Performance-based assessments for analog integrated circuit competencies

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The purpose of these assessments is for instructors to accurately measure the learning of their electronics students, in a way that melds theoretical knowledge with hands-on application. In each assessment, students are asked to predict the behavior of a circuit from a schematic diagram and component values, then they build that circuit and measure its real behavior. If the behavior matches the predictions, the student then simulates the circuit on computer and presents the three sets of values to the instructor. If not, then the student then must correct the error(s) and once again compare measurements to predictions. Grades are based on the number of attempts required before all predictions match their respective measurements.

You will notice that no component values are given in this worksheet. The *instructor* chooses component values suitable for the students' parts collections, and ideally chooses different values for each student so that no two students are analyzing and building the exact same circuit. These component values may be hand-written on the assessment sheet, printed on a separate page, or incorporated into the document by editing the graphic image.

This is the procedure I envision for managing such assessments:

1. The instructor hands out individualized assessment sheets to each student.
2. Each student predicts their circuit's behavior at their desks using pencil, paper, and calculator (if appropriate).
3. Each student builds their circuit at their desk, under such conditions that it is impossible for them to verify their predictions using test equipment. Usually this will mean the use of a multimeter only (for measuring component values), but in some cases even the use of a multimeter would not be appropriate.
4. When ready, each student brings their predictions and completed circuit up to the instructor's desk, where any necessary test equipment is already set up to operate and test the circuit. There, the student sets up their circuit and takes measurements to compare with predictions.
5. If any measurement fails to match its corresponding prediction, the student goes back to their own desk with their circuit and their predictions in hand. There, the student tries to figure out where the error is and how to correct it.
6. Students repeat these steps as many times as necessary to achieve correlation between all predictions and measurements. The instructor's task is to count the number of attempts necessary to achieve this, which will become the basis for a percentage grade.
7. (OPTIONAL) As a final verification, each student simulates the same circuit on computer, using circuit simulation software (Spice, Multisim, etc.) and presenting the results to the instructor as a final pass/fail check.

These assessments more closely mimic real-world work conditions than traditional written exams:

- Students cannot pass such assessments only knowing circuit theory or only having hands-on construction and testing skills – they must be proficient at both.
- Students do not receive the "authoritative answers" from the instructor. Rather, they learn to validate their answers through real circuit measurements.
- Just as on the job, the work isn't complete until *all errors* are corrected.
- Students must recognize and correct their own errors, rather than having someone else do it for them.
- Students must be fully prepared on exam days, bringing not only their calculator and notes, but also their tools, breadboard, and circuit components.

Instructors may elect to reveal the assessments before test day, and even use them as preparatory labwork and/or discussion questions. Remember that there is absolutely nothing wrong with "teaching to

the test" *so long as the test is valid.* Normally, it is bad to reveal test material in detail prior to test day, lest students merely memorize responses in advance. With performance-based assessments, however, there is no way to pass without truly understanding the subject(s).

Competency: **Voltage comparator**   Version:

Schematic

Given conditions

+V = $R_{pot1} = R_{pot2} =$

Parameters

	Predicted	Measured		
V_{out}			$V_{in(+)} = $ _____	$V_{in(-)} = $ _____
V_{out}			$V_{in(+)} = $ _____	$V_{in(-)} = $ _____
V_{out}			$V_{in(+)} = $ _____	$V_{in(-)} = $ _____
V_{out}			$V_{in(+)} = $ _____	$V_{in(-)} = $ _____

Fault analysis

Suppose component [   ] fails   ☐ open   ☐ other _____
                                   ☐ shorted

What will happen in the circuit?

<u>file 01999</u>

Answer 1
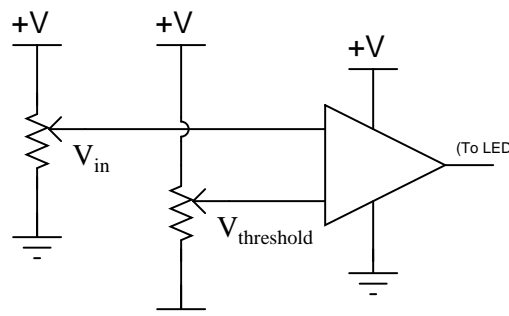
Use circuit simulation software to verify your predicted and measured parameter values.

Notes 1

You may wish to use either an operational amplifier or a true comparator for this exercise. Whether or not the specific device has rail-to-rail output swing capability is your choice as well.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Question 2

Competency: **Voltage comparator with LED**   Version:

Description

Design and build a comparator circuit that turns on
an LED when the specified condition is met.

Given conditions

The LED will turn on when (instructor checks one)

+V =

☐ V_{in} exceeds $V_{threshold}$

☐ V_{in} falls below $V_{threshold}$

Schematic   *Label each comparator input terminal (+ and -) and
show how the LED connects to the comparator output!*

+V   +V   +V

V_{in}

$V_{threshold}$ (To LED)

Parameters

LED energizes
when it should   ☐   (Yes/No)

file 02765

Answer 2

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 2

Students are free to connect the LED to the comparator in any way they choose (current-sourcing or current-sinking).

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Voltage comparator with hysteresis**   Version:

Schematic

Given conditions

+V = $R_{pot1} = R_{pot2} =$

V_{ref} (VR$_1$ setting) = $R_1 =$ $R_2 =$

Parameters

	Predicted	Measured	
V_{UT}			(upper threshold voltage)
V_{LT}			(lower threshold voltage)

Fault analysis

Suppose component [   ] fails   ☐ open   ☐ other _____
                                  ☐ shorted

What will happen in the circuit?

Answer 3

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 3

You may wish to use either an operational amplifier or a true comparator for this exercise. Whether or not the specific device has rail-to-rail output swing capability is your choice as well.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp voltage follower**   Version:

Schematic

Given conditions

$+V =$ $R_{pot} =$ $V_{TP1} =$

$-V =$

Parameters

	Predicted	Measured
V_{out}		
A_V (ratio)		
A_V (dB)		
V_{TP1} resulting in *latch-up*		

Inverting . . . ☐

or noninverting? ☐

Measured

Rail-to-rail output swing? ☐ (Yes/No)

file 01968

Answer 4

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 4

Use a dual-voltage, regulated power supply to supply power to the opamp.
I have had good success using the following values:
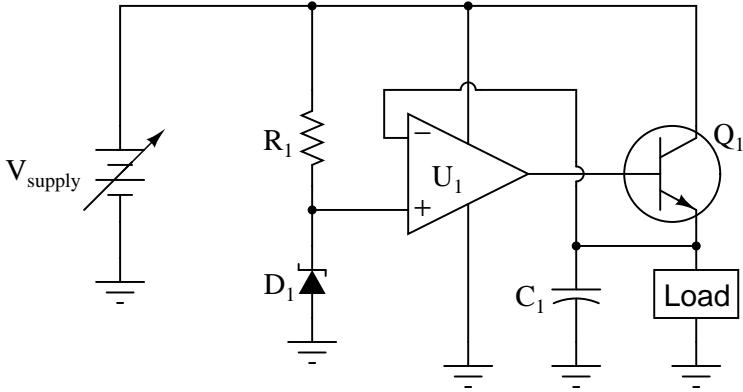
- +V = +12 volts
- -V = -12 volts
- V_{TP1} = Any voltage well between +V and -V
- R_{pot} = 10 kΩ linear potentiometer
- U_1 = TL081 BiFET operational amplifier (or one-half of a TL082)

In order to demonstrate latch-up, you must have an op-amp capable of latching up. Thus, you should avoid op-amps such as the LM741 and LM1458. I recommend using an op-amp such as the TL082 for this exercise because it not only latches up, but also does not swing its output voltage rail-to-rail. Students need to see both these common limitations when they first learn how to use op-amps.

In case your students ask, test point **TP1** is for measuring the output of the potentiometer rather than as a place to inject external signals into. All you need to connect to **TP1** is a voltmeter!

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Linear voltage regulator circuit**   Version:

Schematic

Given conditions

V_{supply} (min) = R_1 =   Load =

V_{supply} (max) = V_{zener} = C_1 =

Parameters

	Predicted	Measured		Calculated
$V_{in(+)}$			P_{Q1}	
V_{load}				
$V_B (Q_1)$				

Fault analysis

Suppose component [   ] fails   ☐ open   ☐ other _____

                                              ☐ shorted

What will happen in the circuit?

Answer 5

Use circuit simulation software to verify your predicted and measured parameter values.
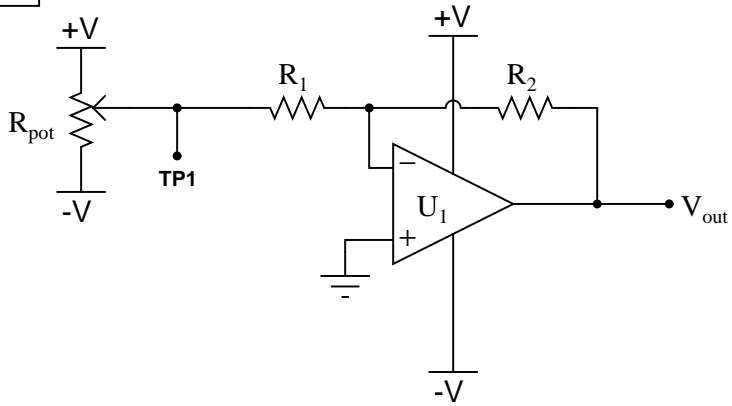
Notes 5

Use a power transistor for this circuit, as general-purpose signal transistors may not have sufficient power dissipation ratings to survive the loading students may put them through! I recommend a small DC motor as a load. An electric motor offers an easy way to increase electrical loading by placing a mechanical load on the shaft. By doing this, students can see for themselves how well the circuit maintains load voltage (resisting voltage "sag" under increasing load current).

I have found that this circuit is excellent for getting students to understand how negative feedback really works. Here, the opamp adjusts the power transistor's base voltage to *whatever it needs to be* in order to maintain the load voltage at the same level as the reference set by the zener diode. Any sort of loss incurred by the transistor (most notably V_{BE}) is automatically compensated for by the opamp.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp noninverting amplifier**   Version:

Schematic

Given conditions

+V = R_{pot} = V_{TP1} =

-V = R_1 = R_2 =

Parameters

	Predicted	Measured
V_{out}		
A_V (ratio)		
A_V (dB)		

Fault analysis

Suppose component [   ] fails   ☐ open   ☐ other _____
                                  ☐ shorted
What will happen in the circuit?

file 01969

Answer 6

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 6

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- V_{TP1} = Any voltage well between +V and -V not resulting in output saturation
- R_1 = 10 kΩ
- R_2 = 27 kΩ
- R_{pot} = 10 kΩ linear potentiometer
- U_1 = TL081 BiFET operational amplifier (or one-half of a TL082)

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp inverting amplifier**   Version:

Schematic

Given conditions

+V = R_{pot} = V_{TP1} =

-V = R_1 = R_2 =

Parameters

	Predicted	Measured
V_{out}		
A_V (ratio)		
A_V (dB)		

Fault analysis

Suppose component ⬚ fails   ☐ open   ☐ other _____
                              ☐ shorted

What will happen in the circuit?

file 01970

Answer 7

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 7

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- V_{TP1} = Any voltage well between +V and -V not resulting in output saturation
- R_1 = 10 kΩ
- R_2 = 27 kΩ
- R_{pot} = 10 kΩ linear potentiometer
- U_1 = TL081 BiFET operational amplifier (or one-half of a TL082)

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Op-amp amplifier circuit w/specified gain**   Version:

Description

Design and build an op-amp amplifier circuit
with a voltage gain (A_V) that is within tolerance
of the gain specified.

Given conditions

$V_{in} =$ Inverting ☐

A_V (ratio) $=$

                                              Non-inverting ☐
Tolerance$_{A_v} =$

Schematic   *Show all component values!*

Parameters

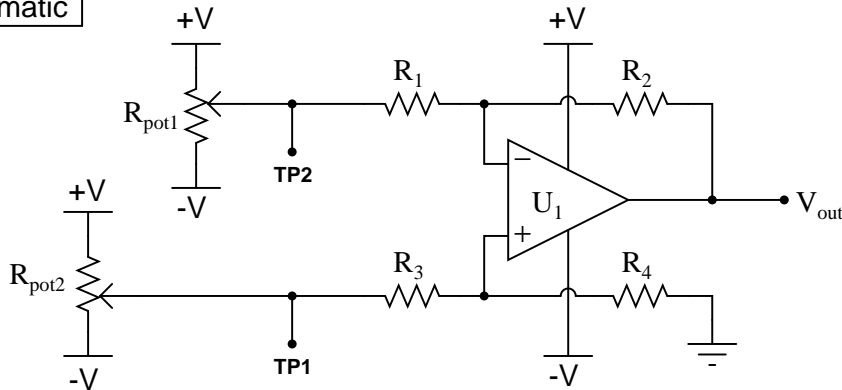|	Measured		Calculated	
V_{in}		A_V (ratio)		
V_{out}		Error$_{A_v}$		$\dfrac{A_{V(actual)} - A_{V(ideal)}}{A_{V(ideal)}} \times 100\%$

file 02132

Answer 8

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 8

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp difference amplifier**   Version:

Schematic

Given conditions

+V = $R_{pot1} = R_{pot2} =$ $R_1 =$ $R_2 =$

-V = $R_3 =$ $R_4 =$

Parameters

	Predicted	Measured	
V_{out}			$V_{TP1} =$ ____ V $V_{TP2} =$ ____ V
V_{out}			$V_{TP1} =$ ____ V $V_{TP2} =$ ____ V
V_{out}			$V_{TP1} =$ ____ V $V_{TP2} =$ ____ V
V_{out}			$V_{TP1} = V_{TP2} =$ ____ V ⎤ *Common*
V_{out}			$V_{TP1} = V_{TP2} =$ ____ V ⎦ *mode voltage*

	Predicted	Calculated		
A_V (ratio)			Differential	$\dfrac{V_{out}}{V_{TP1} - V_{TP2}}$

	Predicted	Calculated		
A_V (ratio)			Common-mode	$\dfrac{\Delta V_{out}}{\Delta V_{in}}$

file 02466

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Answer 9

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 9

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify all four resistors as equal value, between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.). This will ensure a differential voltage gain of unity. If you *want* to have a different voltage gain, then by all means specify these resistor values however you see fit!

Differential gain is calculated by averaging the quotients of each measured V_{out} value with its respective $V_{in(+)} - V_{in(-)}$ differential input voltage. Common-mode gain is calculated by dividing the difference in output voltages (ΔV_{out}) by the difference in common-mode input voltages (ΔV_{in}).

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Precision rectifier, half wave**   Version:

Schematic

Given conditions

+V =   -V = $R_1 = R_2 =$ $R_{pot} =$

Parameters

	Predicted	Measured	
V_{out}			$V_{TP1} =$ ___
V_{out}			$V_{TP1} =$ ___
V_{out}			$V_{TP1} =$ ___

Fault analysis

Suppose component [ ] fails   ☐ open   ☐ other _____
                               ☐ shorted

What will happen in the circuit?

file 02540

Answer 10

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 10

Choose both positive input voltage values and negative input voltage values, so that students may predict and measure the output of this circuit under both types of conditions. The choice of diodes is not critical, as any rectifier diodes will work. The two resistor values should be equal, and at least as high as the potentiometer value. I recommend a 10 kΩ potentiometer and 15 kΩ resistors.

A good follow-up question to ask is what would be required to change the polarity of this half-wave precision rectifier circuit.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Precision rectifier, full wave**   Version:

Schematic

Given conditions

$R_{pot} =$

$+V =$ $-V =$ $R_1 = R_2 = R_3 = R_4 = R_5 =$

Parameters

	Predicted	Measured	
V_{out}			$V_{TP1} = $ _____
V_{out}			$V_{TP1} = $ _____
V_{out}			$V_{TP1} = $ _____

Fault analysis

Suppose component [ ] fails   ☐ open   ☐ other _____
                                ☐ shorted

What will happen in the circuit?

file 02560

Answer 11

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 11

Choose both positive input voltage values and negative input voltage values, so that students may predict and measure the output of this circuit under both types of conditions. The choice of diodes is not critical, as any rectifier diodes will work. All resistor values need to be equal, and at least as high as the potentiometer value. I recommend a 10 kΩ potentiometer and 15 kΩ resistors.

A good follow-up question to ask is what would be required to change the polarity of this full-wave precision rectifier circuit.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Positive peak follower-and-hold circuit**   Version:

Schematic

Given conditions

+V = $R_{pot} =$ $R_3 =$ $D_1 = D_2 =$

-V = $R_1 = R_2 =$ $C_1 =$ $U_1 = U_2 =$

Parameters

(Set V_{in} to -V, push reset)   Step 1

	Predicted	Measured		
V_{out}			$V_{TP1} = $ ____	Step 2
V_{out}			$V_{TP1} = $ ____	Step 3
V_{out}			*(Push reset)*	Step 4
V_{out}			$V_{TP1} = $ ____	Step 5
V_{out}			$V_{TP1} = $ ____	Step 6
V_{out}			$V_{TP1} = $ ____	Step 7

file 02640

Answer 12

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 12
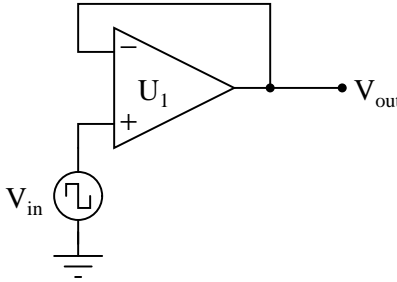
Choose values for V_{in} that show the circuit's ability to "hold" the last highest (most positive) input voltage.

I have found these values to work well:

- +V = +12 volts
- -V = -12 volts
- $R_1 = R_2 = 10$ kΩ
- $R_3 = 10$ kΩ
- $R_{pot} = 10$ kΩ
- $C_1 = 1$ μF (non-electrolytic, low leakage polyester or ceramic)
- $D_1 = D_2 = 1N4148$ switching diode
- $U_1 = U_2 = TL082$ dual BiFET opamp

The TL082 opamp works well in this circuit for three reasons: first, it is a dual opamp, providing both necessary opamps in a single 8-pin package. Second, its JFET input stage provides the low input bias currents necessary to avoid draining the capacitor too rapidly. Third, it is free from latch-up, which makes it possible to reset the capacitor voltage to the full (negative) rail voltage and still have a valid output.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp slew rate** Version:

Schematic

Given conditions

+V =   V$_{in}$ =

-V =   f =

Instructions

Adjust input signal amplitude and frequency until the opamp is
no longer able to follow it, and the output resembles a triangle
waveform. The slope of the triangle wave will be the slew rate.

Parameters

	Measured	Advertised
$+ \dfrac{dv}{dt}$ (max.)		
$- \dfrac{dv}{dt}$ (max.)		

file 02567

Answer 13

Use circuit simulation software to verify your predicted and measured parameter values.

___
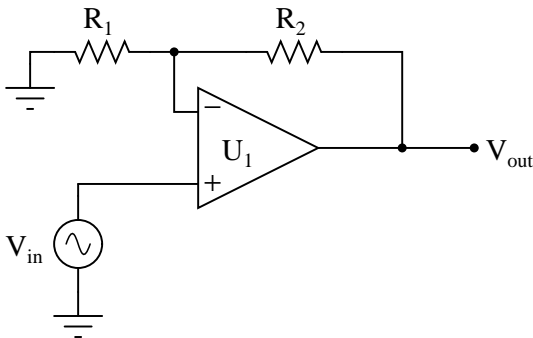
Notes 13

Use a dual-voltage, regulated power supply to supply power to the opamp. I recommend using a "slow" op-amp to make the slewing more easily noticeable. If a student chooses a relatively fast-slew op-amp such as the TL082, their signal frequency may have to go up into the megahertz range before the slewing becomes evident. At these speeds, parasitic inductance and capacitance in their breadboards and test leads will cause bad "ringing" and other artifacts muddling the interpretation of the circuit's performance.

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- V_{in} = 4 V peak-to-peak, at 300 kHz
- U_1 = one-half of LM1458 dual operational amplifier

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Question 14

Competency: **Opamp gain-bandwidth product**				Version:	

Schematic

Given conditions

+V =   Unity-gain frequency of opamp =

-V =

Instructions

$$f = f_{-3dB} \text{ when } V_{out} = \frac{V_{out(max)}}{\sqrt{2}}$$

Keep V_{in} low enough that V_{out} remains sinusoidal (undistorted)
Predict and measure f_{-3dB} at three different gains (A_{CL})
Calculate gain-bandwidth product (GBW) at those gains, and then average.

Parameters

	Predicted	Measured	$(R_2 / R_1) + 1$		Calculated
f_{-3dB}			@ A_{CL} =	GBW	
f_{-3dB}			@ A_{CL} =	GBW	
f_{-3dB}			@ A_{CL} =	GBW	
				$GBW_{average}$	

file 02360

Answer 14

Use circuit simulation software to verify your predicted and measured parameter values.

___

Notes 14

The purpose of this exercise is to empirically determine the gain-bandwidth product (GBW) of a closed-loop opamp amplifier circuit by setting it up for three different closed-loop gains (A_{CL}), measuring the cutoff frequency (f_{-3dB}) at those gains, and calculating the product of the two ($A_{CL}f_{-3dB}$) at each gain. Since this amplifier is DC-coupled, there is no need to measure a lower cutoff frequency in order to calculate band*width*, just the high cutoff frequency.

What GBW tells us is that any opamp has the tendency to act as a low-pass filter, its cutoff frequency being dependent on how much gain we are trying to get out of the opamp. We can have large gain at modest frequencies, or a high bandwidth at modest gain, but not both! This lab exercise is designed to let students see this limitation. As they set up their opamp circuits with greater and greater gains ($\frac{R_2}{R_1} + 1$), they will notice the opamp "cut off" like a low-pass filter at lower and lower frequencies.

For the "given" value of unity-gain frequency, you must consult the datasheet for the opamp you choose. I like to use the popular TL082 BiFET opamp for a lot of AC circuits, because it delivers good performance at a modest price and excellent availability. However, the GBW for the TL082 is so high (3 MHz typical) that breadboard and wiring layout become issues when testing at low gains, due to the resulting high frequencies necessary to show cutoff. The venerable 741 is a better option because its gain-bandwidth product is significantly lower (1 to 1.5 MHz typical).

It is very important in this exercise to maintain an undistorted opamp output, even when the closed-loop gain is very high. Failure to do so will result in the f_{-3dB} points being skewed by slew-rate limiting. What we're looking for here are the cutoff frequencies resulting from loss of small-signal open-loop gain (A_{OL}) inside the opamp. To maintain small-signal status, we must ensure the signal is not being distorted!

Some typical values I was able to calculate for GBW product are 3.8×10^6 for the BiFET TL082, 1.5×10^6 for the LM1458, and around 800×10^3 for the LM741C.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp active integrator**   Version:

Schematic

Given conditions

+V = V_{in} = R_1 = C_1 =

-V =   f = R_2 =

Parameters

	Predicted	Measured	
V_{out}			*With sinusoidal input*
θ			

	Predicted waveshape	Measured waveshape	
V_{out}			*Sine wave input*
V_{out}			*Triangle wave input*
V_{out}			*Square wave input*

file 02565

Answer 15

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 15

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- V_{in} = 1 V peak-to-peak, at 10 kHz
- R_1 = 10 kΩ
- R_2 = 100 kΩ
- C_1 = 0.001 μF
- U_1 = one-half of LM1458 dual operational amplifier

A good follow-up activity for this circuit is to change the input frequency, and predict/measure the phase shift (Θ) between input and output for sinusoidal waveforms. The results may be surprising, especially if you are accustomed to the behavior of a *passive* integrator circuit.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp active differentiator**   Version:

Schematic

C_1 R_1

V_{in} U_1 V_{out}

Given conditions

+V = V_{in} = R_1 = C_1 =

-V =   f = R_2 =

Parameters

	Predicted	Measured	
V_{out}			*With sinusoidal input*
θ			

	Predicted waveshape	Measured waveshape	
V_{out}			*Sine wave input*
V_{out}			*Triangle wave input*
V_{out}			*Square wave input*

file 02566

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Answer 16

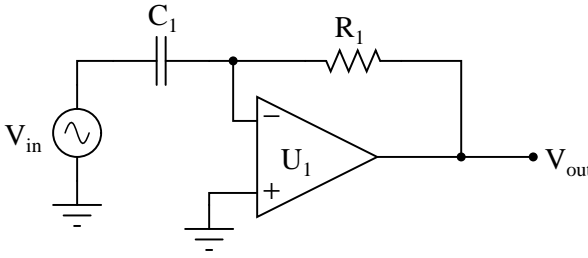Use circuit simulation software to verify your predicted and measured parameter values.

___

Notes 16

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- V_{in} = 1 V peak-to-peak, at 1 kHz
- R_1 = 1 kΩ
- C_1 = 0.1 μF
- U_1 = one-half of LM1458 dual operational amplifier

A good follow-up activity for this circuit is to change the input frequency, and predict/measure the phase shift (Θ) between input and output for sinusoidal waveforms. The results may be surprising, especially if you are accustomed to the behavior of a *passive* differentiator circuit.

Students may become dismayed if they see a "noisy" output waveform, especially if they have just completed the active integrator circuit exercise. Explain to them that noise on the output of a differentiator circuit is quite normal due to the proper function of a differentiator: to provide voltage amplification proportional to the frequency of the signal. This means that even a little high-frequency noise on the input will show up on the output in magnified form. Remind them that this is what differentiators are supposed to do, and it is not some idiosyncrasy of the circuit.

Active differentiator circuits are great for displaying distortions in the input waveform. While pure sine waves in should produce pure sine waves out, and pure triangle waves in should produce pure square waves out, deviations from these "pure" waveform types will produce output waveforms that obviously deviate from their ideal forms. Usually, a "distorted" output does not indicate a fault in the circuit, but rather a subtle distortion in the input signal that would otherwise go unseen due to its miniscule magnitude.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **First order active lowpass filter**   Version:

Schematic

Given conditions

+V = R_1 =

                              C_1 =

-V = R_{comp} =

Parameters

            Predicted   Measured

f_{-3dB} [   ]   [   ]

Fault analysis

Suppose component [   ] fails   ☐ open   ☐ other _____
                                         ☐ shorted
What will happen in the circuit?

Answer 17

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 17

I recommend setting the function generator output for 1 volt, to make it easier for students to measure the point of "cutoff". You may set it at some other value, though, if you so choose (or let students set the value themselves when they test the circuit!).

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the "X-Y" mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

Be sure to choose component values that will yield a frequency well within the range that the specified opamp can handle! It would be foolish, for example, to specify a cutoff frequency in the megahertz range if the particular opamp being used was an LM741.

Competency: **First order active highpass filter**   Version:

Schematic

Given conditions

+V = R_1 = C_1 =

-V = R_{comp} =

Parameters

	Predicted	Measured
f_{-3dB}		

Fault analysis

Suppose component [   ] fails   ☐ open   ☐ other _____
                                       ☐ shorted

What will happen in the circuit?

file 02767

Answer 18

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 18

I recommend setting the function generator output for 1 volt, to make it easier for students to measure the point of "cutoff". You may set it at some other value, though, if you so choose (or let students set the value themselves when they test the circuit!).

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the "X-Y" mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

Be sure to choose component values that will yield a frequency well within the range that the specified opamp can handle! It would be foolish, for example, to specify a cutoff frequency in the megahertz range if the particular opamp being used was an LM741.

Competency: **Sallen-Key active lowpass filter**   Version:

Schematic

Given conditions

+V = R_1 = C_1 =

-V = R_2 = C_2 =

                       R_{comp} =

Parameters

              Predicted   Measured

f_{-3dB} [   ]   [   ]

Fault analysis

Suppose component [   ] fails   ☐ open   ☐ other _____
                                    ☐ shorted

What will happen in the circuit?

file 02577

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 19

I recommend setting the function generator output for 1 volt, to make it easier for students to measure the point of "cutoff". You may set it at some other value, though, if you so choose (or let students set the value themselves when they test the circuit!).

For capacitors, I recommend students choose three (3) capacitors of equal value if they wish to build the Sallen-Key circuit with a Butterworth response (where $C_2 = 2C_1$). Capacitor C_1 will be a single capacitor, while capacitor C_2 will be two capacitors connected in parallel. This generally ensures a more precise 1:2 ratio than choosing individual components.

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the "X-Y" mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

Values that have proven to work well for this exercise are given here, although of course many other values are possible:

- +V = +12 volts
- -V = -12 volts
- R_1 = 10 kΩ
- R_2 = 10 kΩ
- R_{comp} = 20 kΩ (actually, two 10 kΩ resistors in series)
- C_1 = 0.001 μF
- C_2 = 0.002 μF (actually, two 0.001 μF capacitors in parallel)
- U_1 = one-half of LM1458 dual operational amplifier

This combination of components gave a predicted cutoff frequency of 11.25 kHz, with an actual cutoff frequency (not factoring in component tolerances) of 11.36 kHz.

Competency: **Sallen-Key active highpass filter**   Version:

Schematic

Given conditions

+V = R_1 = C_1 =

-V = R_2 = C_2 =

R_{comp} =

Parameters

Predicted   Measured

f_{-3dB}

Fault analysis

Suppose component [   ] fails   ☐ open   ☐ other _____

☐ shorted

What will happen in the circuit?

file 02578

Answer 20

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 20

I recommend setting the function generator output for 1 volt, to make it easier for students to measure the point of "cutoff". You may set it at some other value, though, if you so choose (or let students set the value themselves when they test the circuit!).

For resistors, I recommend students choose three (3) resistors of equal value if they wish to build the Sallen-Key circuit with a Butterworth response (where $R_2 = \frac{1}{2}R_1$). Resistor R_1 will be a single resistor, while resistor R_2 will be two resistors connected in parallel. This generally ensures a more precise 1:2 ratio than choosing individual components.

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the "X-Y" mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

Values that have proven to work well for this exercise are given here, although of course many other values are possible:

- +V = +12 volts
- -V = -12 volts
- R_1 = 10 kΩ
- R_2 = 5 kΩ (actually, two 10 kΩ resistors in parallel)
- R_{comp} = 10 kΩ
- C_1 = 0.002 μF (actually, two 0.001 μF capacitors in parallel)
- C_2 = 0.002 μF (actually, two 0.001 μF capacitors in parallel)
- U_1 = one-half of LM1458 dual operational amplifier

This combination of components gave a predicted cutoff frequency of 11.25 kHz, with an actual cutoff frequency (not factoring in component tolerances) of 11.11 kHz.

Competency: **Active RC filter circuit design**   Version:

Description

> Design and build an active RC filter circuit with a
> cutoff frequency specified by the instructor.

Given conditions

(instructor checks one)

$f_{-3dB} =$ High-pass ☐   Low-pass ☐

Schematic   *Show all component values!*

Parameters

          Predicted   Measured

f_{-3dB} ☐ ☐

file 02133

Answer 21
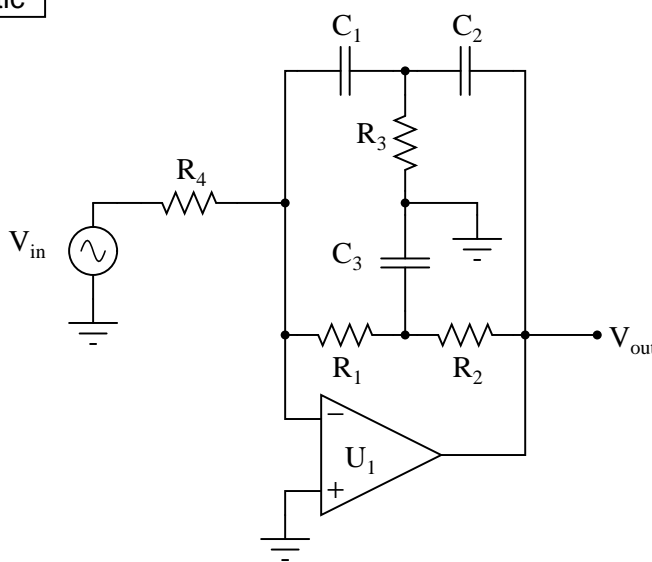
Use circuit simulation software to verify your predicted and measured parameter values.

Notes 21

Use a sine-wave function generator for the AC voltage source. Specify a cutoff frequency within the audio range.

I recommend setting the function generator output for 1 volt, to make it easier for students to measure the point of "cutoff". You may set it at some other value, though, if you so choose (or let students set the value themselves when they test the circuit!).

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the "X-Y" mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

Competency: **Twin-T active bandpass filter**   Version:

| Schematic |

| Given conditions |

+V = R_1 = R_3 = C_1 = C_3 =

-V = R_2 = R_4 = C_2 =

| Parameters |

          Predicted   Measured

f_{center}

Answer 22

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 22

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the "X-Y" mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

Values that have proven to work well for this exercise are given here, although of course many other values are possible:

- +V = +12 volts
- -V = -12 volts
- R_1 = 10 kΩ
- R_2 = 10 kΩ
- R_3 = 5 kΩ (actually, two 10 kΩ resistors in parallel)
- R_4 = 100 kΩ
- C_1 = 0.001 μF
- C_2 = 0.001 μF
- C_3 = 0.002 μF (actually, two 0.001 μF capacitors in parallel)
- U_1 = one-half of LM1458 dual operational amplifier

This combination of components gave a predicted center frequency of 15.92 kHz, with an actual cutoff frequency (not factoring in component tolerances) of 15.63 kHz.

Competency: **Twin-T active bandstop filter**   Version:

Schematic

Given conditions

+V = R_1 = R_3 = C_1 = C_3 =

-V = R_2 = R_4 = C_2 =

Parameters

	Predicted	Measured
f_{notch}		

file 02589

Answer 23

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 23

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the "X-Y" mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

Values that have proven to work well for this exercise are given here, although of course many other values are possible:

- +V = +12 volts
- -V = -12 volts
- R_1 = 10 kΩ
- R_2 = 10 kΩ
- R_3 = 5 kΩ (actually, two 10 kΩ resistors in parallel)
- R_4 = 20 kΩ (actually, two 10 kΩ resistors in series)
- C_1 = 0.001 μF
- C_2 = 0.001 μF
- C_3 = 0.002 μF (actually, two 0.001 μF capacitors in parallel)
- U_1 = one-half of LM1458 dual operational amplifier

This combination of components gave a predicted notch frequency of 15.92 kHz, with an actual cutoff frequency (not factoring in component tolerances) of 15.87 kHz.

Competency: **Opamp relaxation oscillator**	Version:

Schematic

Given conditions

+V = R_1 = R_3 =

-V = R_2 = C_1 =

Parameters

	Predicted	Measured
V_{out} (pk-pk)		
f_{out}		

Fault analysis

Suppose component [ ] fails   ☐ open   ☐ other _____
                                ☐ shorted

What will happen in the circuit?

file 02568

49

Answer 24

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 24

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- R_1 = 10 kΩ
- R_2 = 10 kΩ
- R_3 = 10 kΩ
- C_1 = 0.1 μF
- U_1 = one-half of LM1458 dual operational amplifier

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp triangle wave generator**　　　Version:

Schematic

Given conditions

+V =　　　　R$_1$ =　　　　R$_3$ =　　　　R$_5$ =　　　　C$_2$ =

-V =　　　　R$_2$ =　　　　R$_4$ =　　　　C$_1$ =

Parameters

	Predicted	Measured
V$_{out}$ (pk-pk)		
f$_{out}$		

Fault analysis

Suppose component [　　] fails　☐ open　☐ other _____

　☐ shorted

What will happen in the circuit?

Answer 25

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 25

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- R_1 = 10 kΩ
- R_2 = 10 kΩ
- R_3 = 10 kΩ
- R_4 = 10 kΩ
- R_5 = 100 kΩ
- C_1 = 0.1 μF
- C_2 = 0.47 μF
- U_1 = one-half of LM1458 dual operational amplifier
- U_2 = other half of LM1458 dual operational amplifier

It is a good idea to choose capacitor C_2 as a larger value than capacitor C_1, so that the second opamp does not saturate.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp Wien bridge oscillator**   Version:

Schematic

Given conditions

+V = $R_1 = R_2 =$ $R_{pot} =$

-V = $C_1 = C_2 =$

Parameters

	Predicted	Measured
f_{out}		

Fault analysis

Suppose component [ ] fails   ☐ open   ☐ other _____

☐ shorted

What will happen in the circuit?

file 02636

Answer 26

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 26

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- $R_1 = R_2 = 10$ kΩ
- $R_{pot} = 10$ kΩ multi-turn
- $C_1 = C_2 = 0.001$ μF
- U_1 = one-half of LM1458 dual operational amplifier

Note that due to the lack of automatic gain control in this circuit, the potentiometer adjustment is *very* sensitive! Students will have to finely adjust the multi-turn potentiometer to achieve a good sine wave (meeting the Barkhausen criterion).

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp Wien bridge oscillator w/limiting**   Version:

Schematic

Given conditions

+V = $R_1 = R_2 =$ $R_{pot} =$

-V = $C_1 = C_2 =$ $R_3 = R_4 =$

Parameters

	Predicted	Measured
f_{out}		

Fault analysis

Suppose component ⬚ fails   ☐ open   ☐ other _____
                             ☐ shorted
What will happen in the circuit?

file 02700

Answer 27

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 27

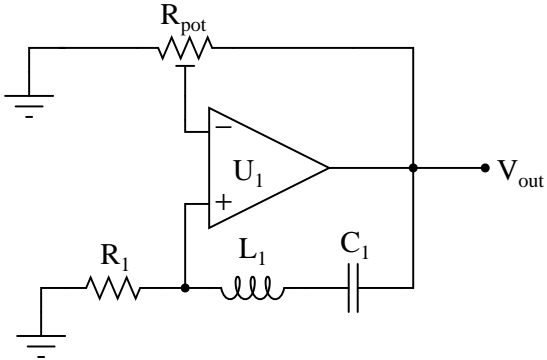Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- $R_1 = R_2 = 10$ kΩ
- $R_3 = R_4 = 10$ kΩ
- $R_{pot} = 10$ kΩ multi-turn
- $C_1 = C_2 = 0.001$ μF
- $D_1 = $ 1N4148
- $D_2 = $ 1N4148
- $U_1 = $ one-half of LM1458 dual operational amplifier

With the presence of the amplitude-limiting diodes D_1 and D_2, the potentiometer adjustment is not nearly as sensitive as without. Try removing both diodes to see what happens when there is no amplitude limiting at all! Students will have to finely adjust the multi-turn potentiometer to achieve a good sine wave (meeting the Barkhausen criterion). With the diodes in place, however, you may adjust the potentiometer for a loop gain just above unity with the only consequence being slight distortion of the waveform rather than severe distortion.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp LC resonant oscillator**   Version:

Schematic

Given conditions

+V = R_1 = L_1 =

-V = C_1 = R_{pot} =

Parameters

        Predicted   Measured

f_{out}

Calculations

file 02637

Answer 28

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 28

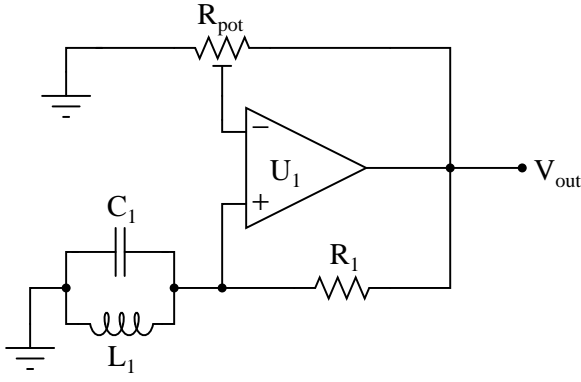Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- R_1 = 10 kΩ
- R_{pot} = 10 kΩ multi-turn
- C_1 = 0.001 μF or 0.47 μF
- L_1 = 100 mH
- U_1 = one-half of LM1458 dual operational amplifier

Note that due to the lack of automatic gain control in this circuit, the potentiometer adjustment is *very* sensitive! Students will have to finely adjust the multi-turn potentiometer to achieve a good sine wave (meeting the Barkhausen criterion).

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp LC resonant oscillator**	Version:

Schematic

Given conditions

+V = R_1 = L_1 =

-V = C_1 = R_{pot} =

Parameters

	Predicted	Measured
f_{out}		

Calculations

file 02638

Answer 29

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 29

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- R_1 = 10 kΩ
- R_{pot} = 10 kΩ multi-turn
- C_1 = 0.001 μF or 0.47 μF
- L_1 = 100 mH
- U_1 = one-half of LM1458 dual operational amplifier

Note that due to the lack of automatic gain control in this circuit, the potentiometer adjustment is *very* sensitive! Students will have to finely adjust the multi-turn potentiometer to achieve a good sine wave (meeting the Barkhausen criterion).

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp LC resonant oscillator w/limiting**   Version:

Schematic

Given conditions

+V =   R$_1$ =   L$_1$ =   R$_2$ = R$_3$ =

-V =   C$_1$ =   R$_{pot}$ =

Parameters

	Predicted	Measured
f$_{out}$		

Calculations

Answer 30

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 30

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- R_1 = 10 kΩ
- $R_2 = R_3$ = 1 kΩ
- R_{pot} = 10 kΩ multi-turn
- C_1 = 0.001 μF or 0.47 μF
- L_1 = 100 mH
- $D_1 = D_2$ = 1N4148
- U_1 = one-half of LM1458 dual operational amplifier

With the presence of the amplitude-limiting diodes D_1 and D_2, the potentiometer adjustment is not nearly as sensitive as without. Try removing both diodes to see what happens when there is no amplitude limiting at all! Students will have to finely adjust the multi-turn potentiometer to achieve a good sine wave (meeting the Barkhausen criterion). With the diodes in place, however, you may adjust the potentiometer for a loop gain just above unity with the only consequence being slight distortion of the waveform rather than severe distortion.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Opamp oscillator w/specified frequency**   Version:

Description

Design and build an opamp oscillator circuit to output
a *sine-wave* AC voltage at a frequency within the
specified tolerance.

Given conditions

+V =   f =   Tolerance$_f$ =

Schematic   *Show all component values!*

Parameters

Measured   Calculated

f [   ]   Error$_f$ [   ] $\dfrac{f_{(actual)} - f_{(ideal)}}{f_{(ideal)}} \times 100\%$
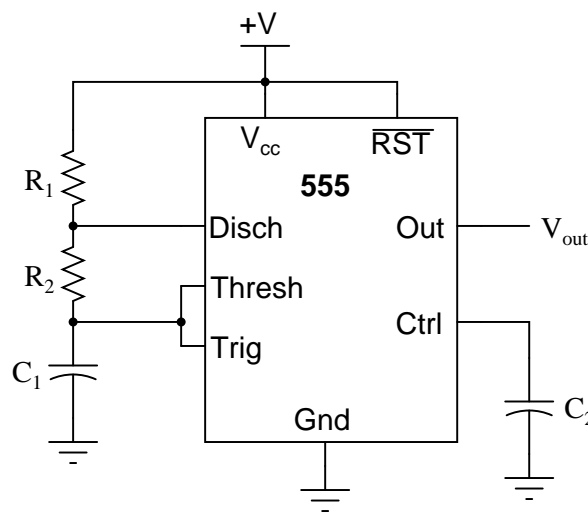
file 02764

Answer 31

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 31

Students are free to choose any oscillator design that meets the criteria: sinusoidal output at a specified frequency.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Astable 555 timer**   Version:

Schematic

Given conditions

+V = $R_1 =$ $R_2 =$

-V = $C_1 =$ $C_2 =$

Parameters

	Predicted	Measured
t_{high}		
t_{low}		
f_{out}		

Fault analysis

Suppose component ⬚ fails   ☐ open   ☐ other _____

☐ shorted

What will happen in the circuit?

Answer 32

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 32

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **555 oscillator w/specified frequency**	Version:

Description
Design and build a 555 oscillator (astable multivibrator) circuit to output a frequency within the specified tolerance.

Given conditions
+V =   f =   Tolerance$_f$ =

Schematic	*Show all component values!*

Parameters

Measured   Calculated

f [   ]   Error$_f$ [   ] $\dfrac{f_{(actual)} - f_{(ideal)}}{f_{(ideal)}} \times 100\%$

file 02862

Answer 33

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 33

Students are free to choose any duty cycle they wish. The only performance criterion is output frequency.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.