Operational Amplifiers

Lab 2

EEE 334
Circuits II

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Student ID:	**********

Report Completed on: **9/15/2023**

Arizona State University

INTRODUCTION

This labs’ main focus is to allow the student to become more comfortable with analyzing various operational amplifier circuits such as inverting amplifier, non-inverting amplifier, integrating amplifier, and differentiating amplifier. This allows the student to understand the basics of each of these operational amplifiers while also getting valuable practice utilizing the ADK software, LTSpice Software, physically building the amplifiers, and further practice with a handheld multimeter.

Figure 1 was removed due to it only being a photo of myself

Figure 1 Lab Set-Up Selfie Photo

EQUIPMENT and COMPONENTS USED

For this lab the following items were used to conduct the experiments and findings:

- *Digital Multimeter*
- *ADK (Analog Discovery 2)*
- *Large Breadboard*
- *Analog Parts Kit*
- *TI-nspire CX II Calculator*
- *Resistors used: 1x1kΩ, 1x10kΩ*
- *Capacitors used: 1x0.01µF*

Course of Action

This section covers the processes that need to be done for each part. There will be a detailed description of what needs to be found and accomplished. The completed results mentioned in this section will be found in the results section.

***Note: Most tables or figures listed in the paragraph text are hyper link by control clicking.*

2.1 Inverting Amplifier

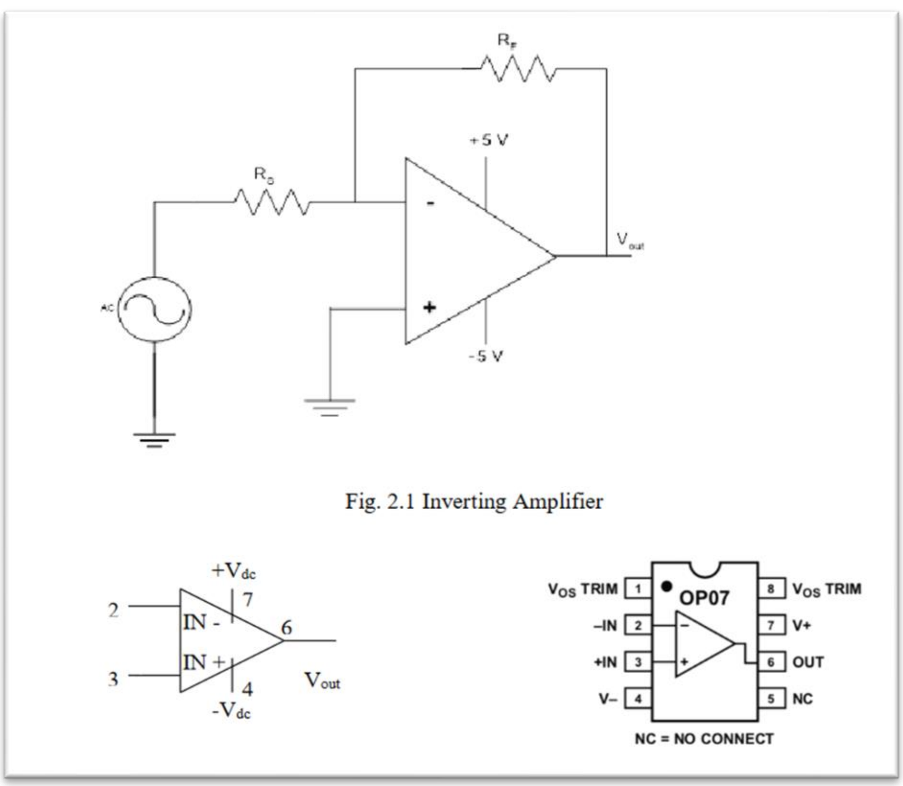


Fig. 2.1 Inverting Amplifier

Figure 2 Inverting Amplifier

For the first section of the lab, the main focus will be on the inverting amplifier. Similar to lab 1 the course of action will be to first; hand calculate the closed loop voltage gain of the amplifier. Once this is obtained the inverting amplifier will then be built in LTSpice simulation software. Once built the circuit will be analyzed with a transient analysis along with an AC sweep to find the frequency response for the transfer function. With these two analyses the f_t or the unity gain can be determined and then this value will be checked against the factory specifications to see if the results are similar. Once all the prior steps have been completed the physical inverting amplifier will be built to be analyzed against the simulated results from LTSpice and the hand calculations. However, before the physical circuit is built the resistor values to be used (10kΩ and 1kΩ) will be measured with the handheld multimeter to determine their actual values. Lastly, once the circuit is built and working the waveforms oscilloscope and waveforms multimeter will be used to check the results once again.

2.2 Non-Inverting Amplifier

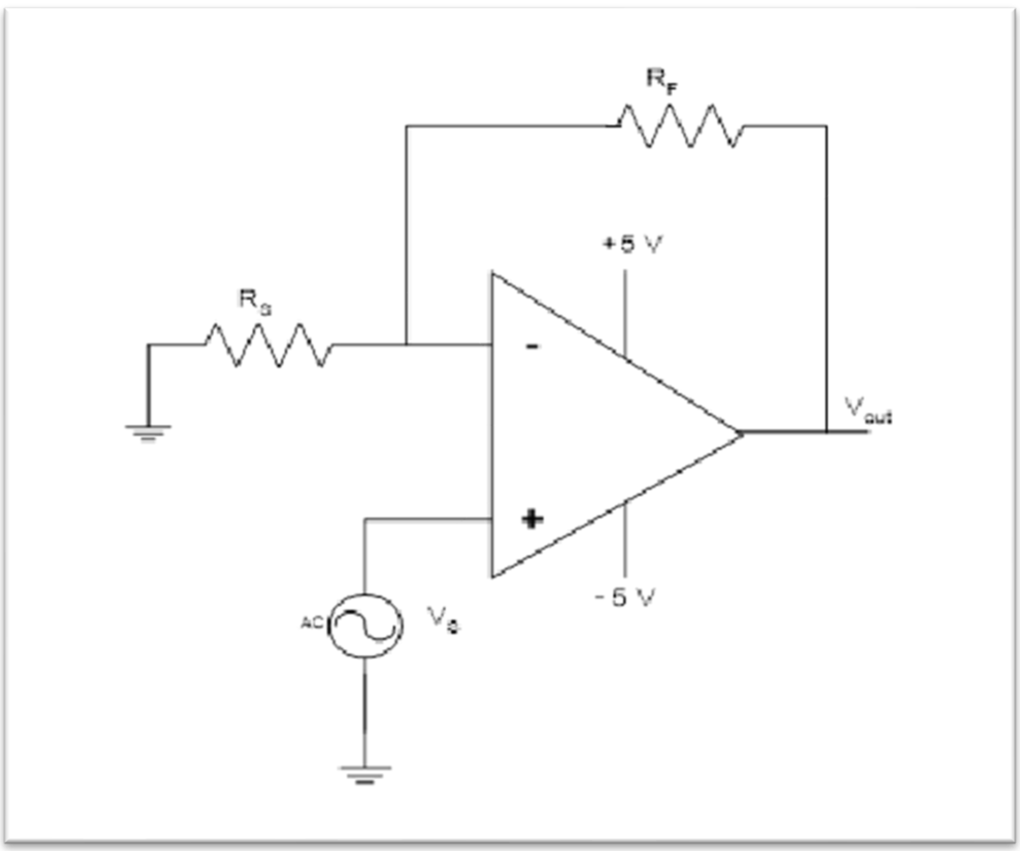


Figure 3 Non-Inverting Amplifier

For section 2.2 this will be very similar to section 2.1, the inverting amplifier. To start off, hand calculations will be run to determine the overall gain the non-inverting amplifier will have on the Vs signal. Once these calculations have been completed. The non-inverting amplifier will be built in LTSpice. Once the circuit is built and determined to be built correctly a Transient Analysis will be run and these results can be used to calculate the gain for the simulated circuit with hopes that that hand calculations and the simulated results will be similar with very low percent error. Once this is completed an AC Sweep will be ran on Vout of the amplifier to obtain the Frequency Response of the overall Amplifier. With this information calculations will be run utilizing LTSpice .op commands to find the Max Gain, f_{3dB} point, and the f_t point also known as the unity gain frequency. Lastly, a physical non-inverting amplifier will be built. Before the circuit is built the resistor values will be measured and logged for their accuracy against the expected values. Once built the circuit will be analyzed for accuracy with the waveform's oscilloscope and voltmeter. These results will then be used to calculate the gain and all these values will be checked against each stage for the percentage errors to verify the circuit was built and working as intended.

2.3 Integrating Amplifier

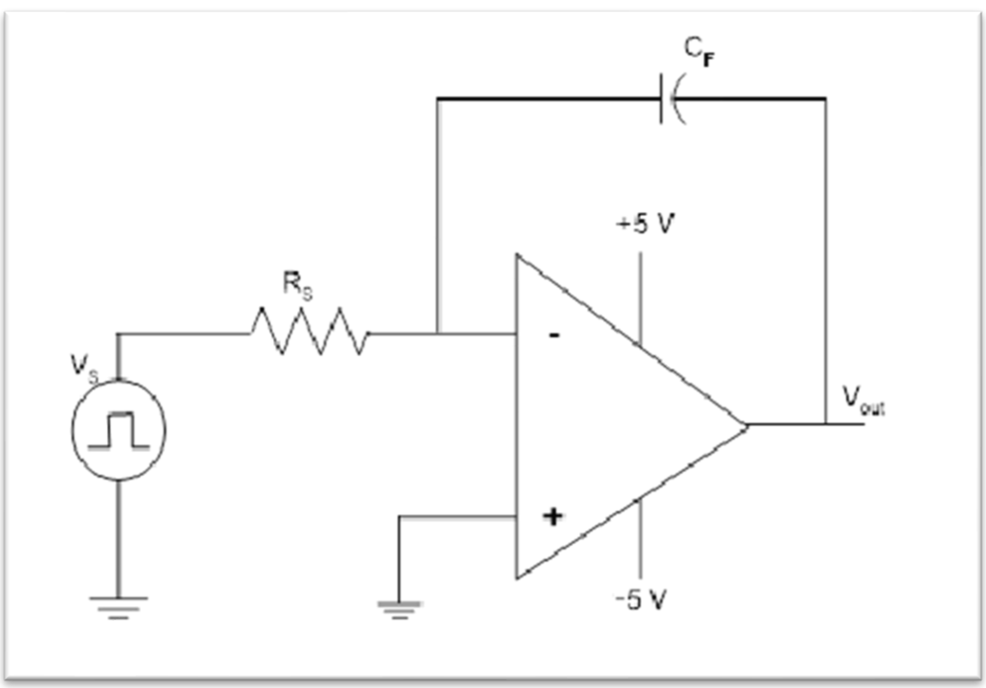


Figure 4 Integrating Amplifier

For section 2.3, this amplifier is a little different from the previous two. The amplifier that will be focused here is the integrating amplifier. The analysis, however, will be fairly the same as the previous two but a few extra things will be done to further analyze the amplifier. First, hand calculations will be accomplished to find the gain for this particular amplifier. Once this is completed the amplifier will be built in LTSpice. When starting to analyze the amplifier a square wave is needed. Once the circuit is built a transient analysis will be accomplished. For this section and the next, the focus will be on the $Vout_{rms}$ and Vin_{rms} this is different from the first two sections where Vpp was used. Once the transient analysis is accomplished the relationship between Vs and Vout will be determined along with the gain calculations using $Vout_{rms}$ and Vin_{rms}. Once the LTSpice analysis is completed then the physical build of the integrating amplifier will be accomplished. However, prior to the build, the components such as resistor and capacitor will be checked and verified to be close to the values stated to be used in the lab. Once the circuit is built the analysis will be verified with ADK waveforms oscilloscope and the input and output signal will be checked with the ADK voltmeter. Lastly, the relationship between the input and output signal will be checked against the results from the hand calculations and LTSpice simulations and the percentage error will be logged.

2.4 Differentiating Amplifier

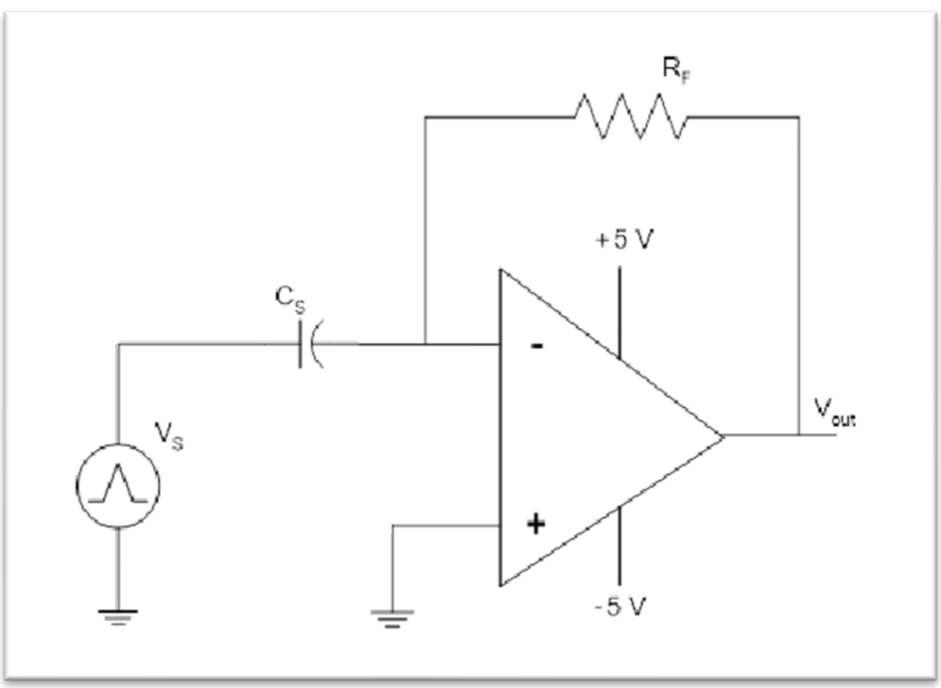


Figure 5 Differentiating Amplifier

For the last section 2.4, the focus will be on a differentiating amplifier. This last section will also be similar to the previous integrating amplifier when it comes to the analysis process. First the gain will be hand calculated and the calculation results will be posted. Next the differentiating amplifier will be built in LTSpice with the source voltage Vs being a triangular wave form with an amplitude of 1V along with a frequency of 1k Hz. For a final time, a transient analysis will be performed to analyze Vs and Vout. During this analysis the 100Ω resistor that was placed to simulate a real voltage source will be removed and another analysis will be done to see what happened to the circuit. From these results the gain will be calculated from the simulation along with the relationship between Vs and Vout. Lastly, the physical circuit will be built along with the components that will be used will be measured to make sure they are in an allowable tolerance to allow the circuit to behave as it was simulated. Once this is completed the ADK waveform software will be used to analyze the results. The first analysis will be with the waveforms oscilloscope and the second will be with the ADK voltmeter. Due to the natural oscillation from the oscilloscope readings the voltmeter Vrms values will be used to calculate the gain of the physical circuit along with analyzing the relation between the input and output wave forms. Once all this has been completed an error analysis will be logged from each part to compare the results achieved.

RESULTS

2.1 Inverting Amplifier

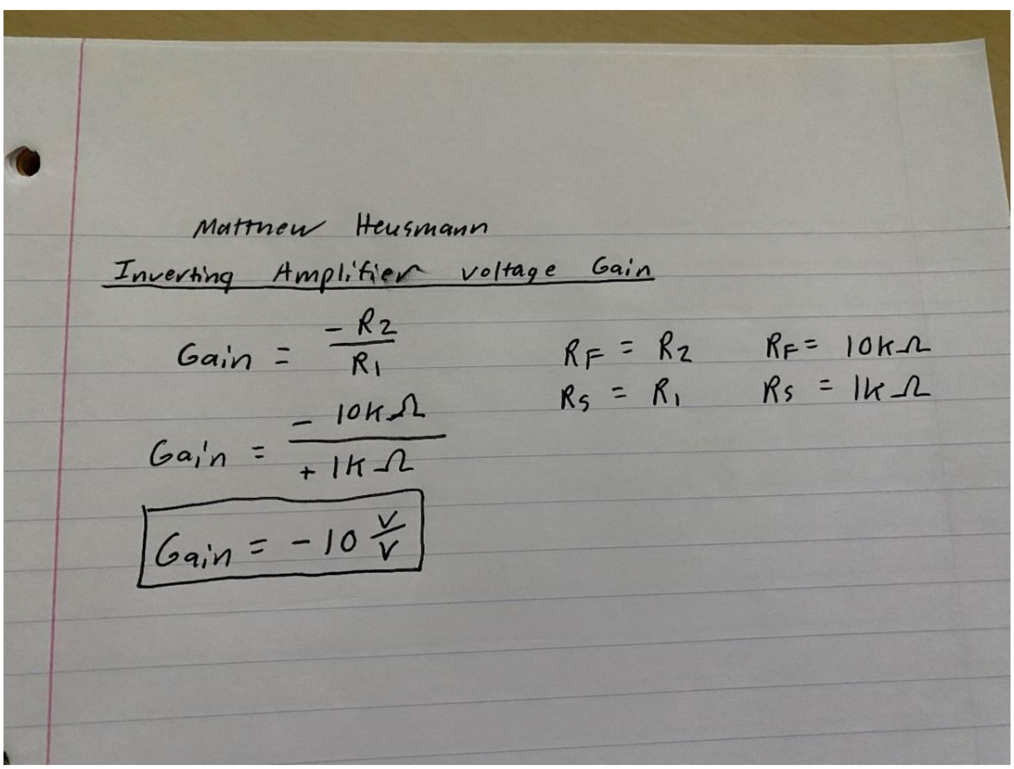


Figure 6 Inverting Amplifier Voltage Gain Hand Calculations

From the hand calculations above the voltage gain is calculated to be $\boldsymbol{Gain = -10\frac{V}{V}}$.

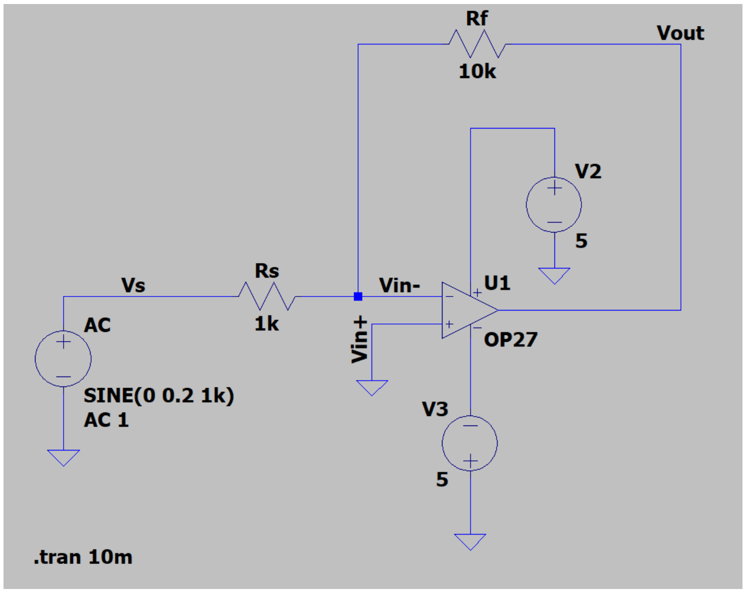


Figure 7 Inverting Amplifier LTSpice

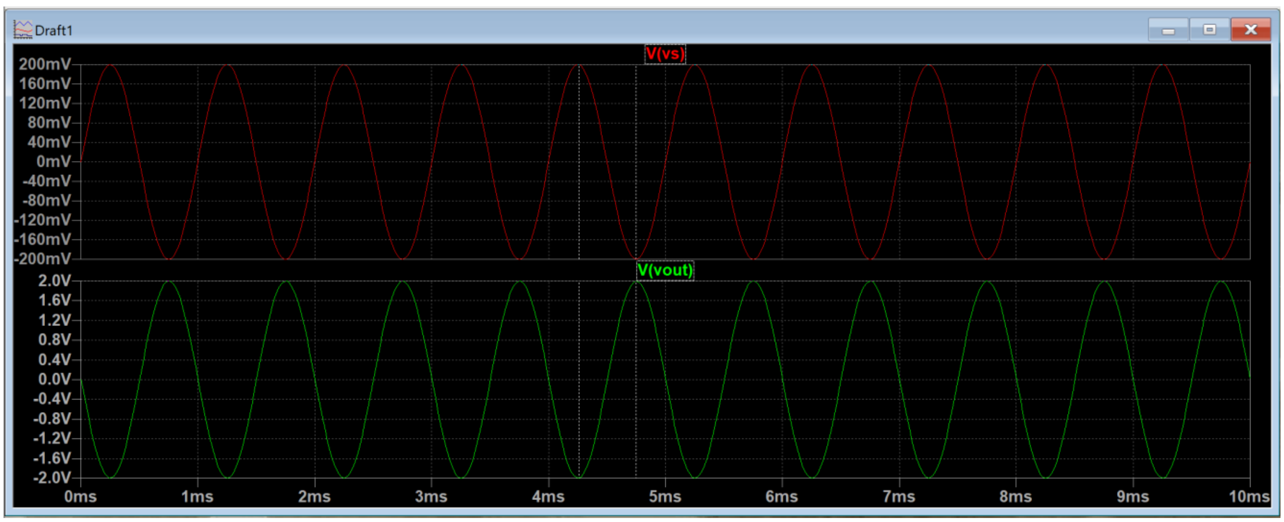


Figure 8 LTSpice Transient Analysis of Vout and Vs

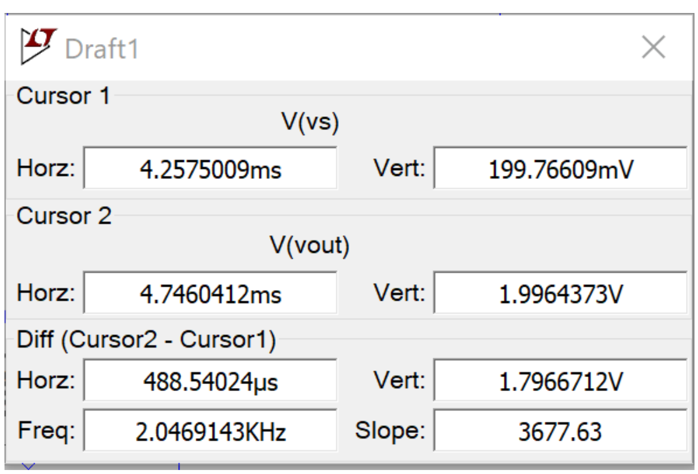
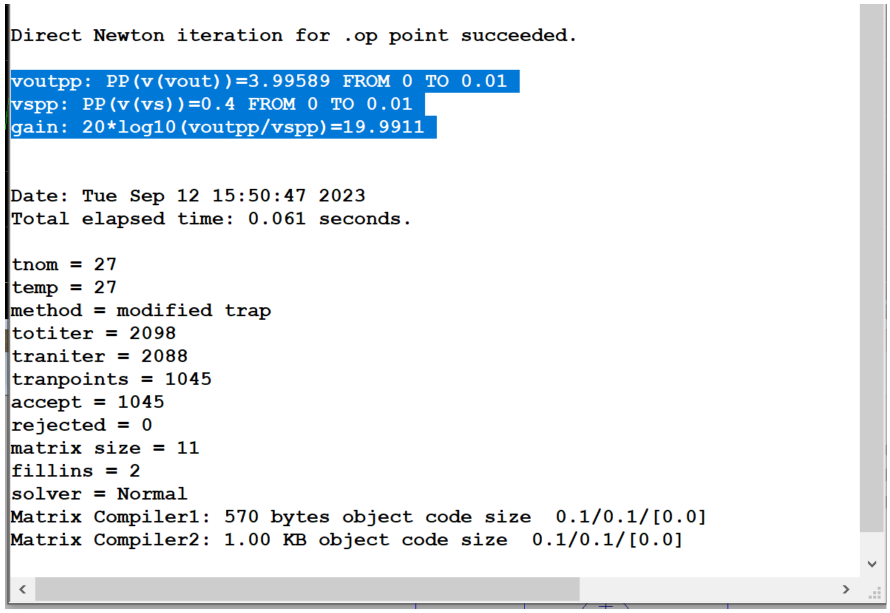


Figure 9 LTSpice Transient Analysis of Vout and Vs Results



```
Direct Newton iteration for .op point succeeded.

voutpp: PP(v(vout))=3.99589 FROM 0 TO 0.01
vspp: PP(v(vs))=0.4 FROM 0 TO 0.01
gain: 20*log10(voutpp/vspp)=19.9911


Date: Tue Sep 12 15:50:47 2023
Total elapsed time: 0.061 seconds.

tnom = 27
temp = 27
method = modified trap
totiter = 2098
traniter = 2088
tranpoints = 1045
accept = 1045
rejected = 0
matrix size = 11
fillins = 2
solver = Normal
Matrix Compiler1: 570 bytes object code size  0.1/0.1/[0.0]
Matrix Compiler2: 1.00 KB object code size  0.1/0.1/[0.0]
```

Figure 10 Calculated Gain in dB using LTSpice

From the three figures above the inverting amplifier was built in LTSpice and a transient analysis was run to see the results of Vout and Vs. From those results it can be seen that the Vs used was 0.4Vpp and 1kHz. This result can be seen above with the red graph. With a close approximation of 199.77mV peak and a -199.77Vp, these values are due to not allowing the cursor to be 100% accurate when placing. So, it can be concluded the correct signal was used for Vs. As for the Vout, from the green graph above an inverted signal with a Vp of -1.996V and +1.996V was read, again the reason for the off values is due to the error in cursor placement but it can be concluded that the correct value of 4Vpp is shown. From the equation for the gain this can be determined by $\frac{Vout}{Vs}$. So, from the results of the graph the calculation would be $\frac{\mathbf{4}Vpp}{\mathbf{0.4}Vpp} = \mathbf{10}\,\frac{V}{V}$ and since the signal is inverted from the original the calculated result would be a **gain of -10** $\frac{V}{V}$. This is the same result as the hand calculation.

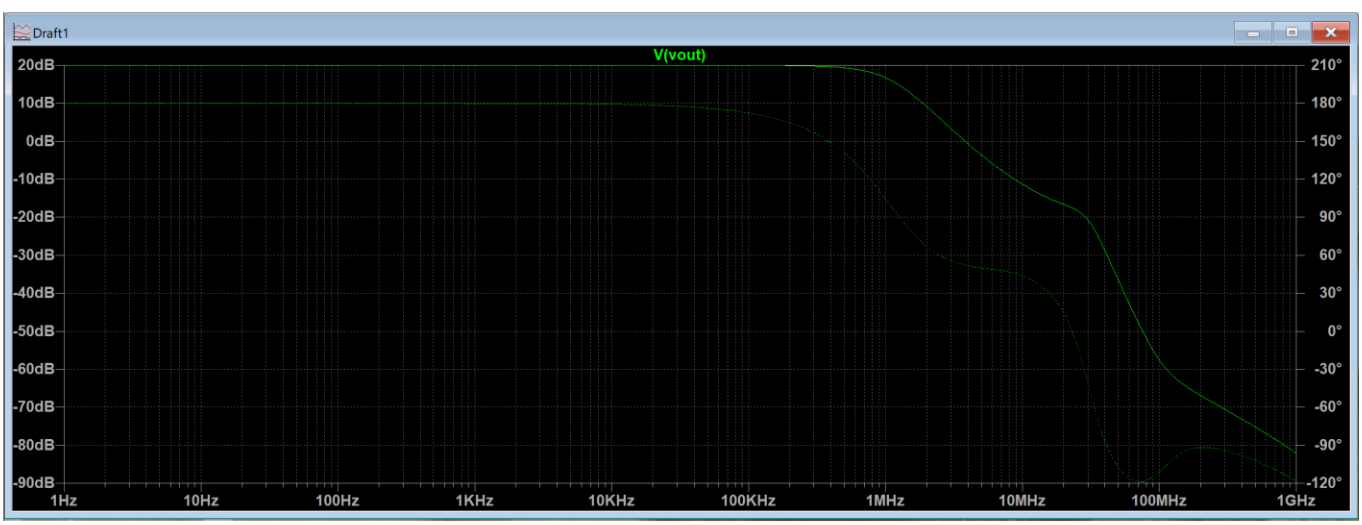


Figure 11 Inverting Amplifier Frequency Response in LTSpice

```
Direct Newton iteration for .op point succeeded.

ft: mag(v(vout)/v(vs))=1 AT 3.8203e+006
maxgain: MAX(mag(v(vout)))=(20dB,0°) FROM 1 TO 1e+009
f-3db: mag(v(vout))=maxgain-3 AT 973683


Date: Tue Sep 12 17:58:40 2023
Total elapsed time: 0.051 seconds.

tnom = 27
temp = 27
method = trap
totiter = 27
traniter = 0
tranpoints = 0
accept = 0
rejected = 0
matrix size = 12
fillins = 2
solver = Normal
Matrix Compiler1:      35 opcodes
Matrix Compiler2: 1.04 KB object code size
```

Figure 12 Inverting Amplifier Frequency Response Calculations in LTSpice

From the inverting amplifier frequency response calculation utilizing LTSpice the results were as follows: f_{3dB} point = **973.7kHz** which is also **16.902dB,** the **Max Gain in dB = 20dB** and **F_t = $\boldsymbol{3.8MHz}$.**

For the physical build of the inverting amplifier the two resistors will be measured, and their values will be stated below:
Measure Resistors used: **R_s = 983 Ω, R_f = 9810 Ω**

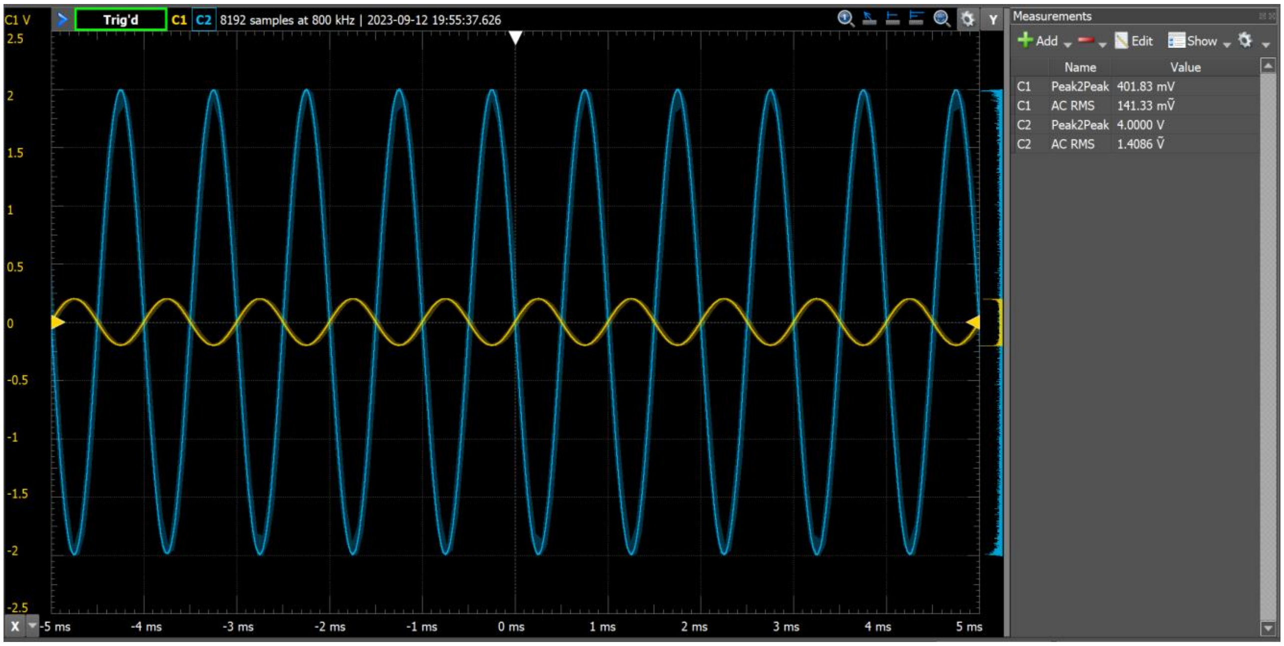


Figure 13 Waveforms Oscilloscope Inverting Amplifier Results

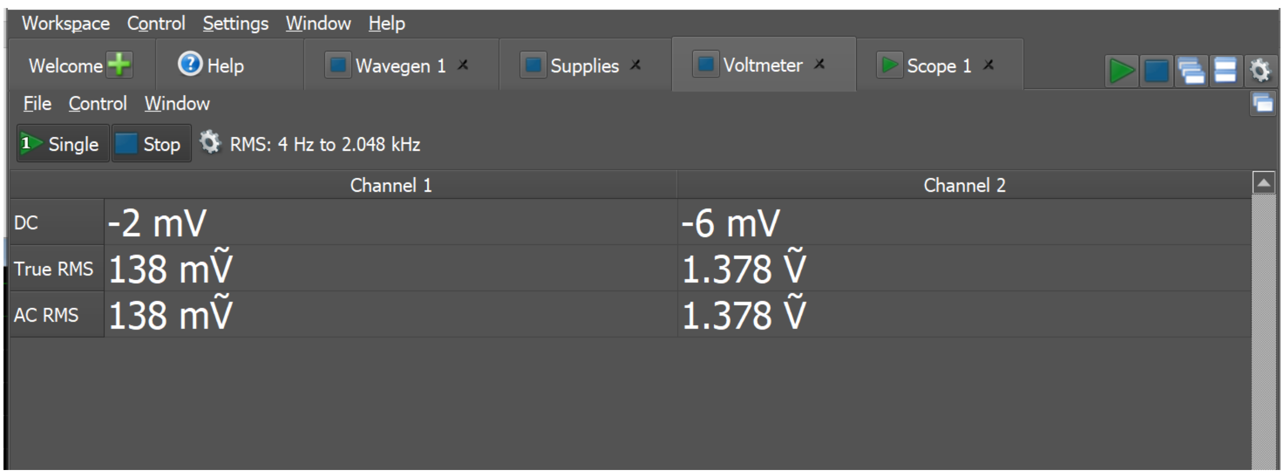


Figure 14 Waveforms Voltmeter Inverting Amplifier Results

From the two waveform figures above, it can be seen that channel one is representing the Vs signal going into the circuit. The results from channel one was that Vs was 401.83mV Vpp very close to the value that is expected. As follows channel 2 represents the Vout signal, the result is 4Vpp exactly what is expected. This can be further backed up by the voltmeter reading from the ADK voltmeter. From this result the gain can be calculated $\frac{(1.378*2\sqrt{2})Vpp}{(0.138*2\sqrt{2})Vpp} = -9.986\frac{V}{V}$. This result is negative due to the signal being inverted from the Vs signal that was input into the circuit. The reason for the $2\sqrt{2}$ in the calculation is due to converting the Vrms value the voltmeter give to a Vpp value since everything thus far has been shown in Vpp.

The table below is presented so the results from each section can easily be seen. From these results it can be determined that the hand calculations, LTSpice Simulations, and Multimeter values are well within the allowable limit and the circuit is behaving as designed. There is a very small percentage error with the multimeter readings, however this is explained by the physical limitations in circuit hardware. This would be best explained from the measured resistor values when compared to the simulated resistor values. The physical resistors are very close but not exact to the simulated values. Even this small error of 0.14% is extremely accurate for physical results.

Table 1 Percent Error Results for Inverting Amplifier

	Theoretical	**LTSpice**	**ADK Multimeter Values**
Gain ($\frac{V}{V}$)	-10	-10	-9.986
% ERROR	0%	0%	0.14%

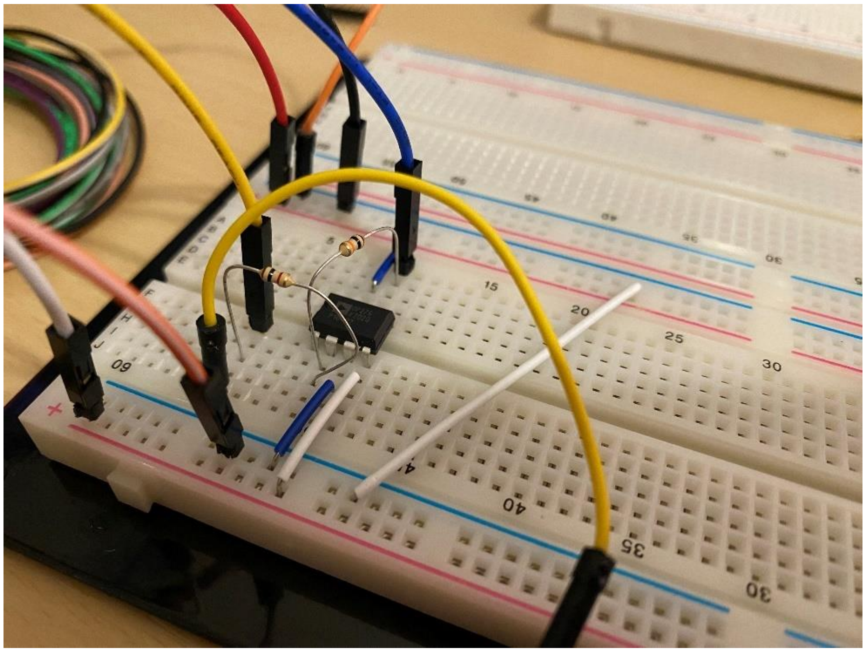


Figure 15 Physical Build of Inverting Amplifier

2.2 Non-Inverting Amplifier

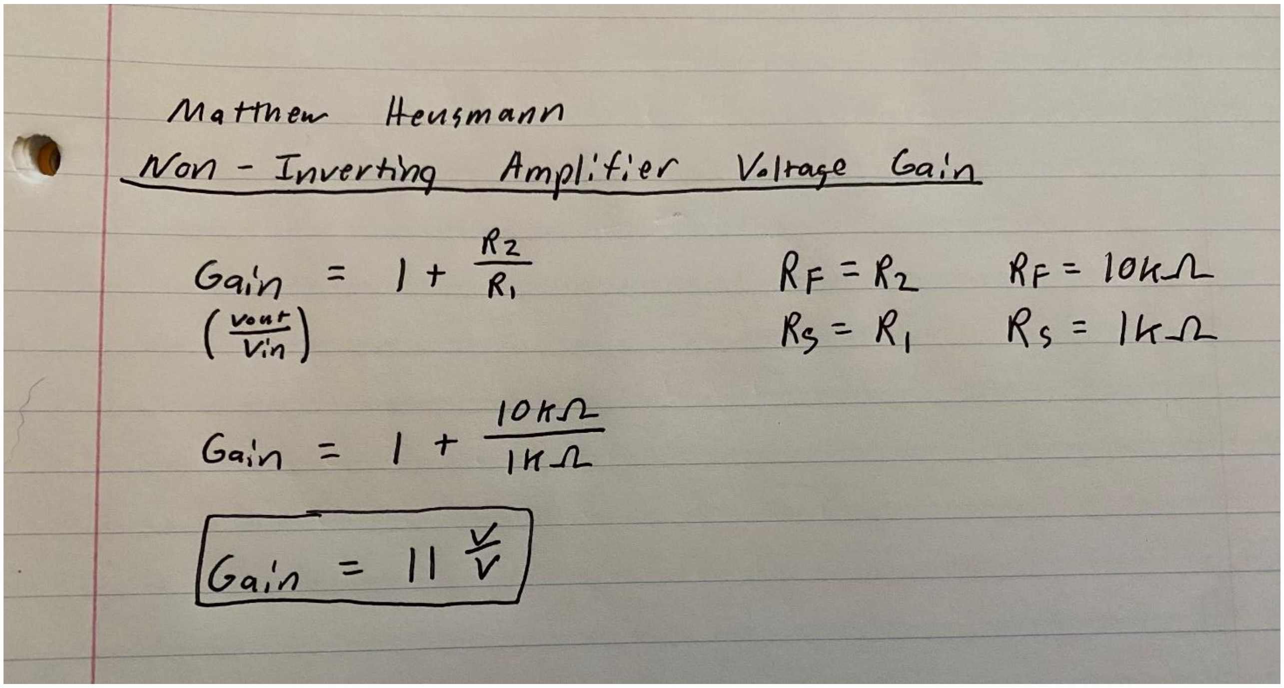


Figure 16 Non-Inverting Amplifier Hand Calculations

From the hand calculations above the voltage gain for the non-inverting amplifier is calculated to be $\boldsymbol{Gain\ =\ 11\frac{V}{V}}$.

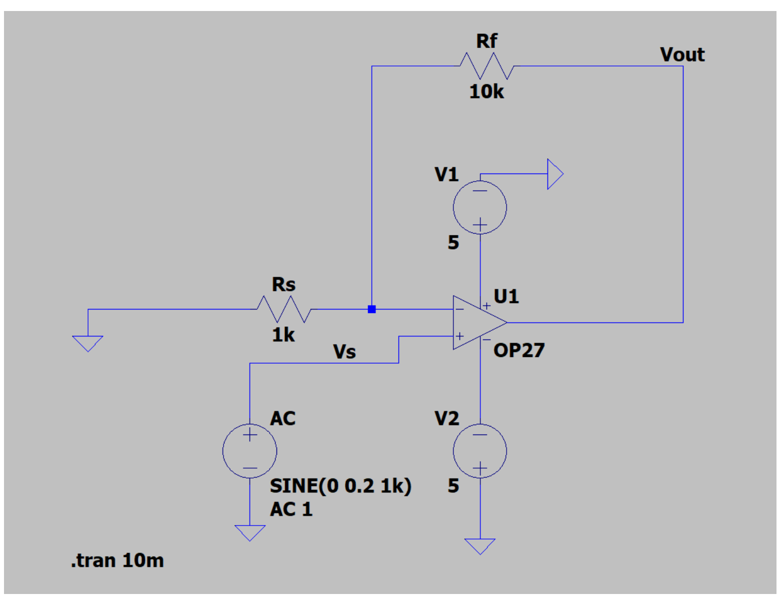


Figure 17 Non-Inverting Amplifier LTSpice

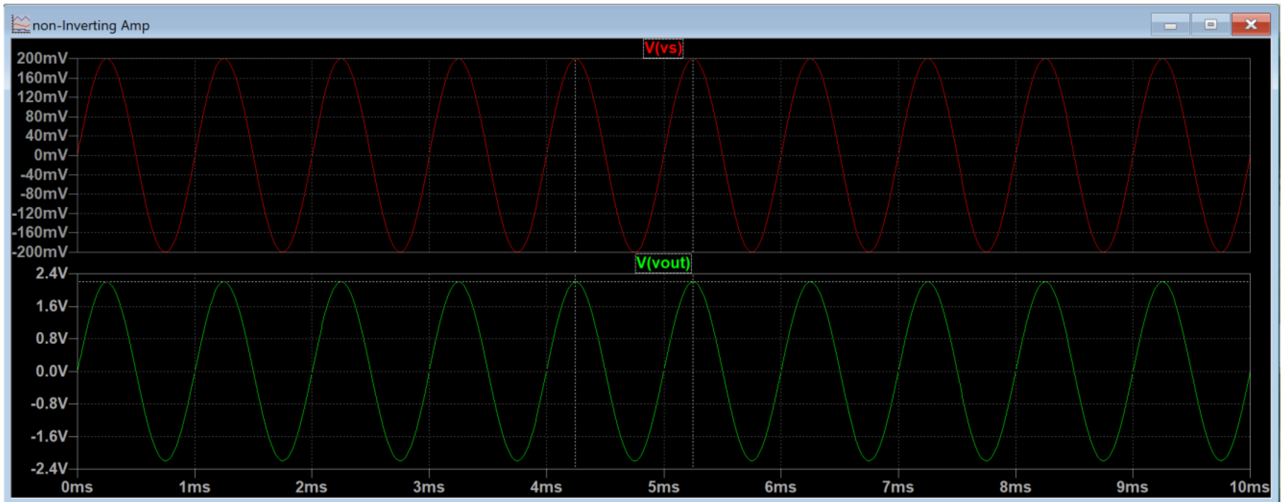


Figure 18 LTSpice Transient Analysis of Vout and Vs Non-Inverting Amplifier

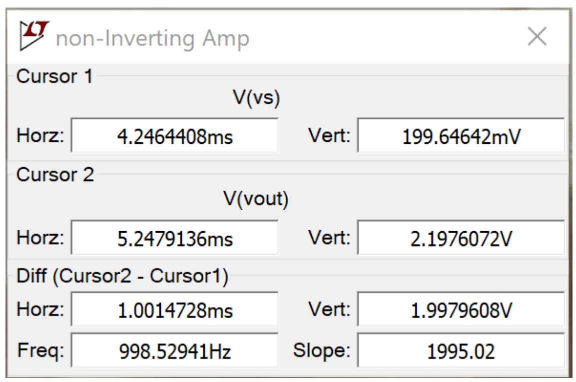


Figure 19 LTSpice Transient Analysis of Vout and Vs Results

```
Direct Newton iteration for .op point succeeded.

voutpp: PP(v(vout))=4.39583 FROM 0 TO 0.01
vspp: PP(v(vs))=0.4 FROM 0 TO 0.01
gain: 20*log10(voutpp/vspp)=20.8196


Date: Wed Sep 13 17:08:54 2023
Total elapsed time: 0.082 seconds.

tnom = 27
temp = 27
method = modified trap
totiter = 2147
traniter = 2120
tranpoints = 1061
accept = 1057
rejected = 4
matrix size = 12
fillins = 3
solver = Normal
Matrix Compiler1: 652 bytes object code size  0.1/0.1/[0.1]
Matrix Compiler2: 1.15 KB object code size  0.1/0.1/[0.1]
```

Figure 20 Calculated Gain in dB using LTSpice

From the three figures above the non-inverting amplifier was built in LTSpice and a transient analysis was run to see the results of Vout and Vs. From utilizing .op commands in LTSpice Vs came out be calculated as 0.4Vpp. This result can be seen above with the red graph. It can be concluded that correct signal was used for Vs. As for the Vout, from the green graph above and utilizing the .op commands the Vout was calculated to be 4.396Vpp with an expected gain of 11 V/V it can be concluded that this is the correct value shown in the results. From the equation for the gain this can be determined by $\frac{Vout}{Vs}$. So, from the results of calculated values the gain calculation would be $\frac{4.396Vpp}{0.4Vpp} = \mathbf{10.99}\frac{V}{V}$. This is very close to hand calculation and could even be rounded up to be 11 thus making it exactly the hand calculation results.

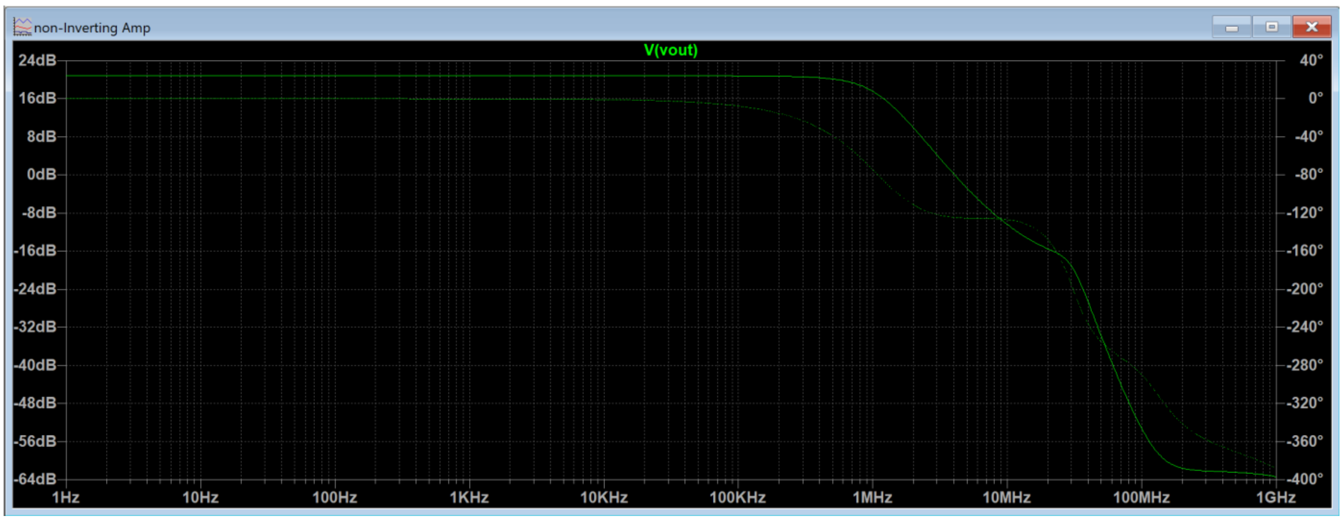


Figure 21 Non-Inverting Amplifier Frequency Response in LTSpice

```
Circuit: * C:\Users\Matt Heusmann\Desktop\Fall school items\Ci

Direct Newton iteration for .op point succeeded.

ft: mag(v(vout)/v(vs))=1 AT 4.06139e+006
maxgain: MAX(mag(v(vout)))=(20.8278dB,0°) FROM 1 TO 1e+009
f3db: mag(v(vout))=maxgain-3 AT 925311


Date: Wed Sep 13 17:28:03 2023
Total elapsed time: 0.043 seconds.

tnom = 27
temp = 27
method = trap
totiter = 27
traniter = 0
tranpoints = 0
accept = 0
rejected = 0
matrix size = 12
fillins = 3
solver = Normal
Matrix Compiler1:       38 opcodes
Matrix Compiler2: 1.15 KB object code size
```

Figure 22 Non-Inverting Amplifier Frequency Response Calculations in LTSpice

From the non-inverting frequency response calculations utilizing LTSpice the results were as follows: **f_{3dB} point = 925kHz** which is also **18.06dB, Max Gain (dB) = 20.828dB** and **F_t = $4.06MHz$.**

For the physical build of the non-inverting amplifier the two resistors will be measured, and their values will be stated below:
Measure Resistors used: **R_s = 983 Ω, R_f = 9810 Ω**

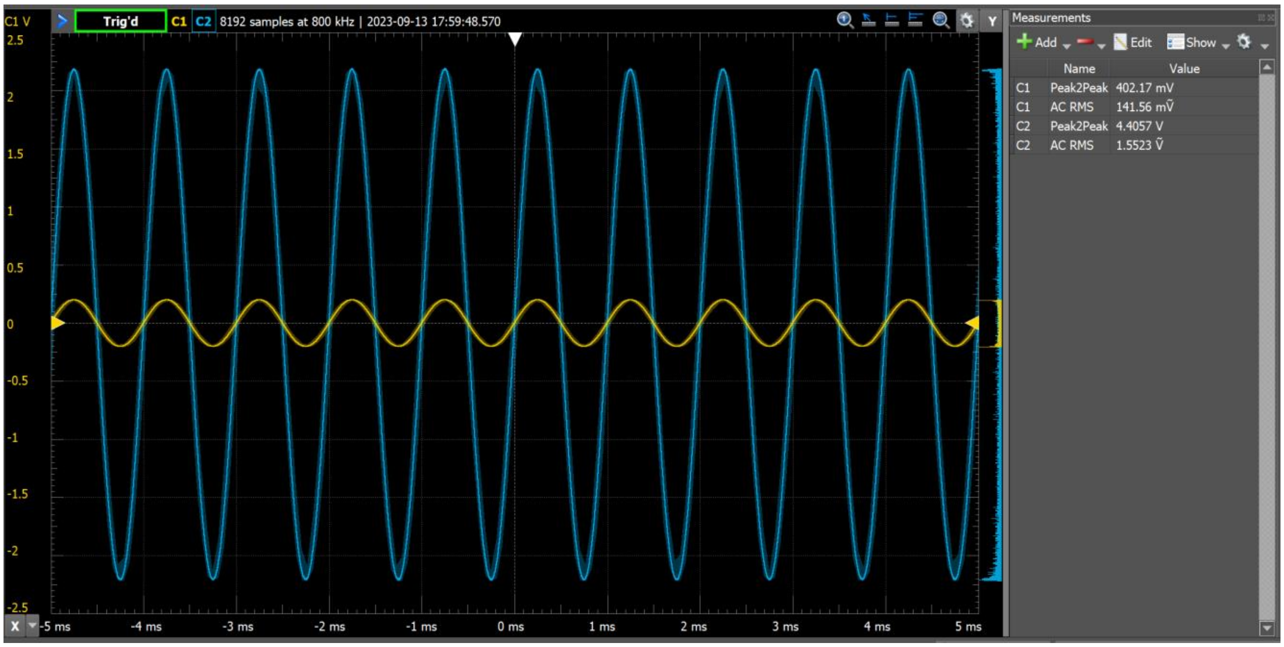


Figure 23 Waveforms Oscilloscope Non-Inverting Amplifier Results

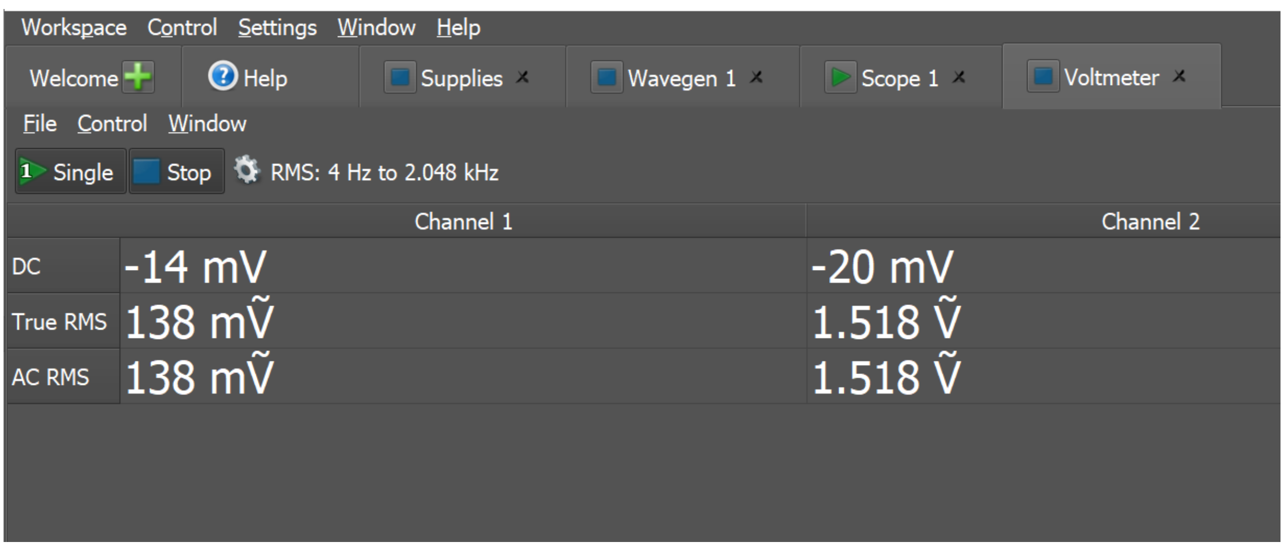


Figure 24 Waveforms Voltmeter Non-Inverting Amplifier Results

From the two waveform figures above of the non-inverting amplifier, it can be seen that channel one (yellow) is representing the Vs signal going into the circuit. The results from channel one was that Vs was 402.17mV Vpp, very close to the value that is expected. As for channel 2 (blue) representing the Vout signal, the result is 4.406 Vpp very close to the expected value of 4.4Vpp. Another set of voltmeter readings were taken from the ADK voltmeter. From this result the gain can be calculated $\frac{(1.518*2\sqrt{2})Vpp}{(0.138*2\sqrt{2})Vpp} = \mathbf{11}\frac{V}{V}$. Again, the reason for the $2\sqrt{2}$ in the calculation is due to converting the Vrms value the voltmeter give to a Vpp value since everything thus far has been shown in Vpp. From these results the exact expected result was achieved.

Lastly for the non-inverting amplifier all of the data over the gain for this operational amplifier was entered into the table below for easy viewing. From the data results again, this amplifier stayed very accurately from hand calculation to LTSpice and then to physical implementation. The only error seen was that of LTSpice but even then, it is still only 0.09% error which is almost nothing. So, it can be concluded that the non-inverting amplifier was calculated, simulated, and built correctly. It is surprising even though the resistor values are the same as the inverting amplifier. However, the results of this amplifier seem more accurate than that of the inverting amplifier.

Table 2 Percent Error Results for Non-Inverting Amplifier

	Theoretical	**LTSpice**	**ADK Multimeter Values**
Gain	$11\frac{V}{V}$	$10.99\frac{V}{V}$	$11\frac{V}{V}$
% ERROR	0%	0.09%	0%

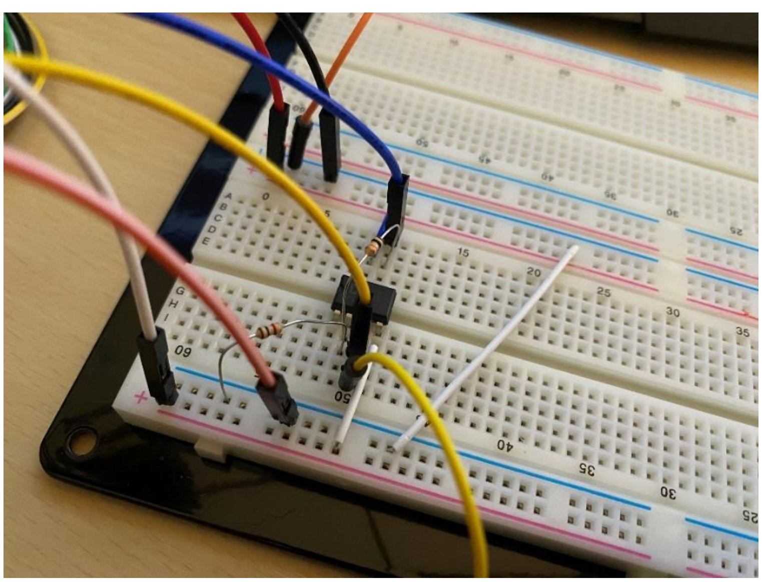


Figure 25 Physical Build of Non-Inverting Amplifier

2.3 Integrating Amplifier

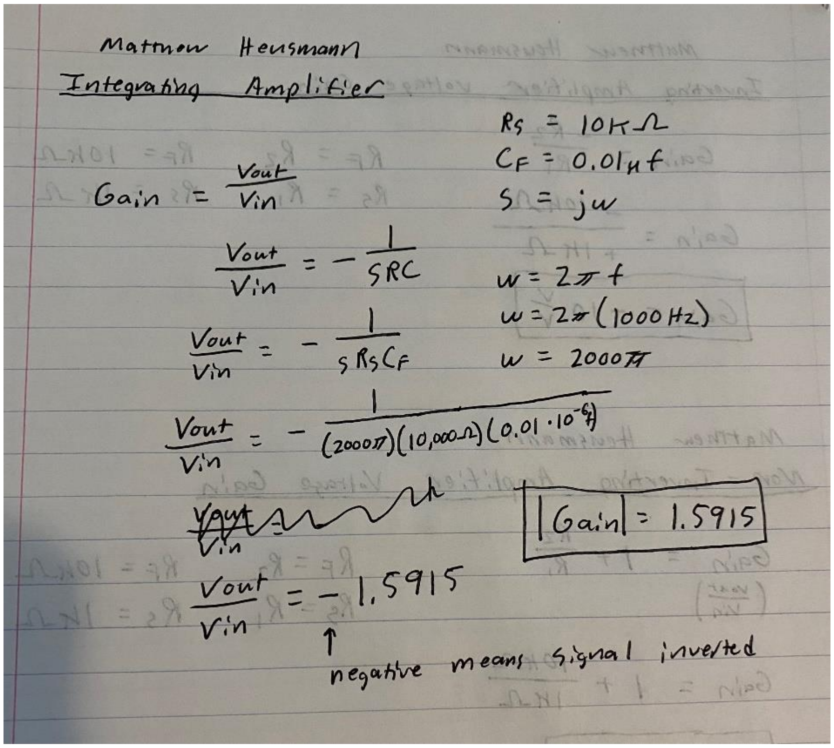


Figure 26 Integrating Amplifier Hand Calculations

From the hand calculations above the voltage gain for the integrating amplifier is calculated to be $\boldsymbol{Gain = -1.5915}\frac{\boldsymbol{V}}{\boldsymbol{V}}$. It is negative due to the signal being inverted.

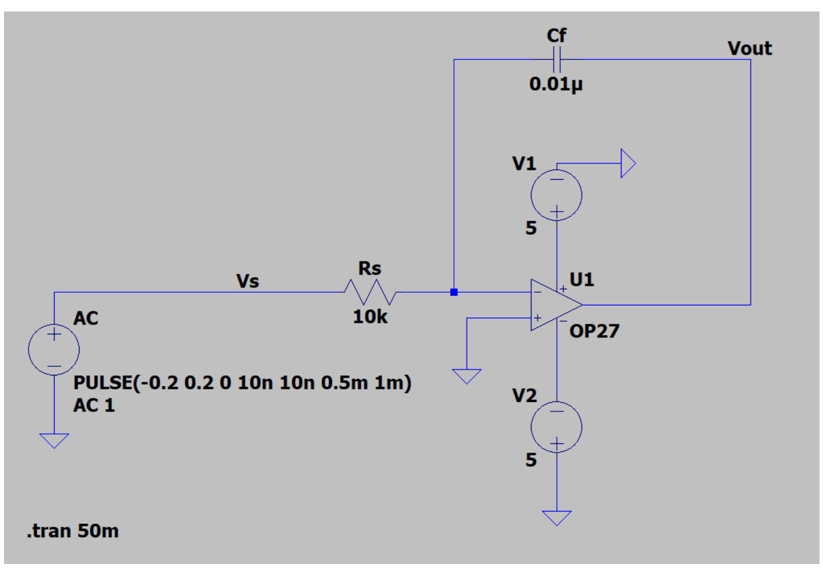


Figure 27 Integrating Amplifier in LTSpice

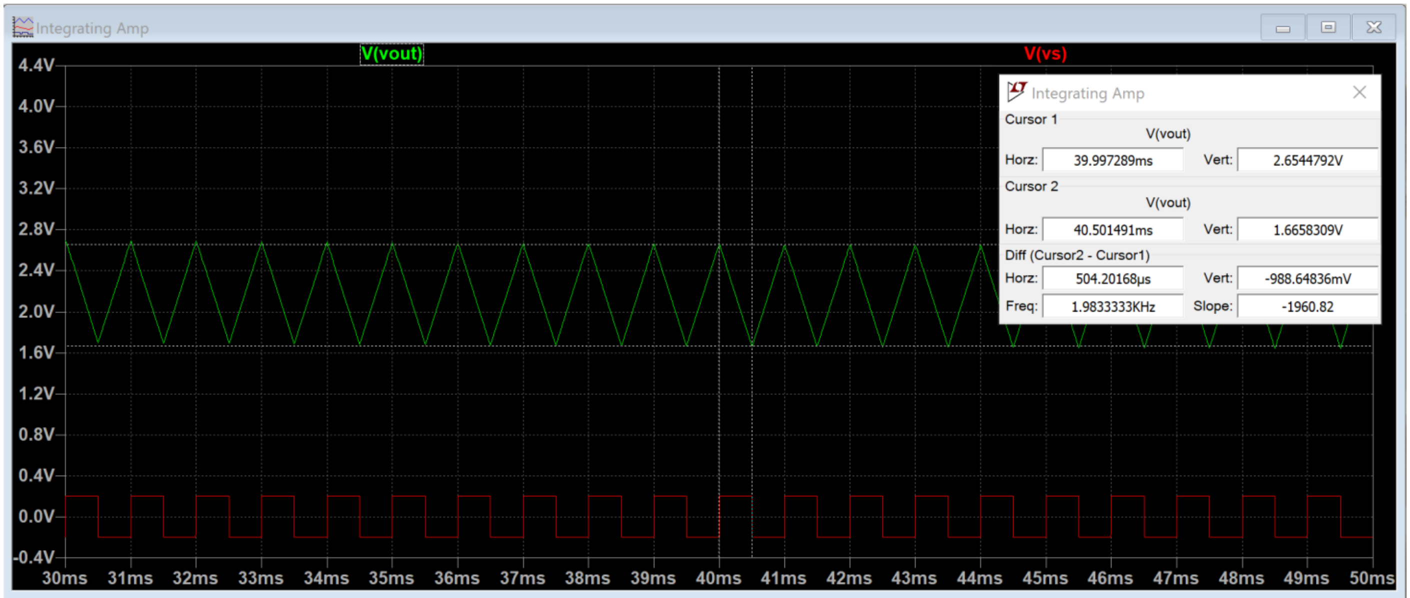


Figure 28 Transient Analysis of Integrating Amplifier

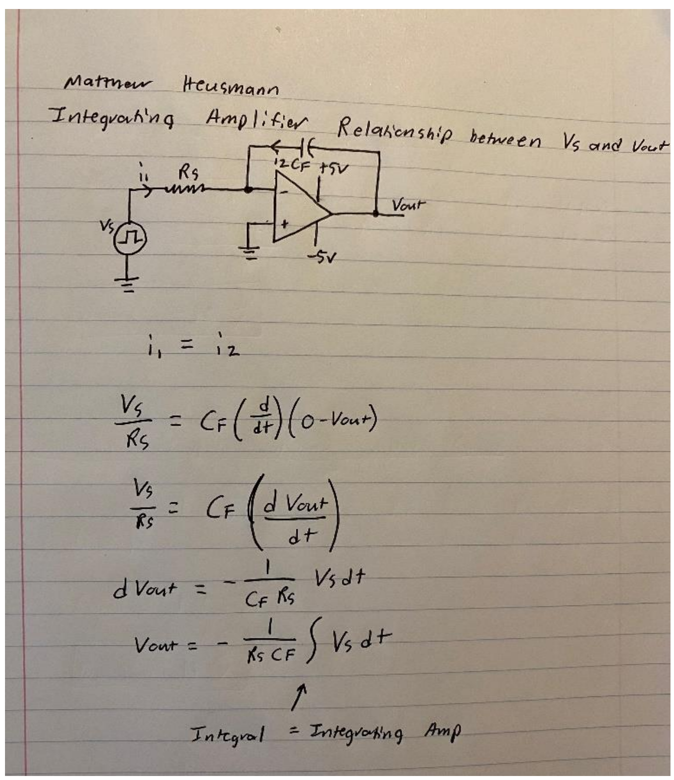
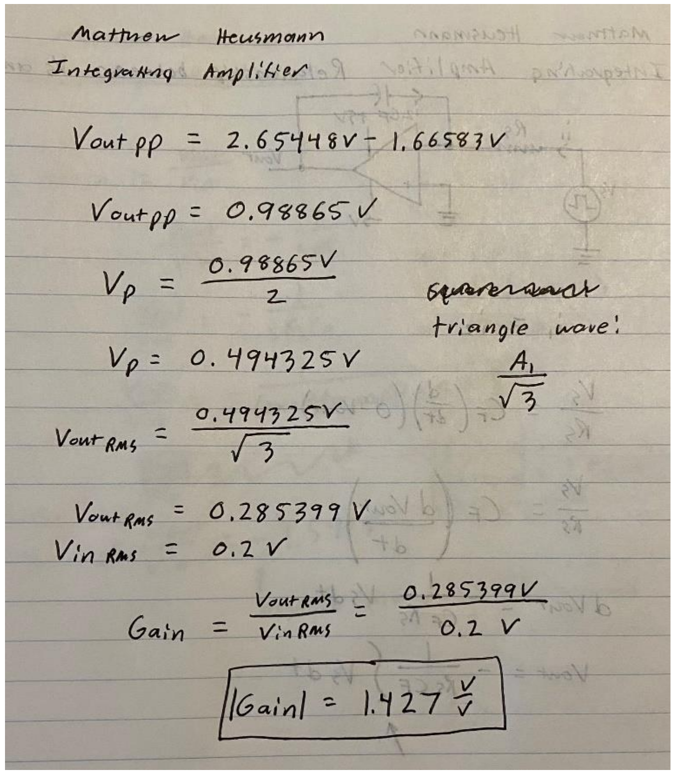


Figure 29 Relationship between Vs and Vout for Integrating Amplifier


Matthew Heusmann

Integrating Amplifier

$$V_{out\,pp} = 2.65448V - 1.66583V$$

$$V_{out\,pp} = 0.98865\,V$$

$$V_p = \frac{0.98865V}{2}$$

~~square wave~~ triangle wave: $\frac{A_1}{\sqrt{3}}$

$$V_p = 0.494325V$$

$$V_{out\,RMS} = \frac{0.494325V}{\sqrt{3}}$$

$$V_{out\,RMS} = 0.285399\,V$$

$$V_{in\,RMS} = 0.2\,V$$

$$Gain = \frac{V_{out\,RMS}}{V_{in\,RMS}} = \frac{0.285399V}{0.2\,V}$$

$$\boxed{|Gain| = 1.427\,\frac{V}{V}}$$

Figure 30 Calculated Gain from LTSpice Results

From the three figures above a transient analysis was run on the integrating amplifier. From these results the relationship between Vs and Vout was established in Figure 29 and the Vrms calculation was accomplished in Figure 30. From the gain calculation it was determined the **Gain = 1.427** $\frac{V}{V}$. Now this is a little off from the hand calculations and this error is caused by not allowing the cursor to be placed exactly where is needed to obtain the exact values for accuracy.

For the physical build of the integrating amplifier the resistor and capacitor will be measured, and their values will be stated below:

Measure components used: **R_s = 9810 Ω, C_F = 8.8nF**

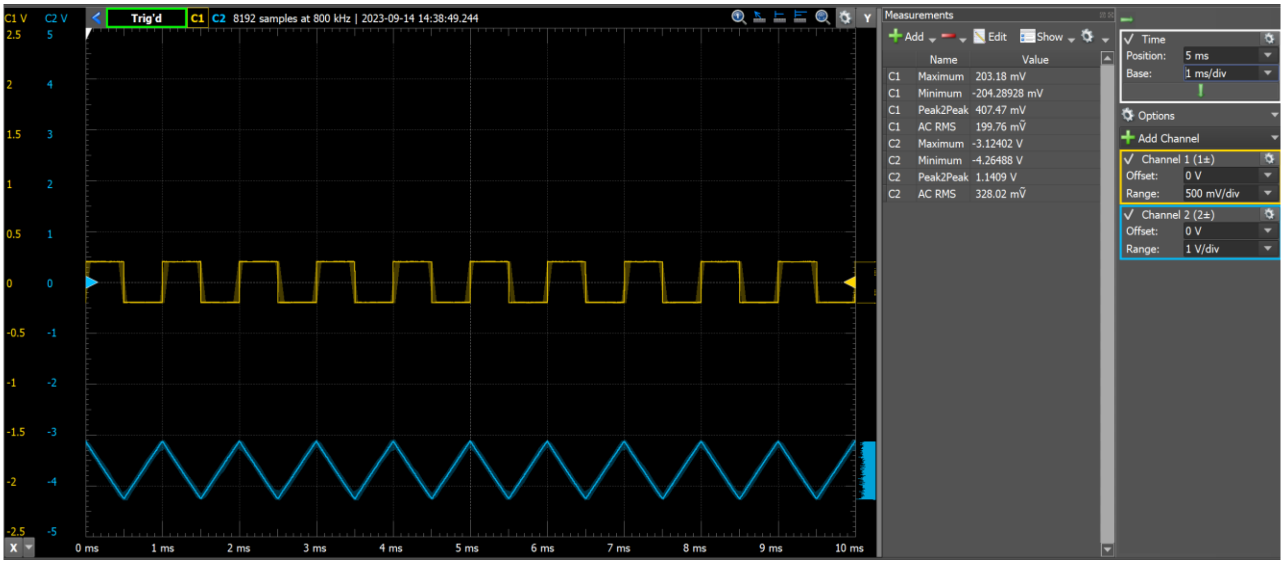


Figure 31 Waveforms Oscilloscope of Integrating Amplifier Results

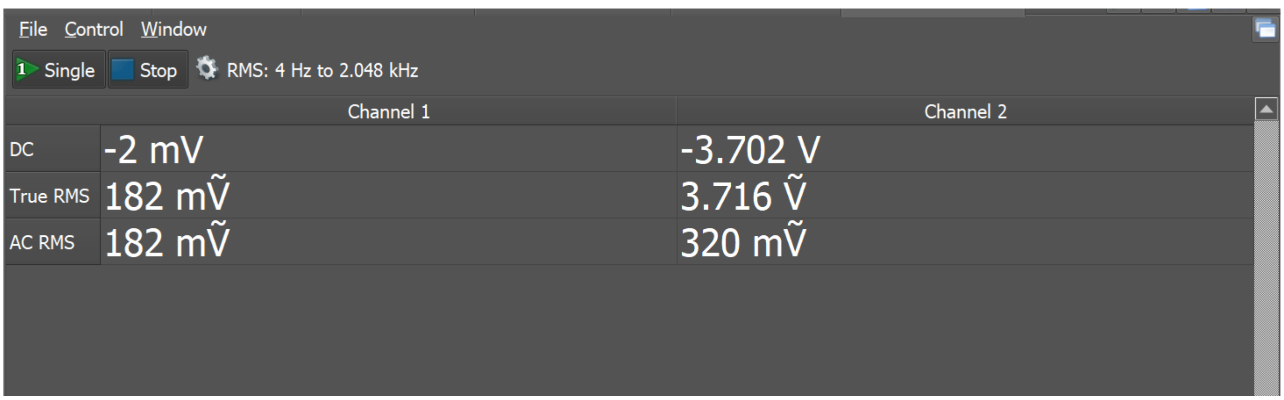
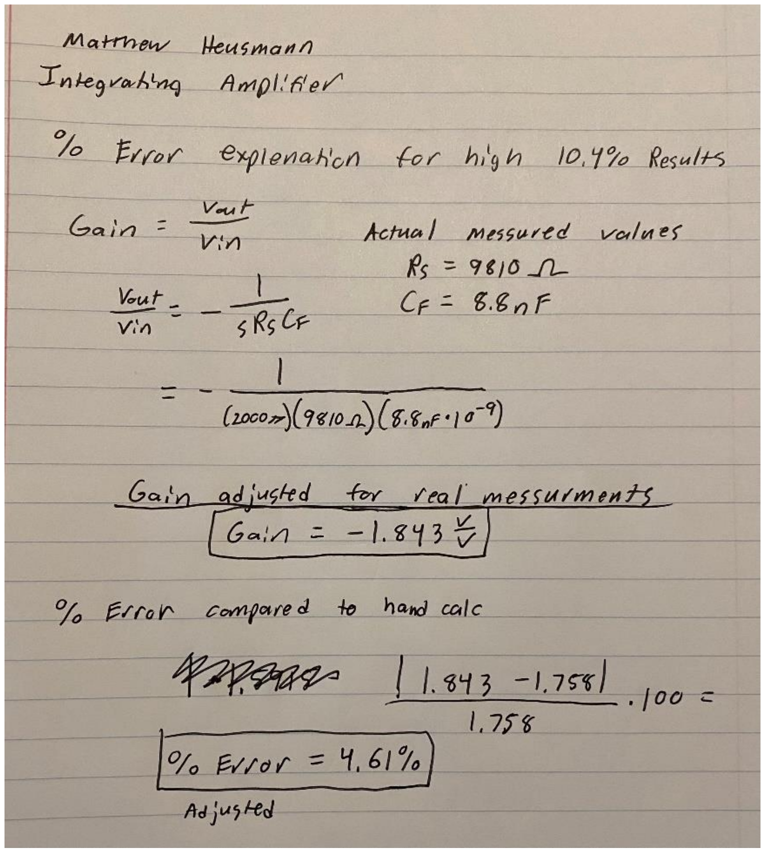


Figure 32 Waveforms Voltmeter of Integrating Amplifier Results

From the two waveform figures above (figures 31-32) from the integrating amplifier, it can be seen that channel one (yellow) is representing the Vs signal going into the circuit. The results from channel one was that Vs was 407.47mV Vpp pretty close to the value that is expected. As for channel 2 (blue) representing the Vout signal, the result is 1.1409 Vpp. This value is slightly off from the expected value from LTSpice being 0.989Vpp. The reason for this error is due to the fact that the oscilloscope measurements are not very accurate due to the constant oscillation from the signal. For this reason, the ADK voltmeter results will be used to calculate the physical circuits gain. From the voltmeter readings the gain can be calculated $\left|\frac{\mathbf{320mVout_{RMS}}}{\mathbf{182mVin_{RMS}}}\right| = \mathbf{1.758}\frac{\boldsymbol{V}}{\boldsymbol{V}}$. Again, it should be remembered that due to this being an inverted integrating amplifier the gain would be $-\mathbf{1.758}\frac{\boldsymbol{V}}{\boldsymbol{V}}$ since the output signal is inverted from the input signal. From these results when compared to the LTSpice and hand calculations you can see that the values are still off from the expected results. This is best explained by the error in the capacitor and resistance physical values. Due to the capacitor needing to be 10nF or 0.01µF and the measured value being 8.8nF this would cause a slight error in the result thus explaining this error.

For Table 3 below, this is an easy viewing to see the percent error through each step of the processes. At first glance you will see that this percentage errors seem fairly high at around 10% this is alarming and not the ideal results wanted. In the figure below, hand calculations were done to adjust the theoretical value to the measured components used. As can be seen the new % error is now around 4% much better and in 5% range to accept that the circuit is behaving as intended with slight physical errors still involved but not bad enough to dig deep into it.



Matthew Heusmann

Integrating Amplifier

% Error explanation for high 10.4% Results

$$\text{Gain} = \frac{V_{out}}{V_{in}}$$

Actual messured values

$R_S = 9810\ \Omega$

$C_F = 8.8nF$

$$\frac{V_{out}}{V_{in}} = -\frac{1}{sR_SC_F}$$

$$= -\frac{1}{(2000\pi)(9810\Omega)(8.8nF \cdot 10^{-9})}$$

Gain adjusted for real messurments

$$\boxed{\text{Gain} = -1.843\ \frac{V}{V}}$$

% Error compared to hand calc

$$\frac{|1.843 - 1.758|}{1.758} \cdot 100 =$$

$$\boxed{\%\ \text{Error} = 4.61\%}$$

Adjusted

Figure 33 Adjusted % Error Calculation for Measured Values Integrating Amplifier

Table 3 Percent Error Results for Integrating Amplifier

	Theoretical	**LTSpice**	**ADK Multimeter Values**
Gain	-1.592 $\frac{V}{V}$	-1.427 $\frac{V}{V}$	-1.758 $\frac{V}{V}$
% ERROR	0%	10.3%	10.4% Adjusted Fig 33 (4.61%)

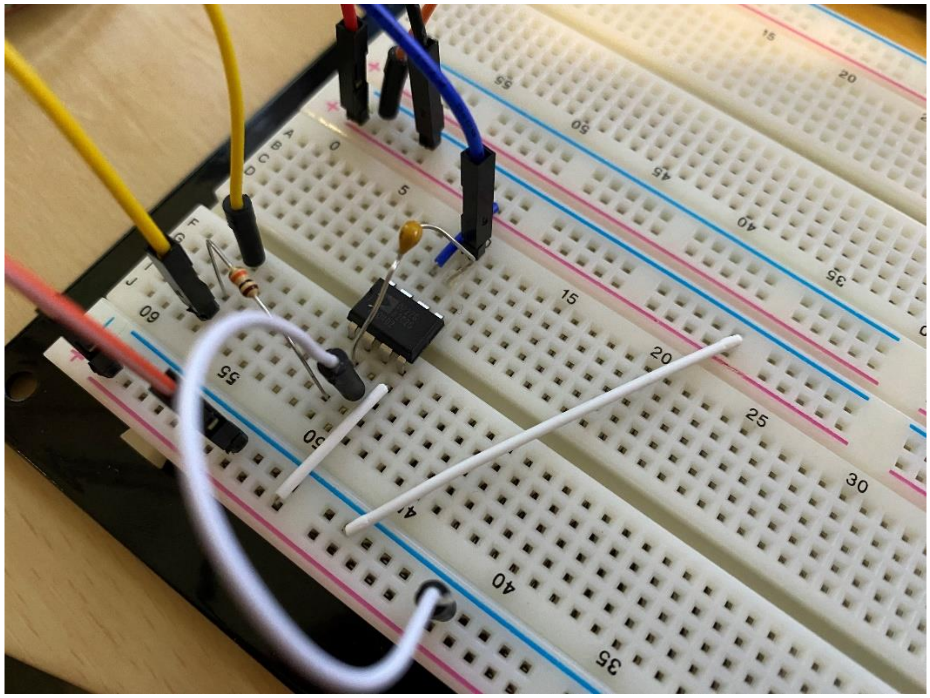


Figure 34 Physical Build of Integrating Amplifier

2.4 Differentiating Amplifier

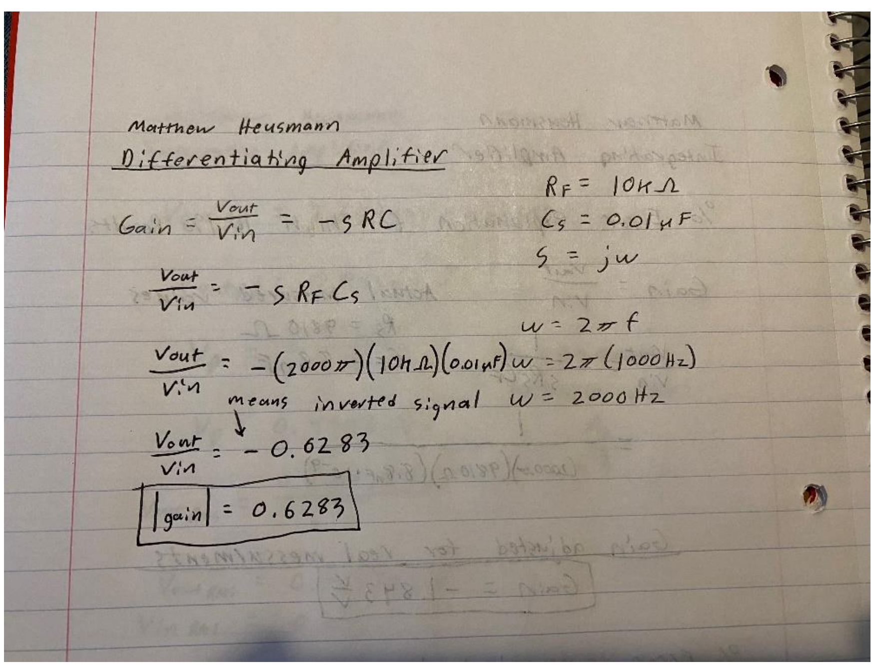


Figure 35 Differentiating Amplifier Hand Calculations

From the hand calculations above the voltage gain for the integrating amplifier is calculated to be $\boldsymbol{Gain} = -\mathbf{0.6283}\frac{V}{V}$. It is negative due to the signal being inverted.

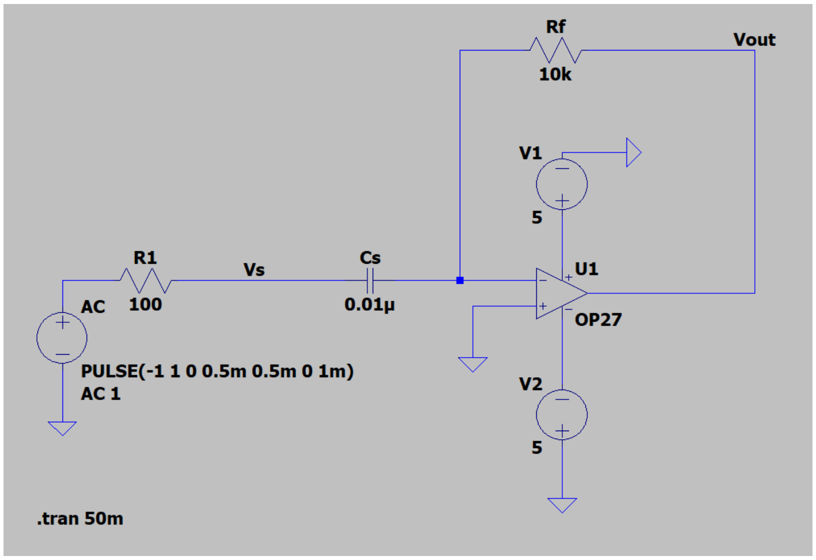


Figure 36 Differentiating Amplifier in LTSpice

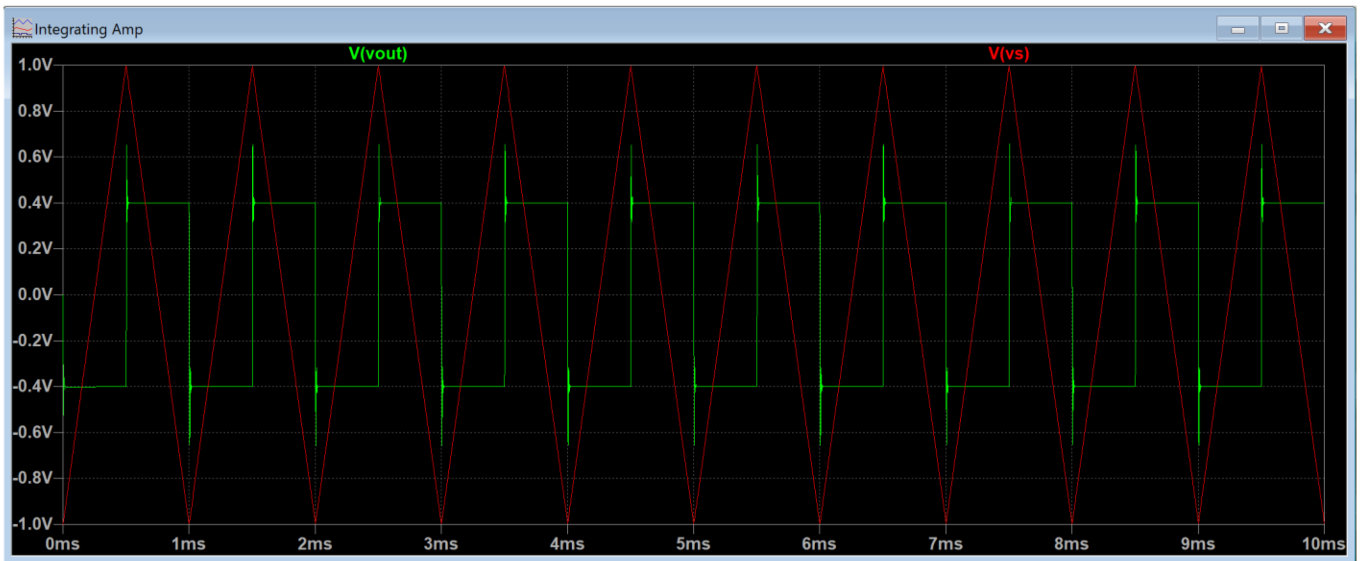


Figure 37 Transient Analysis of Differentiating amplifier with 100Ω

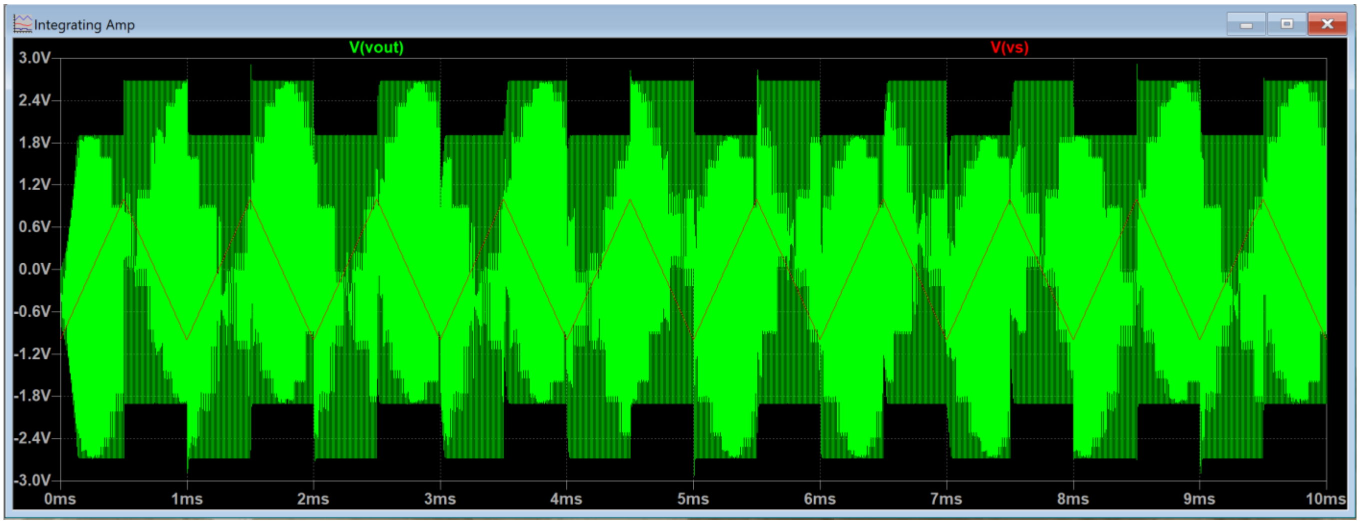


Figure 38 Transient Analysis of Differentiating amplifier without 100Ω

From the figures 37 and 38 above it can be seen that when inserting a 100Ω resistor to simulate a real voltage source the extreme number of oscillations are almost completely gone when compared to figure 38. Figure 38 would most definitely not be ideal due to this high oscillation.

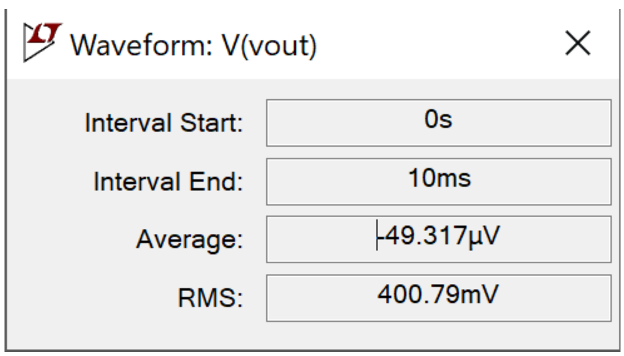


Figure 39 Vout RMS Value calculation taken from Diff Amp Transient Analysis

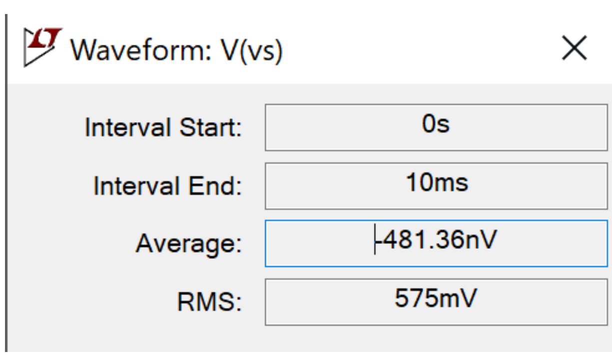


Figure 40 Vin RMS Value calculation taken from Diff Amp Transient Analysis

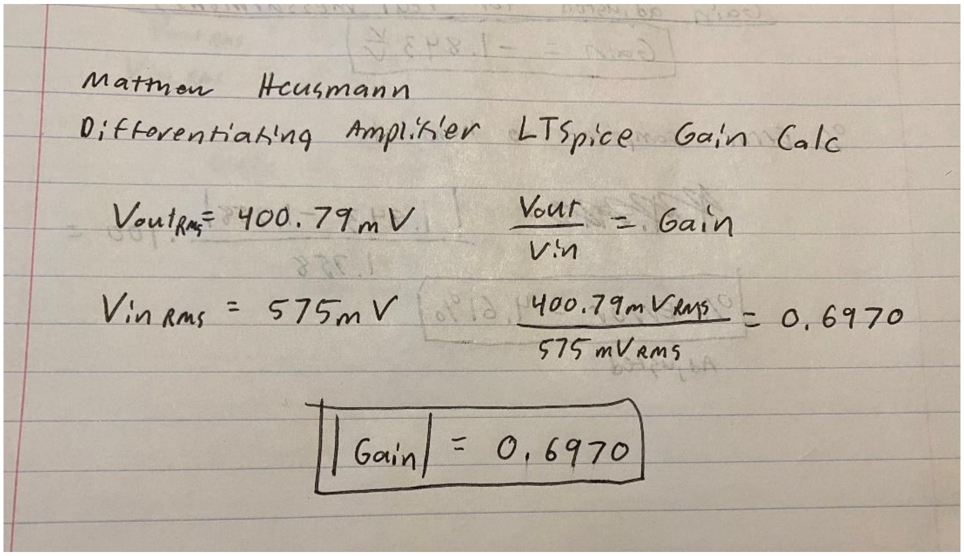


Figure 41 Calculated Gain from LTSpice Results

From figures 39-41 above a transient analysis was run on the differentiating amplifier. From these results the Vrms calculation was accomplished in figure 41. From the gain calculation it was determined the **Gain = 0.6970** $\frac{V}{V}$. Also, the relationship between Vs and Vout is that the derivative of Vs would result in Vout thus the reason it is called a differentiating amplifier.

For the physical build of the integrating amplifier the resistor and capacitor will be measured, and their values will be stated below:
Measure components used: **R_F = 9810 Ω, C_S = 8.8nF**

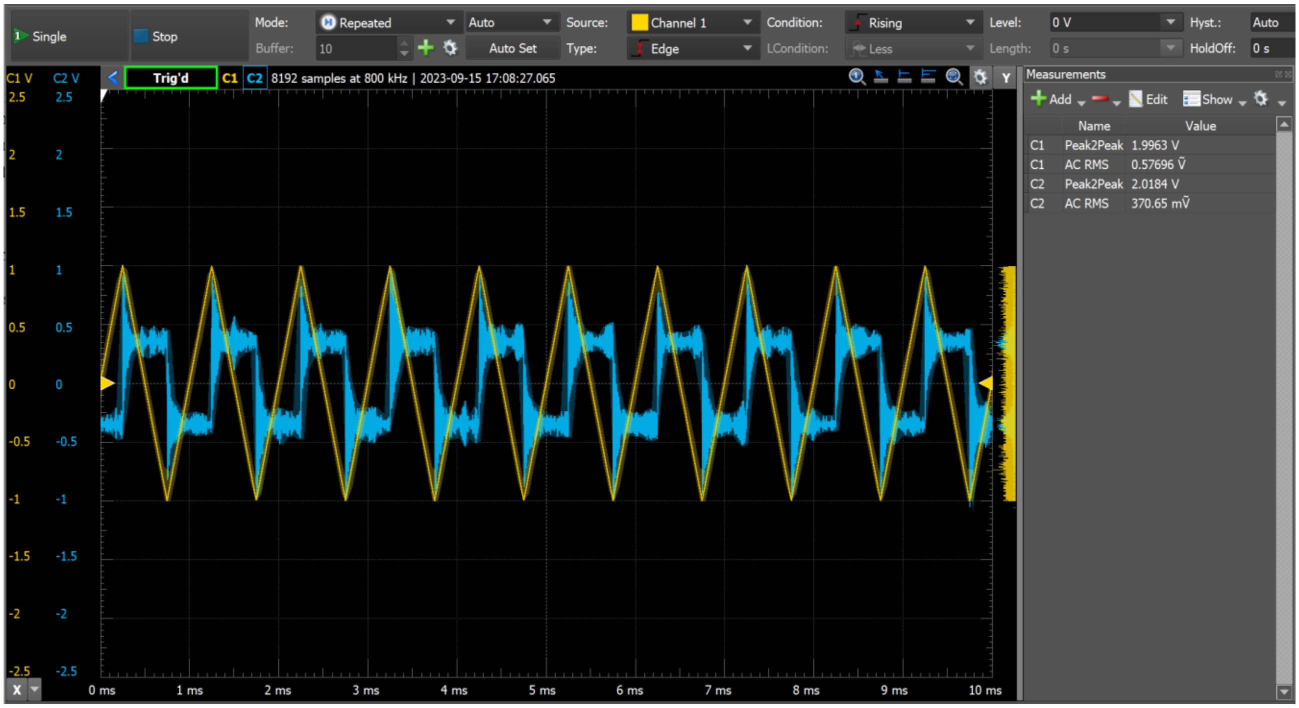


Figure 42 Waveforms Oscilloscope of Differentiating Amplifier without 100Ω resistor

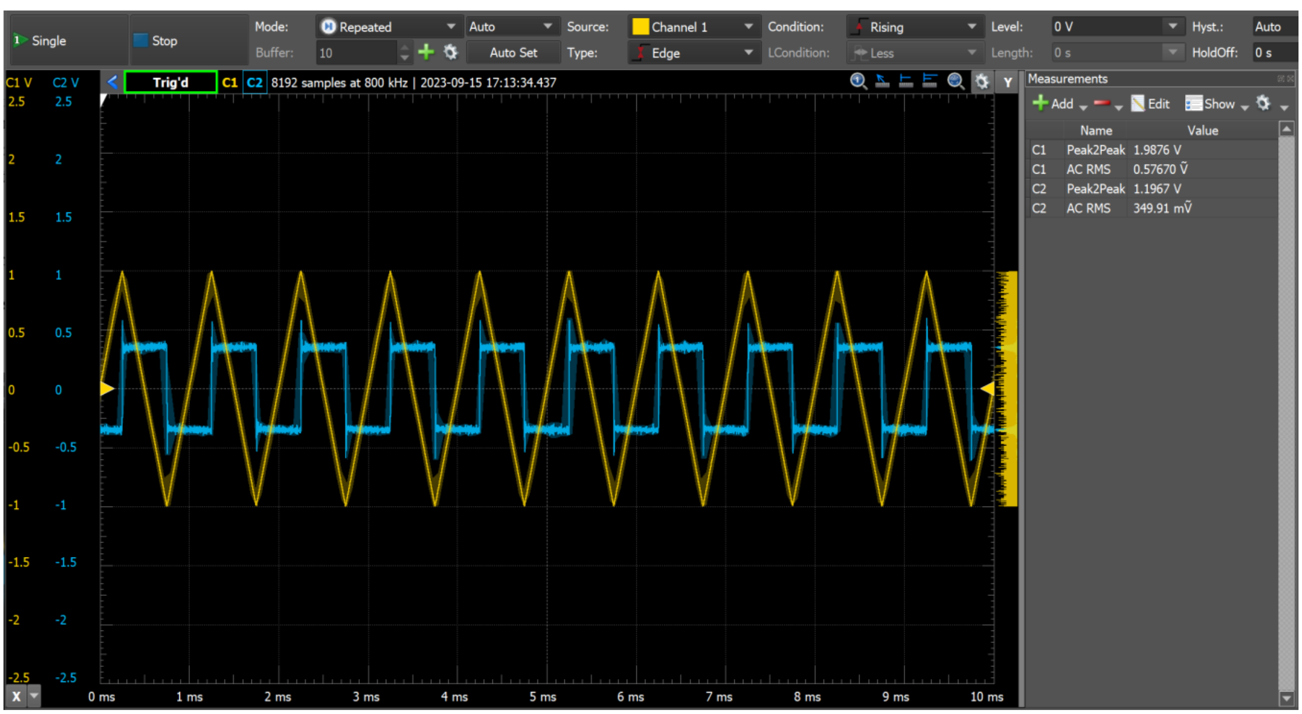


Figure 43 Waveforms Oscilloscope of Differentiating Amplifier with 100Ω resistor

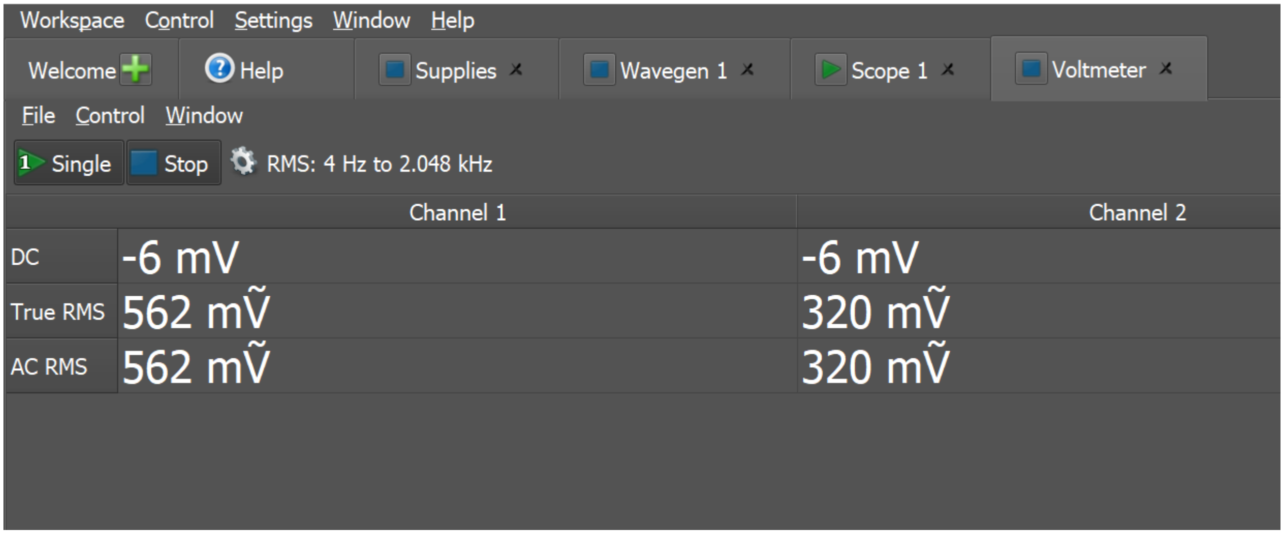
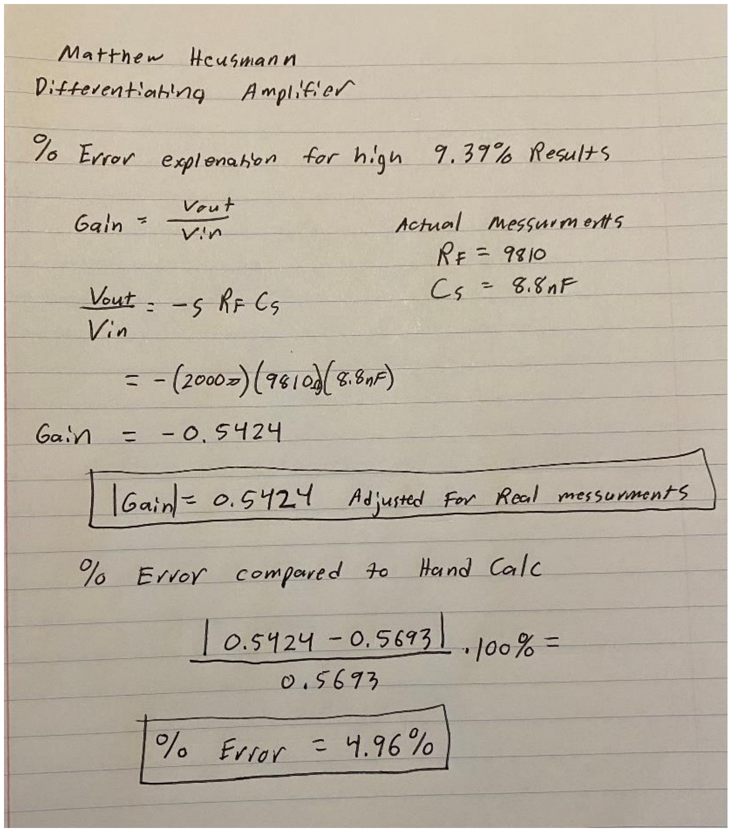


Figure 44 Waveforms Voltmeter of Differentiating Amplifier Results

Analyzing figures 42-44 from the differentiating amplifier, first the circuit was built without the 100Ω resistor simulating a real voltage source as seen in figure 42. In figure 43 the 100Ω resistor was added and from those results it can be seen that similar to the LTSpice results, it did in fact smooth out the oscillations. For the rest of this analysis results figure 43 and 44 will be referenced. Upon further analysis, channel one (yellow) represents the Vs signal going into the circuit. The results from channel one was that Vs was 1.9876V Vpp pretty close to the value that is expected. As for channel 2 (blue) representing the Vout signal, the result is 1.1967 Vpp. This value is slightly off from the expected value from LTSpice being 1.1336Vpp. The reason for this error is due to the fact that the oscilloscope measurements are not very accurate due to the constant oscillation from the signal. For this reason, the ADK voltmeter results will be used to calculate the physical circuits gain. From the voltmeter readings the gain can be calculated $\left|\frac{\mathbf{320}mVout_{RMS}}{\mathbf{562}mVin_{RMS}}\right| = \mathbf{0.5693}\frac{V}{V}$. Again, it should be remembered that due to this being an inverted integrating amplifier the gain would be $-\mathbf{0.5693}\frac{V}{V}$ since the output signal is inverted from the input signal. From these results when compared to the LTSpice and hand calculations you can see that the values are significantly off from the expected results around 10% error. This is best explained by the error in the capacitor and resistance physical values. Due to the capacitor needing to be 10nF or 0.01µF and the measured value being 8.8nF this would cause a slight error in the result thus explaining this error.

Lastly, from Table 4 below this was made for an easy viewing to see the percent error through each step of the processes. You will see that these percentage errors seem fairly high at around 10%, this is alarming and not the ideal results wanted. In the figure below, hand calculations were done to adjust the theoretical value to the measured components used. As can be seen in Figure 45 the new 4.96% error is much better and in 5% range to accept that the circuit is behaving as intended with slight physical errors still involved but in the required parameters.


Matthew Heusmann
Differentiating Amplifier

% Error explanation for high 9.39% Results

Gain = $\frac{V_{out}}{V_{in}}$

Actual messurments
$R_F = 9810$
$C_S = 8.8nF$

$\frac{V_{out}}{V_{in}} = -s R_F C_S$

$= -(2000\pi)(9810\Omega)(8.8nF)$

Gain $= -0.5424$

$\boxed{|Gain| = 0.5424 \text{ Adjusted For Real messurments}}$

% Error compared to Hand Calc

$\frac{|0.5424 - 0.5693|}{0.5693} \cdot 100\% =$

$\boxed{\% \text{ Error} = 4.96\%}$

Figure 45 Adjusted % Error Calculation for Measured Values for Differentiating Amplifier

Table 4 Percent Error Results for Differentiating Amplifier

	Theoretical	**LTSpice**	**ADK Multimeter Values**
Gain	$-0.6283\frac{V}{V}$	-0.6970 $\frac{V}{V}$	$-0.5693\frac{V}{V}$
% ERROR	0%	10.93%	9.39% Adjusted Fig (4.96%)

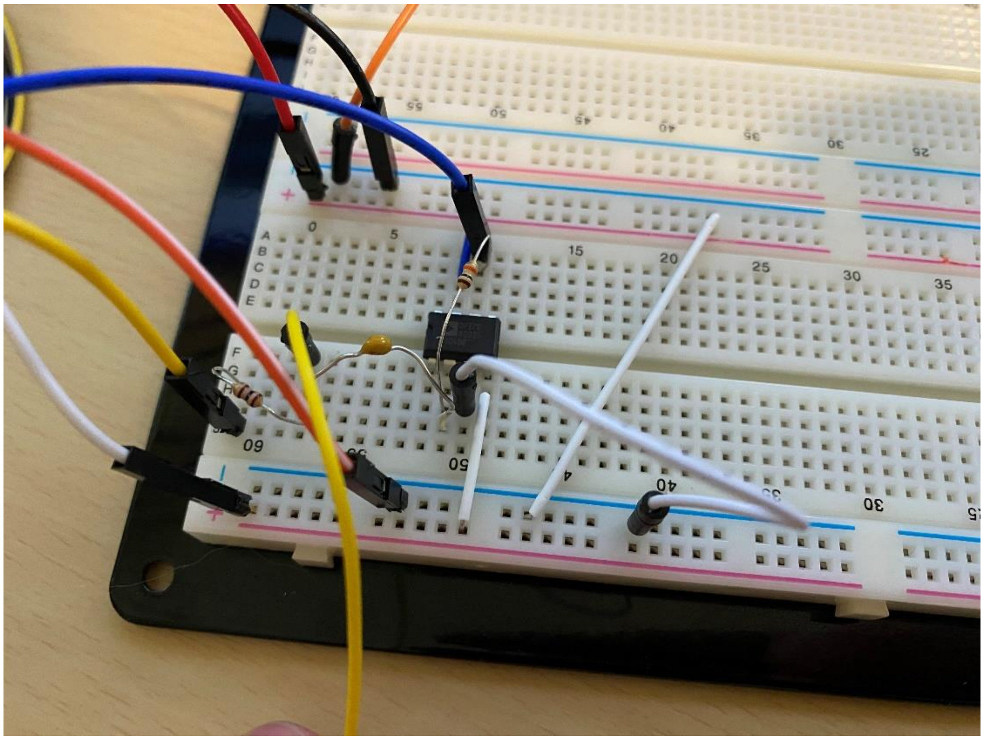


Figure 46 Physical Build of Differentiating Amplifier

CONCLUSION

This lab's main purpose was to allow the student to get a deeper understanding of how each of the four operational amplifiers fundamentally work utilizing OP27 amplifier. Along with the relationship between Vout and Vs over these different amplifiers.

For the first section 2.1 the focus was on the inverting amplifier, a very useful amplifier and was the fundamental base for three out of the four operational amplifiers. The hand calculation gain came out to be **-10 V/V**, the negative again representing the inverted signal. With this hand calculation result it was compared against both the LTSpice and the physical built circuit on the breadboard. From this comparison the gains across all experiment were very close to <0.14% error this is exceptional and validates that the amplifiers gain can be calculated with $-\frac{Rf}{Rs}$.

As for the second section 2.2, this focus was shifted to the opposite of the first amplifier being the Non-Inverting Amplifier. This amplifier behaves similar to the first, however the signal will no longer be inverted but the gain is slightly different from the inverting amplifier. From the hand calculations the gain came out to be **11 V/V**. When comparing this gain to the LTSpice and physical build again an extremely low % error of very close to 0%. This was another exceptional result thus confirming the equation utilized in the hand calculation being $1+\frac{Rf}{Rs}$. Also note that since this gain was positive both Vout and Vs are in phase with each other unlike section 2.1 where the two signals were out of phase.

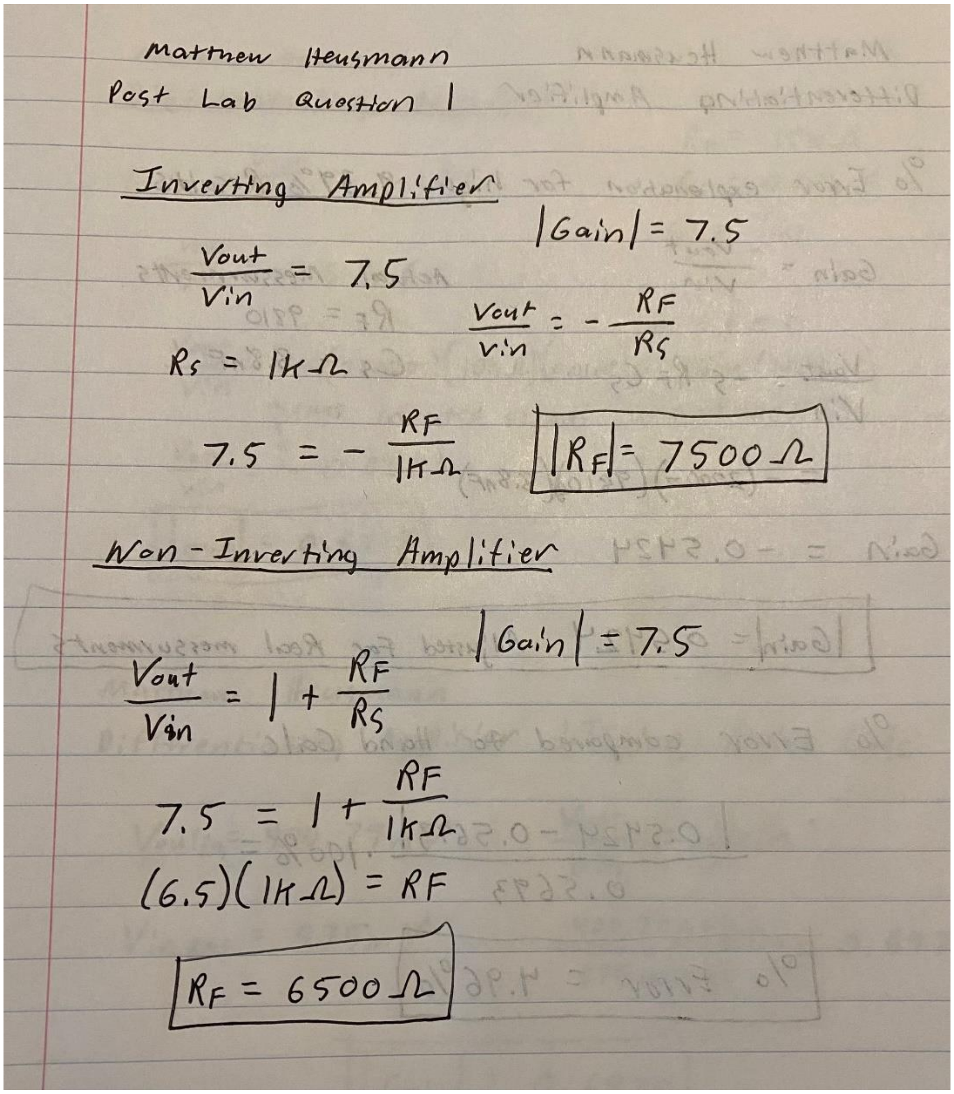
In section 2.3. this amplifier became a little more interesting, the amplifier that was focused here was the integrating amplifier. As in the name of the amplifier this amplifier's purpose is to integrate Vs and the result from this is Vout. For a deeper dive into how Vout relates to Vs please see Figure 29. From the hand calculation the gain came out to be **-1.592 V/V.** After the completion of the analysis of LTSpice and the physical circuit, one major issue stands out. From this amplifier the percentage errors seem to be significantly higher than the previous two amplifiers, being around 10%. This is alarming because this can pose issues for someone who would be interested in the amplifier design. However, with a deeper analysis of this issue much of the error percentage is coming from the components used such as the resistor and the capacitor. The required resistor value was supposed to be 10kΩ and the required capacitor at .01µF or 10nF. From the measured components used in the physical circuit these values were a little off such as the resistor being 9810Ω and the capacitor being about 8.8nF. With this information an adjusted calculation was taken in Figure 33. With this new calculation it can be seen that the percentage error came out to be 4.61% this is in the allowable tolerance to conclude that the integrating amplifier abides by Vout = -1/sRCf $\int Vs\,dt$.

Lastly section 2.4 was focused on the differentiating amplifier. Again, as the name suggests this amplifier takes the derivative of Vs and the result is Vout. What is unique about this experiment was that the circuit in LTSpice was analyzed without a 100Ω resistor acting as the resistance that would simulate a real voltage source and with the 100Ω resistor. From this analysis it was seen that having the 100Ω resistor greatly helps in reducing the oscitations in the waveform thus allowing the circuit to behave more as intended. The gain calculation came out to be $\boldsymbol{-0.6283\frac{V}{V}}$ and comparing this calculation against LTSpice and the physical built yet again the percentage error results were high around 10%. So, the same approach was taken here since the same resistor and capacitor was used another adjustment calculation was done in Figure 45 once this was completed the adjustment percent error came out to be 4.96% much better from the 9% from before. Since this new error calculation was in the 5% tolerance range it can be concluded that everything was behaving as expected.

This lab overall was super fun to accomplish and play around with operational amplifiers. When reading about them in textbooks an idea is somewhat formed, however not a great understanding is really accomplished. Now this lab has been completed, a significantly strong foundation is established when dealing with these amplifier circuits.

POST LAB QUESTIONS

1. Determine the new values of R_f without changing R_s in the circuits, to achieve a theoretical Gain of 7.5 for an Inverting Amplifier and Non-Inverting Amplifier.



Matthew Heusmann

Post Lab Question 1

Inverting Amplifier

$|Gain| = 7.5$

$\frac{V_{out}}{V_{in}} = 7.5$

$\frac{V_{out}}{V_{in}} = -\frac{R_F}{R_S}$

$R_S = 1k\Omega$

$7.5 = -\frac{R_F}{1k\Omega}$ $\boxed{|R_F| = 7500\Omega}$

Non-Inverting Amplifier

$|Gain| = 7.5$

$\frac{V_{out}}{V_{in}} = 1 + \frac{R_F}{R_S}$

$7.5 = 1 + \frac{R_F}{1k\Omega}$

$(6.5)(1k\Omega) = R_F$

$\boxed{R_F = 6500\Omega}$

2. Use LTSpice to implement and discuss the outcomes of the followings:

   a. Applying a sinusoidal input signal of 2Vpp and 4kHz in the inverting op-amp shown in Fig. 2.1, as a substitute of 0.4Vpp and 1kHz.

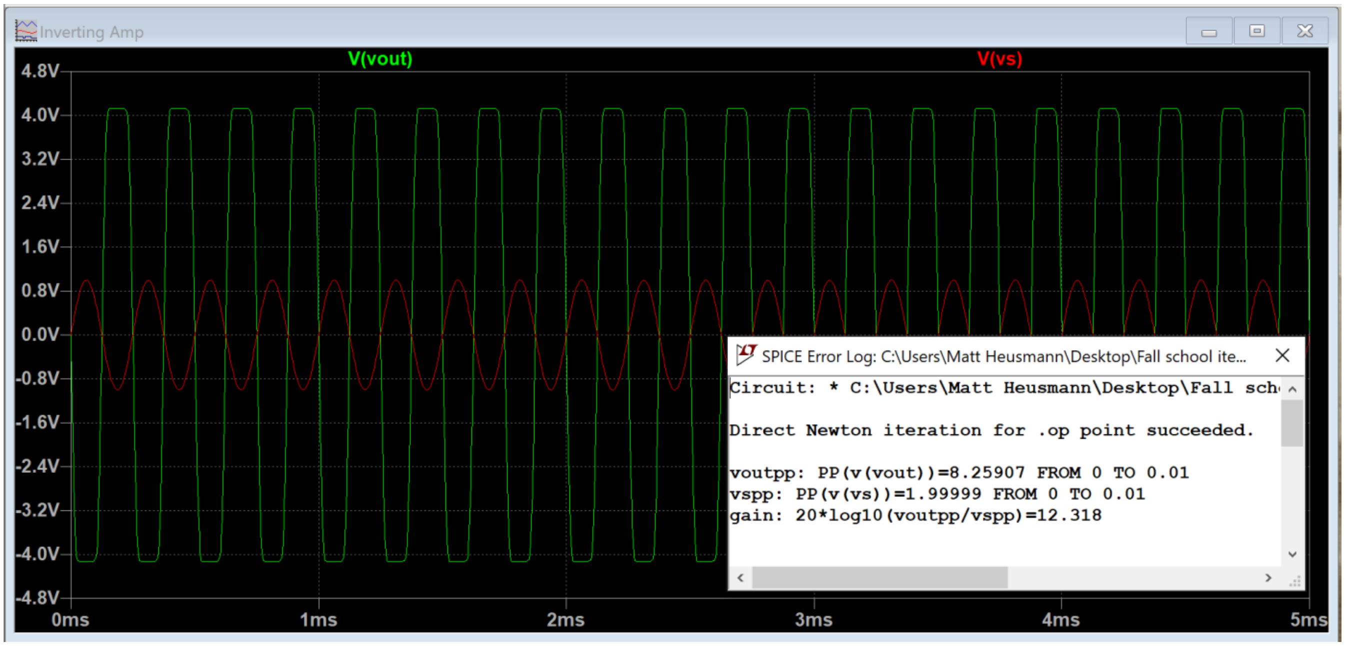


Figure 47 Transient Analysis of Post Lab Question 2a

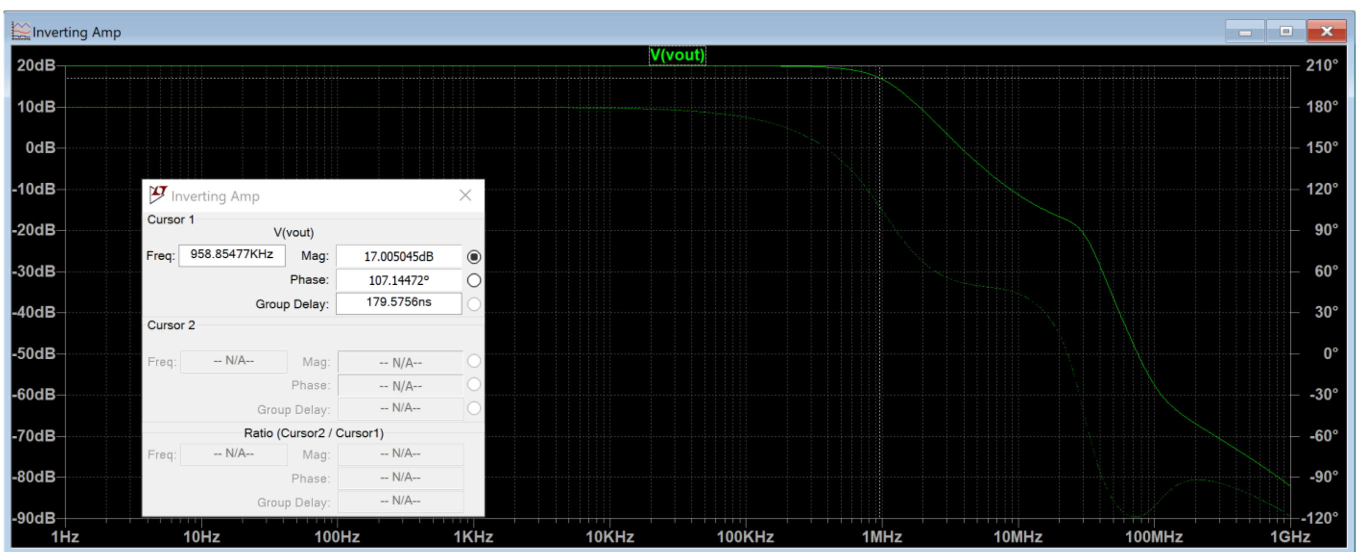


Figure 48 Frequency Response of Post Lab Question 2a

From the results above for post lab question 2a, interestingly enough when modifying the Vpp voltage to Vs and changing the Hz this does not affect the ft or f_{3dB} of the circuit the only effect on it was a change in the gain.

b. Modifying the capacitor CF to be .005uf for the integrating op-amp circuit instead of .01uf.

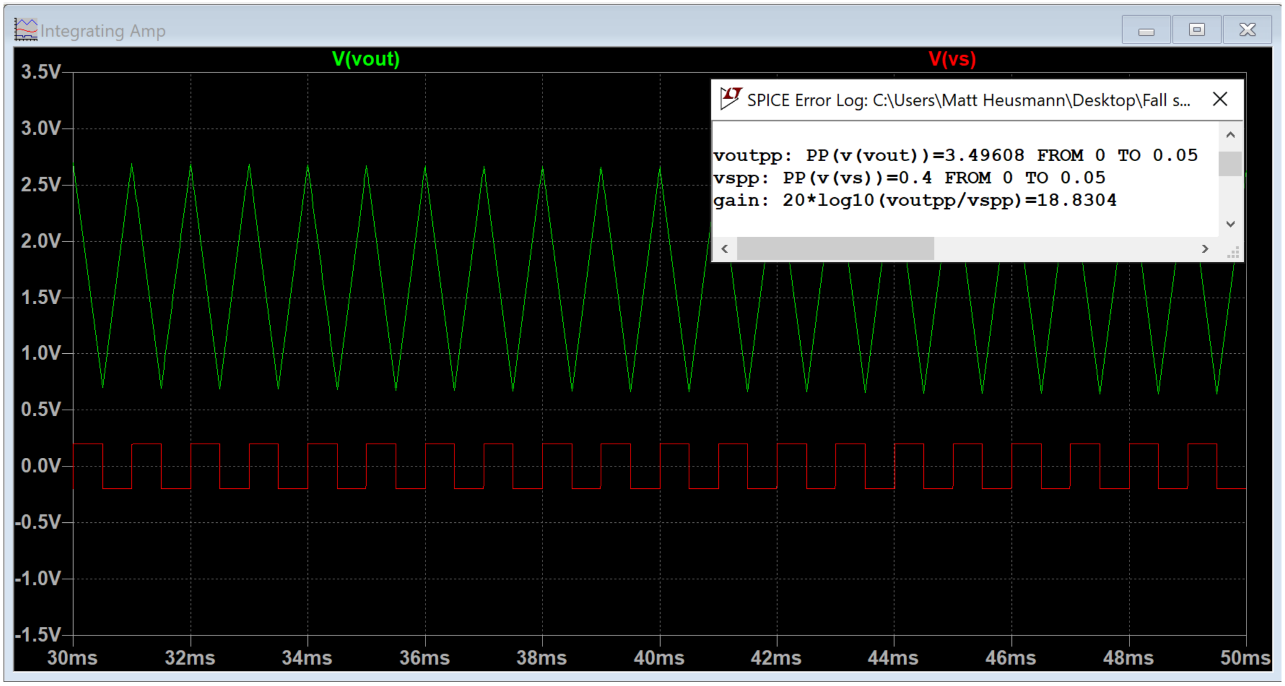


Figure 49 Transient Analysis of Post Lab Question 2b

With altering the capacitor to a value of .005μF the only change seen was the fact that the Vout is changed from the original. With this result this means that the gain will be affected, and this is true since this new gain is **2.564** $\frac{V}{V}$.

3. Discuss the purpose of connecting the op-amp as shown in the circuit of Fig. 2.6? Explain the function of the circuit.

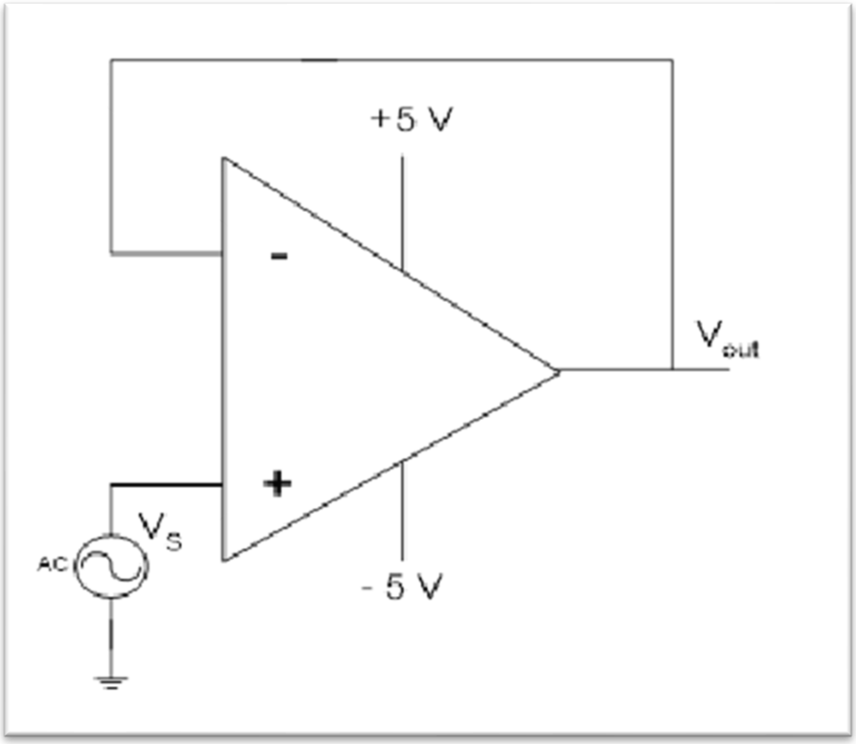


Figure 50 Post Lab Question 3 Circuit Diagram

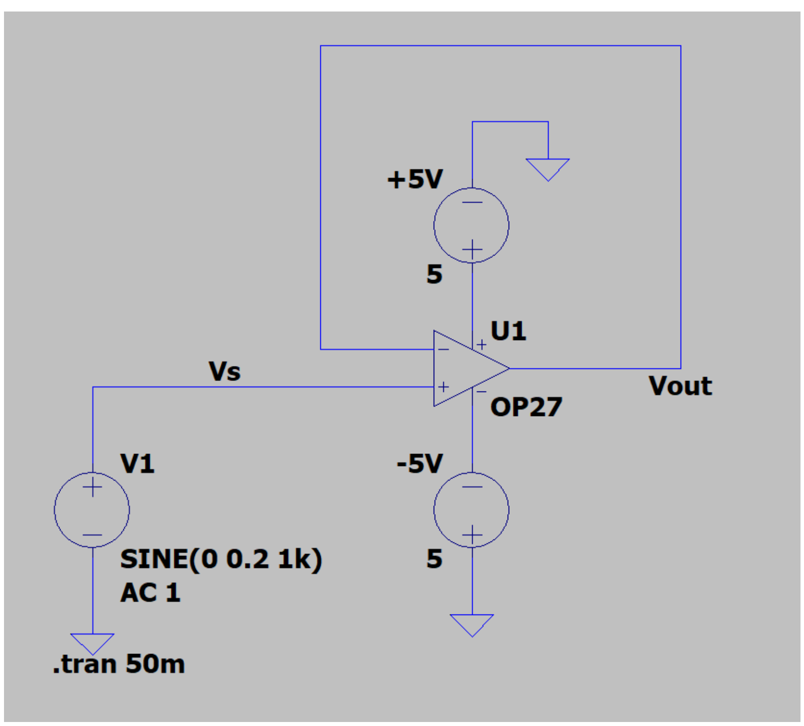


Figure 51 Post Lab Question 3 Circuit Diagram in LTSpice

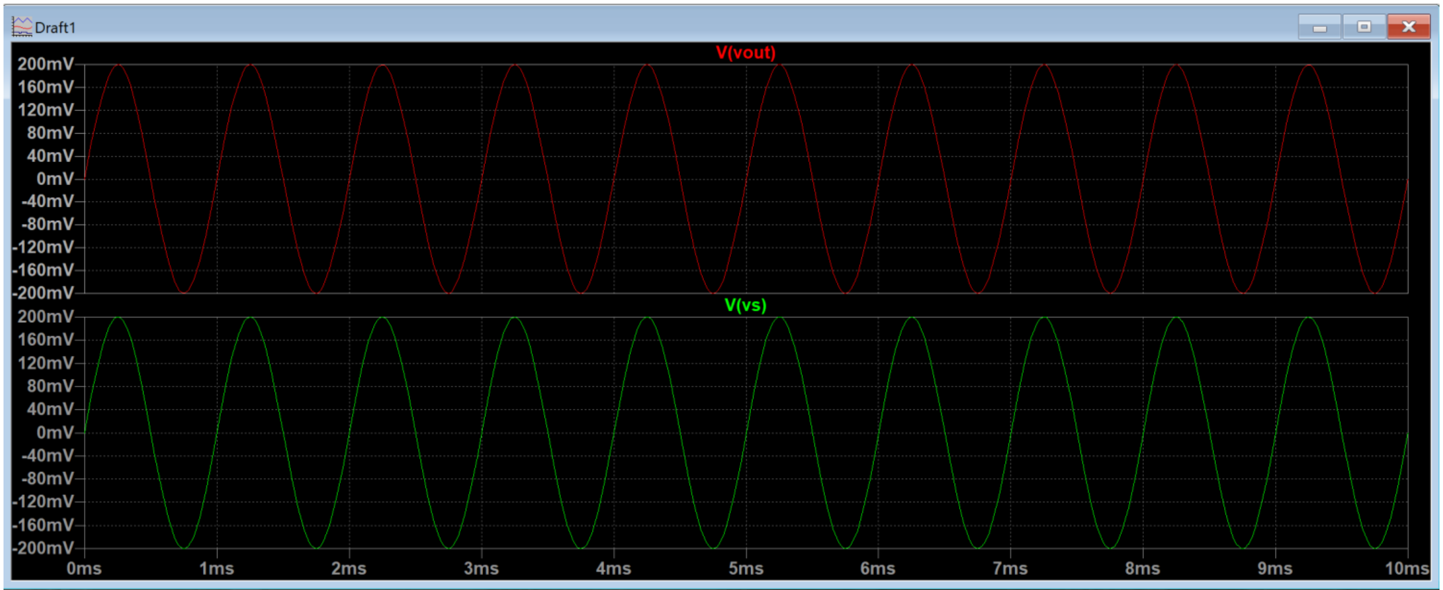


Figure 52 Post Lab Question 3 Transient Analysis in LTSpice

From analyzing figures 51-52 and understanding the fundamentals of op amps. It can be deduced that the Voltage into the + terminal = the voltage at the – terminal. So Vout would equal Vin or $\frac{V_{out}}{V_{in}} = 1$. This would essentially be the unity gain.