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Lab 3: Introduction to Operational Amplifiers

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Objective

Gain practical experience with OP-AMPS through building integrated circuits and using analytical tools, including the oscilloscope, to analyze.

Theory

Note: Theories, concepts, and proofs heavily quoted from “Fundamentals of Electric Circuits” 5th edition.

OP-AMP

An active circuit element designed to perform mathematical operations of addition, subtraction, multiplication, division, differentiation, and integration. The op-amp consists of a complex arrangement of resistors, transistors, capacitors, and diodes. For this lab, however, op-amps will be treated as a black-box with four inputs and one output, as seen in the figure 1.1. The (-) and (+) specify inverting and noninverting inputs, respectively. Positive and negative power supplies are connected to +Vss and -Vss, respectively. The op-amp senses the difference between the inverting and noninverting inputs, multiplies it by the gain A, and causes the resulting voltage to appear at the output.

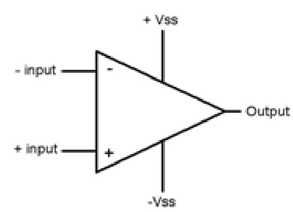


Figure 1.1

$$V_{out} = A\left(V_{in(+)} - V_{in(-)}\right)$$ **Theorem 1.1**

The output voltage is limited by the input power supply voltages, +Vss and -Vss. That is,

$$-Vss \leq V_{out} \leq +Vss$$ **Theorem 1.2 (See Appendix)**

To facilitate the understanding of op-amp circuits, ideal op-amps are generally assumed. Two important properties of the ideal op-amp are:

1. The currents into both the inverting and noninverting inputs are 0. (Principle of open.)
2. For feedback applications, the voltage across $V_{in(+)}$ and $V_{in(-)}$ is 0. (Principle of virtual short.)

D.C. Amplifier

The inverting amplifier reverses the polarity of the input signal while amplifying it. Both the input voltage and feedback are connected to the op-amps negative (-) input. As proven below, the output voltage is directly determined by the feedback resistor, R2, and the input resistor R3. A voltmeter connected across V4 and common ground is used to analyze the output voltage.

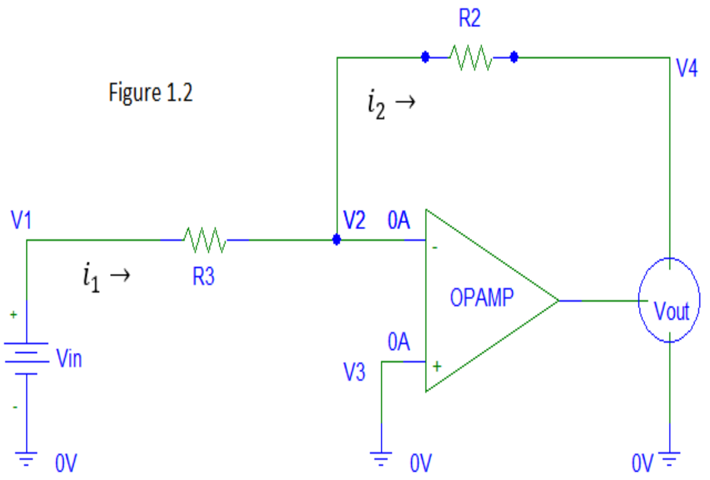


Figure 1.2

$$Note: V_1 = V_{in}, V_4 = V_{out}$$

$$Note: V_3 = V_2 = 0V$$ Principle of Virtual Short

$$Note: Current\ @\ opamp's\ (\pm) = 0A$$ Principle of Open

$$i_1 + 0A = i_2$$ $KCL\ @\ V_2$

$$\frac{V_1 - V_2}{R_3} = \frac{V_2 - V_4}{R_2}$$ Nodal Analysis

$$\frac{V_1 - 0}{R_3} = \frac{0 - V_4}{R_2}$$ Substitute value of V_2

$$V_4 = -\frac{R_2}{R_3} V_1$$ Solve for V_{out}

$$V_{out} = -\frac{R_2}{R_3} V_{in}$$ **Equation 1.1**

A.C. Amplifier

Same principle as the D.C. inverting amplifier except the input voltage is Alternating Current type. (A.C.) An oscilloscope connected across V4 and common ground is used to analyze the output voltage V_{pp} (Peak to Peak) and V_{rms} (DC-Equivalent Voltage).

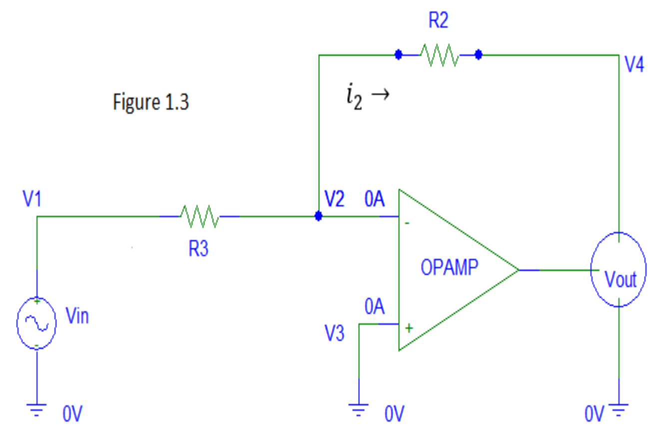


Figure 1.3

Unity Gain Inverter

Same principle as the D.C./A.C. inverting amplifier except that the resistances of R2 and R3 are equal, or ideally so. This op-amp configuration is generally used to transfer a voltage from a circuit with a high output impedance level, to a second circuit with a low impedance level. Because resistor values vary, for this lab Equation 1.1 will still be used to determine the amplification value.

Non-Inverting Op-Amp

The noninverting amplifier is an op amp circuit designed to provide a positive voltage gain. Unlike the inverting op-amp, the input voltage and feedback are connected to the positive (+) input of the op-amp. Though the gain is slightly different than the inverting amplifier, the value is still dependent upon the loopback resistor, R2, and the input resistor, R3. See proof below.

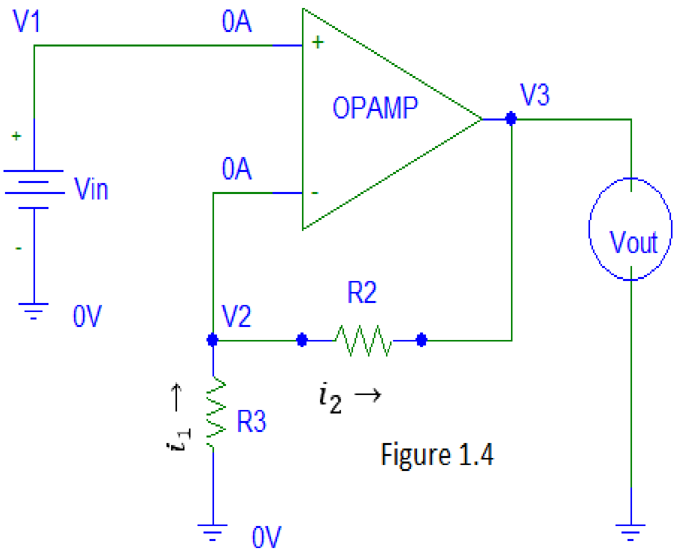


Figure 1.4

$$Note: V_1 = V_{in}, V_3 = V_{out}$$

$$Note: V_1 = V_2 = V_{in}$$ Principle of Virtual Short

$$Note: Current\ @\ opamp's\ (\pm) = 0A$$ Principle of Open

$$i_1 + 0A = i_2 \qquad KCL\ @\ V_2$$

$$\frac{0 - V_2}{R_3} = \frac{V_2 - V_3}{R_2}$$ Nodal Analysis

$$\frac{V_3}{R_2} = \frac{V_2}{R_2} + \frac{V_2}{R_3}$$

$$V_3 = V_2 + \frac{R_2 V_2}{R_3}$$

$$V_3 = V_2\left(1 + \frac{R_2}{R_3}\right)$$ Solve for V_{out}

$$V_{out} = V_{in}\left(1 + \frac{R_2}{R_3}\right)$$ **Equation 1.2**

Summing Op-Amp

The summing amplifier is an op amp circuit that combines several inputs and produces an output that is the weighted sum of the inputs. As seen in figure 1.5, several input voltages all connect to V2, the negative (-) input of the op-amp. As proven below, the output voltage is the combination of each input, which is amplified based upon the loopback resistor and the input's input resistor. The same idea can be applied in a noninverting architect, in which each voltage input would produce an output voltage based upon equation 1.2.

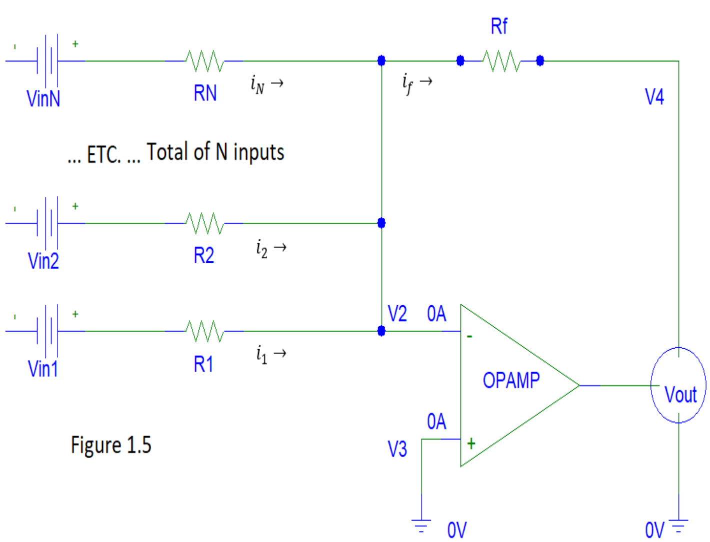


Figure 1.5

$$Note: V_4 = V_{out}$$

$$Note: V_2 = V_3 = 0V$$ Principle of Virtual Short

$$Note: Current\ @\ opamp's\ (\pm) = 0A$$ Principle of Open

$$i_1 + i_2 + \cdots + i_N + 0A = i_f \qquad KCL\ @\ V_2$$

$$\frac{(V_{in1} - 0)}{R_1} + \frac{V_{in2} - 0}{R_2} + \cdots + \frac{V_{inN} - 0}{R_N} = \frac{0 - V_4}{R_f}$$ Nodal Analysis

$$\frac{V_4}{R_f} = \frac{-V_{in1}}{R_1} - \frac{V_{in2}}{R_2} - \cdots - \frac{V_{inN}}{R_N}$$ Solve for V_{out}

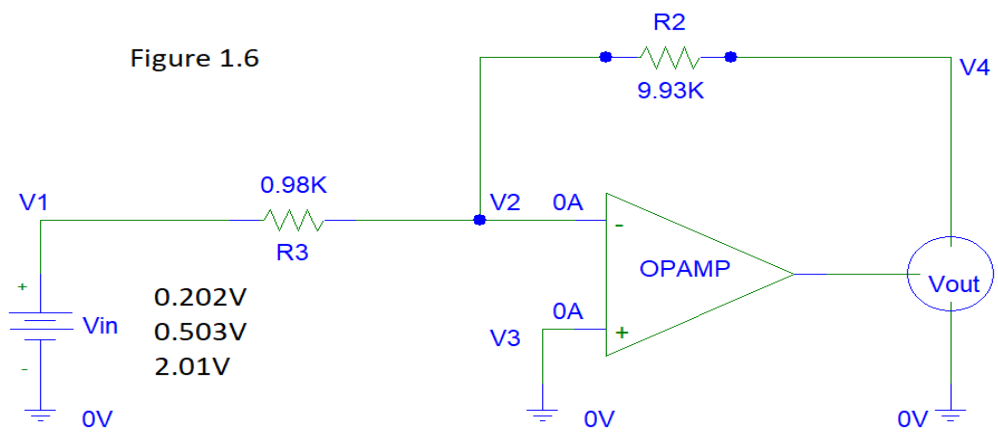
$$V_{out} = -V_{in1}\left(\frac{R_f}{R_1}\right) - V_{in2}\left(\frac{R_f}{R_2}\right) - \cdots - V_{inN}\left(\frac{R_f}{R_N}\right)$$ **Equation 1.3**

Procedure

Part 1:

A D.C. amplifier, as seen in figure 1.6, was built. The feedback resistor, R2, was measured at 9.93K-ohms, and the input resistor, R3, was measured at .98K-ohms. The output voltage was measured for three different input voltages. (0.202V, 0.503V, and 2.01V)

Figure 1.6

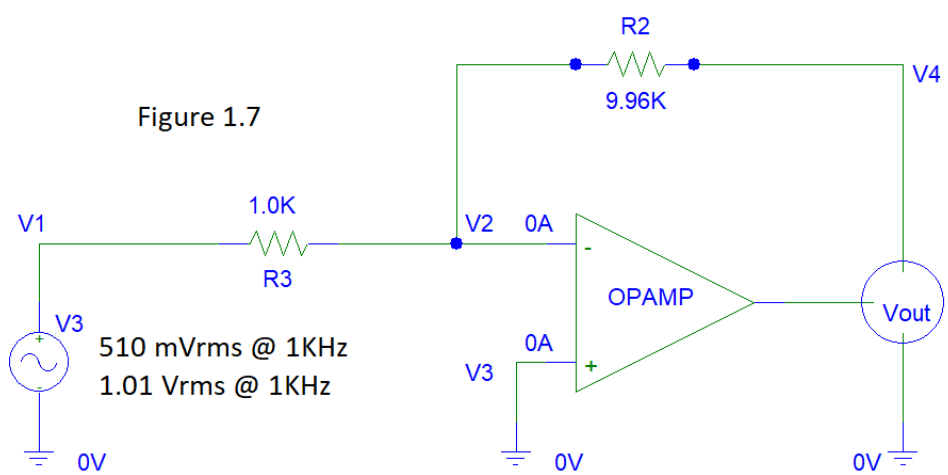


V_{in}	Feedback Resistor	Input Resistor	Amplification (Calculation 1.2)	Theoretical Vout	Measured Vout	% Error (Calculation 1.1)
0.202V	9.93K	0.98K	10.13	-2.05V	2.05V	0
0.503V	9.93K	0.98K	10.13	-5.10V	-5.07V	0.59
2.01	9.93K	0.98K	10.13	-20.37V	-7.92V	61.10

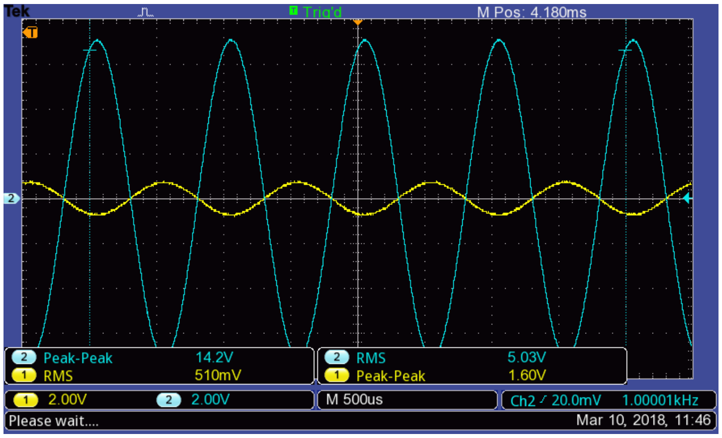
Part 2:

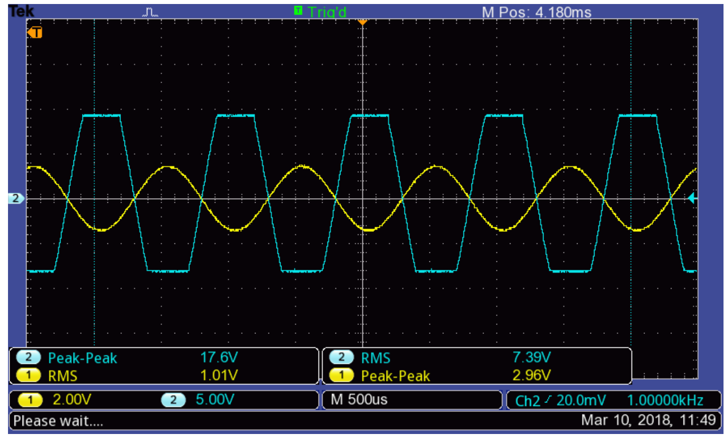
An A.C. amplifier, as seen in figure 1.7, was built. The feedback resistor, R2, was measured at 9.96K-ohms, and the input resistor, R3, was measured at 1.00K-ohms. The output voltage was measured for an A.C. input of 503mV_{RMS} @ 1KHz, and for 0.998V_{RMS} @ 1KHZ.

Figure 1.7



V_{in}	Feedback Resistor	Input Resistor	Amplification (Calculation 1.2)	Theoretical Vout	Measured Vout	% Error (Calculation 1.1)
510 mVrms	9.96K	1.0K	9.96	-5.08 Vrms	-5.03V	0.98
1.01 Vrms	9.96K	1.0K	9.96	-10.06 Vrms	-7.39V	26.5





Part 3a:

A D.C. unity gain inverter, as seen in figure 1.8, was built. The feedback resistor, R2, was measured at 9.93K-ohms, and the input resistor, R3, was measured at 9.95K-ohms. The output voltage was measured for D.C. input voltages of 3.01V and 5.00V.

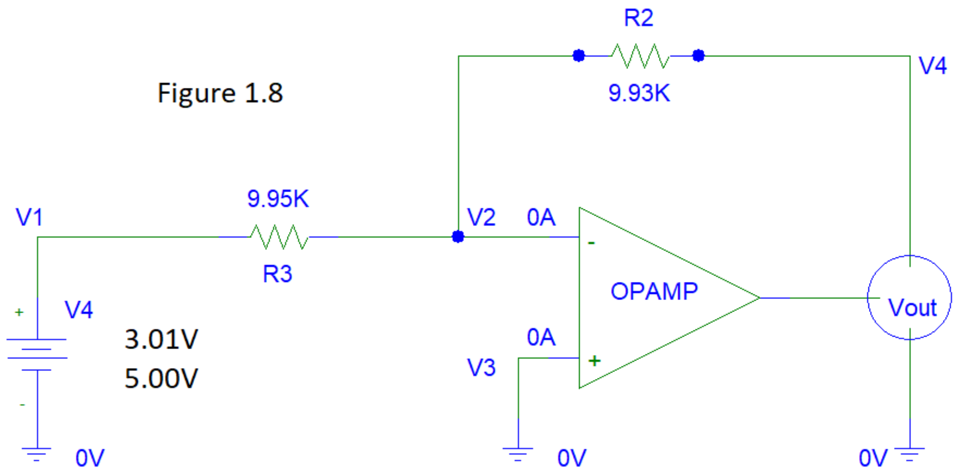


Figure 1.8

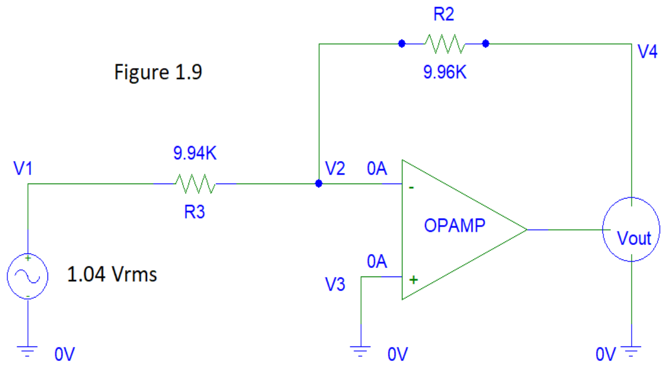
V_{in}	Feedback Resistor	Input Resistor	Amplification (Calculation 1.2)	Theoretical Vout	Measured Vout	% Error (Calculation 1.1)
3.01V	9.93K	9.95K	.998	-3.00V	3.01V	0.33
5.00V	9.93K	9.95K	.998	-4.99V	-4.99V	0

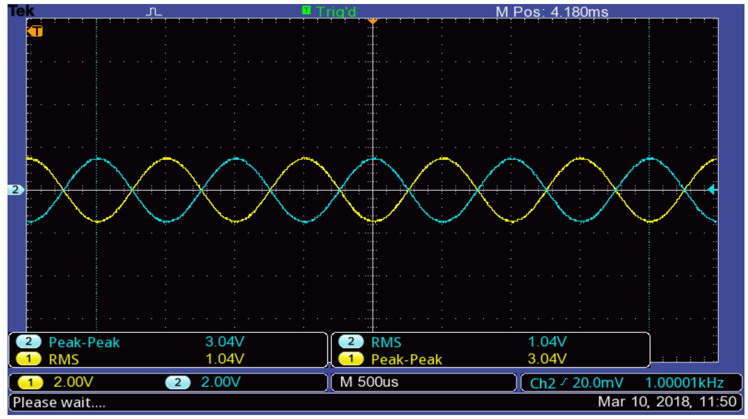
Part 3b:

An A.C. unity gain inverter, as seen in figure 1.9, was built. The feedback resistor, R2, was measured at 9.96K-ohms, and the input resistor, R3, was measured at 9.94K-ohms. The input voltage was set to 1.04 V_{RMS} @ 1KHz, and the output voltage was analyzed and measured with an oscilloscope.

V_{in}	Feedback Resistor	Input Resistor	Amplification (Calculation 1.2)	Theoretical Vout	Measured Vout	% Error (Calculation 1.1)
1.04 Vrms	9.96K	9.94K	1.002	-1.04V	-1.04V	0

Figure 1.9





Part 4a:

A D.C. noninverting amplifier, as seen in figure 1.10, was built. The feedback resistor, R2, was measured at 9.93K-ohms, and the input resistor, R3, was measured at 0.99K-ohms. The output voltage was measured for D.C. input voltages of 0.200V, 0.501V, and 2.01V.

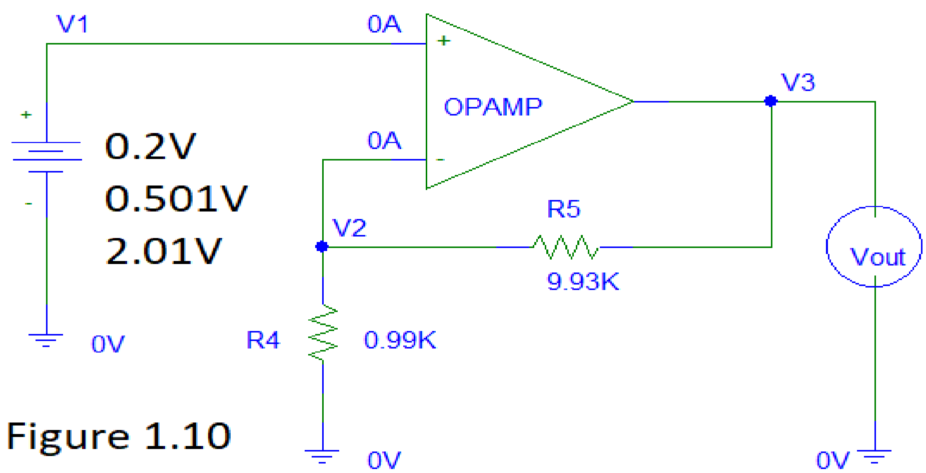


Figure 1.10

V_{in}	Loopback Resistor	Input Resistor	Amplification (Calculation 1.3)	Theoretical Vout	Measured Vout	% Error (Calculation 1.1)
0.200V	9.93K	0.99K	11.03	2.21V	2.20V	0.45
0.501V	9.93K	0.99K	11.03	5.53V	5.54V	0.18
2.01	9.93K	0.99K	11.03	22.17V	9.25V	58.23

Part 4b:

An A.C. noninverting amplifier, as seen in figure 1.11, was built. The feedback resistor, R2, was measured at 9.96K-ohms, and the input resistor, R3, was measured at 1.0K-ohms. The output voltage was measured for A.C. input 509 V_{RMS}.

V_{in}	Loopback Resistor	Input Resistor	Amplification (Calculation 1.3)	Theoretical Vout	Measured Vout	% Error (Calculation 1.1)
509 mVrms	9.96K	1.0K	10.96	5.58V	5.54V	0.72

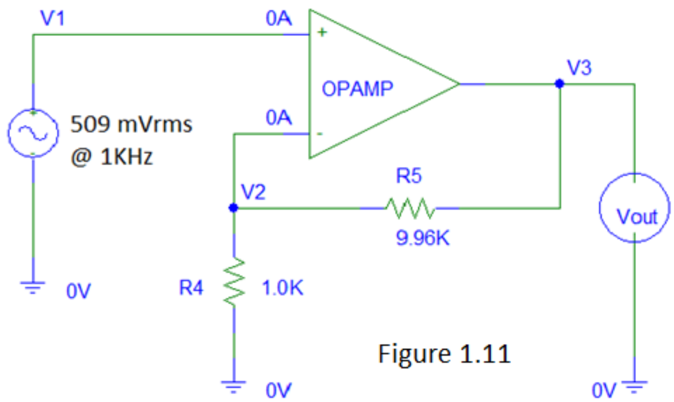
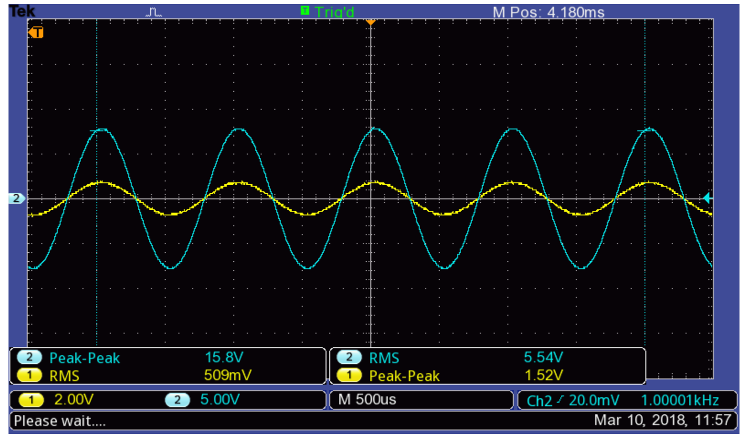


Figure 1.11



Part 5:

Three summing op-amp circuits were built. The first was a dual D.C. voltage input of 2.00V and 3.00V, with a feedback resistor value of 9.96K-ohm and input resistor values of 9.95K-ohm and 9.92k-ohm, as seen in figure 1.12. The 9.92K-ohm was then swapped with a 4.65K-ohm resistor and the input voltages were changed to 2.00V and 2.48V, as seen in figure 1.13. Output voltages were then measured with a voltmeter.

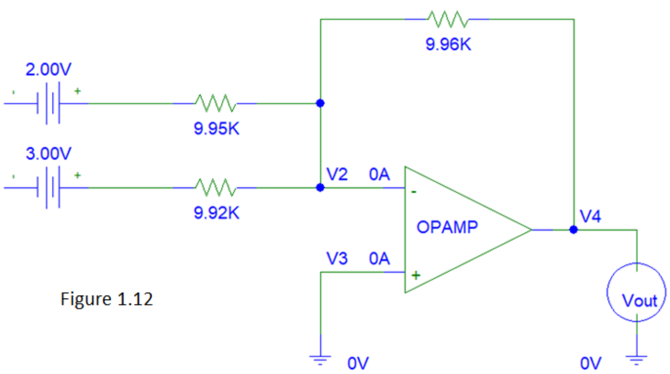


Figure 1.12

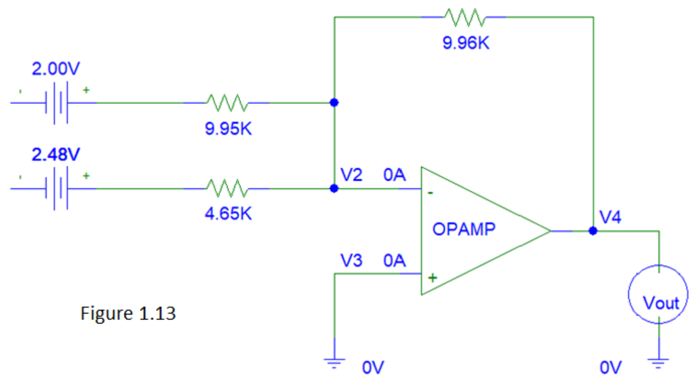


Figure 1.13

V_{in}	Loopback Resistor	Input Resistor	Amplification (Calculation 1.4)	Theoretical Vout	Measured Vout	% Error (Calculation 1.1)
2.00V	9.96K	9.95K	1.001	2.002V + 3.012V =	-4.97	0.88
3.00V		9.92K	1.004	-5.014		
2.00V	9.96K	9.95K	1.001	2.002V + 5.312V =	-7.27V	0.55
2.48V		4.65K	2.142	-7.31V		

The third circuit was built with one D.C. voltage source and one A.C. voltage source. Connected in series with the A.C. source is a 100 µF capacitor. The feedback resistor was measured at 9.96K-ohms, the D.C. input resistor was measured at 9.94K-ohm, and the A.C. input resistor was measured at 9.92K-ohm, as seen in figure 1.14. The resulting output voltage was then analyzed and measured with an oscilloscope.

V_{in}	Loopback Resistor	Input Resistor	Amplification (Calculation 1.4)	Theoretical Vout	Measured Vout	% Error (Calculation 1.1)
2.00V	9.96K	9.94K	1.002	-1.42V	-1.45	2.11
1.41 Vrms		9.92K	1.004			

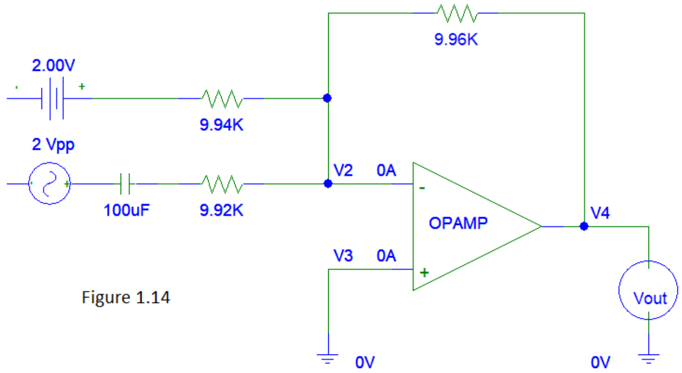
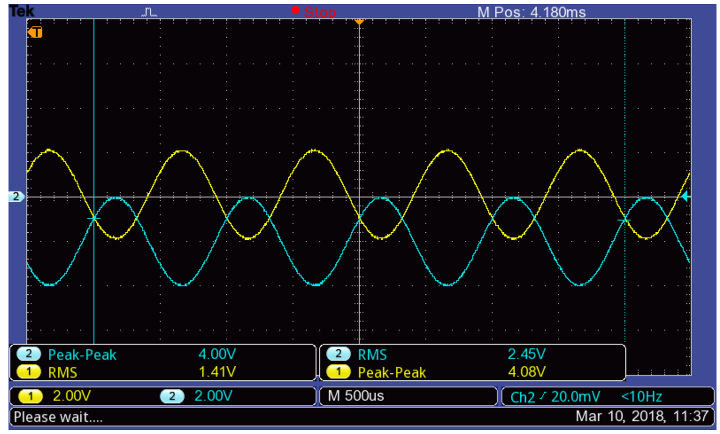

9.96K
2.00V
9.94K
2 Vpp
100uF
9.92K
V2
0A
OPAMP
V4
V3
0A
Vout
0V
0V

Figure 1.14


Tek
Stop
M Pos: 4.180ms
Peak-Peak 4.00V
RMS 1.41V
RMS 2.45V
Peak-Peak 4.08V
2.00V
2.00V
M 500us
Ch2 20.0mV <10Hz
Please wait....
Mar 10, 2018, 11:37

Data & Calculations

Complete Data Table

V_{in}	Loopback Resistor	Input Resistor	Amplification	Theoretical Vout	Measured Vout	% Error
Part 1						
0.202V	9.93K	0.98K	10.13	-2.05V	2.05V	0
0.503V	9.93K	0.98K	10.13	-5.10V	-5.07V	0.59
2.01	9.93K	0.98K	10.13	-20.37V	-7.92V	61.10
Part 2						
510 mVrms	9.96K	1.0K	9.96	-5.08 Vrms	-5.03V	0.98
1.01 Vrms	9.96K	1.0K	9.96	-10.06 Vrms	-7.39V	26.5
Part 3						
3.01V	9.93K	9.95K	.998	-3.00V	3.01V	0.33
5.00V	9.93K	9.95K	.998	-4.99V	-4.99V	0
1.04 Vrms	9.96K	9.94K	1.002	-1.04V	-1.04V	0
Part 4						
0.200V	9.93K	0.99K	11.03	2.21V	2.20V	0.45
0.501V	9.93K	0.99K	11.03	5.53V	5.54V	0.18
2.01	9.93K	0.99K	11.03	22.17V	9.25V	58.23
509 mVrms	9.96K	1.0K	10.96	5.58V	5.54V	0.72
Part 5						
2.00V 3.00V	9.96K	9.95K 9.92K	1.001 1.004	2.002V + 3.012V = -5.014	-4.97	0.88
2.00V 2.48V	9.96K	9.95K 4.65K	1.001 2.142	2.002V + 5.312V = -7.31V	-7.27V	0.55
2.00V 1.41 Vrms	9.96K	9.94K 9.92K	1.002 1.004	-1.42V	-1.45	2.11

Calculation 1.1

$$\%Error \rightarrow \frac{|V_{theoretical} - V_{measured}|}{|V_{theoretical}|} x\ 100$$

$Example$: Part 1:

$$\frac{|5.10 - 5.07|}{5.10} * 100 = 0.59\%$$

Calculation 1.2

$$Use\ Equation\ 1.1$$

$$V_{out} = -\frac{R_2}{R_3}V_{in}$$

Example: Part 3

$$V_{out} = -\left(\frac{9.93}{9.95}\right)(3.01) = \ -3.00$$

Calculation 1.3

$$Use\ Equation\ 1.2$$

$$V_{out} = V_{in}\left(1 + \frac{R_2}{R_3}\right)$$

Example: Part 4a

$$V_{out} = 0.200V\left(1 + \frac{9.93K}{0.99K}\right) = 2.21$$

Calculation 1.4

$$Use\ Equation\ 1.3$$

$$V_{out} = -V_{in1}\left(\frac{R_f}{R_1}\right) - V_{in2}\left(\frac{R_f}{R_2}\right) - \cdots - V_{inN}\left(\frac{R_f}{R_N}\right)$$

Example: Part 5a

$$V_{out} = -2.00V\left(\frac{9.96K}{9.95K}\right) - 3.00V\left(\frac{9.96K}{9.92K}\right) = \ -5.01$$

Discussion of Results

Part 1:

Experiment went as expected. The differences in input voltages were successfully amplified and inverted. Output voltages for the 0.202V and .503V yielded very low percent errors. The 2V input yielded a 61.10%. This output was expected because the supply voltages were limited to -10V and +10V. See Theorem 1.2 and Op-Amp output voltage saturation in appendix. As verification, the supply voltages were temporarily bumped up to +/- 25V, which in turn allowed the output voltage reading to reach its predicted value.

Part 2:

Experiment went as expected. The observed sine wave was inverted and amplified based upon input voltage difference and amplification value. As in par 1 circuit 3, the second circuit resulted in a high percent error of 26.5%. Once again, this is due to Op-Amp output voltage saturation. Verification of this was done by increasing the supply voltages to +/- 25V which in turn allowed the output voltage reading to reach its predicted value and form a nice, non-clipped, sine wave.

Part 3:

Experiment went as expected. The difference in input voltages was successfully inverted while keeping the about same voltage value. Very low percent errors were yielded.

Part 4:

Experiment went as expected. The differences in input voltages were successfully amplified for both the D.C. and A.C. circuits. Once again, the effects of Op-Amp output voltage saturation was seen for the third D.C. circuit (2V input), resulting in a percent error of 58.23%.

Part 5:

Experiment went as expected. The differences in input voltages were successfully amplified, added together, and inverted for both the D.C. and A.C. circuits. Of special note was the behavior of the mixed D.C. and A.C. circuit. Analyzing the oscilloscope output, the sine wave has indeed been inverted. Instead of adding to the amplitude of the wave, however, the D.C. amplification vertically offsets the wave by -2V, which is the calculated amplified output voltage for the D.C. input voltage.

Appendix

Op-Amp Output Voltage Saturation