

# Operational Amplifiers & Linear Integrated Circuits: Theory and Application

Laboratory Manual/3E



James M. Fiore



# Operational Amplifiers & Linear Integrated Circuits: Theory and Application

## Laboratory Manual

by

James M. Fiore

Version 3.1.6, 16 October 2024

This **Laboratory Manual for Operational Amplifiers & Linear Integrated Circuits: Theory and Application, Third Edition** is copyright James M. Fiore, and released under the terms of a Creative Commons license:



This work is freely redistributable for non-commercial use, share-alike with attribution

Published by James M. Fiore via [dissidents](http://dissidents.com)

ISBN13: 978-1796855623

For more information or feedback, contact:

James Fiore, Professor Emeritus

[oer@jimfiore.org](mailto:oer@jimfiore.org)

[jfiore@mvcc.edu](mailto:jfiore@mvcc.edu)

For the latest revisions, related titles, and links to low cost print versions, go to:

[www.mvcc.edu/jfiore](http://www.mvcc.edu/jfiore) or my mirror sites [www.dissidents.com](http://www.dissidents.com) and [www.jimfiore.org](http://www.jimfiore.org)

*YouTube Channel: [Electronics with Professor Fiore](https://www.youtube.com/channel/UCv0t01111111111111111111)*

Cover art, *Canadian Shield II*, by the author

# Introduction

This manual is the companion to the OER (Open Educational Resource) Operational Amplifiers & Linear Integrated Circuits/3E text. It is intended for use in an operational amplifiers course and is appropriate for either a two or four year electrical engineering technology curriculum. The manual contains sufficient exercises for a typical 15 week course using a two to three hour practicum period. The topics cover basic differential amplifiers through active filters. For equipment, each lab station should include a dual adjustable DC power supply, a dual trace oscilloscope, a function generator and a quality DMM. Some exercises also make use of a distortion analyzer and a low distortion generator (generally, THD below 0.01%), although these portions may be bypassed. For components, a selection of standard value ¼ watt carbon film resistors ranging from a few ohms to a few mega ohms is required along with an array of typical capacitor values (film types recommended below 1 µF and aluminum electrolytics above). A 100 ohm 5 watt power resistor is needed for the Linear Regulator exercise. A 10k Ω potentiometer will also be useful for the DC Offset exercise. Active devices include small signal diodes such as the 1N914 or 1N4148, the NZX5V1B and NZX3V3B Zeners (or 1N751/1N5231 and 1N5226 in a pinch), small signal NPNs such as the 2N3904 or 2N2222, a medium power NPN transistor such as the 2N5192G, and a variety of inexpensive op amps such as the 741, LF351 or TL081, LF411 and LM318. Most circuits use standard  $\pm 15$  VDC power supplies. All DC supplies should be bypassed with 1 µF capacitors positioned as close to the IC and ground as possible. The DC supplies are not drawn in detail on the schematics in order to reduce visual clutter, although the bypass capacitors are included in the parts lists as a reminder.

Each exercise begins with an Objective and a Theory Overview. The Equipment List follows with space provided for model and serial numbers, and measured values of components. Schematics are presented next along with the step-by-step procedure. Many exercises include sections on troubleshooting and/or design. Computer simulations are often presented as well, and almost any quality simulation package such as Multisim, PSpice, [LTspice](#) or [TINA-TI](#) can be used. All data tables are grouped together, typically with columns for the theoretical and experimental results, along with a column for the percent deviations between them. Finally, a group of appropriate questions are presented.

Other laboratory manuals in this series include DC and AC Electrical Circuits, Semiconductor Devices (diodes, bipolar transistors and FETs), Computer Programming with Python™ and Multisim™, and Embedded Controllers Using C and Arduino. Texts are also available for Embedded Controllers as well as Semiconductor Devices. Workbooks are available for DC and AC Electrical Circuits. All of these titles are Open Educational Resources using a Creative Commons non-commercial share-alike with attribution license. The latest versions may be found at my MVCC site: [www.mvcc.edu/jfiore](http://www.mvcc.edu/jfiore) and at my mirror site: [www.dissidents.com](http://www.dissidents.com)

## A Note from the Author

This manual was created to accompany the text *Operational Amplifiers & Linear Integrated Circuits: Theory and Application*. It was designed for our ABET accredited AAS program in Electrical Engineering Technology. I am indebted to my students, co-workers and the MVCC family for their support and encouragement of this project. The text and this manual were published originally via the traditional route. When the opportunity arose, as a long-time supporter and contributor to the Open Educational Resource movement, I decided to re-release these titles using a Creative Commons non-commercial, share-alike license. I encourage others to make use of this manual for their own work and to build upon it. If you do add to this effort, I would appreciate a notification.

*“We need not stride resolutely towards catastrophe, merely because those are the marching orders.”*

*- Noam Chomsky*

# Table of Contents

1. <a href="#">Decibels and Bode Plots</a>	.	.	.	.	.	8
2. <a href="#">The Differential Amplifier</a>	.	.	.	.	.	14
3. <a href="#">The Op Amp Comparator</a>	.	.	.	.	.	22
4. <a href="#">The Non-inverting Voltage Amplifier</a>	.	.	.	.	.	28
5. <a href="#">The Inverting Voltage Amplifier</a>	.	.	.	.	.	34
6. <a href="#">The Op Amp Differential Amplifier</a>	.	.	.	.	.	38
7. <a href="#">Parallel-Series and Series-Series Negative Feedback</a>	.	.	.	.	.	44
8. <a href="#">Gain-Bandwidth Product</a>	.	.	.	.	.	50
9. <a href="#">Slew Rate and Power Bandwidth</a>	.	.	.	.	.	56
10. <a href="#">The Non-compensated Op Amp</a>	.	.	.	.	.	60
11. <a href="#">DC Offset</a>	.	.	.	.	.	64
12. <a href="#">The Operational Transconductance Amplifier</a>	.	.	.	.	.	70
13. <a href="#">Precision Rectifiers</a>	.	.	.	.	.	74
14. <a href="#">Function Generation</a>	.	.	.	.	.	80
15. <a href="#">The Linear Regulator</a>	.	.	.	.	.	86
16. <a href="#">The Triangle-Square Generator</a>	.	.	.	.	.	90
17. <a href="#">The Wien Bridge Oscillator</a>	.	.	.	.	.	94
18. <a href="#">The Integrator</a>	.	.	.	.	.	98
19. <a href="#">The Differentiator</a>	.	.	.	.	.	102
20. <a href="#">VCVS Filters</a>	.	.	.	.	.	106
21. <a href="#">The Multiple Feedback Filter</a>	.	.	.	.	.	114
22. <a href="#">The State-Variable Filter</a>	.	.	.	.	.	120
Appendix A: <a href="#">Creating Graphs Using a Spreadsheet</a>	.	.	.	.	.	128
Appendix B: <a href="#">Manufacturer's Datasheet Links</a>	.	.	.	.	.	130

# 1. Decibels and Bode Plots

## Objective

In this exercise, the usage of decibel measurements and Bode plots will be examined. The investigation will include the relationship between ordinary and decibel gain, and the decibel-amplitude and phase response of a simple lag network.

## Theory Overview

The decibel is a logarithmic-based measurement scheme. It is based on ratios of change. Positive values indicate an increase while negative values indicate a decrease. Decibel schemes can be used for gains and, with minor modification, signal levels. A Bode plot shows the variations of gain (typically expressed in decibels) and phase across a range of frequencies for some particular circuit. These will prove to be very valuable in later design and analysis work.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 1.2, The Decibel

Section 1.3, Bode Plots

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Decibel-reading voltmeter	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

(1) 100n F	actual: _____
(1) 100 $\Omega$	actual: _____
(1) 1k $\Omega$	actual: _____
(1) 4k7 $\Omega$	actual: _____
(2) 10k $\Omega$	actual: _____
(1) 22k $\Omega$	actual: _____



## Schematics

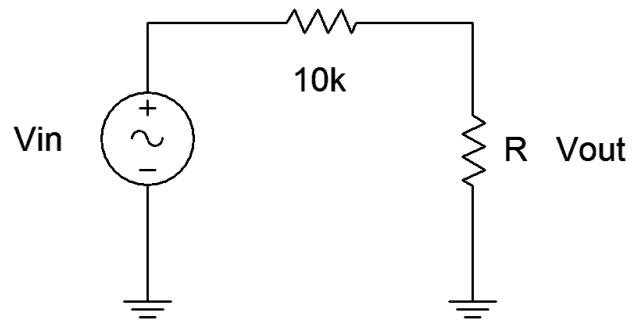


Figure 1

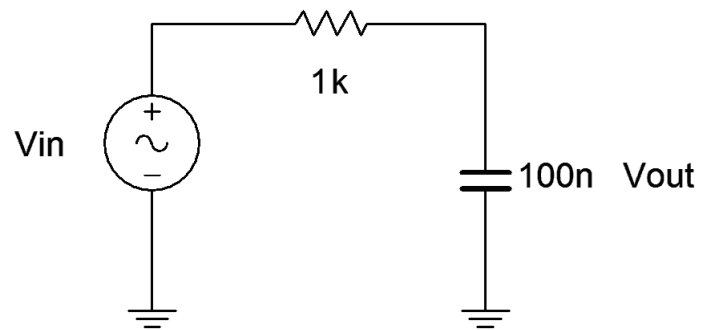


Figure 2

## Procedure

1. Calculate the voltage gains (losses) for the voltage divider of Figure 1 for the resistor values specified, and record them in Table 1. Also, convert each of the ordinary gains into decibel form.
2. Assemble the circuit of Figure 1 using the 22k resistor.
3. Set the generator to a 100 Hz sine wave, 0 dBV (Note: If the meter is calibrated in dBu, then use 0 dBu).
4. Apply the generator to the circuit. Measure and record the output voltage in Table 1 using the decibel-reading voltmeter. Also, compute the resulting experimental decibel voltage gain and gain deviation.
5. Repeat step 4 for the remaining resistor values in Table 1.
6. To create a simple Bode plot, the lag network of Figure 2 will be used. Assemble this circuit and record its theoretical critical frequency in Table 2.
7. Set the generator to a 1 kHz sine wave, 0 dBV.
8. Apply the generator to the circuit. Determine the experimental critical frequency by adjusting the frequency of the generator until the circuit's output voltage is  $-3$  dBV. Record the measured frequency in Table 2.
9. Set the generator to a sine wave at one-tenth of the experimental critical frequency.
10. Adjust the generator's output level to 0 dBV.
11. Apply the generator to the circuit. Measure and record the output level in decibels in Table 3. Also, measure and record the phase angle between the input and output waveforms and record it in Table 3.
12. Repeat steps 9 through 11 for the remaining frequencies listed in Table 3.
13. Using the values from Table 3, create a Bode plot for this circuit using a log scaled horizontal axis (i.e., semi-log paper).

## Computer Simulation

14. Build the lag network of Figure 2 in a simulator and run an AC Analysis. Be sure to run this from at least one decade below the critical frequency to at least one decade above. Also, use a decibel scale for the gain amplitude. Compare the results to the Bode plot generated in Step 13 and include this graph with the technical report.

## Data Tables

R	$A_v$ Theory	$A_v'$ Theory	$V_{out}'$	Experimental $A_v'$	% Deviation
22k $\Omega$					
10k $\Omega$					
4k7 $\Omega$					
1k $\Omega$					
100 $\Omega$					

Table 1

Theoretical $f_c$	
Experimental $f_c$	

Table 2

Factor	Frequency	$A_v'$	Phase
$.1 f_c$			
$.2 f_c$			
$.5 f_c$			
$f_c$			
$2 f_c$			
$5 f_c$			
$10 f_c$			

Table 3

## Questions

1. Is the logarithmic nature of the decibel apparent in the data of Table 1?
2. Using the plot created in step 13, determine the slope in dB-per-octave in the region above  $f_c$ .
3. What would the plot of step 13 look like if ordinary gains had been used instead of decibel gains?



## 2. The Differential Amplifier

### Objective

In this exercise, the performance of a differential amplifier will be examined. The investigation will include the DC parameters of input bias and offset current, and output offset voltage. The AC parameters of interest are the differential and common-mode gains, and the resulting common-mode rejection-ratio (CMRR).

### Theory Overview

The ideal differential amplifier is perfectly symmetrical producing identical DC input bias currents and output collector voltages. Several factors ranging from the mismatch of transistor parameters to resistor tolerances prevent perfect symmetry in a practical circuit. The DC quality of the circuit can be expressed in terms of the mismatches. The difference between the input bias currents is known as the input offset current. The difference between the output collector voltages is known as the output offset voltage. For AC performance, the primary items of concern are the differential and common-mode gains. The ideal differential amplifier will only amplify differential input signals, and thus, has a common-mode gain of zero. Due to component mismatches and internal design limits, the common-mode gain is never zero, allowing some portion of the common-mode input signal to make its way to the output. The measure of the suppression of common-mode signals is given by the common-mode rejection-ratio, or CMRR. CMRR can be found by dividing the differential gain by the common-mode gain.

### Reference

*Fiore, Op Amps and Linear Integrated Circuits*  
Section 1.6, The Differential Amplifier

### Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

(3) Small signal NPN transistors (2N3904, 2N2222, etc.)

(2) 100 $\Omega$	actual: _____
(2) 330 $\Omega$	actual: _____
(2) 470 $\Omega$	actual: _____
(1) 3k3 $\Omega$	actual: _____
(2) 4k7 $\Omega$	actual: _____
(1) 5k6 $\Omega$	actual: _____
(1) 10k $\Omega$	actual: _____
(2) 22k $\Omega$	actual: _____
(1) 33k $\Omega$	actual: _____

2N3904 Datasheet: <https://www.onsemi.com/pub/Collateral/2N3903-D.PDF>

## Schematics

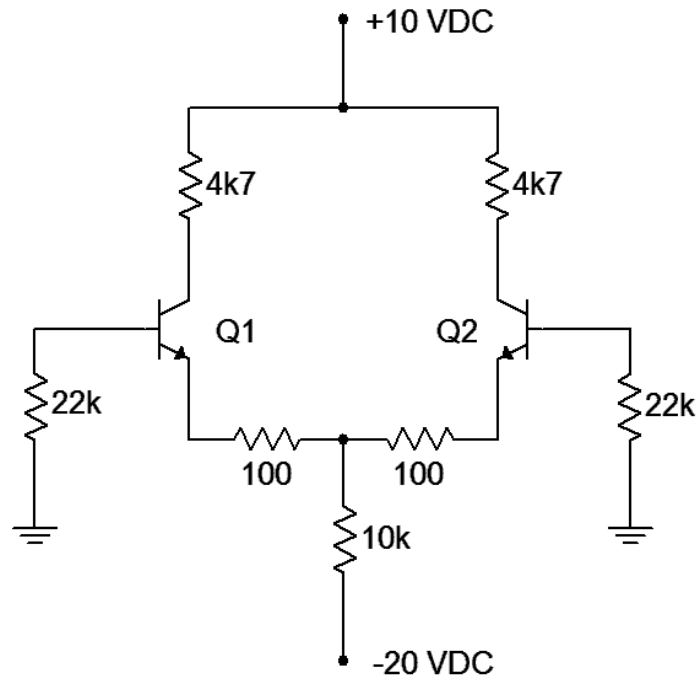


Figure 1

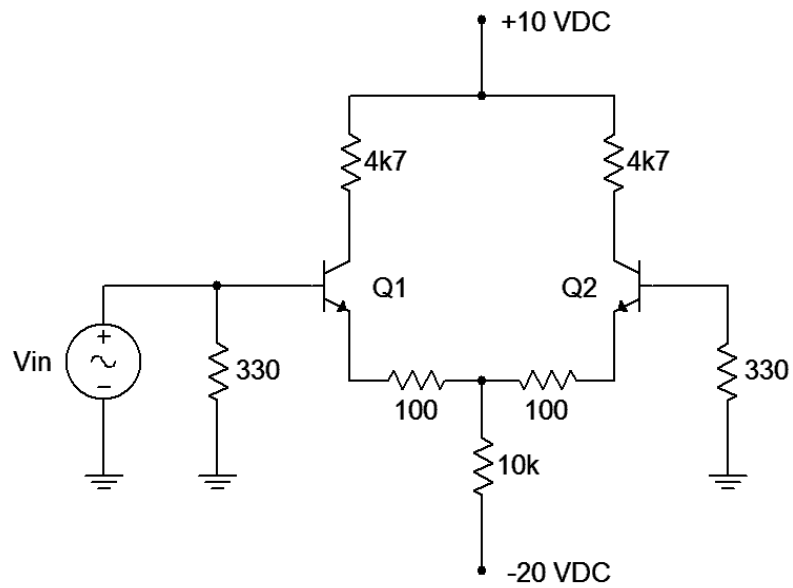


Figure 2

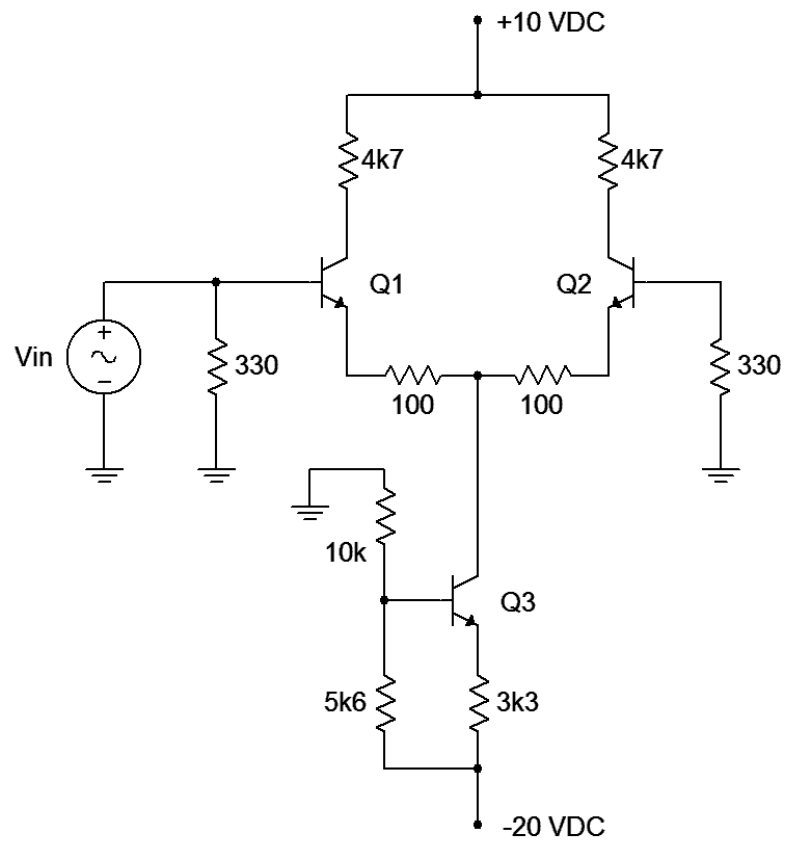


Figure 3



# Procedure

## DC Parameters

1. Assume that the transistors of Figure 1 have a current gain of 150. Calculate the base currents and collector voltages for the amplifier of Figure 1 and record them in Table 1. Also, compute and record the theoretical (ideal) input offset current and output offset voltage.
2. Assemble the circuit of Figure 1.
3. Measure and record the base currents in Table 1. (Note: You may wish to measure the voltage across the base resistors and compute the base currents if the DMM cannot measure small DC currents.) Based on these currents, compute and record the experimental input bias and offset currents along with the corresponding deviations.
4. Measure and record the collector voltages in Table 1. Based on these voltages, compute and record the experimental output offset voltage and the corresponding deviation.

## AC Parameters

5. Calculate the differential voltage gain and collector voltages for the amplifier of Figure 2 using an input of 20 millivolts, and record them in Table 2.
6. Assemble the circuit of Figure 2.
7. Set the generator to a 1 kHz sine wave, 20 millivolts peak.
8. Apply the generator to the amplifier. Measure and record the AC collector voltages in Table 2 while noting the phase relative to the input. Also, compute the resulting experimental voltage gain from the input to collector one, and the deviations.
9. Apply the generator to both inputs. Set the generator's output to 1 volt peak.
10. Measure the AC voltage at collector one and record it in Table 3.
11. Based on the value measured in step 10, compute and record the common-mode gain and CMRR in Table 3.

## Improved CMRR

12. Assemble the circuit of Figure 3. This circuit uses an improved tail current source that exhibits much higher internal impedance than the circuit of Figure 2. This should yield a decrease in common mode gain which, in turn, should yield an improved CMRR. Note that the new circuit sets up virtually the

same tail current, therefore producing approximately the same DC parameters and differential gain as the original.

13. Repeat steps 9 through 11 recording the results in Table 4.

### Troubleshooting

14. Continuing with the amplifier of Figure 3, turn the signal down to 0. Estimate and then measure the results for each individual error presented in Table 5.

### Computer Simulation

15. Build the amplifier of Figure 2 in a simulator and run a Transient Analysis echoing steps 5 through 8. Compare the results to the data found in Table 2.

## Data Tables

DC Quantity	Theoretical	Experimental	% Deviation
$I_{B1}$			
$I_{B2}$			
$I_{in-bias}$			
$I_{in-offset}$			
$V_{C1}$			
$V_{C2}$			
$V_{out-offset}$			

Table 1

AC Quantity	Theoretical	Experimental	% Deviation
$V_{C1}$			
$V_{C2}$			
$A_v$			

Table 2

$V_{C1}$	
$A_{cm}$	
CMRR	

Table 3

$V_{C1}$	
$A_{cm}$	
CMRR	

Table 4

Error	Quantity	Estimate	Actual
3k3 is replaced with 33k	$V_{C1}$ DC		
$Q_1$ 's 4k7 is 470	$V_{C1}$ DC		
Both 4k7 are 470	$V_{C1}$ DC		

Table 5

## Questions

1. How might the input offset current of Figure 1 be reduced?
2. What are some causes of output offset voltage in the circuit of Figure 1?
3. What are the effects if the two collector resistors not identical in value?
4. What is the significance of a high CMRR?
5. How significant is the change in CMRR when using the improved current source? Based on the improvement, estimate the internal impedance of the current source.



# 3. The Op Amp Comparator

## Objective

In this exercise, the performance of a typical op amp will be examined in the open-loop mode. This circuit is often referred to as a comparator. The investigation will include the effect of both DC and AC input signals.

## Theory Overview

The open-loop voltage gain of the typical op amp is very high, approaching 100,000 at low frequencies. With such a high gain, even minute differences between the inverting and non-inverting input signals will be magnified to the point of causing saturation. Thus, if the non-inverting input signal exceeds the inverting input signal, the output will be at positive saturation. If the signals are reversed, then negative saturation results. If both inputs are identical, then the output will go to either positive or negative saturation, depending on the internal offsets of the op amp.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 2.2, What Is An Op Amp?

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

(1) General purpose op amp (741, 351, 411, 081, etc.)

(2)  $1\mu\text{F}$  actual: \_\_\_\_\_

(1)  $2\text{k}\Omega$  actual: \_\_\_\_\_

(1)  $4\text{k}\Omega$  actual: \_\_\_\_\_

(2)  $10\text{k}\Omega$  actual: \_\_\_\_\_

(1)  $15\text{k}\Omega$  actual: \_\_\_\_\_

(1)  $22\text{k}\Omega$  actual: \_\_\_\_\_

LM741 Datasheet: <http://www.ti.com/lit/ds/symlink/lm741.pdf>

LF351 Datasheet: <https://www.st.com/resource/en/datasheet/lf351.pdf>

LF411 Datasheet: <http://www.ti.com/lit/ds/symlink/lf411.pdf>

TL081 Datasheet: <http://www.ti.com/lit/ds/symlink/tl081.pdf>

## Schematic

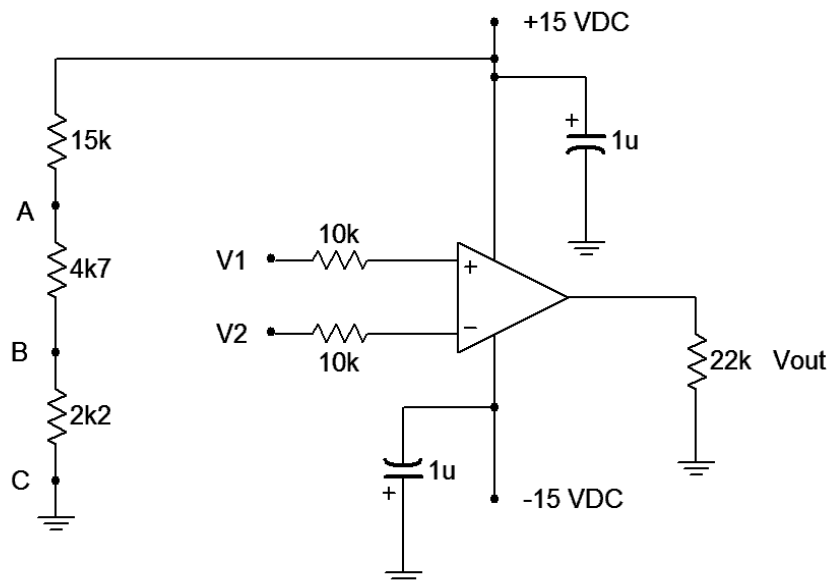


Figure 1

## Procedure

1. Calculate the voltages at points A, B, and C, and record them in Table 1.
2. Assemble the circuit of Figure 1.
3. Using the input combinations listed in Table 2, apply the appropriate signals to  $V_1$  and  $V_2$ . Measure the output signal using the oscilloscope, and record the values in Table 2.
4. Connect  $V_1$  to a 10 volt peak-to-peak 1 kHz sine wave. Make sure the oscilloscope inputs are set to DC Coupling, and then connect probe 1 to  $V_1$ , probe 2 to  $V_2$  and probe 3 to  $V_{out}$ .
5. Connect  $V_2$  to point A. Measure the output voltage and save a copy of the oscilloscope display as Graph 1.
6. Connect  $V_2$  to point B. Measure the output voltage and save a copy of the oscilloscope display as Graph 2.
7. Connect  $V_2$  to point C. Measure the output voltage and save a copy of the oscilloscope display as Graph 3.

## Computer Simulation

8. Build the circuit of Figure 1 in a simulator and run a Transient Analysis echoing steps 4 through 7. Compare the results to the waveforms generated experimentally.

## Data Tables

Connection Node	Voltage
A	
B	
C	

Table 1



$V_1$	$V_2$	$V_{out}$
A	A	
A	B	
A	C	
B	A	
B	B	
B	C	
C	A	
C	B	
C	C	

Table 2

## Questions

1. What happens when  $V_1 > V_2$ ? Why?
2. What happens when  $V_1 < V_2$ ? Why?

3. What happens when  $V_1 = V_2$ ? Why?
4. Explain the differences in the waveforms recorded in Graphs 1 through 3.
5. How would the waveform displays be altered if the oscilloscope inputs were set to AC Coupling instead of DC Coupling in step 4?
6. How would the results of this exercise change if the op amp had a very low gain, say only 1 or 2?



# 4. The Non-inverting Voltage Amplifier

## Objective

In this exercise, the performance of the non-inverting voltage amplifier will be examined. The investigation will include the effect of feedback resistors on setting voltage gain, stability of gain with differing op amps, and input impedance.

## Theory Overview

The non-inverting voltage amplifier is based on series-parallel negative feedback. As the ideal voltage-controlled voltage source, this amplifier exhibits high input impedance, low output impedance, and stable voltage gain. The voltage gain is set by the two feedback resistors,  $R_i$  and  $R_f$ .

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 3.4, The Four Variants of Negative Feedback

Section 4.2, Inverting and Non-inverting Amplifiers

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

### For Distortion Measurement Only

(1) Low distortion sine source	model: _____	srn: _____
(1) Distortion analyzer	model: _____	srn: _____

## Components

(3) General purpose op amps (1 each of 741, 351, 318, 411, 081, etc.)	
(2) $1\mu F$	actual: _____
(1) $1k\ \Omega$	actual: _____
(1) $4k7\ \Omega$	actual: _____
(1) $10k\ \Omega$	actual: _____
(1) $22k\ \Omega$	actual: _____

(1) 33k  $\Omega$       actual: \_\_\_\_\_  
(1) 47k  $\Omega$       actual: \_\_\_\_\_  
(1) 100k  $\Omega$     actual: \_\_\_\_\_

LM741 Datasheet: <http://www.ti.com/lit/ds/symlink/lm741.pdf>

LF351 Datasheet: <https://www.st.com/resource/en/datasheet/lf351.pdf>

LF411 Datasheet: <http://www.ti.com/lit/ds/symlink/lf411.pdf>

LM318 Datasheet: <http://www.ti.com/lit/ds/symlink/lm318-n.pdf>

TL081 Datasheet: <http://www.ti.com/lit/ds/symlink/tl081.pdf>

## Schematics

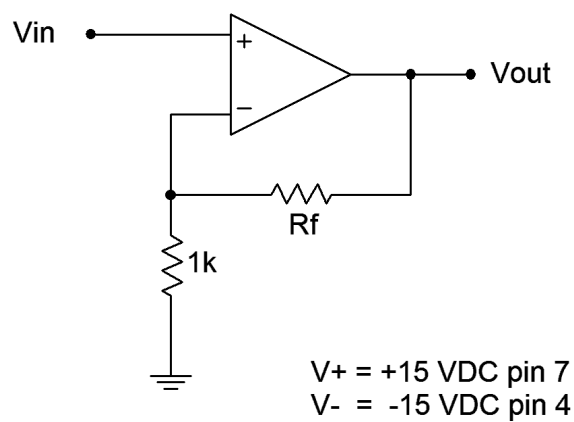


Figure 1

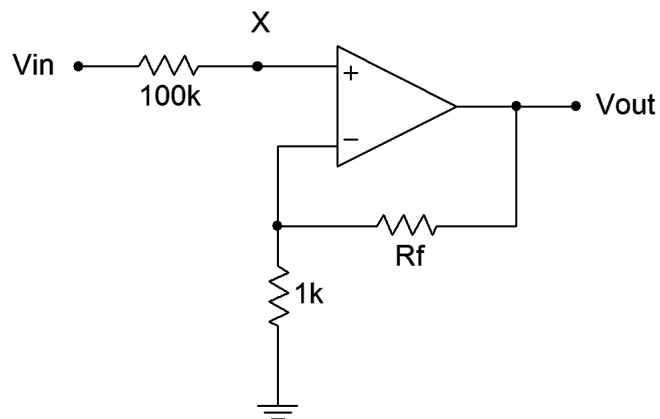


Figure 2

## Procedure

1. The voltage gain of the non-inverting amplifier can be determined accurately from the feedback resistors  $R_i$  and  $R_f$ . Calculate the voltage gains for the amplifier of Figure 1 for the  $R_f$  values specified, and record them in Table 1.
2. Assemble the circuit of Figure 1 using the  $4k7\ \Omega$  resistor.
3. Set the generator to a 1 kHz sine wave, 100 millivolts peak.
4. Apply the generator to the amplifier. Measure and record the output voltage in Table 1. Also, compute the resulting experimental voltage gain and gain deviation.
5. Repeat step 4 for the remaining  $R_f$  values in Table 1.
6. For any given  $R_i$ ,  $R_f$  combination, the voltage gain should be stable regardless of the precise op amp used, even if it is of an entirely different model. To verify this, first set  $R_f$  to  $22k\ \Omega$ .
7. Set the generator to a 1 kHz sine wave, 100 millivolts peak.
8. Apply the generator to the amplifier. Measure and record the output voltage in Table 2. Also, compute the resulting experimental voltage gain and gain deviation.
9. Repeat step 8 for two other op amps.
10. It is not practical to use an ohmmeter to determine the input impedance of an active circuit. Instead, input impedance can be found by utilizing the voltage divider effect. Modify the circuit by adding the extra input resistor as shown in Figure 2.
11. Set  $R_f$  to  $4k7\ \Omega$ .
12. Set the generator to a 200 Hz sine wave, 1 volt peak.
13. Apply the generator to the amplifier. Use a DMM to measure and record the AC potential from  $V_{in}$  to point X (i.e.,  $V_A$ , the voltage across the  $100k$ ) in Table 3. Using KVL, determine the voltage from point X to ground ( $V_B$ ) and record in Table 3 (don't forget to compensate for peak versus RMS readings). Finally, compute the resulting input impedance by using the voltage divider rule. Note: If the DMM is not sensitive enough and registers 0 volts for  $V_A$ , it is safe to assume that  $Z_{in}$  is considerably larger than the  $100k\ \Omega$  sensing resistor.

## Distortion Measurement

14. Return to the amplifier of Figure 1 with  $R_f$  set to  $10\text{k}\Omega$ . If available, the LF351 is a good choice for the op amp in this portion. Replace the general purpose generator with the low distortion sine source set to  $1\text{ kHz}$ . Adjust its output level so that the output of the op amp is approximately  $0\text{ dBV}$ .
15. Apply the distortion analyzer to the output of the op amp, read the resulting THD percentage and record it in Table 4.
16. Repeat steps 14 and 15 using the remaining  $R_f$  values in Table 4.

## Troubleshooting

17. Continuing with the amplifier of Figure 1, reset  $R_f$  to  $4\text{k}\Omega$ . Estimate and then measure the results for each individual error presented in Table 5.

## Data Tables

$R_f$	Theoretical $A_v$	$V_{out}$	Experimental $A_v$	% Deviation
$4\text{k}\Omega$				
$10\text{k}\Omega$				
$22\text{k}\Omega$				
$33\text{k}\Omega$				
$47\text{k}\Omega$				

Table 1

Op Amp	Theoretical $A_v$	$V_{out}$	Experimental $A_v$	% Deviation
1				
2				
3				

Table 2

$V_A$	$V_B$	$Z_{in}$

Table 3

$R_f$	% THD
10k $\Omega$	
22k $\Omega$	
47k $\Omega$	

Table 4



Error	Quantity	Estimate	Actual
R <sub>i</sub> 's third band is orange	V <sub>out</sub>		
f <sub>in</sub> is 100 Hz	V <sub>out</sub>		
R <sub>i</sub> is swapped with R <sub>f</sub>	V <sub>out</sub>		
+ and – signal input pins swapped	V <sub>out</sub>		

Table 5

## Questions

1. What is the effect as R<sub>f</sub> is increased?
2. How does the voltage gain vary as the op amp is changed?
3. Does the non-inverting voltage amplifier exhibit a predictable and stable voltage gain?
4. What can be said about the input impedance of this type of amplifier?
5. What is the relationship between gain, feedback and distortion?

# 5. The Inverting Voltage Amplifier

## Objective

In this exercise, the performance of the inverting voltage amplifier will be examined. The investigation will include the effect of feedback resistors on setting voltage gain, stability of gain with differing op amps, and the concept of virtual ground.

## Theory Overview

The inverting voltage amplifier is based on parallel-parallel negative feedback. This amplifier exhibits modest input impedance, low output impedance, and stable inverting voltage gain. The voltage gain is set by the two feedback resistors,  $R_i$  and  $R_f$ .

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*  
Section 4.2, Inverting and Non-inverting Amplifiers

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

(3) General purpose op amps (1 each of 741, 351, 318, 411, 081, etc.)	
(2) $1\mu F$	actual: _____
(1) $1k\ \Omega$	actual: _____
(1) $4k7\ \Omega$	actual: _____
(1) $10k\ \Omega$	actual: _____
(1) $22k\ \Omega$	actual: _____
(1) $33k\ \Omega$	actual: _____
(1) $47k\ \Omega$	actual: _____

## Schematic

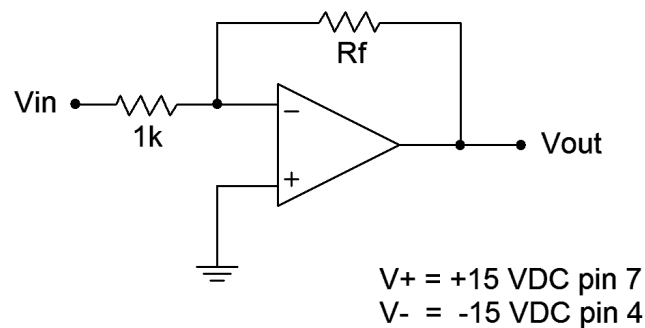


Figure 1

## Procedure

1. The voltage gain of the inverting amplifier can be determined accurately from the feedback resistors  $R_i$  and  $R_f$ . Calculate the voltage gains for the amplifier of Figure 1 for the  $R_f$  values specified, and record them in Table 1.
2. Assemble the circuit of Figure 1 using the  $4k7\ \Omega$  resistor.
3. Set the generator to a 1 kHz sine wave, 100 millivolts peak.
4. Apply the generator to the amplifier. Measure and record the output voltage in Table 1, noting its phase relative to the input. Also, compute the resulting experimental voltage gain and gain deviation.
5. Repeat step 4 for the remaining  $R_f$  values in Table 1.
6. For any given  $R_i$ ,  $R_f$  combination, the voltage gain should be stable regardless of the precise op amp used, even if it is of an entirely different model. To verify this, first set  $R_f$  to  $22k\ \Omega$ .
7. Set the generator to a 1 kHz sine wave, 100 millivolts peak.
8. Apply the generator to the amplifier. Measure and record the output voltage in Table 2. Also, compute the resulting experimental voltage gain and gain deviation.
9. Repeat step 8 for two other op amps.

10. The concept of virtual ground is very important. A virtual ground exists at the inverting input of the op amp in this circuit. Ideally, the voltage at this point should be very close to 0. Through voltage divider effect, this implies that all of the input signal must be dropping across  $R_i$ , and thus  $R_i$  must establish the input impedance of the amplifier.
11. Set  $R_f$  to  $4k7\ \Omega$ .
12. Set the generator to a 200 Hz sine wave, 1 volt peak.
13. Apply the generator to the amplifier. Use a DMM to measure and record the AC potential at the inverting terminal of the op amp. Record the value in Table 3.

### Computer Simulation

14. Build the circuit in a simulator and run a Transient Analysis echoing steps 2 through 5. Compare the results to the waveforms generated experimentally.
15. Repeat step 14 but this time use the Distortion or Fourier Analysis to compare voltage gain to THD.

### Data Tables

$R_f$	$A_v$ Theory	$V_{out}$	Phase	Experimental $A_v$	% Deviation
$4k7\ \Omega$					
$10k\ \Omega$					
$22k\ \Omega$					
$33k\ \Omega$					
$47k\ \Omega$					

Table 1

Op Amp	$A_v$ Theory	$V_{out}$	Experimental $A_v$	% Deviation
1				
2				
3				

Table 2

$V_{\text{inverting-input}}$	
------------------------------	--

Table 3

## Questions

1. What is the effect as  $R_f$  is increased?
2. How does the voltage gain vary as the op amp is changed?
3. Does the inverting voltage amplifier exhibit a predictable and stable voltage gain?
4. What can be said about the input impedance of this type of amplifier?
5. Based on the simulation, what is the relationship between gain, feedback and distortion for this circuit?

# 6. The Op Amp Differential Amplifier

## Objective

In this exercise, the performance of an op amp based differential amplifier will be examined. The investigation will include the effects of differential gain and common-mode rejection ratio (CMRR).

## Theory Overview

An op amp differential amplifier can be created by combining both a non-inverting voltage amplifier and an inverting voltage amplifier in a single stage. Proper gain matching between the two paths is essential to maximize the common-mode rejection ratio. Differential gain is equal to the gain of the inverting path.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 4.2, Inverting and Non-inverting Amplifiers

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

(2) General purpose op amps (741, 351, etc.)	
(2) 1 $\mu$ F	actual: _____
(2) 10 k $\Omega$	actual: _____
(1) 15 k $\Omega$	actual: _____
(1) 22 k $\Omega$	actual: _____
(2) 100 k $\Omega$	actual: _____
(1) 10 k $\Omega$ potentiometer	

# Schematics

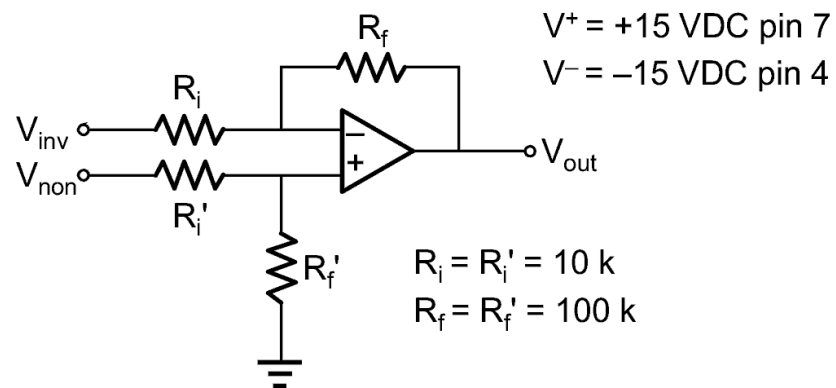


Figure 1

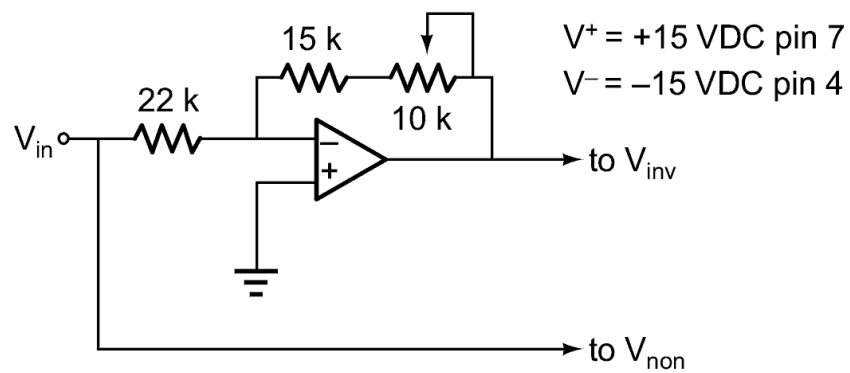


Figure 2

## Procedure

1. This circuit can be examined through the use of the Superposition Theorem. The contribution of each input can be measured individually, combined, and then compared with common-mode and differential inputs.
2. Calculate the differential voltage gain for the amplifier and record it in Table 1
3. Assemble the circuit of Figure 6.1. Try to get the  $R_i/R_f$  ratio as close as possible to the  $R_i/R_f$  ratio, even if you have to mix and match several resistors.
4. Set the generator to a 1 kHz sine wave, 500 millivolts peak.
5. Apply the generator to the  $V_{inv}$  input, and ground the  $V_{non}$  input.
6. Measure and record the output voltage in Table 2, noting the phase relative to the input. Also, compute the resulting voltage gain.
7. Swap the inputs by connecting the  $V_{non}$  input to the generator, and grounding the  $V_{inv}$  input.
8. Measure and record the output voltage in Table 2, noting the phase relative to the input. Also, compute the resulting voltage gain.
9. Compare the results of step 6 to step 8. The gains should be identical except that one is inverting while the other is non-inverting. Calculate the results of adding the two output signals and place the values in Table 3.
10. To measure the common-mode gain, connect both inputs to the generator (removing the  $V_{inv}$  ground). Record the output voltage and resulting gain in Table 3.
11. Assemble the circuit of Figure 2. Adjust the potentiometer to set the voltage gain to precisely  $-1$ . This circuit is a simple phase-splitter and is used to generate a differential input signal.
12. Connect the circuit of Figure 2 to the original circuit as shown.
13. Measure and record the output voltage in Table 3.
14. Based on the results of Table 3, compute the experimental common-mode rejection ratio and place it in Table 4.



## Data Tables

Theoretical Differential Gain	
-------------------------------	--

Table 1

Input	$V_{out}$	Phase	$A_v$
$V_{inv}$			
$V_{non}$			

Table 2

Circuit	$V_{out}$	$A_v$
Superposition		
Common-mode		
Differential		

Table 3

Experimental CMRR	
-------------------	--

Table 4

## Questions

1. What controls the differential gain?
2. Why is it important to match the resistor ratios in step 3?
3. Why is it important to set the gain of the phase-splitter to precisely one in step 11?
4. What determines the theoretical maximum CMRR for the op amp differential amplifier?



# 7. Parallel-Series and Series-Series Negative Feedback

## Objective

In this exercise, the performance of the current-source amplifiers will be examined. The investigation will include the effect of feedback resistors on setting gain for both the parallel-series inverting current amplifier and the series-series non-inverting voltage-to-current transducer.

## Theory Overview

Series-output feedback connections create controlled current sources. This means that the load current will be constant in spite of changes in load impedance. Two variants are possible. Parallel-input connections create a current-sensing circuit, thus P-S feedback forms a current-controlled current-source, or ideal current amplifier. The current gain is set by the two feedback resistors,  $R_i$  and  $R_f$ . Series-input connections create a voltage-sensing circuit, thus S-S feedback forms a voltage-controlled current-source, or voltage-to-current transducer. The transconductance is set by the feedback resistor  $R_i$ .

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 3.4, The Four Variants of Negative Feedback

Section 4.2, Inverting and Non-inverting Amplifiers

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

(1) General purpose op amp (741, 351, 411, 081, etc.)	
(2) $1\mu F$	actual: _____
(1) $100\ \Omega$	actual: _____
(2) $1k\ \Omega$	actual: _____
(1) $2k2\ \Omega$	actual: _____

(1) $3k3\ \Omega$	actual: _____
(1) $4k7\ \Omega$	actual: _____
(2) $10k\ \Omega$	actual: _____
(2) $22k\ \Omega$	actual: _____

## Schematics

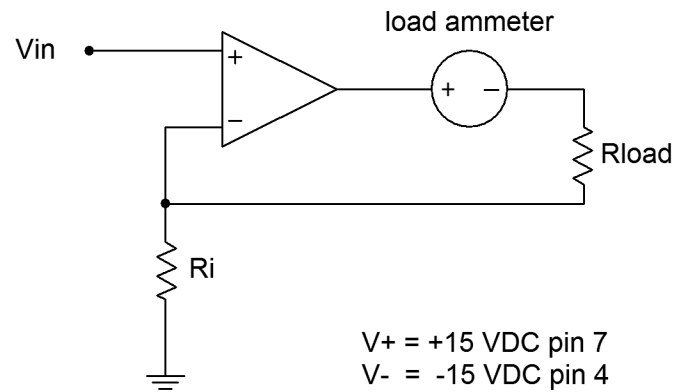


Figure 1

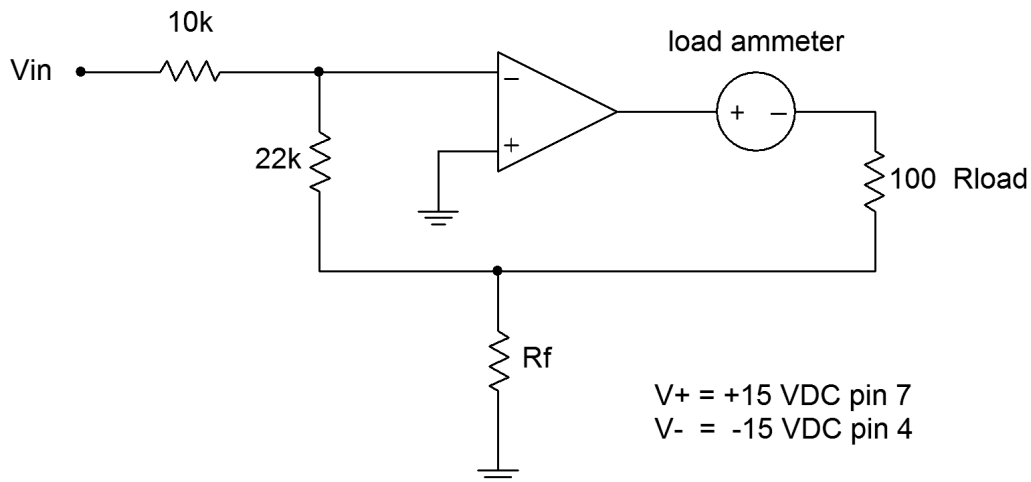


Figure 2

## Procedure

### Series-Series Voltage-to-Current Transducer

1. The transconductance of the voltage-to-current transducer can be determined from  $R_i$ . Based on the  $R_i$  values, calculate the expected  $I_{load}$  for the circuit of Figure 1, and record them in Table 1.
2. Assemble the circuit of Figure 1 using  $R_i = 1k\ \Omega$  and  $R_{load} = 100\ \Omega$ .
3. Set the generator to a 100 Hz sine wave, 1 volt peak.
4. Apply the generator to the amplifier. Measure and record the load current in Table 1. Also, compute the resulting theoretical versus experimental deviation.
5. Repeat step 4 for the remaining  $R_i$  values in Table 1.
6. Since the circuit behaves as a constant current source, the value of the load resistance should have no effect on the load current (within normal parameters). To verify this, change  $R_{load}$  to  $1k\ \Omega$  and repeat steps 4 and 5, using Table 2.

### Parallel-Series Current Amplifier

7. The gain of the current amplifier can be determined from  $R_i$  and  $R_f$ . Based on these values, calculate the expected  $A_i$  and  $I_{load}$  for the circuit of Figure 2, and record them in Table 3.
8. Assemble the circuit of Figure 2 using  $22k\ \Omega$  for  $R_f$ .
9. Set the generator to a 100 Hz sine wave, 1 volt peak. Note that the  $10k\ \Omega$  resistor at the input serves to convert the voltage from the generator into a current. With the values specified, the input current should be approximately 100 microamps.
10. Apply the generator to the amplifier. Measure and record the load current in Table 3. Also, compute the resulting current deviation.
11. Repeat step 10 for the remaining  $R_f$  values in Table 3.

### Troubleshooting

12. Utilizing the circuit of Figure 2, suppose that all of the results found in Table 3 are approximately 10 times smaller than they should be. Consider and test at least two plausible causes for this scenario, and include the results in the technical report.

## Data Tables

$R_i$	$I_{load} 100\ \Omega$ Theory	$I_{load} 100\ \Omega$ Experiment	% Deviation
1k $\Omega$			
2k2 $\Omega$			
3k3 $\Omega$			
4k7 $\Omega$			
10k $\Omega$			

Table 1

$R_i$	$I_{load} 1k\ \Omega$ Theory	$I_{load} 1k\ \Omega$ Experiment	% Deviation
1k $\Omega$			
2k2 $\Omega$			
3k3 $\Omega$			
4k7 $\Omega$			
10k $\Omega$			

Table 2

$R_f$	$A_i$ Theory	$I_{load}$ Theory	$I_{load}$ Experiment	% Deviation
22k $\Omega$				
10k $\Omega$				
4k7 $\Omega$				
2k2 $\Omega$				

Table 3

## Questions

1. What is the effect as  $R_i$  is increased in the circuit of Figure 1?
2. Does the load impedance play an appreciable role in setting the load current?
3. What is the effect as  $R_f$  is decreased in the circuit of Figure 2?
4. In practical voltage-source circuits, the load impedance can be too small, forcing the op amp into current limiting with resulting distortion. Are there similar limits in the current-source circuits?





# 8. Gain-Bandwidth Product

## Objective

In this exercise, the upper frequency limit of a typical amplifier will be examined. The investigation will include the effect of voltage gain on  $f_2$ . Two different measurement techniques will be employed: direct measurement of the 3 dB frequency, and indirect measurement via rise time.

## Theory Overview

The upper break frequency,  $f_2$ , of a typical amplifier is a function of the circuit gain and the op amp's unity-gain frequency,  $f_{unity}$ . Typical op amps exhibit a 20 dB per decade roll off slope in their open-loop response. When negative feedback is applied, this results in a direct tradeoff between closed-loop gain and  $f_2$ . Any increase in gain results in an equivalent decrease in  $f_2$ , and vice versa. In other words, the product of closed-loop gain and  $f_2$  must be a constant. This constant can be found on a device data sheet as either  $f_{unity}$  or GBW (short for Gain-BandWidth product).

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 5.3, Gain-Bandwidth Product

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

- (1) Medium speed op amp (351, 411, 081, etc., do **not** use 741 or similar)
- (2) 1 $\mu$  F      actual: \_\_\_\_\_
- (1) 220  $\Omega$       actual: \_\_\_\_\_
- (1) 4k7  $\Omega$       actual: \_\_\_\_\_
- (1) 10k  $\Omega$       actual: \_\_\_\_\_
- (1) 22k  $\Omega$       actual: \_\_\_\_\_
- (1) 33k  $\Omega$       actual: \_\_\_\_\_
- (1) 47k  $\Omega$       actual: \_\_\_\_\_

## Schematic

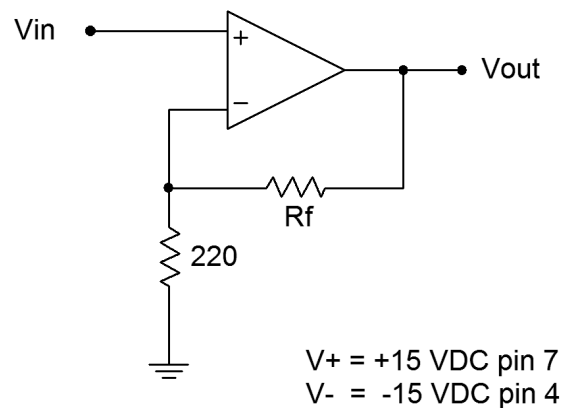


Figure 1

## Procedure

1. The upper break frequency,  $f_2$ , of the amplifier in Figure 1 can be determined from its voltage gain and the  $f_{unity}$  of the op amp. Calculate the  $f_2$  values for the amplifier of Figure 1 for the  $R_f$  values specified, and record them in Table 1.
2. Assemble the circuit of Figure 1 using the 4k7  $\Omega$  resistor.
3. Set the generator to a 100 Hz sine wave.
4. Apply the generator to the amplifier and adjust its level to achieve a 5 volt peak signal out of the op amp. Measure the input voltage and compute the resulting voltage gain. Record this voltage gain in Table 1.
5. Increase the frequency until the op amp's output voltage drops 3 dB (i.e., to 0.707 times 5 volts peak). Record this frequency in Table 1 as the experimental  $f_2$ .
6. Compute the experimental  $f_{unity}$  by multiplying the experimental voltage gain by the experimental  $f_2$ , and enter this value in Table 1.
7. Repeat steps 3 through 6 for the remaining  $R_f$  values in Table 1. Note that the values in the experimental  $f_{unity}$  column should be consistent with the  $f_{unity}$  specified in the device data sheet.

8. An alternate method to determine  $f_2$  is to measure the rise time of an output square wave. To follow this method, first set the generator to a 1 kHz square wave.
9. Apply the generator to the amplifier and adjust its level to achieve a 2 volt peak signal out of the op amp. Measure the rise time and record this value in Table 2. An accurate measurement is important, so be sure to expand the time base so that the rising edge fills the majority of the oscilloscope display.
10. Use the rise time to compute the experimental  $f_2$ , and record this value in Table 2.
11. Compute the experimental  $f_{unity}$  by multiplying the experimental voltage gain from Table 1 by the experimental  $f_2$  found in step 10, and enter this value in Table 2.
12. Repeat steps 9 through 11 for the remaining  $R_f$  values in Table 2. Note that the values in the experimental  $f_{unity}$  column should be consistent with those found in Table 1.

### Computer Simulation

13. Build the circuit in a simulator and run an AC Analysis for each resistor listed in Table 1. Be sure to run the plot from 100 Hz to approximately  $f_{unity}$  and use a decibel scale for the gain amplitude. Record the simulation  $f_2$  results in Table 3 and compare them to the  $f_2$  values measured in Tables 1 and 2. Include the graph for the 4k7 with the technical report.

### Data Tables

$R_f$	$f_2$ Theory	$A_v$ Experiment	$f_2$ Experiment	$f_{unity}$ Experiment
4k7 $\Omega$				
10k $\Omega$				
22k $\Omega$				
33k $\Omega$				
47k $\Omega$				

Table 1

$R_f$	$T_{rise}$ Experiment	$f_2$ Experiment	$f_{unity}$ Experiment
4k7 $\Omega$			
10k $\Omega$			
22k $\Omega$			
33k $\Omega$			
47k $\Omega$			

Table 2

$R_f$	$f_2$ Simulation
4k7 $\Omega$	
10k $\Omega$	
22k $\Omega$	
33k $\Omega$	
47k $\Omega$	

Table 3

## Questions

1. What is the effect on  $f_2$  as  $A_v$  is increased?
2. What is the effect on rise time as  $A_v$  is increased?
3. Is  $f_{unity}$  a constant across a wide range of voltage gains?
4. How would the results of this exercise differ if an op amp with a considerably higher  $f_{unity}$  was used?



# 9. Slew Rate and Power Bandwidth

## Objective

In this exercise, the effects of slew rate on pulse and sinusoidal waveforms will be examined.

## Theory Overview

Slew rate places an upper “speed limit” on the rate of change of output voltage. This tends to slow the rising and falling edges of pulse signals, turning them into a trapezoidal shape. In the case of sinusoidal signals, slew rate limiting tends to turn waves into a more triangular shape. The maximum non-slewed sine wave frequency for a given output amplitude is termed the power bandwidth, or  $f_{\max}$ . Any output signal that exceeds the power bandwidth at the stated output amplitude will exhibit slew rate induced distortion. Slew rate is determined by the internal characteristics of a given op amp. In most op amps, circuit gain or feedback resistor values do not affect the slew rate.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 5.4, Slew Rate and Power Bandwidth

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

(3) General purpose op amps (1 each of 741, 351, 081, 411, etc., do **not** use 318 or similar)

(2) 1 $\mu$ F	actual: _____
(1) 2k2 $\Omega$	actual: _____
(1) 10k $\Omega$	actual: _____
(1) 22k $\Omega$	actual: _____
(1) 33k $\Omega$	actual: _____
(1) 47k $\Omega$	actual: _____



## Schematic

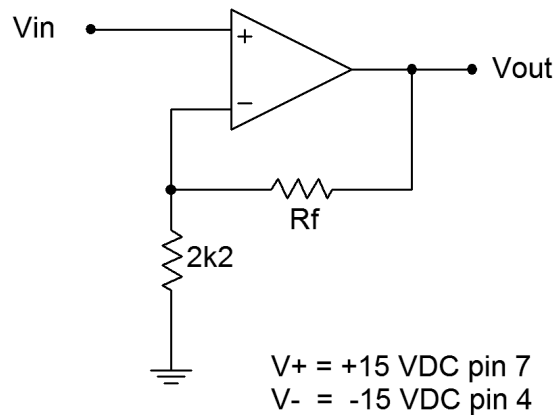


Figure 1

## Procedure

1. Calculate the voltage gains for the amplifier of Figure 1 for the  $R_f$  values specified, and record them in Table 1.
2. Look up the typical slew rates for the three op amps and place them in Table 2.
3. Assemble the circuit of Figure 1 using the  $22k\ \Omega$  resistor and the slowest op amp.
4. Set the generator to a 1 kHz square wave.
5. Apply the generator to the amplifier and adjust the generator's amplitude to achieve a clipped signal at the output of the op amp. Make sure that the edges of the waveform are sharp, and not rounded. Expand the time scale so that the rising edge fills the oscilloscope display. Measure and record the slew rate in Table 1.
6. Repeat step 5 for the remaining  $R_f$  values in Table 1.
7. Set  $R_f$  to  $10k\ \Omega$ . Set the generator to a 1 kHz square wave.
8. Apply the generator to the amplifier and adjust the generator's amplitude to achieve a clipped signal at the output of the op amp. Save a copy of the oscilloscope display showing approximately one cycle of the waveform. Measure and record the slew rate in Table 2.

9. Repeat step 8 for the other op amps in Table 2.
10. Using a peak sine wave output of 10 volts, compute the theoretical power bandwidth for each of the op amps in Table 3.
11. Set the generator to a 1 kHz sine wave.
12. Apply the generator to the amplifier and adjust the generator's amplitude to achieve a 10 volt peak signal at the output of the op amp.
13. While monitoring the amplifier's output signal with the oscilloscope, increase the frequency until slew rate limiting occurs (the waveform will start to appear triangular). The point at which slew rate limiting just begins is not easy to discern by eye. If the waveform is triangular, then the op amp is well into slew rate limiting. Gradually decrease the frequency until the waveform distortion just seems to disappear. Record the frequency as the experimental  $f_{\max}$  in Table 3.
14. Repeat steps 11 through 13 for the remaining op amps in Table 3.

### Computer Simulation

15. Build the circuit in a simulator and run a Transient Analysis for each op amp used in Table 2, echoing steps 7 through 9. Be sure to set the time scale so that at least one but no more than two cycles are plotted. Compare these to the corresponding oscilloscope images and include the graphs with the technical report.

### Data Tables

$R_f$	$A_v$ Theory	Slew Rate Experiment
22k $\Omega$		
33k $\Omega$		
47k $\Omega$		

Table 1

Op Amp	Slew Rate Theory	Slew Rate Experiment
1		
2		
3		

Table 2

Op Amp	$f_{\max}$ Theory	$f_{\max}$ Experiment	% Deviation
1			
2			
3			

Table 3

## Questions

1. Does voltage gain affect slew rate?
2. How does the slew rate affect power bandwidth?
3. How does the output amplitude affect power bandwidth?
4. Is it possible for triangle waves to suffer from slew rate limiting?

# 10. The Non-compensated Op Amp

## Objective

In this exercise, the performance of a typical non-compensated op amp, the 301, will be examined. The investigation will include the effect of the external compensation capacitor on voltage gain, closed-loop bandwidth and slew rate.

## Theory Overview

Op amps usually contain an internal compensation capacitor,  $C_c$ . This capacitor enforces a 20 dB per decade gain slope up to the unity-gain frequency, and allows stable voltage gains down to unity. Unfortunately, this will not normally produce optimal values for small signal bandwidth and slew rate for gains considerably greater than unity. In the case where unity-gain stability is not required, a smaller value for  $C_c$  may be used, resulting in improved bandwidth and slew rate. Non-compensated op amps include connections for an external compensation capacitor that can be adjusted for optimal performance.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 5.4, Slew Rate and Power Bandwidth

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM capable of measuring in dB	model: _____	srn: _____

## Components

(1) LM301 op amp	
(2) 1 $\mu$ F	actual: _____
(1) 150 pF	actual: _____
(1) 33 pF	actual: _____
(1) 10 pF	actual: _____
(1) 22 k $\Omega$	actual: _____
(1) 47 k $\Omega$	actual: _____
(1) 100 k $\Omega$	actual: _____

LM301 Data sheet: <http://www.ti.com/lit/ds/symlink/lm101a-n.pdf>

## Schematic

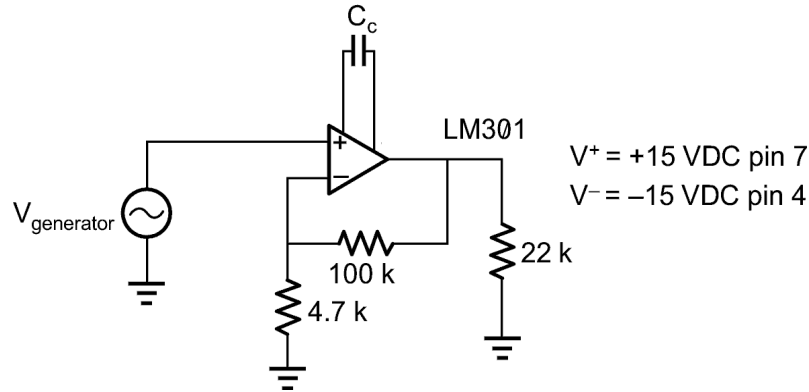


Figure 1

## Procedure

1. Notice that Figure 10.1 is a series-parallel non-inverting voltage amplifier. Calculate the theoretical voltage gain for the amplifier and record it in Table 1.
2. Assemble the circuit using  $C_c = 150\text{ pF}$ .
3. Set the generator to a 100 Hz sine wave.
4. Set the output voltage of the op amp to 1 volt peak. Measure and record the input voltage in Table 2. Also, compute the resulting voltage gain.
5. Using the decibel-reading voltmeter, increase the input frequency until the op amp's output voltage drops 3 dB from its value at 100 Hz. If a dB meter is not available, use the oscilloscope to find the frequency at which the op amp's output voltage drops to 0.707 times the 100 Hz value. (Note that  $-3\text{ dB}$  corresponds to a factor of 0.707.) Record the frequency in Table 2.
6. Change the generator to a 10 kHz square wave.
7. Increase the generator's amplitude so that the output of the op amp is obviously slewed, about 10 volts peak (straight lines for the leading and trailing edges).
8. Measure the slew rate and record it in Table 2.
9. Repeat steps 3 through 8 using  $C_c = 33\text{ pF}$  and  $C_c = 10\text{ pF}$ .

## Data Tables

Theoretical voltage gain	
--------------------------	--

Table 1

$C_c$	$V_{in}$	$A_v$	$f_2$	SR
150 pF				
33 pF				
10 pF				

Table 2

## Questions

1. How does  $f_2$  vary with  $C_c$ ?
2. How does  $A_v$  vary with  $C_c$ ?
3. How does slew rate vary with  $C_c$ ?

5. How does this op amp compare with a typical compensated op amp such as the 741?

# 11. DC Offset

## Objective

In this exercise, the effect of DC offsets will be examined. The investigation will include the effect of voltage gain and op amp on the magnitude of offset, as well as standard techniques to null or remove offsets.

## Theory Overview

A DC offset is an undesirable effect. Due to internal mismatches in the op amp, a DC signal may be present at the output of an amplifier. This generally does not present a problem for an AC amplifier, but it does lead to ambiguity in the output of a DC amplifier. A DC offset may be either positive or negative. The magnitude of the offset is proportional to the gain of the amplifier and the size of the feedback resistors. It also depends on the “luck of the draw,” in other words, just how well matched the internals of a given op amp happen to be.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 5.5, Offsets

## Equipment

- |                          |              |            |
|--------------------------|--------------|------------|
| (1) Dual DC power supply | model: _____ | srn: _____ |
| (1) DMM                  | model: _____ | srn: _____ |

## Components

- (2) General purpose op amps (741, 351, 081, etc., do **not** use 411 or similar precision device)
- |                                |               |
|--------------------------------|---------------|
| (2) 1 $\mu$ F                  | actual: _____ |
| (2) 1k $\Omega$                | actual: _____ |
| (1) 4k7 $\Omega$               | actual: _____ |
| (1) 10k $\Omega$               | actual: _____ |
| (1) 22k $\Omega$               | actual: _____ |
| (1) 33k $\Omega$               | actual: _____ |
| (1) 47k $\Omega$               | actual: _____ |
| (1) 10k $\Omega$ potentiometer |               |



## Schematics

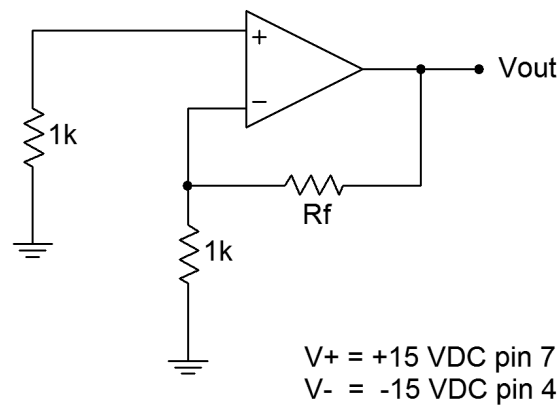


Figure 1

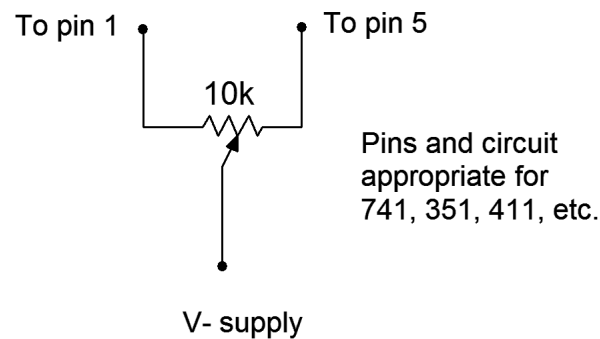


Figure 2

## Procedure

1. Note that the circuit of Figure 1 is a non-inverting voltage amplifier. Calculate the voltage gains for the amplifier of Figure 1 for the  $R_f$  values specified, and record them in Table 1.
2. The worst case output offset may be approximated by multiplying the worst case  $V_{os}$  found in the op amp's data sheet by the voltage gain. This ignores the effect of the feedback resistor values. Calculate the offsets for the gains found in step 1, and record the values in Table 1.
3. Assemble the circuit of Figure 11.1 using the  $4k7 \Omega$  resistor.
4. Measure and record the DC output offset voltage in Table 1.
5. Repeat step 4 for the remaining  $R_f$  values in Table 1.

6. Compute the resulting experimental  $V_{os}$  values by dividing the output offsets by the corresponding voltage gains. The experimental  $V_{os}$  values should be no larger than the value specified in the data sheet, although they may be considerably smaller. Finally, compute the offset deviations. Note that the  $V_{os}$  and deviation values should be fairly constant through the table.
7. Since the actual  $V_{os}$  of any given op amp can range between  $\pm V_{os}$  worst case, a different device may produce considerably different values from those in Table 1. To verify this, repeat steps 3 through 6 for a second op amp, and record your results in Table 2.
8. Manufacturers normally allow for output nulling through the addition of external circuitry. Modify the circuit by adding the components shown in Figure 2. Using the 47k  $\Omega$  resistor for  $R_f$ , adjust the potentiometer to null the output. Also, record the DC output voltage with the potentiometer fully clockwise and fully counterclockwise.

### Computer Simulation

9. Build the circuit of Figure 1 in a simulator using a 741 op amp and 47k for  $R_f$ . Run a DC Operating Point analysis to determine the DC output voltage. Compare this to the results measured in Tables 1 and 2. Repeat the simulation with all resistors 10 times larger, and again with all resistors 100 times larger.

### Data Tables

$R_f$	$A_v$ Theory	$V_{out}$ Theory	$V_{out}$ Experiment	$V_{os}$ Experiment	% Deviation
4k7 $\Omega$					
10k $\Omega$					
22k $\Omega$					
33k $\Omega$					
47k $\Omega$					

Table 1

$R_f$	$A_v$ Theory	$V_{out}$ Theory	$V_{out}$ Experiment	$V_{os}$ Experiment	% Deviation
4k7 $\Omega$					
10k $\Omega$					
22k $\Omega$					
33k $\Omega$					
47k $\Omega$					

Table 2

Potentiometer	$V_{out}$
CW	
CCW	

Table 3

## Questions

1. What is the effect on output offset voltage as the voltage gain is increased?





# 12. The Operational Transconductance Amplifier

## Objectives

In this exercise, an application of the operational transconductance amplifier (OTA) will be examined. The application is that of a voltage-controlled amplifier (VCA). The VCA has use in a variety of areas including automatic gain control, audio level compressors and amplitude modulators.

## Theory Overview

The gain of the OTA is a function of a programming current,  $I_{abc}$ . Since  $I_{abc}$  may be derived from other electronic signals, complex dynamic gains are possible. Further, because the OTA tends to behave as an ideal current source (i.e., it exhibits a high output impedance), a constant voltage output is best rendered through the use of a following current-to-voltage transducer. Finally, the OTA can only tolerate fairly small input signals, so some form of input attenuation is normally used.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 6.7, Operational Transconductance Amplifier

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(2) Function generators	model: _____	srn: _____
	model: _____	srn: _____
(1) Triple DC power supply	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

(1) 3080 OTA (or 13600 or 13700 with alternate pin-out)

(1) FET input op amp (351, 411, 081, etc.)

(2) 1 $\mu$ F	actual: _____
(2) 470 $\Omega$	actual: _____
(2) 22 k $\Omega$	actual: _____
(1) 33 k $\Omega$	actual: _____
(2) 47 k $\Omega$	actual: _____

(1) 100 k $\Omega$       actual: \_\_\_\_\_

(1) 10 k $\Omega$  potentiometer

LM3080 Data sheet: <http://www.ti.com/lit/ds/symlink/lm3080.pdf>

LM13700 Data sheet: <http://www.ti.com/lit/ds/symlink/lm13700.pdf>

## Schematic

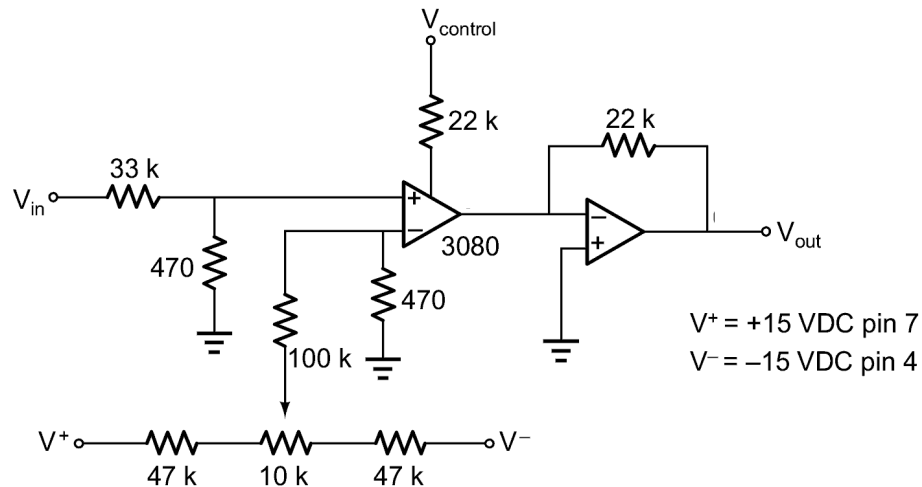


Figure 1

## Procedure

1. Assemble the circuit of Figure 1. Note that the power supplies are only  $\pm 5$  VDC, not the usual  $\pm 15$  VDC.
2. For proper operation, it is very important that any DC input signals be nulled. Failure to do so will cause the control signal to “leak” into the output. To null the circuit, first tie the left end of the 33 k $\Omega$  resistor to ground. Also, tie  $V_{\text{control}}$  to ground. Finally, adjust the potentiometer until  $V_{\text{out}}$  is 0 VDC. The circuit is now nulled. Unhook the resistor and control points from ground in order to continue to the next step.
3. Set  $V_{\text{control}}$  to  $-3$  VDC. If a third output is not available on the DC power supply, the  $-3$  VDC potential may be derived from the  $-5$  VDC supply and appropriate divider resistors.
4. Set the main generator to a 100 kHz sine wave, 1 volt peak.
5. Apply the generator to the circuit input. Measure and record the output voltage in Table 1. Also, compute the resulting experimental voltage gain.

6. Repeat steps 3 through 5 for the remaining  $V_{\text{control}}$  values in Table 1.
7. Using the data from Table 1, plot the gain versus control voltage characteristic as Graph 1.
8. Set the second generator to a 1 kHz sine wave, 1 volt peak. Apply the second generator to the  $V_{\text{control}}$  point.
9. Set the main generator to a 1 volt peak 100 kHz sine wave, and connect it to the circuit input.
10. Measure and record the output waveform as Graph 2.
11. Change the main generator to a 1 volt peak 100 kHz triangle wave and record the resulting output waveform as Graph 3.

## Data Tables

$V_{\text{control}}$	$V_{\text{out}}$	$A_v$
-3 VDC		
-2 VDC		
-1 VDC		
0 VDC		
+1 VDC		
+2 VDC		
+3 VDC		

Table 1



## Questions

1. What is the effect as  $V_{\text{control}}$  is increased?
2. Is the control/gain relationship linear?
3. What is the purpose of the second op amp in Figure 1?
4. Explain how the control signal “leaks” into the output signal if the circuit is not nulled properly.
5. Based on Graphs 2 and 3, does this circuit appear to be a good candidate for an amplitude modulator?

# 13. Precision Rectifiers

## Objective

In this exercise, precision half-wave and full-wave rectifiers will be examined. The investigation will include the accuracy of rectification and peak detection.

## Theory Overview

Simple passive diode circuits cannot rectify small signals accurately. The forward bias potential of the diode acts as a constant barrier. By placing the diode inside the feedback loop of an op amp, the forward bias potential can be compensated for to a great extent. Both half-wave and full-wave circuits can be created in this fashion. Further, the addition of load capacitance can be used to create a simple envelope detector. On the downside, the frequency response of precision rectifiers is limited by the op amp(s) used.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 7.2, Precision Rectifiers

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

(2) General purpose op amps (741, 351, 411, 081, etc.)

(2) Small-signal diodes (1N914, 1N4148, etc.)

(3) 1 $\mu$  F      actual: \_\_\_\_\_

(1) 10n F      actual: \_\_\_\_\_

(1) 22k  $\Omega$       actual: \_\_\_\_\_

(6) Equal value resistors in the range of 10k  $\Omega$  to 100k  $\Omega$

actual: \_\_\_\_\_

actual: \_\_\_\_\_

1N4148/1N914 Datasheet: <https://www.onsemi.com/pub/Collateral/1N914-D.PDF>

# Schematics

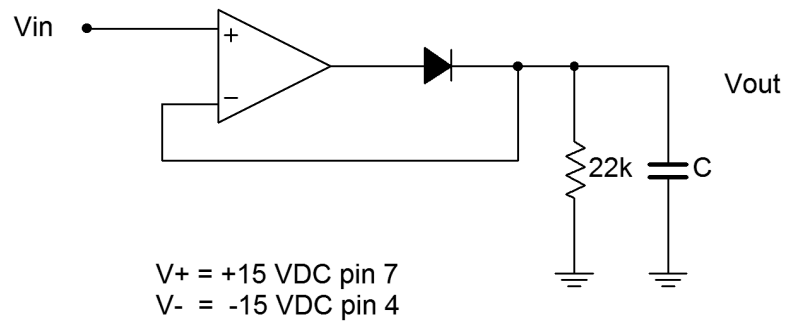


Figure 1

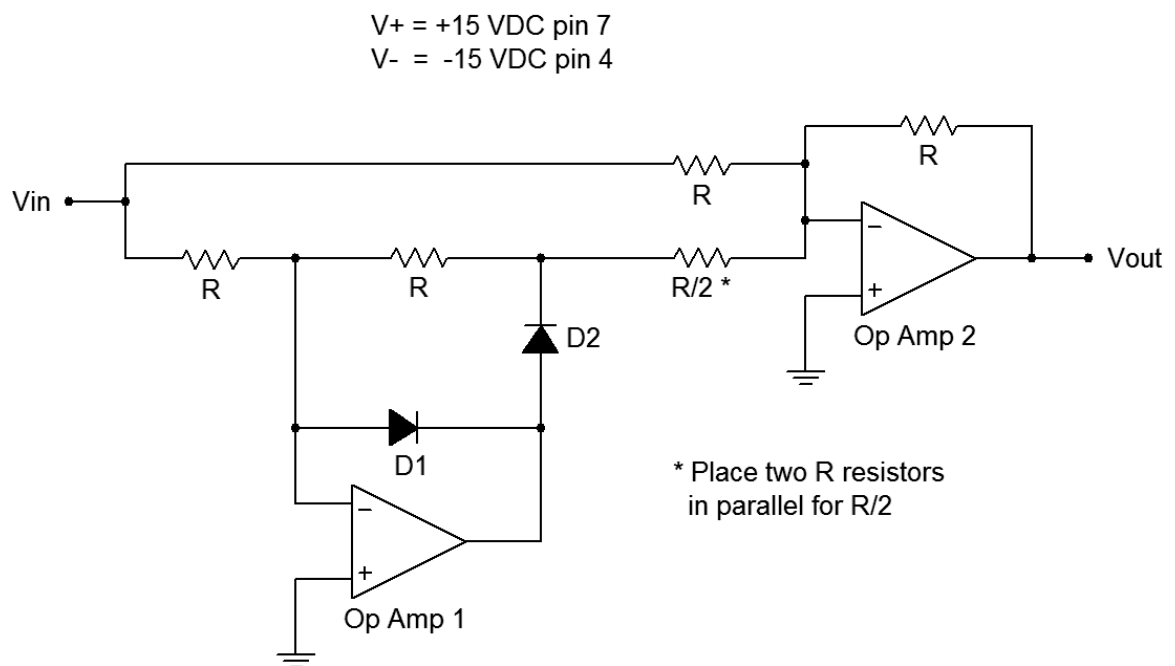


Figure 2

# Procedure

## Precision Half-wave Rectifier and Detector

1. The circuit of Figure 1 is a precision half-wave rectifier. Without C, the circuit responds as an “ideal diode” allowing only positive half-waves through. The addition of C turns the circuit into peak detector or analog pulse-stretcher. Since all of the circuits in this exercise can produce DC components in the output signals, it is very important to take measurements with the oscilloscope input set to **DC coupled**.
2. Assemble the circuit of Figure 1 without the load capacitor.
3. Set the generator to a 1 kHz sine wave, and set its output voltage to 1 volt peak.
4. Measure  $V_{out}$  and save a copy of the oscilloscope display as Graph 1. Also measure and save the waveform at the output pin of the op amp as Graph 2.
5. Reverse the diode, measure  $V_{out}$  and save a copy of the oscilloscope display as Graph 3.
6. While monitoring the load voltage, increase the frequency of the generator and note how the distortion in the waveform increases. If a considerably faster or slower op amp is available (in terms of  $f_{unity}$  and slew rate), repeat this process and compare the frequencies at which the two op amps start to distort.
7. Return the diode to its original orientation and add  $C = 10\text{n F}$ .
8. Apply a 1 volt peak 1 kHz pulse waveform with 10% duty cycle to the input of the circuit.
9. Measure  $V_{out}$  and save a copy of the oscilloscope display as Graph 4.
10. Replace the 10n F load capacitor with a 1  $\mu$  F capacitor. Measure and save the  $V_{out}$  waveform as Graph 5.

## Precision Full-wave Rectifier

11. Decide on a value for R in Figure 2 and assemble it. The actual value of R is not critical. The important thing is that the resistors should be close in value, preferably within a few percent of each other.
12. Set the generator to a 1 kHz sine wave, and set its output voltage to 1 volt peak.
13. Record the waveforms at the cathode of  $D_2$  and at  $V_{out}$  as Graph 6.

14. Reverse the polarity of the diodes and record the waveforms at  $D_2$  and at  $V_{out}$  as Graph 7.
15. Try several different input wave shapes (square, triangle, ramp, etc.) while monitoring  $V_{out}$  and note the resulting shapes.
16. Set the generator to a 1 volt peak 100 Hz sine wave and place the oscilloscope in XY mode.
17. For Graph 8, plot the transfer characteristic of the circuit by placing the X (horizontal) probe at the generator, and the Y (vertical) probe at the load ( $V_{out}$ ).

### Troubleshooting

18. Continuing with the circuit of Figure 2, estimate and then measure the results for each individual error presented in Table 1.

### Computer Simulation

19. Build the circuit of Figure 1 in a simulator using a 351 op amp and without the load capacitor. Run a Transient Analysis to determine the voltages at the output pin of the op amp and at  $V_{out}$ . Compare the waveforms to those recorded as Graphs 1 and 2.

### Data Table

Error	Quantity	Estimate	Actual
$R/2$ is simply $R$	$V_{out}$		
$D_2$ is shorted	$V_{out}$		
$R_i$ of op amp 1 is open	$V_{out}$		

Table 1

## Questions

1. What is the effect of flipping the diode in Figure 1?
2. How does the output waveform of the op amp itself compare with the load waveform?
3. What is the effect of increasing load capacitance in Figure 1?
4. In general, what can be said about the use of op amps with high slew rates and  $f_{unity}$  values in precision rectifiers?
5. What is the effect of flipping the diodes in Figure 2?
6. Briefly describe what each half of Figure 2 is doing.
7. What would be the effect of doubling  $R_f$  of the second op amp of Figure 2?



# 14. Function Generation

## Objective

In this exercise, the concept of function generation will be examined. The investigation will include the use of both biased diode networks and Zener diodes. Increasing as well as decreasing gain curves will be used.

## Theory Overview

The gain of an amplifier can be nonlinear if the feedback resistors themselves are nonlinear. By shunting feedback resistors with resistor-diode networks, the effective feedback resistance decreases as the input signal increases. If this network is placed across  $R_i$ , then an increasing gain function will be created. If the network is placed across  $R_f$ , then a decreasing gain function will be created. By combining several resistor-diode sections, complex transfer curves can be created.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 7.4, Function Generation

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

- (1) General purpose op amp (741, 351, 411, 081, etc.)
- (2) General purpose switching diodes (1N914, 1N4148, etc.)
- (2) 5.1 volt Zener diodes (NZX5V1B or 1N5231)
- (2) 3.3 volt Zener diodes (NZX3V3B or 1N5226)
- (2) 1 $\mu$  F      actual: \_\_\_\_\_
- (1) 4k7  $\Omega$       actual: \_\_\_\_\_
- (2) 10k  $\Omega$       actual: \_\_\_\_\_
- (1) 12k  $\Omega$       actual: \_\_\_\_\_
- (1) 15k  $\Omega$       actual: \_\_\_\_\_
- (1) 22k  $\Omega$       actual: \_\_\_\_\_



- (1) 33k  $\Omega$       actual: \_\_\_\_\_  
 (1) 47k  $\Omega$       actual: \_\_\_\_\_  
 (1) 56 k $\Omega$       actual: \_\_\_\_\_

1N4148/1N914 Datasheet: <https://www.onsemi.com/pub/Collateral/1N914-D.PDF>

NZX Series Datasheet: [https://assets.nexperia.com/documents/data-sheet/NZX\\_SER.pdf](https://assets.nexperia.com/documents/data-sheet/NZX_SER.pdf)

## Schematics

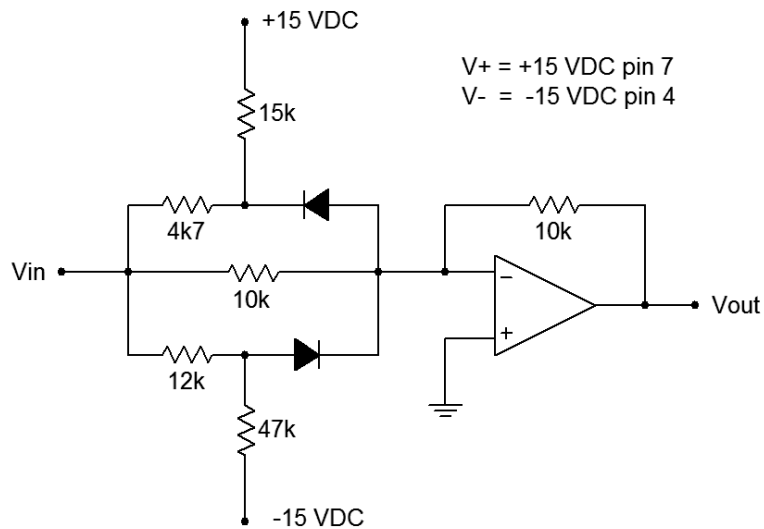


Figure 1

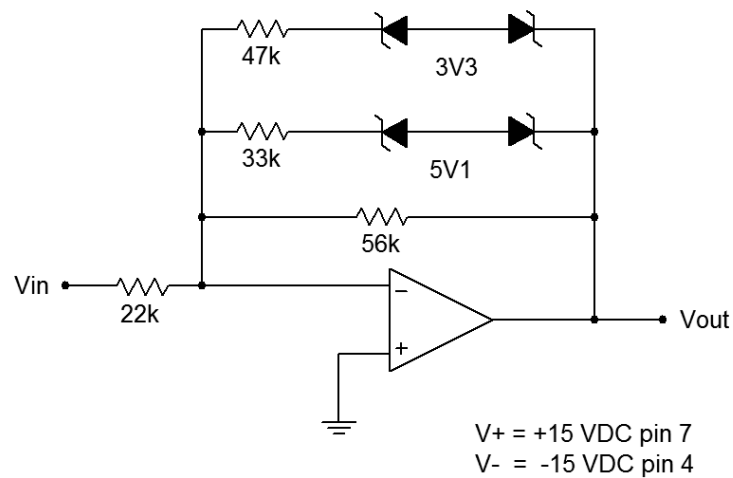


Figure 2

# Procedure

## Biased Diode Network

1. Calculate the break-points and slopes for the input/output transfer curve of the circuit in Figure 1. Record these values in Table 1.
2. Assemble the circuit of Figure 1.
3. Set the generator to a 1 volt peak 100 Hz triangle wave.
4. While monitoring the output of the op amp, increase the amplitude of the triangle wave and note how the shape of the wave changes. Save the display of the output voltage as Graph 1.
5. Switch the oscilloscope to XY mode. Switch the inputs to ground in order to center the spot. Connect the input voltage to the X (horizontal) channel, and the output of the op amp to the Y (vertical) channel.
6. Switch the input channels to **DC Coupled**. Save the resulting input/output transfer curve as Graph 2.

## Zener Diode Network

7. Calculate the break-points and slopes for the input/output transfer curve of the circuit in Figure 2. Record these values in Table 2.
8. Assemble the circuit of Figure 2.
9. Switch the oscilloscope back to Volts vs. Time mode.
10. Repeat steps 3 through 6, saving the displays as Graphs 3 and 4, respectively.

## Troubleshooting

11. Continuing with the circuit of Figure 2, estimate and then measure the results for each individual error presented in Table 3.

## Data Tables

Base voltage gain	
Positive break-point	
Gain beyond positive break-point	
Negative break-point	
Gain beyond negative break-point	

Table 1

Base voltage gain	
First break-point	
Gain beyond first break-point	
Second break-point	
Gain beyond second break-point	

Table 2

Error	Quantity	Estimate	Actual
33k swapped with 47k	$V_{out}$		
22k swapped with 56k	$V_{out}$		
One 5V1 Zener backwards	$V_{out}$		

Table 3

## Questions

1. What would happen in Figure 1 if the 12k  $\Omega$  and 4k7  $\Omega$  were swapped?
2. What happens in Figure 2 when the 33k  $\Omega$  and 47k  $\Omega$  are swapped?
3. Does the value of the DC power supply have any effect on the break-points of the circuit of Figure 1?
4. What is the effect of increasing the 22k  $\Omega$  in Figure 2?
5. What would the transfer curve look like if Figures 1 and 2 were cascaded?



# 15. The Linear Regulator

## Objective

In this exercise, the performance of a simple op amp-based linear regulator will be examined. The investigation will include the effect of scaling resistors on the load voltage and the usage of a current pass transistor.

## Theory Overview

Regulators are used to create a stable, clean DC voltage to power other electronic systems. The regulator voltage should not change as its load changes. A linear regulator may be based on a series-parallel feedback loop, using an op amp as a controller. The op amp compares a scaled version of the load voltage to a reference voltage. By changing either the reference or the scaling factor, a range of load voltages may be obtained. Because op amps typically produce insufficient current to drive many loads, a current pass transistor is used to boost output current capability.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 8.3, Linear Regulators

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Adjustable DC power supply	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

- (1) General purpose op amp (741, 351, 411, 081, etc.)
- (1) Medium power NPN transistor (2N5190G-2N5192G)
- (1) Zener diode around 5.1 volts (NZX5V1B, 1N751)

(2) 1 $\mu$ F	actual: _____
(1) 2k2 $\Omega$	actual: _____
(2) 47k $\Omega$	actual: _____
(2) 100k $\Omega$	actual: _____
(1) 100 $\Omega$ 5 watt	actual: _____

2N5192G Datasheet: [http://www.onsemi.com/pub\\_link/Collateral/2N5191-D.PDF](http://www.onsemi.com/pub_link/Collateral/2N5191-D.PDF)

NZX5V1B Datasheet: [https://assets.nexperia.com/documents/data-sheet/NZX\\_SER.pdf](https://assets.nexperia.com/documents/data-sheet/NZX_SER.pdf)

## Schematic

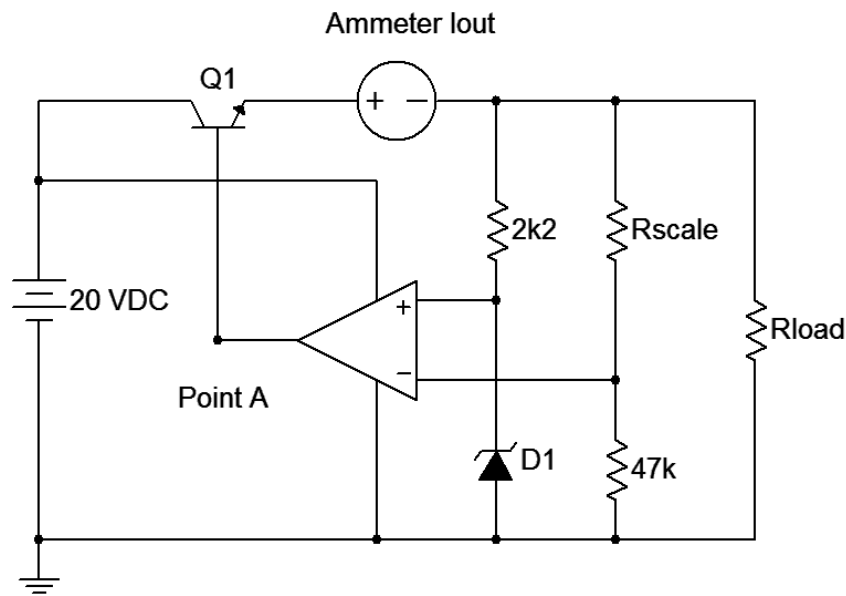


Figure 1

## Procedure

1. In this exercise, a DC source is being used to simulate the output of a rectified and filtered power source in the interest of simplicity.
2. Note that the op amp is acting as a series-parallel feedback amplifier where the load voltage is equal to  $V_{Zener}(1+R_{scale}/47k\ \Omega)$ . Changes to the load resistor should cause no change in the load voltage. Also, note that  $I_{out}$  is equal to the transistor's  $\beta$  times the output current of the op amp. The transistor is therefore being used as a current booster, and because it is located inside of the feedback loop, it should not affect the load voltage.
3. Connect the circuit of Figure 1 using an  $R_{scale}$  of 47k  $\Omega$ , and an  $R_{load}$  of 100k  $\Omega$ .
4. Calculate and record the values for  $V_{load}$ ,  $I_{load}$ ,  $I_{out}$ , and  $I_{out-op-amp}$  in Table 1. A typical  $\beta$  would be in the range of 50 to 100, depending on the pass transistor used.
5. Measure and record the values for  $V_{load}$ ,  $I_{load}$ ,  $I_{out}$ , and  $I_{out-op-amp}$  (i.e., at point A) in Table 2.
6. Change  $R_{scale}$  to 100k  $\Omega$  and repeat steps 4 and 5.
7. Change  $R_{scale}$  back to 47k  $\Omega$ , change  $R_{load}$  to 100  $\Omega$  and repeat steps 4, 5, and 6.

## Computer Simulation

8. One limitation of the preceding exercise is that it does not show how well the regulator suppresses AC ripple that might exist on the input power source. This can be accomplished easily in a simulator. Build the circuit in a simulator using  $R_{load}$  equal to  $100\ \Omega$  and  $R_{scale}$  equal to  $100k\ \Omega$ . To create the ripple, simply insert an AC power source in series with the 20 volt DC source (i.e., inserted between ground and the negative terminal of the 20 volt source). Set the AC source to 120 Hz and 2 volts peak. This will mimic filtered full-wave rectified 60 Hz power ripple. Run a Transient Analysis to determine the load voltage. In the technical report, include a plot of the simulated load voltage along with the voltage applied to the collector of the pass transistor.

## Data Tables

$R_{load}$	$R_{scale}$	$V_{load}$	$I_{load}$	$I_{out}$	$I_{out-op-amp}$
$100k\ \Omega$	$47k\ \Omega$				
$100k\ \Omega$	$100k\ \Omega$				
$100\ \Omega$	$47k\ \Omega$				
$100\ \Omega$	$100k\ \Omega$				

Table 1 (Theoretical)



$R_{load}$	$R_{scale}$	$V_{load}$	$I_{load}$	$I_{out}$	$I_{out-op-amp}$
100k $\Omega$	47k $\Omega$				
100k $\Omega$	100k $\Omega$				
100 $\Omega$	47k $\Omega$				
100 $\Omega$	100k $\Omega$				

Table 2 (Experimental)

## Questions

1. How do the load voltage and current vary with the scale resistor?
2. How do the load voltage and current vary with the load resistor?
3. What is the relationship between  $I_{out}$  and  $I_{out-op-amp}$ ?
4. What is the relationship between  $I_{out}$  and  $I_{load}$ ?
5. How could this circuit be modified to produce a load voltage of 12 volts?
6. What is the maximum load current that can be obtained without damage to any of the devices?

# 16. The Triangle-Square Generator

## Objective

In this exercise, a simultaneous triangle-square wave generator is examined. The investigation will include the effect of capacitance on output frequency, and the role of op amp speed in determining ideal wave shapes.

## Theory Overview

The triangle-square generator consists of two main parts: a comparator and a ramp generator or integrator. The circuit is self-sustaining by nature. The ramp generator requires a square wave input. It gets this signal from the comparator. The comparator in turn generates the square wave from the triangle wave appearing at the output of the ramp generator. The output frequency is determined primarily by the RC timing values of the ramp generator, and secondarily by the switching thresholds of the comparator. The practical output frequency limit is set by the bandwidth and slew rate of the op amps. At higher frequencies, slew rate limiting will noticeably slow the edges of the square wave. This will impact the output of the ramp generator and will affect both the linearity of the wave shapes and the output frequency.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 9.2, Op Amp Oscillators

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

(2) Low speed op amps (741)

(2) Medium speed op amps (351, 411, 081, etc.)

(2) 1 $\mu$ F	actual: _____
(1) 1n F	actual: _____
(1) 10n F	actual: _____
(1) 10k $\Omega$	actual: _____
(1) 22k $\Omega$	actual: _____
(1) 33k $\Omega$	actual: _____

## Schematic

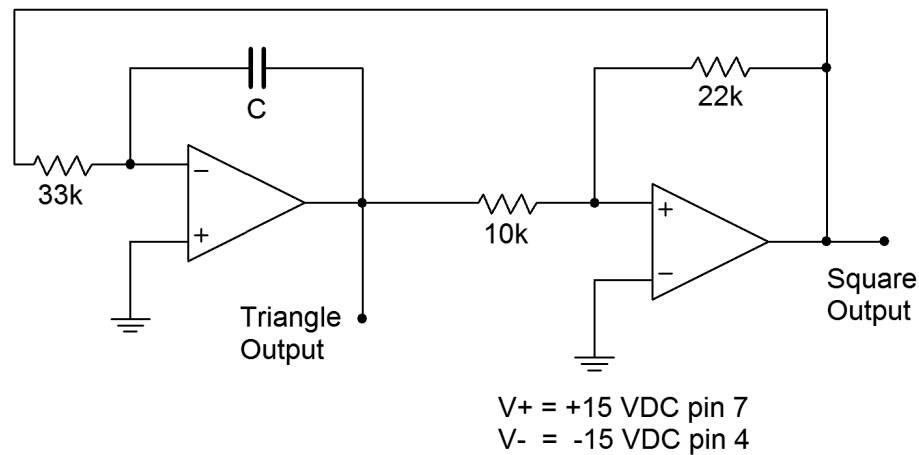


Figure 1

## Procedure

1. Using 10n F for the capacitor, determine the theoretical output frequency and the peak value of the triangle wave. Record these items in Table 1.
2. Construct the circuit of Figure 1 using the 10n F capacitor and the **medium speed** op amps.
3. Record the output frequency and amplitude of the triangle wave in Table 1 and determine the deviation between the theoretical and experimental results.
4. Save a copy of the oscilloscope displaying the triangle and square waves as Graph 1.
5. Replace the capacitor with the 1n F unit. Determine the theoretical output frequency and the peak value of the triangle wave using this new value, and record the results in Table 2.
6. Record the output frequency and amplitude of the triangle wave in Table 2 and determine the deviation between the theoretical and experimental results.
7. Save the triangle and square wave display as Graph 2. Pay particular attention to the leading and trailing edges of the square wave. Are the wave shapes identical to those created with the first capacitor?

8. Return the 10n F capacitor to the circuit, replacing the 1n F unit.
9. Replace the medium speed op amps with the **low speed** op amps.
10. Save the triangle and square wave display as Graph 3. Pay particular attention to the leading and trailing edges of the square wave. Are the wave shapes identical to those created with the faster op amps?

### Troubleshooting

11. Estimate and then measure the results for each individual error presented in Table 3.

## Data Tables

	Theoretical	Experimental	% Deviation
$f_{out}$			
$V_{out}$			

Table 1

	Theoretical	Experimental	% Deviation
$f_{out}$			
$V_{out}$			

Table 2

Error	Quantity	Estimate	Actual
10k swapped with 22k	Square Output		
33k swapped with 22k	Triangle Output		
Input pins of Op Amp 2 swapped	Square Output		

Table 3

## Questions

1. How does the oscillation frequency vary with capacitance?
2. What sets the output amplitude of the triangle and square waves?
3. By comparing Graphs 1 and 12, what sorts of non-ideal behavior occur at higher output frequencies?
4. By comparing Graphs 1 and 3, what are the advantages of using a medium speed op amp such as a 351 over a slower device such as a 741?
5. In general, what do you think the output waveforms would look like if the low speed op amps had been used with the 1n F capacitor?

# 17. The Wien Bridge Oscillator

## Objective

In this exercise, a Wien bridge sine wave generator is examined. The investigation will include the effect of capacitance on output frequency and gain control of the op amp.

## Theory Overview

The Wien bridge is a four element resistor-capacitor network that can be thought of as a combination of lead and lag networks. As such, it attenuates very high and very low frequencies. At its critical frequency, where the magnitude of  $X_c$  equals  $R$ , the bridge voltage produces no phase shift and exhibits a modest signal loss of  $1/3$ . An op amp with a voltage gain of 3 may be used to overcome this loss, and as long it produces no additional phase shift, the system can produce stable oscillation at the critical frequency. A non-inverting amplifier is ideally suited to this task. The gain needs to be slightly greater than 3 to begin oscillation and should fall back to 3 to maintain oscillation. The gain variation may be achieved through the use of limiting diodes in the negative feedback network.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 9.2, Op Amp Oscillators

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

(1) Low speed op amp (741)	
(1) Medium speed op amp (351, 411, 081, etc.)	
(2) $1\mu F$	actual: _____
(2) $1n F$	actual: _____
(2) $10n F$	actual: _____
(2) $100n F$	actual: _____
(1) $2k7 \Omega$	actual: _____
(1) $5k6 \Omega$	actual: _____
(3) $10k \Omega$	actual: _____

## Schematic

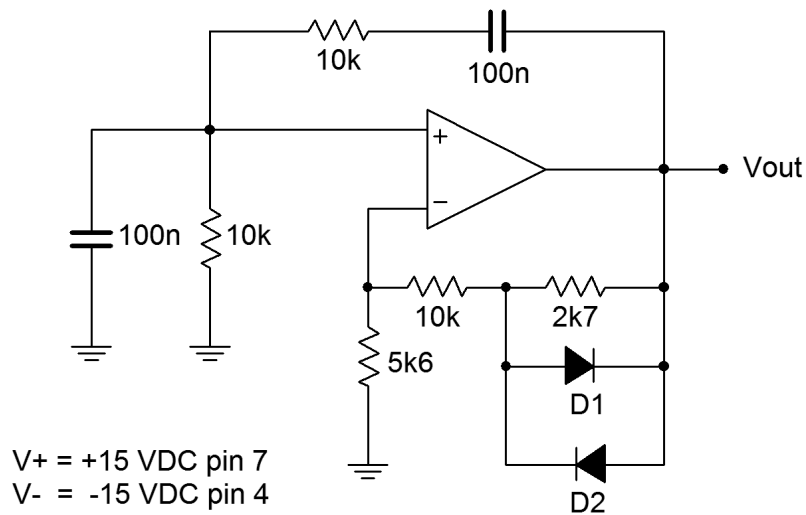


Figure 1

## Procedure

1. Determine the theoretical output frequency for the circuit of Figure 1. Also, estimate the output amplitude. Record these in Table 1.
2. Construct the circuit of Figure 1 using the medium speed op amp.
3. Record the output frequency and amplitude of the sine wave in Table 1 and determine the deviation between the theoretical and experimental results.
4. Save a copy of the oscilloscope display of the output wave as Graph 1.
5. Replace the capacitors with the 10n F units. Determine the theoretical output frequency using this new value and record the result in Table 2.
6. Record the output frequency and amplitude of the wave in Table 2 and determine the deviation between the theoretical and experimental results.
7. Save a copy of the oscilloscope display of the output wave as Graph 2.
8. Replace the capacitors with the 1n F units. Determine the theoretical output frequency using this new value and record the result in Table 2.

9. Record the output frequency and amplitude of the wave in Table 2 and determine the deviation between the theoretical and experimental results.
10. Save a copy of the oscilloscope display of the output wave as Graph 3.
11. Replace the medium speed op amp with the low speed op amp and examine the output.
12. Save a copy of the oscilloscope display of the output wave as Graph 4. Swap out the capacitors with the 10n F and then the 100 nF units. Are the wave shapes identical to those created with the faster op amp?
13. In order for this circuit to oscillate, the forward gain of the op amp must compensate for the loss through the Wien bridge, in this case, a gain of 3 is required. To verify this, open the 5k6 resistor. This will drop the gain to about 1 and oscillation should cease.

### Computer Simulation

14. One of the trickier parts of this oscillator is getting the op amp gain adjusted properly. If it is too high, the signal will be distorted. In this circuit, the initial gain is greater than 3 but as the signal grows, the two diodes turn on, partially shunting the 2k7 and reducing the effective value of  $R_f$ , and hence, the voltage gain. To demonstrate this, build the circuit in the simulator with a 741 op amp and 10n F capacitors. First perform a Transient Analysis and inspect the output wave shape. Replace the 2k7 with larger values and note the effect on the wave shape. Finally, return the resistor to 2k7, delete the two diodes and observe the new wave shape.

### Data Tables

	Theoretical	Experimental	% Deviation
$f_{out}$			
$V_{out}$			

Table 1



	Theoretical	Experimental	% Deviation
$f_{out}$			
$V_{out}$			

Table 2

	Theoretical	Experimental	% Deviation
$f_{out}$			
$V_{out}$			

Table 3

## Questions

1. How does the oscillation frequency vary with capacitance?
2. By comparing Graphs 1, 2, and 3, what sorts of non-ideal behavior occur at higher output frequencies?
3. By comparing Graphs 3 and 4, what are the advantages of using a medium speed op amp such as a 351 over a slower device such as a 741?
4. In general, what do you think the output waveforms would look like if the medium speed op amp had been used with a 100p F capacitor?

# 18. The Integrator

## Objective

In this exercise, the concept of waveform integration will be examined. The investigation will include the effect of frequency on accurate and useful integration. Several waveshapes will be utilized.

## Theory Overview

The concept of integration is usually described as “finding the area under the curve”. There are many uses for this function, including waveshaping and analog computing. An ordinary amplifier ideally changes only the amplitude of the input signal. An integrator can change the waveform of the input signal, for example, turning a square wave into a triangle wave. A practical integrator cannot be used at just any frequency. There exists a useful range of integration, outside of which the circuit does not produce the desired effect.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 10.2, Integrators

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

(1) Medium speed FET-input op amp (351, 411, 081, etc.)	
(2) 1 $\mu$ F	actual: _____
(1) 10 nF	actual: _____
(1) 910 $\Omega$	actual: _____
(1) 1 k $\Omega$	actual: _____
(1) 10 k $\Omega$	actual: _____

## Schematic

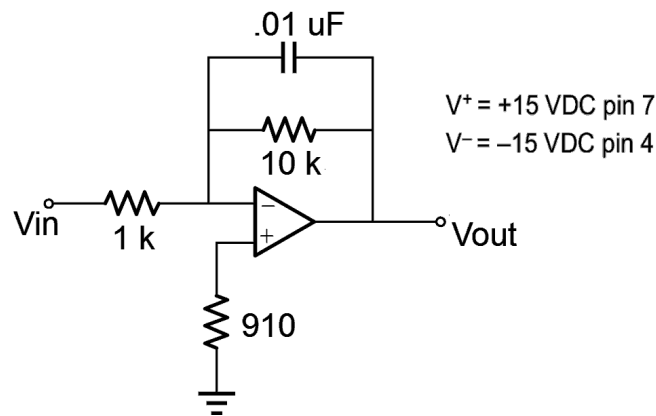


Figure 1

## Procedure

1. Derive the equation for  $V_{out}$  for the circuit of Figure 1. Calculate the lowest usable (“integratable”) frequency,  $f_{low}$ . Record these items in Table 1.
2. Calculate the integrator’s output voltage for the following inputs and record them in Table 2:
  - 1 volt peak sine wave at 2 times  $f_{low}$
  - 1 volt peak sine wave at 10 times  $f_{low}$
  - 1 volt peak square wave at 2 times  $f_{low}$
  - 1 volt peak square wave at 10 times  $f_{low}$
1. Assemble the integrator circuit.
2. Save the display of the output of the integrator for each of the inputs listed in step 2, above. Call these Graphs 1 through 4, respectively. It is very important to note the phase of the output waveform with respect to the input waveform.
3. Apply a 1 volt peak sine wave one decade *below*  $f_{low}$ . Save the output signal as Graph 5. Does the circuit appear to be integrating?
4. Apply a 1 volt peak square wave one decade *below*  $f_{low}$ . Save the output signal as Graph 6. Does the circuit appear to be integrating?

## Data Tables

Equation for $V_{out}$	
$f_{low}$	

Table 1

Input Signal	Output Signal
1 volt peak sine wave at 2 times $f_{low}$	
1 volt peak sine wave at 10 times $f_{low}$	
1 volt peak square wave at 2 times $f_{low}$	
1 volt peak square wave at 10 times $f_{low}$	

Table 2

## Questions

1. What happens to the accuracy of integration as the input frequency is increased?
2. At very low frequencies, does the integrator behave more like a true integrator, or like an amplifier?

3. What are the advantages of using a medium speed FET-input op amp such as a 351 over a slower bipolar device such as a 741?
  
  
  
  
  
  
  
  
  
  
4. What is the purpose of the  $10\text{ k}\Omega$  resistor?
  
  
  
  
  
  
  
  
  
  
5. What is the purpose of the  $910\ \Omega$  resistor?

# 19. The Differentiator

## Objective

In this exercise, the concept of waveform differentiation will be examined. The investigation will include the effect of frequency on accurate and useful differentiation. Several waveshapes will be utilized.

## Theory Overview

The concept of differentiation is usually described as “finding the slope of the curve.” There are many uses for this function, including waveshaping and analog computing. An ordinary amplifier ideally changes only the amplitude of the input signal. A differentiator can change the waveform of the input signal, for example, turning a triangle wave into a square wave. A practical differentiator cannot be used at just any frequency. There exists a useful range of differentiation, outside of which the circuit does not produce the desired effect.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 10.3, Differentiators

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) DMM	model: _____	srn: _____

## Components

(1) Medium speed FET-input op amp (351, 411, 081, etc.)	
(2) 1 $\mu$ F	actual: _____
(1) 10 nF	actual: _____
(1) 1.5 nF	actual: _____
(1) 100 $\Omega$	actual: _____
(1) 1 k $\Omega$	actual: _____

## Schematic

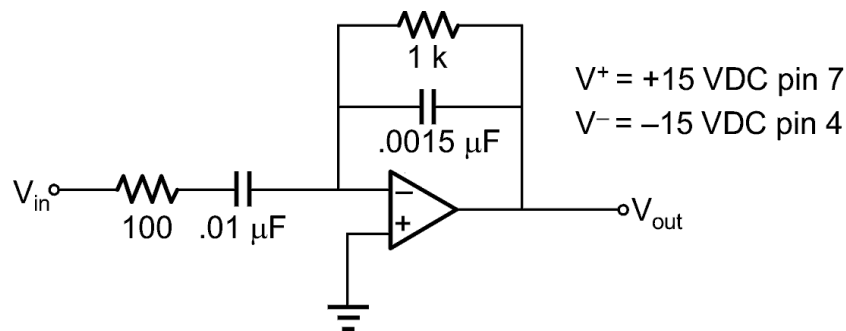


Figure 1

## Procedure

1. Derive the equation for  $V_{out}$  for the circuit of Figure 1. Calculate the highest usable (“differentiable”) frequency,  $f_{high}$ . Record these items in Table 1.
2. Calculate the differentiator’s output voltage for the following inputs and record them in Table 2:
  - 1 volt peak sine wave at one-half  $f_{high}$
  - 1 volt peak sine wave at one-tenth  $f_{high}$
  - 1 volt peak triangle wave at one-half  $f_{high}$
  - 1 volt peak triangle wave at one-tenth  $f_{high}$
1. Assemble the differentiator circuit.
2. Save the display of the output of the differentiator for each of the inputs listed in step 2. Call these Graphs 1 through 4, respectively. It is very important to note the phase of the output waveform with respect to the input waveform.
3. Apply a 1 volt peak sine wave one decade *above*  $f_{high}$ . Save the output signal as Graph 5. Does the circuit appear to be differentiating?
4. Apply a 1 volt peak triangle wave one decade *above*  $f_{high}$ . Save the output signal as Graph 6. Does the circuit appear to be differentiating?

## Data Tables

Equation for $V_{out}$	
$f_{high}$	

Table 1

Input Signal	Output Signal
1 volt peak sine wave at $\frac{1}{2} f_{high}$	
1 volt peak sine wave at $\frac{1}{10} f_{high}$	
1 volt peak triangle wave at $\frac{1}{2} f_{high}$	
1 volt peak triangle wave at $\frac{1}{10} f_{high}$	

Table 2

## Questions

1. What happens to the accuracy of differentiation as the input frequency is decreased?
2. At very high frequencies, does the differentiator behave more like a true differentiator, or like an amplifier?



5. What is the purpose of the 1.5 nF capacitor?

# 20. VCVS Filters

## Objective

In this exercise, the performance of VCVS equal-component high and low pass filters will be examined. The investigation will include the realization of wide bandwidth band pass filters as well.

## Theory Overview

Sallen and Key VCVS filters are very straightforward to implement, utilizing a single op amp to create second order high or low pass filters. The filters are based around a series-parallel non-inverting amplifier. In the equal component variation, the damping or alignment of the filter is set by the amplifier's pass band voltage gain. The corner frequency of the filter is set by the tuning resistors and capacitors.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 11.6, Realizing Practical Filters

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM capable of measuring in dB	model: _____	srn: _____

## Components

(2) General purpose op amps (741, 351, 411, 081, etc.)

(2) 1 $\mu$ F	actual: _____
(2) 10n F	actual: _____
(2) 100n F	actual: _____
(2) 1k5 $\Omega$	actual: _____
(2) 2k2 $\Omega$	actual: _____
(1) 5k6 $\Omega$	actual: _____
(1) 6k8 $\Omega$	actual: _____
(1) 10k $\Omega$	actual: _____
(1) 12k $\Omega$	actual: _____

## Schematics

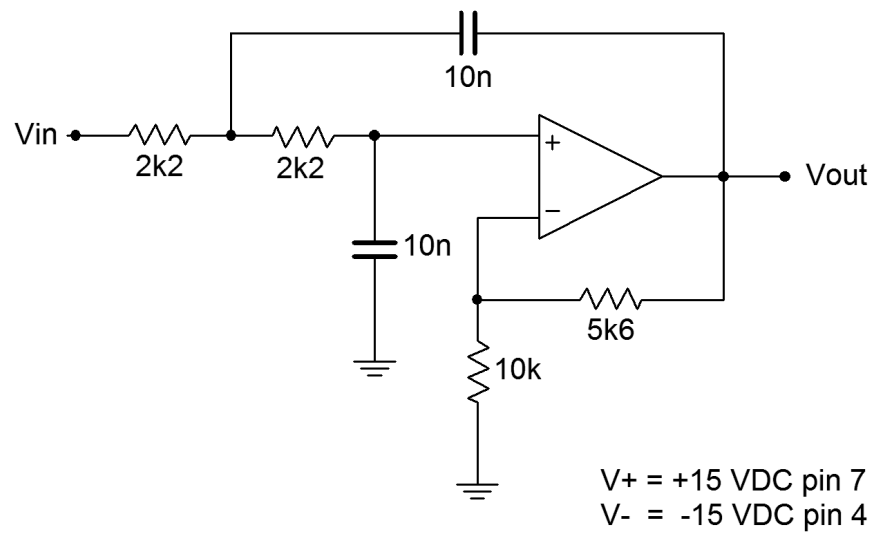


Figure 1

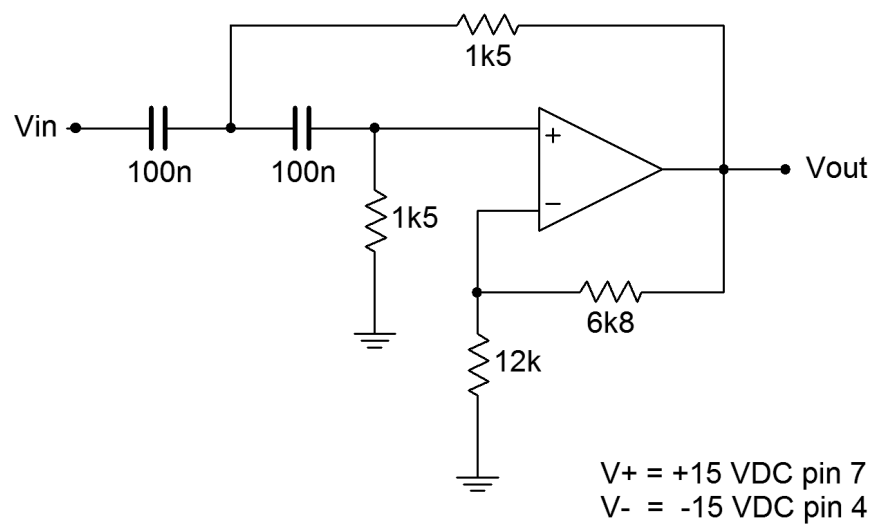


Figure 2

# Procedure

## Low Pass Filter

1. The circuit of Figure 1 is a second order low pass filter. Calculate and record the corner frequency ( $f_2$ ) and mid-band voltage gain in Table 1.
2. Assemble the circuit of Figure 1.
3. To measure the mid-band voltage gain, set the generator to a 1 volt sine wave at about one decade *below*  $f_2$ . Measure the output of the filter and calculate the voltage gain. Record this in Table 1.
4. While monitoring the filter output with the dB meter, sweep the generator frequency about  $f_2$  until the output has fallen 3 dB from its mid-band value. Record this frequency in Table 1.
5. In Table 2, record the dB gain of the filter at 5 frequencies between  $0.1 f_2$  and  $f_2$ , and at 5 frequencies between  $f_2$  and  $10 f_2$ . Using these data, create a semi-log plot of the frequency response of the filter. Note, it may be convenient when graphing if at least some of these frequencies are simple octaves apart, such as  $5 f_2$  and  $10 f_2$ .
6. Do not disassemble the circuit.

## High Pass Filter

7. The circuit of Figure 2 is a second order high pass filter. Calculate and record the corner frequency ( $f_l$ ) and mid-band voltage gain in Table 3.
8. Assemble the circuit of Figure 2.
9. To measure the mid-band voltage gain, set the generator to a 1 volt sine wave at about one decade *above*  $f_l$ . Measure the output of the filter and calculate the voltage gain. Record this in Table 3.
10. While monitoring the filter output with the dB meter, sweep the generator frequency about  $f_l$  until the output has fallen 3 dB from its mid-band value. Record this frequency in Table 3.
11. In Table 4, record the dB gain of the filter at 5 frequencies between  $0.1 f_l$  and  $f_l$ , and at 5 frequencies between  $f_l$  and  $10 f_l$ . Using these data, create a semi-log plot of the frequency response of the filter.

## Band Pass Filter

12. Cascade the high pass and low pass filters.
13. Take several gain readings on both sides of  $f_l$  and  $f_2$ , and record these in Table 5. Again, using these data, create a semi-log plot of the frequency response of the filter.

## Computer Simulation

14. Build the circuit of Figure 1 in a simulator and run an AC Analysis. Be sure to run the plot from 100 Hz to approximately 100 kHz and use a decibel scale for the gain amplitude. Compare the plot to the graph generated from Table 2.

## Data Tables

	Theoretical	Experimental
$f_2$		
$A_v$		

Table 1

Frequency	Gain

Table 2

	Theoretical	Experimental
$f_l$		
$A_v$		

Table 3

Frequency	Gain

Table 4

Frequency	Gain

Table 5



## Questions

1. What is the approximate attenuation slope above  $f_2$ ?
2. What is the approximate attenuation slope below  $f_1$ ?
3. What would be the result of the cascade if the critical frequencies of the two filters were mistakenly transposed?

# 21. The Multiple Feedback Filter

## Objective

In this exercise, the performance of basic band-pass filters will be examined. The investigation will include the investigation of variable Q or bandwidth.

## Theory Overview

Multiple feedback filters are very straightforward to implement, utilizing a single op amp to create second order band-pass filters. The filters are based around a parallel-parallel inverting amplifier. The center frequency of the filter is set by the tuning resistors and capacitors.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 11.7, Band-Pass Filter Realizations

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM capable of measuring in dB	model: _____	srn: _____

## Components

(1) Medium speed op amp (351, 411, 081, etc.)	
(2) 1 $\mu$ F	actual: _____
(2) 10n F	actual: _____
(2) 100n F	actual: _____
(1) 470 $\Omega$	actual: _____
(1) 1k2 $\Omega$	actual: _____
(1) 2k2 $\Omega$	actual: _____
(1) 22k $\Omega$	actual: _____
(1) 39k $\Omega$	actual: _____
(1) 47k $\Omega$	actual: _____
(1) 75k $\Omega$	actual: _____

## Schematic

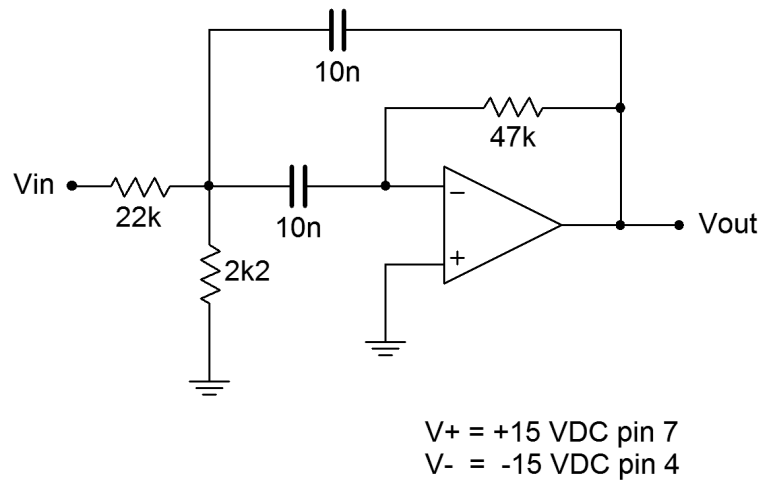


Figure 1

## Procedure

1. The circuit of Figure 1 is a second order band pass filter. Calculate and record the center frequency ( $f_0$ ) and mid-band voltage gain in Table 1.
2. Assemble the circuit of Figure 1 using the medium speed op amp.
3. While monitoring the filter output with the dB meter, sweep the generator frequency about the expected  $f_0$  until a peak is found. Record this frequency in Table 1. Measure the output amplitude, determine the gain and record this in Table 1 as well.
4. In Table 2, record the dB gain of the filter at 5 frequencies between  $0.1 f_0$  and  $f_0$ , and at 5 frequencies between  $f_0$  and  $10 f_0$ . Using these data, plot a graph of the filter response, and determine the bandwidth and Q of the filter.
5. Replace the capacitors with the 100n F units and repeat steps 3 and 4 using Tables 3 and 4.
6. The circuit resistors set the Q of the filter. To alter the Q of this circuit, replace the 2k2 with 1k2, the 22k with 39k, and the 47k with 75k.
7. Repeat steps 3 and 4 using Tables 5 and 6.

## Computer Simulation

8. Build the circuit of Figure 1 in a simulator and run an AC Analysis. Be sure to run the plot from 10 Hz to approximately 100 kHz and use a decibel scale for the gain amplitude. Compare the plot to the graph generated from Table 2.

## Data Tables

	Theoretical	Experimental
$f_0$		
$A_v$		

Table 1

Frequency	Gain

Table 2

	Theoretical	Experimental
$f_0$		
$A_v$		

Table 3

Frequency	Gain

Table 4

	Theoretical	Experimental
$f_0$		
$A_v$		

Table 5

Frequency	Gain

Table 6

## Questions

1. For the original circuit, what is the approximate attenuation slope above  $f_0$ ?
2. For the original circuit, what is the approximate attenuation slope below  $f_0$ ?
3. What is the relationship between circuit capacitance and center frequency  $f_0$ ?
4. How does bandwidth change as Q is altered?
5. Does the ultimate attenuation slope (i.e., at the frequency extremes) change as the Q is altered?

# 22. The State-Variable Filter

## Objective

In this exercise, the performance of a state-variable filter will be examined. The investigation will include the effect of varying  $Q$  and tuning frequency.

## Theory Overview

The state-variable filter, also known as the universal filter, provides several outputs, including high-pass, low-pass, and band-pass connections. The filter offers independent control over bandwidth ( $Q$ ) and tuning frequency ( $f_c$ ). State-variable filters are ideal for applications requiring stable, high  $Q$  response.

## Reference

*Fiore, Op Amps and Linear Integrated Circuits*

Section 11.7, Band-Pass Filter Realizations

## Equipment

(1) Oscilloscope	model: _____	srn: _____
(1) Function generator	model: _____	srn: _____
(1) Dual DC power supply	model: _____	srn: _____
(1) DMM capable of measuring in dB	model: _____	srn: _____

## Components

- (1) General purpose quad op amp (LM348, TL084, LF347, etc.)
- (2) 1  $\mu$ F      actual: \_\_\_\_\_
- (2) 10 nF      actual: \_\_\_\_\_
- (1) 680  $\Omega$       actual: \_\_\_\_\_
- (2) 4.7 k $\Omega$       actual: \_\_\_\_\_
- (2) 6.8 k $\Omega$       actual: \_\_\_\_\_
- (2) 10 k $\Omega$       actual: \_\_\_\_\_
- (2) 15 k $\Omega$       actual: \_\_\_\_\_
- (1) 10 k $\Omega$  potentiometer
- (1) 50 k $\Omega$  dual potentiometer



## Schematic

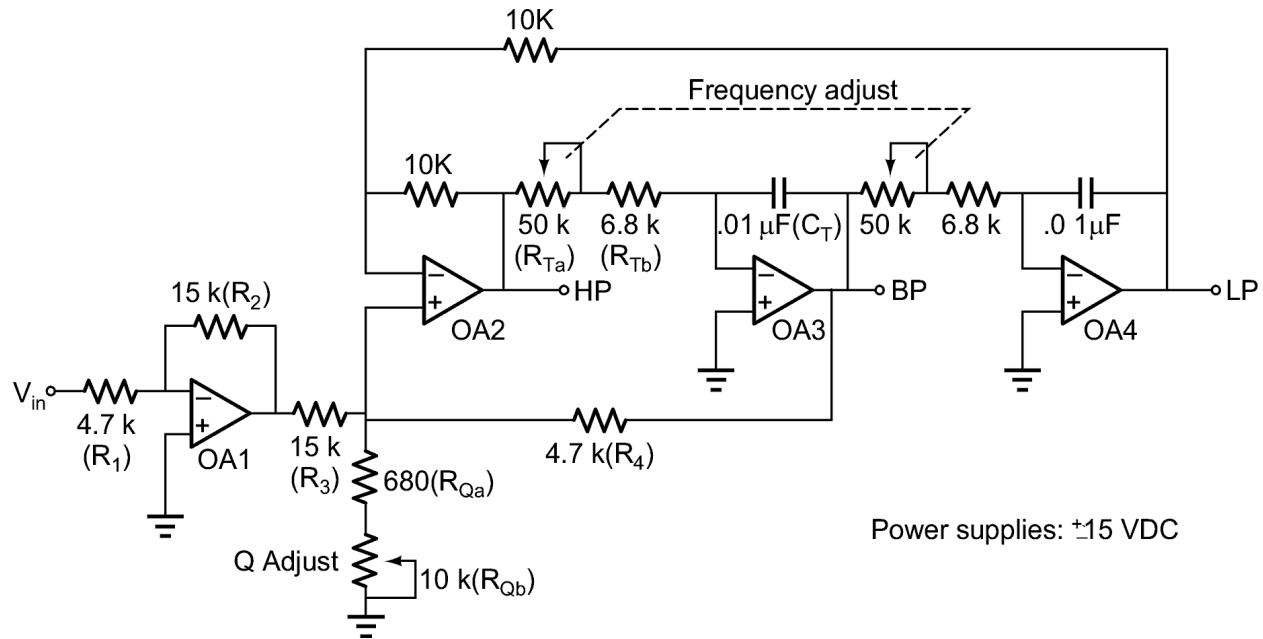


Figure 1

You will find the following formulas useful:

$$f_c = 1/(2\pi R_t C_t)$$

$$A_v \text{ (band-pass gain)} = R_2 R_4 / (R_1 R_3)$$

$$Q = (R_x + R_4) / (2R_x); \quad \text{where } R_x = R_q \parallel R_3$$

## Procedure

### Band-pass Output

1. Assemble the circuit of Figure 1.
2. Calculate the frequency range, Q range, and band-pass gain of the filter. Record these values in Table 1. Note that  $R_t$  varies from 6.8 k $\Omega$  to 56.8 k $\Omega$ , and that  $R_q$  varies from 680  $\Omega$  to 10.68 k $\Omega$ .
3. Set Q to its highest value. This can be accomplished by adjusting the Q potentiometer for minimum resistance.
4. Apply a 0 dBV sine wave at approximately 1 kHz to the input.

5. Set the filter tuning to its highest value. This can be accomplished by adjusting  $R_t$  to minimum.
6. Sweep the input frequency until a peak output is found. Record this frequency and amplitude in Table 2.
7. Record the  $-3$  dB,  $-6$  dB, and  $-10$  dB frequencies on either side of the peak, in Table 2. These amplitudes are relative to the level found at the peak.
8. Set the Q adjust to its lowest value (i.e.,  $R_q$  at maximum) and repeat steps 4 through 7, using Table 3 to record your results.
9. Set the filter tuning to its minimum value (i.e.,  $R_t$  at maximum) and repeat steps 4 through 8, using Tables 4 and 5 to record your results.
10. If a spectrum analyzer is available, verify your readings.

#### High- and Low-pass Outputs

11. Utilize the HP output.
12. Apply a 10 kHz sine wave to the input and adjust the amplitude for a filter output of 0 dBV.
13. By sweeping the input frequency, determine the  $-3$  dB frequencies for  $R_t$  at both extremes. Record these values in Table 6.
14. Determine the attenuation slope by measuring the output signal amplitude using a frequency one decade below the  $-3$  dB frequency. Record this in Table 6.
15. Utilize the LP output.
16. Apply a 100 Hz sine wave to the input and adjust the amplitude for a filter output of 0 dBV.
17. By sweeping the input frequency, determine the  $-3$  dB frequencies for  $R_t$  at both extremes. Record these values in Table 6.
18. Determine the attenuation slope by measuring the output signal amplitude using a frequency one decade above the  $-3$  dB frequency. Record this in Table 6.
19. If a spectrum analyzer is available, verify your readings.

## Data Tables

Maximum Q	
Minimum Q	
Maximum $f_c$	
Minimum $f_c$	
Band-pass Gain	

Table 1

Item	Frequency	Amplitude
Peak		
-3 dB, below		
-6 dB, below		
-10 dB, below		
-3 dB, above		
-6 dB, above		
-10 dB, above		

Table 2

Item	Frequency	Amplitude
Peak		
-3 dB, below		
-6 dB, below		
-10 dB, below		
-3 dB, above		
-6 dB, above		
-10 dB, above		

Table 3

Item	Frequency	Amplitude
Peak		
-3 dB, below		
-6 dB, below		
-10 dB, below		
-3 dB, above		
-6 dB, above		
-10 dB, above		

Table 4

Item	Frequency	Amplitude
Peak		
-3 dB, below		
-6 dB, below		
-10 dB, below		
-3 dB, above		
-6 dB, above		
-10 dB, above		

Table 5

$f_{3db}$ for $R_t$ at minimum	
$f_{3db}$ for $R_t$ at maximum	
Attenuation slope	
$f_{3db}$ for $R_t$ at minimum	
$f_{3db}$ for $R_t$ at maximum	
Attenuation slope	

Table 6

## Questions

1. What is the effect as  $R_q$  is decreased?
2. What is the effect as  $R_t$  is decreased?
3. How does this filter compare to high- and low-pass VCVS filters?
4. How could this circuit be changed in order to control pass-band gain?
5. What effect would altering  $R_{tb}$  have on circuit function?
6. Why is the state-variable filter referred to as a universal filter?

## Appendix A: Creating Graphs Using a Spreadsheet

While nothing beats good data plotting and analysis software (check out [SciDAVis](#) for an excellent free program), you can also create a variety of graphs using spreadsheets such as the one in [Open Office](#) or Excel (Microsoft Office). What follows works for Excel 2007 and Open Office 4. Other versions may have different menus and options. Here's how to take your tabular data from lab and create a graph. These instructions assume you will set the independent axis on the horizontal and the dependent axis as the vertical. This is the typical case but there are exceptions (see note at end). Remember, the independent axis presents the input parameter you set (e.g., a power supply voltage or a mass) and the dependent axis presents the output parameter (i.e., the item you are interested in and have measured as an outcome such as a resulting current or change in position).

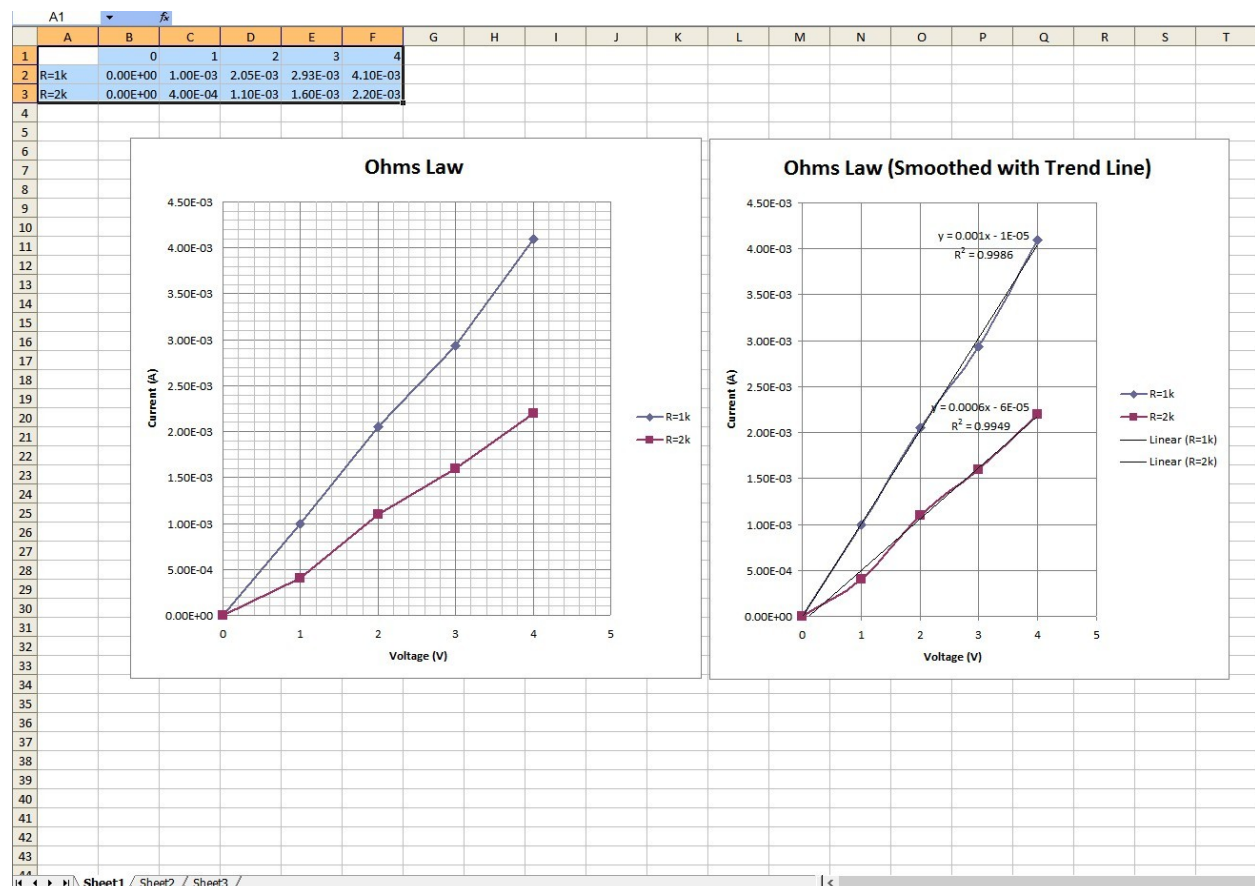
1. Open a new worksheet. In the first column (column A), enter the text for the legend. This is particularly important if you're plotting multiple datasets on a single graph. Starting in the second column (column B), enter values for the horizontal (independent) axis on the first row of the worksheet. In like fashion, enter values for the vertical (dependent) axis on the second row. For multiple trials, enter the values on subsequent rows. For example, if you are setting a series of voltages in a circuit and then measuring the resulting currents, the voltages would be in row one and the currents in row two. If you changed the circuit components, reset the voltages, remeasured the currents and wish to compare the two trials, then the new set of currents would be in row three and so on. Each of these rows would have their identifying legend in column A with the numeric data starting in column B. Specifically, the legend text for the first data set would be in cell \$A\$2 and the numeric values would be in cells \$B\$2 through \$X\$2 (where X is the final data column), for the second set the legend text would be in cell \$A\$3 and the numeric values would be in cells \$B\$3 through \$X\$3, etc.
2. Select/highlight all of the data (click the first cell, in the upper left corner, and drag the mouse over all of the cells used).
3. Select the Insert menu and choose Chart. Ordinarily you will use an **XY Scatter** chart. There are other options but this is the one you'll need in most cases. A simple Line chart is **not** appropriate in most cases. You might get a graph that “sort of” looks correct but the horizontal axis will simply represent the measurement sequence (first, second, third) rather than the value you set.
4. You can customize the appearance of the chart. In general, you can edit items by simply double-clicking on the item or by using a right-mouse click to bring up a property menu. This will allow you to add or alter gridlines, axes, etc. You can also stipulate variations such as using data smoothing, adding a trend line, etc. It is possible to change the axes to logarithmic or alter their range; and fonts, colors and a variety of secondary characteristics may be altered.
5. Once your chart is completed, you may wish to save the worksheet for future reference. To insert the chart into a lab report, select the chart by clicking on it, copy it to the clipboard (Ctrl+C), select the insertion point in the lab report, and paste (Ctrl+V).



6. In those odd instances where you need to reverse the dependent and independent axes such as a VI plot of a diode where currents are set and resulting voltages are measured, but you want the voltage on the horizontal, some spreadsheets have an axis swap function. If not, you'll need to swap the data ranges for the chart axes. For example, following the instructions above, your independent/horizontal axis is row one. The data are in cells \$B\$1 through \$X\$1. The dependent data are in cells \$B\$2 through \$X\$2. These ranges can be seen in the chart's Data Series or Data Range menu or dialog box. It will say something like: "X Values: =Sheet1!\$B\$1:\$F\$1" and "Y Values: =Sheet1!\$B\$2:\$F\$2". Simply swap the row numbers so that it says "X Values: =Sheet1!\$B\$2:\$F\$2" and "Y Values: =Sheet1!\$B\$1:\$F\$1".

7. Data smoothing can be useful to remove the "jaggyness" of some plots. For simple curves, a second degree B-Spline is suggested if you're using Open Office. For data that are expected to be linear, a trend line can be useful to better see the approximation.

Here is an example worksheet showing a plot of two resistors. The first plot is basic, the second uses smoothed data with a linear trend line:



## Appendix B: Manufacturer's Datasheet Links

### Diodes

1N4148/1N914 Datasheet: <https://www.onsemi.com/pub/Collateral/1N914-D.PDF>

NZX Series Datasheet: [https://assets.nexperia.com/documents/data-sheet/NZX\\_SER.pdf](https://assets.nexperia.com/documents/data-sheet/NZX_SER.pdf)

### Transistors

2N3904 Datasheet: <https://www.onsemi.com/pub/Collateral/2N3903-D.PDF>

2N5192G Datasheet: [http://www.onsemi.com/pub\\_link/Collateral/2N5191-D.PDF](http://www.onsemi.com/pub_link/Collateral/2N5191-D.PDF)

### Op amps

LF351 Datasheet: <https://www.st.com/resource/en/datasheet/lf351.pdf>

LF411 Datasheet: <http://www.ti.com/lit/ds/symlink/lf411.pdf>

LM318 Datasheet: <http://www.ti.com/lit/ds/symlink/lm318-n.pdf>

LM741 Datasheet: <http://www.ti.com/lit/ds/symlink/lm741.pdf>

TL081 Datasheet: <http://www.ti.com/lit/ds/symlink/tl081.pdf>