a slew rate of 13V/μs, which is well beyond the requirements of our design, where the peak rate is only 2.6V over 20μs, equivalent to 0.13V/μs. Therefore, the LF411's performance will not be a limiting factor in this context.

Part 1)

For the first circuit we will measure the output without compensation to view the behavior.

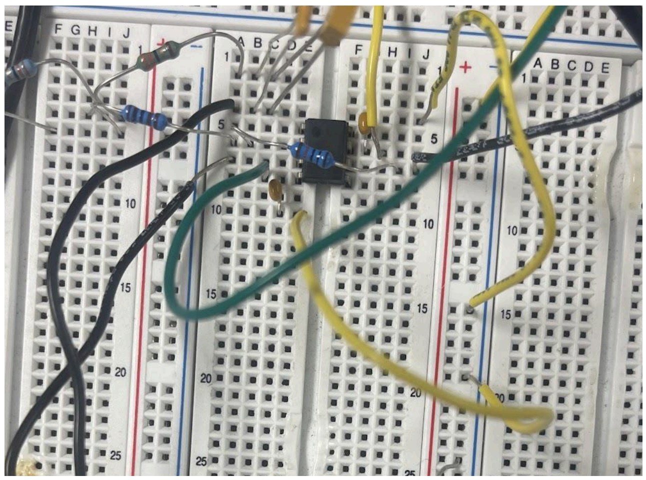


Figure 3.1.1: Breadboard Circuit without Compensation

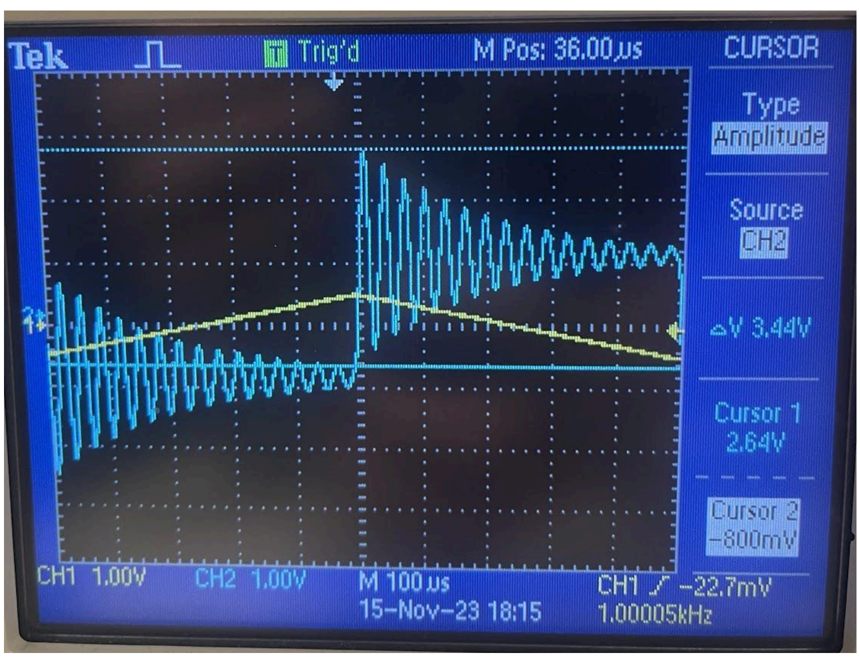


Figure 3.1.2: Oscilloscope Measurements without Compensation

$V_{out}\ (Blue)\ and\ V_{in}\ (Yellow)$

Part 2)

For the second circuit, we will use our simulated values for the Compensation Resistor to determine the accuracy in non-ideal conditions. We also want to find where the overshoot falls out of spec.

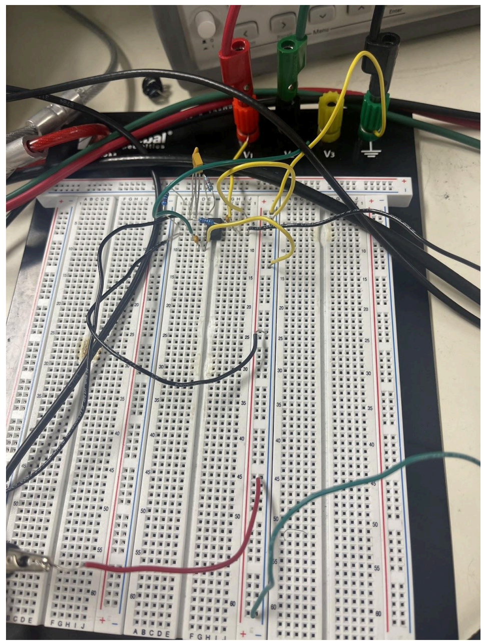


Figure 3.2.1: Breadboard Circuit with $R_C = 1.03K\Omega$

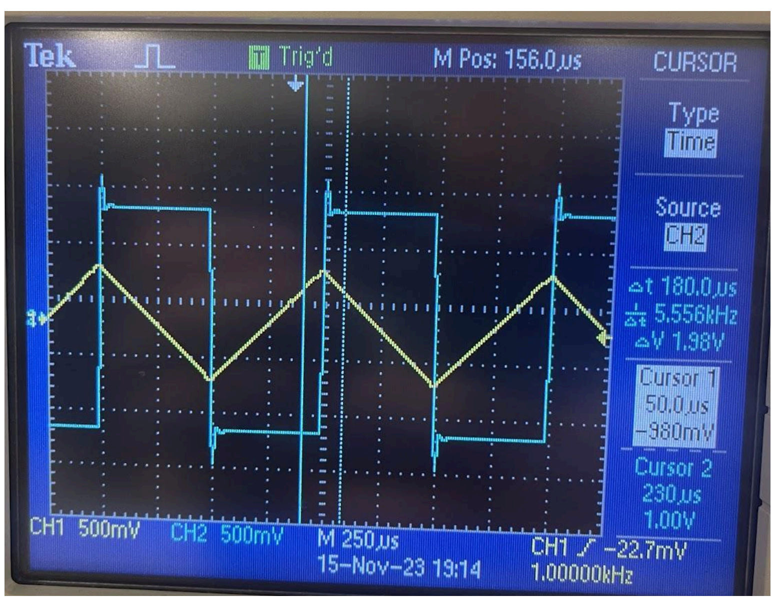


Figure 3.2.2: Oscilloscope Measurements with $R_C = 1.03K\Omega$

$V_{out}\ (Blue)\ and\ V_{in}\ (Yellow)$

$$V_{OUT}Max = 1.3V$$

Calculating Overshoot

$$\text{Overshoot }\% = \left(\frac{V_{OUT}Max - V_2}{V_2 - V_1}\right) x\ 100$$

$$\text{Overshoot }\% = \left(\frac{1.3 - 1}{1 - (-0.98)}\right) x\ 100$$

Overshoot % = **15.15%**

DOES NOT MEET SPEC

Calculating Rise Time

$$V_x = V_1 + 10\% * (V_2 - V_1) = -0.782\ V$$

$$V_y = V_1 + 90\% * (V_2 - V_1) = 0.802\ V$$

$$Rise\ Time\ (t_r) = t_2 - t_1$$

$$t_r = (50.3\mu s) - (42.0\mu s)$$

$$t_r = \mathbf{8.7\mu s}$$

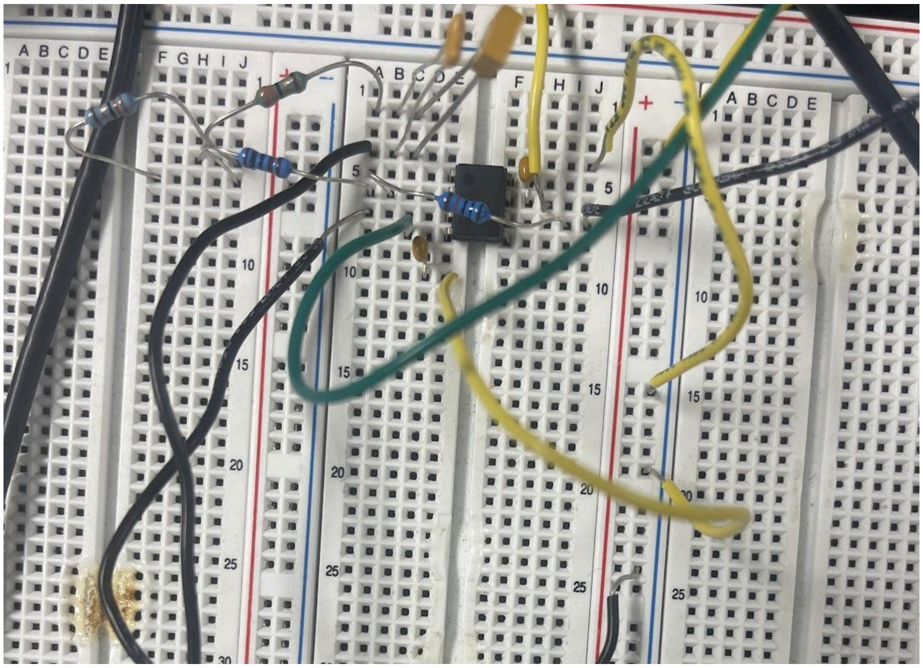


Figure 3.2.3: Breadboard Circuit with $R_C = 1.06K\Omega$

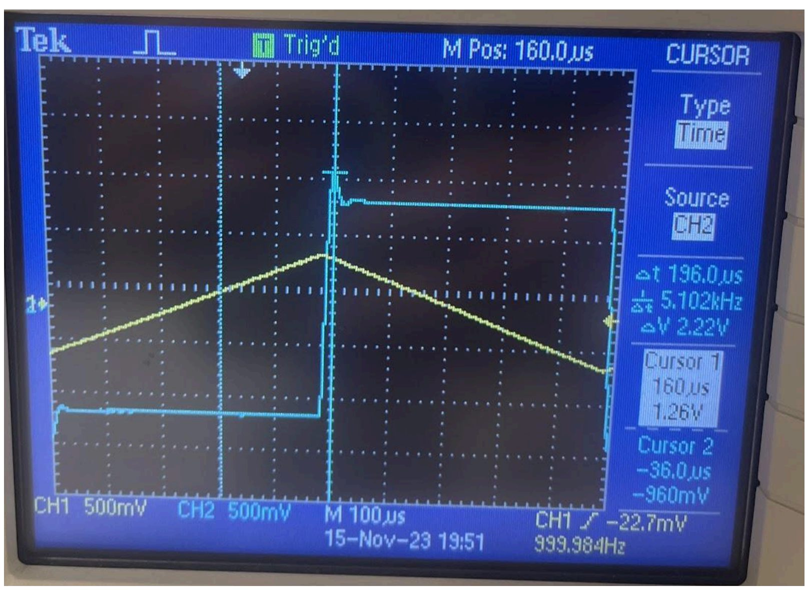


Figure 3.2.4: Oscilloscope Measurements with $R_C = 1.06K\Omega$

$$V_{out}\ (Blue)\ and\ V_{in}\ (Yellow)$$

$$V_{OUT}Max = 1.3V$$

Calculating Overshoot

$$\text{Overshoot \%} = \left(\frac{V_O Max - V_2}{V_2 - V_1}\right) x\,100$$

$$\text{Overshoot \%} = \left(\frac{1.28 - 1}{1 - (-0.96)}\right) x\,100$$

Overshoot % = 14.286%

DOES MEET SPEC

Calculating Rise Time

$$V_x = V_1 + 10\% * (V_2 - V_1) = -0.762\,V$$

$$V_y = V_1 + 90\% * (V_2 - V_1) = 0.822\,V$$

$$Rise\ Time\ (t_r) = t_2 - t_1$$

$$t_r = (151\mu s) - (142\mu s)$$

$$t_r = \mathbf{9\mu s}$$

R_C **Value (Ω)**	**Overshoot (%)**	**Rise Time (μs)**
1.03k	15.15%	8.7
1.6k	14.286%	9

Figure 3.2.5: Table of Measured Rc Values

Part 3)

For this part we will repeat the process as Part 2, except using a Compensation Capacitor instead of a resistor.

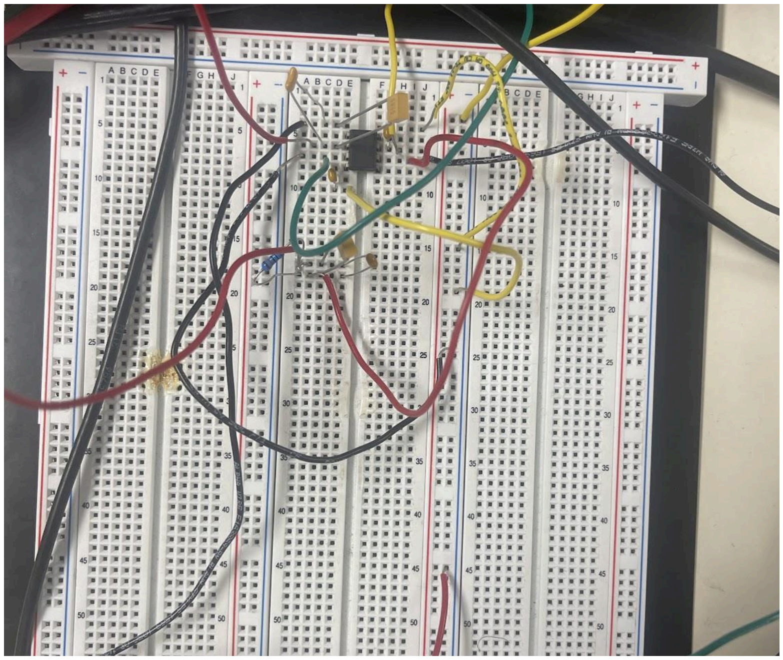


Figure 3.3.1: Breadboard Circuit with a Compensation Capacitor

Figure 3.3.2: Oscilloscope Measurements with $C_C = 515pF$

$$V_{out}\ (Blue)\ and\ V_{in}\ (Yellow)$$

$$V_{OUT}Max = 1.3V$$

Calculating Overshoot

Overshoot %= $\left(\frac{V_O Max - V_2}{V_2 - V_1}\right) x\, 100$

Overshoot %= $\left(\frac{1.28 - 1}{1 - (-0.96)}\right) x\, 100$

Overshoot % = 14.286%

NO OVERSHOOT

Calculating Rise Time

$$V_x = V_1 + 10\% * (V_2 - V_1) = -0.762\, V$$

$$V_y = V_1 + 90\% * (V_2 - V_1) = 0.822\, V$$

$$Rise\ Time\ (t_r) = t_2 - t_1$$

$$t_r = (151\mu s) - (142\mu s)$$

$$t_r = 9\ \mu s$$

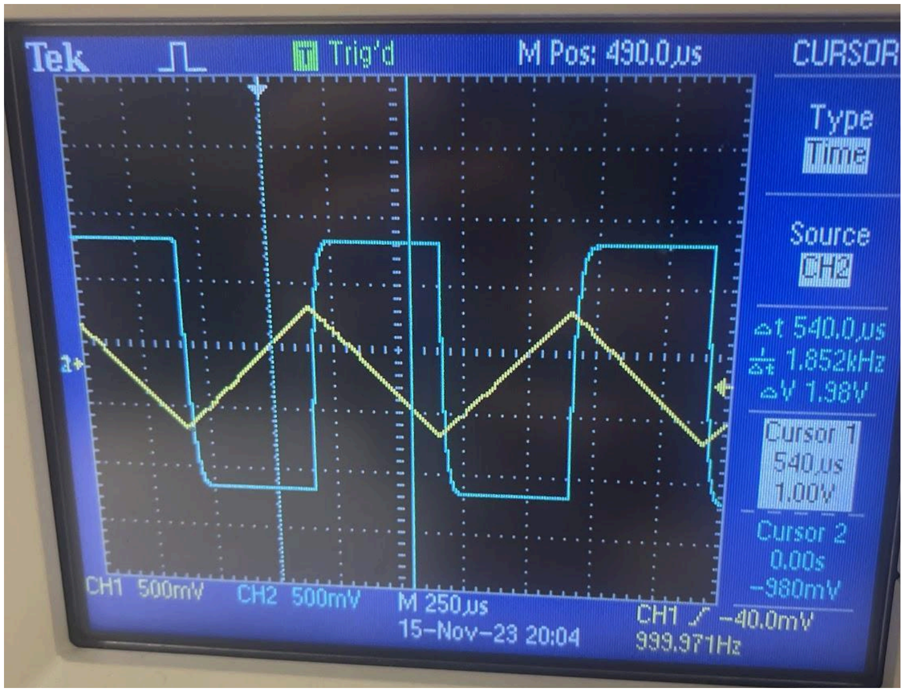


Figure 3.3.3: Oscilloscope Measurements with $C_c = 170pF$

No Overshoot

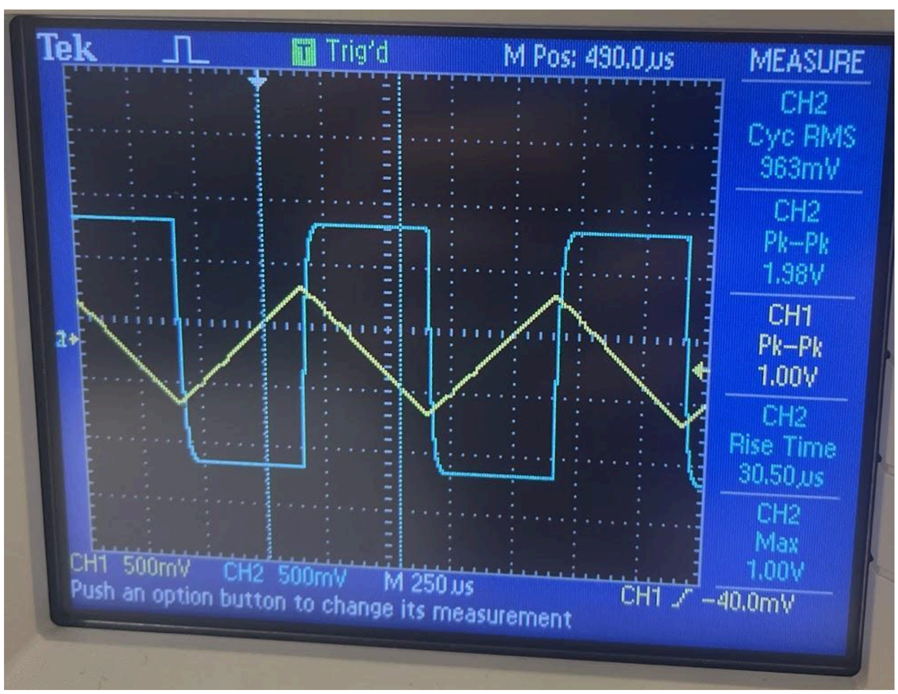


Figure 3.3.4: Oscilloscope Measurements with $C_c = 150pF$

No Overshoot

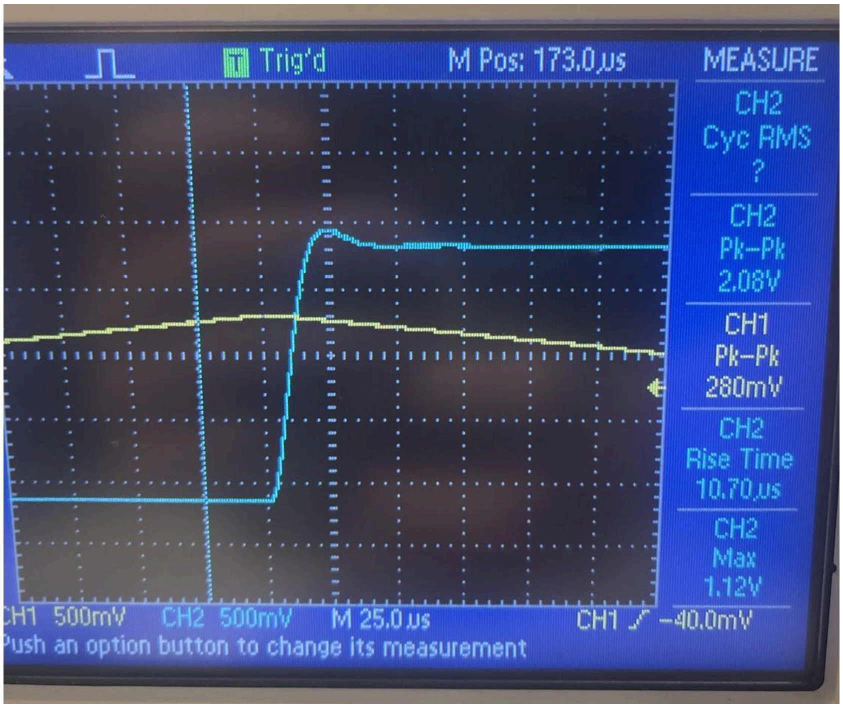


Figure 3.3.5: Oscilloscope Measurements with $C_c = 68pF$

Overshoot = 12%

$t_r = 10.7\ \mu s$

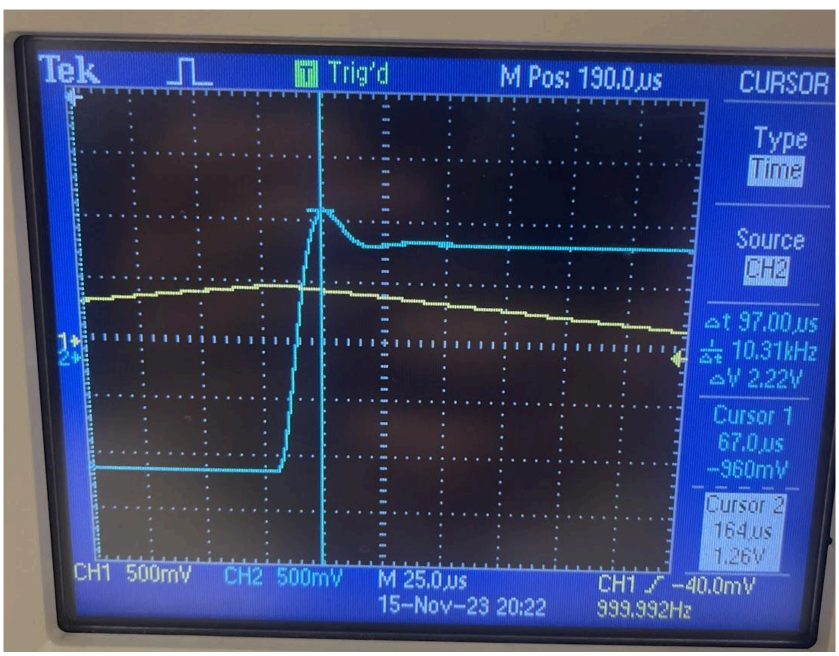


Figure 3.3.6: Oscilloscope Measurements with $C_c = 51pF$

Overshoot = 13.2%

$t_r = 9.4\ \mu s$

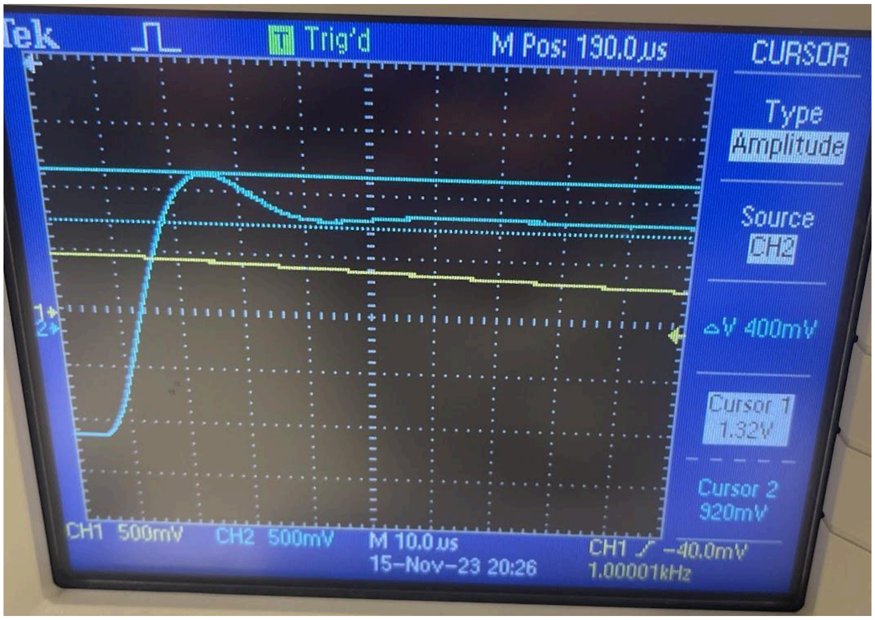


Figure 3.3.7: Oscilloscope Measurements with $C_C = 47pF$

Overshoot = 16.3 %

$t_r = 8.7\ \mu s$

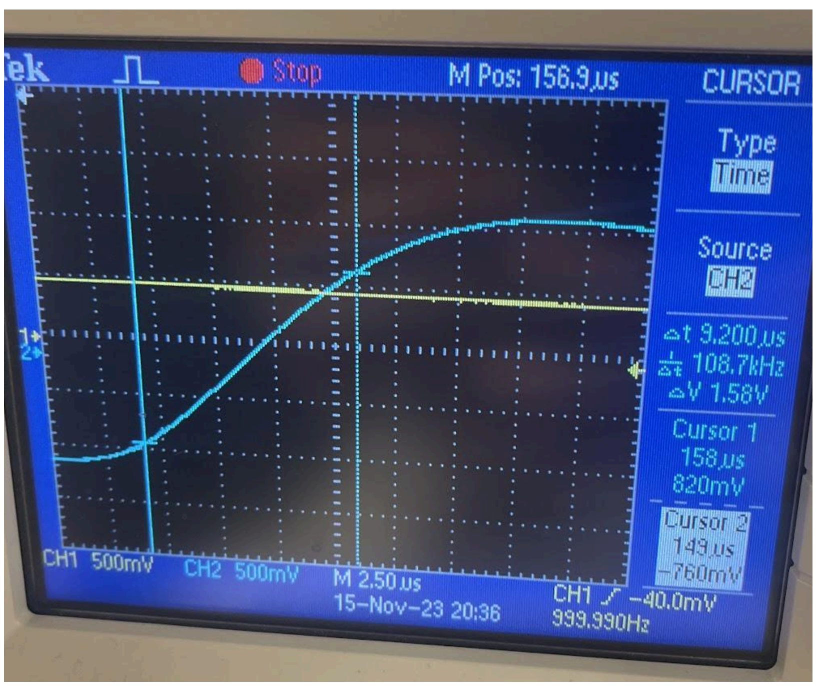


Figure 3.3.8: Oscilloscope Measurements with $C_C = 50.2pF$

Overshoot = 14.2%

$t_r = 9.2\ \mu s$

C_C Value (pF)	Overshoot (%)	Rise Time t_r (µs)
515	No OS	
170	No OS	
150	No OS	
68	12%	10.7
51	13.2%	9.4
50.2	14.2%	9.2
47	16.3%	8.7

Figure 3.3.9: Table of Measured Cc Values

Conclusion

The voltage differentiator circuit underwent analysis using equations, Matlab, PSpice, and practical circuit setups. The resistor and capacitor values that best met the specifications showed consistency across Matlab, PSpice, and actual circuit tests. Our analysis revealed that the simplified op-amp model is generally effective, although it has its limitations. During circuit simulation, we noted discrepancies due to the operational amplifier's inherent inconsistencies not fully captured by our simplified model. Nonetheless, it proved useful for initial estimations in our filter design. In the actual filter implementation, our results deviated from theoretical predictions, possibly due to additional impedances on the breadboard and the use of a simplified model in our calculations. We observed that the step response and PSpice simulations did not fully align with real-world behavior; notably, there was a consistent overshoot stabilizing at a value approximately 15% higher than expected. This led to the necessity of adjusting the compensation impedance, opting for higher resistance or lower capacitance. For future experiments, extending our simulations over longer durations could yield more accurate insights for practical implementation.

MATLAB Code

Part 1) System Level Design

1C

```
s = tf('s')
G1 =2*pi*3e6; r = 100e3; c= 5e-9;
tau = r*c;
T = G1 / (s*(1+s*tau));
figure (1);
%bode(T, {100,1e6}),
%margin(T);
H = T/(1+T);
%step(H, 1e-3);
stepinfo(H)
```

1D (w/ RC)

```
Rc = 1030;
T = G1*(1 + s*Rc*c) / (s*(1 + s*c*(r+Rc)));
%bode(T, {100,1e6});
%margin(T);
H = T/(1+T);
%step(H, 1e-3);
stepinfo(H)
```

1D (w/ CC)

```
Cc = 5.155e-11
T = G1*(1 + s*Cc*r) / (s*(1 + s*r*(c+Cc)));
%bode(T, {100,1e6});
%margin(T);
H = T/(1+T);
%step(H, 1e-3);
%stepinfo(H)
```

1E

```
Rc = 1.885e3;
T = G1*(1 + s*Rc*c) / (s*(1 + s*c*(r+Rc)));
bode(T, {100,1e6});
margin(T);
H = T/(1+T);
step(H, 1e-3);
stepinfo(H)
```