Operational Amplifiers Procedure

Instructional Objectives

1. Assemble a non-inverting amplifier circuit with an op-amp and measure the transfer function or gain of the output voltage over the input voltage of the circuit.
2. Measure the output current limit of **real** op amp.
3. Observe clipping limitations of the op amp when used with AC or DC inputs.
4. Determine a 'reasonable' range for the resistances and gains used for op-amp circuits as dictated by the **real** op-amp.

Procedure

Components needed:
1 - 1Ω, 3 – 100Ω, 2 – 1KΩ, 2 – 3.3KΩ, 1 – 100KΩ, TLV271 Op-amp, 2 – 0.1uF ceramic capacitors.

0.   Make sure you have looked at the Inverting and Non-Inverting amplifier configuration in the theory section.

1.   Assemble the circuit shown in Fig. 1 on a breadboard. This is a non-inverting amplifier circuit as described in the theory section. Note the 8 pin op-amp is a single chip. The op-amp consists of the power supply connection and the op-amp connections. They are shown as separate blocks on the schematic. They are on the same chip. Also pins 1, 5 and 8 have small X's on them. This means those pins are not connected to anything.
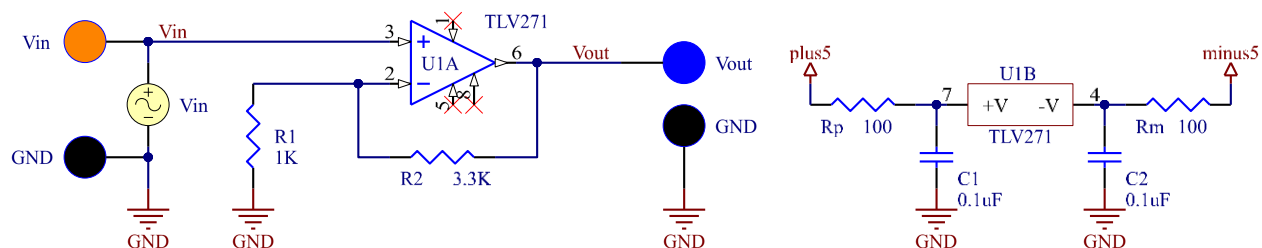

2.

Figure 1: Schematic of a non-inverting amplifier

Use the picture in figure 2 as a construction guide. It is just a guide don't consider it as the only way you can make it. The schematic in Figure 1 is the real circuit. This is not the only way to connect your circuit up on the proto board. It is however the recommended way to minimize errors. The errors will slow down the completion of the lab so minimize them.

- Pin 1 of the op-amp is usually marked with an indented circle.
- In Fig 2: The +5 and -5 volt power supplies are the red and blue mini clips connected to the 100 ohm resistors on the buses near the outer edge of the breadboard. They are the vertical buses that run the whole length of the board. I use Red for +5V and Blue for -5 volts. The bus next to it is usually GND. The +5 and -5 come from the + and – 25V supplies set to 5V. Note if Tracking is turned on you will see that the -25V supply will automatically be set to-5V when the +25V supply is set to +5V. **IMPORTANT: The common of the power supply needs to be connected to the Ground on your breadboard.**
- Two of the vertical buses on the breadboard are GND. The blue bus next to the +5V red bus line and the red bus next to the blue -5V bus. There is an black wire that connects the GND on one side to the GND on the other side.

NOTE: If you are confident you can connect the power supplies directly to pins 4 and 7 of the op-amp you can omit the 100Ω resistors, R_P and R_M. They are only there to protect the op-amp if it gets connected incorrectly.
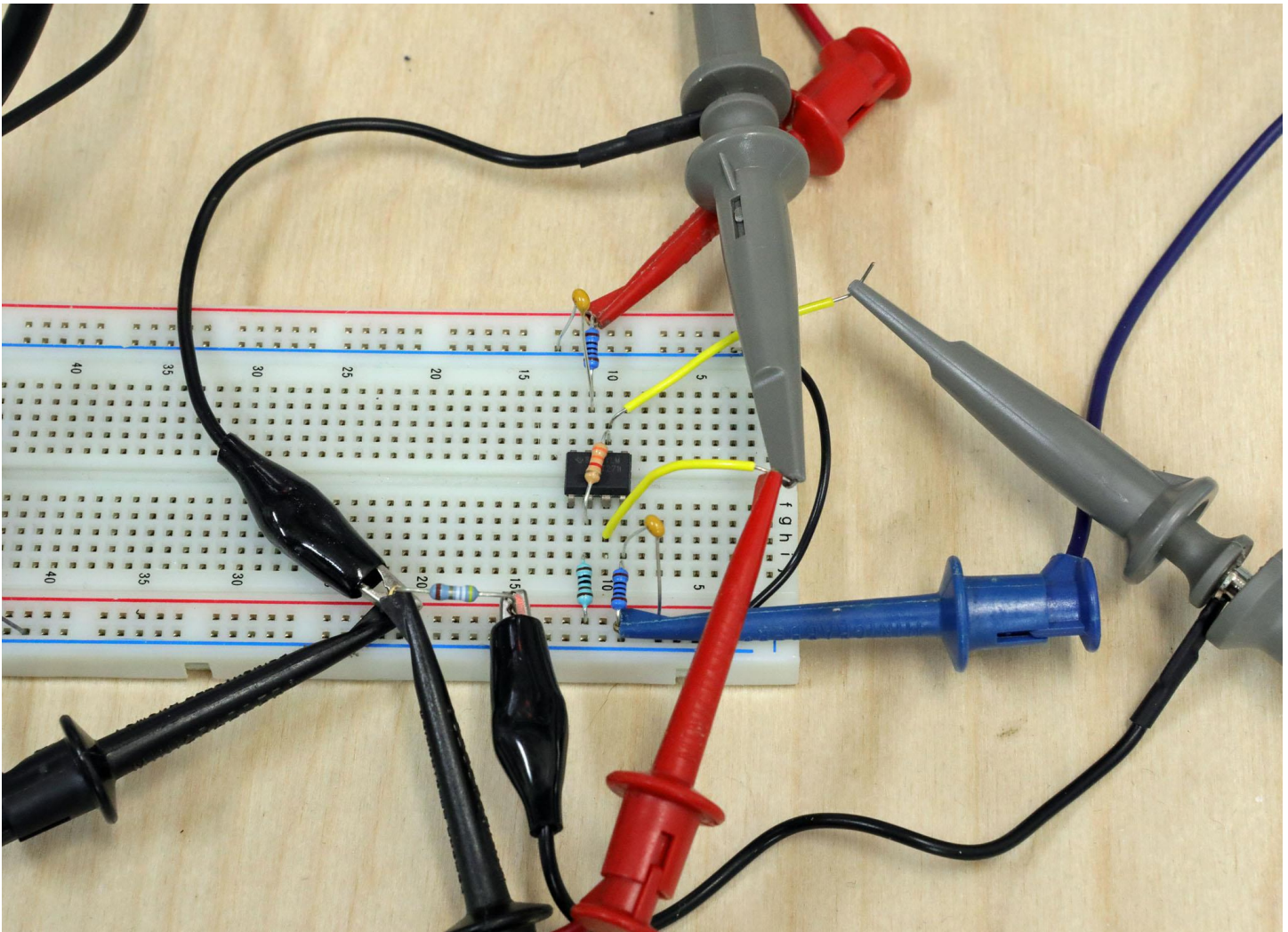
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Figure 2: Non-Inverting Amp with Gain Prototype Example.

Note that there is a plus 5V DC source connected to pin 7 of the op-amp through a 100Ω resistor (Red clip) and a minus 5V source connected to pin 4 through a 100Ω resistor (Blue Clip). Any op-amp always needs external power. The TLV271 will not work without supplies. The 100Ω resistors are not usually needed. We are using them so if there are any mistakes in the building of the circuit the op-amp won't self-destruct. You don't really need them if you are confident the power supplies are properly connected.

Note: The two 0.1uF capacitors connected to pins 4 and 7 are usually referred to as bypass capacitors. The bypass capacitors are your friends. Always use them with op amp circuits! One of the benefits of using these is they prevent the op-amp circuit from oscillating (self-generating a high frequency at the output).

Equipment setup:
1. You will use 3 distinct pieces of equipment.
   - The Power Supplies are the +25V and -25V supply set to +5V and -5V.
     o Remember that using tracking on the power supply means you only have to set the +5V voltage.
   - The Signal Generator is the Wav Gen on the scope for Vin.
     o Red mini clip. No voltage yet.
   - The Oscilloscope will be used to measure up to 4 signals during lab.
     o CH1 to Vin and GND.
     o CH2 to Vout and GND.
     o CH3 and CH4 to other signals and GND.

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- Turn on the supply with the +5 and -5 V and Common connected.
- Measure the -5V and +5V with the DMM. Make sure they are somewhere near 5V in magnitude.
  - If the either voltage is low you probably have a short circuit that must be fixed. You may have ruined the op-amp. Figure out what is wrong and see if it works after correcting the mistake(s).

Always look at the Vout on the scope. It is a great way to make sure the circuit is still working after changes are made. This will also speed up lab completion. You will catch errors early and fix them in a timely manner.

What is the theoretical gain, A = Vout/Vin, of the circuit shown in Fig. 8? A = Gain ___4.3__V/V

3. **Use the DMM** to measure Vin and V_{OUT} for the different DC V_{IN} voltages listed in Table 1 using the circuit shown in Fig. 1. Use the DMM on DC for these measurements. Remember you must set the Wav Gen to put out DC corresponding to the DC input voltages as you go.

V_{IN}	Measured Vin	Measured V_{OUT}	Vin*A	V_{IN}	Measured Vin	Measured V_{OUT}	Vin*A
0 V_{DC}	2.04mV	6.924mV	3.38	-0.5 V_{DC}	-0.502V	-2.135V	4.27
0.5 V_{DC}	0.505V	2.165V	4.27	-1.0 V_{DC}	-1.01V	-4.259V	1.22
1.0 V_{DC}	1.02V	4.367V	4.28	-1.5 V_{DC}	-1.507V	-4.778V	3.057
1.5 V_{DC}	1.515V	4.864V	3.21				

Table 1: DC voltage measurements.

What is the gain A again? ___4.3____
Fill in the Vin*A column in Table 1.
Did measured Vout always match Vin*A? _No_ What was Vin if it didn't? __0V__ __1.5V__ __-1.5V__

So what you just did was measure Vout and Vin for an op-amp circuit. 1 DC voltage at a time. This is not real efficient. There is an easier way to see the Vout and Vin signals with respect to each other.
- First you need a waveform that moves linearly from the lowest voltage of interest to the highest.
- We are in luck there is a triangle waveform that does this.
- Set the signal generator to a 3V_{PP} 1KHz triangle wave with 0V offset and 50% Symmetry.
- The oscilloscope should be connected to Vin and Vout.
- Set the Vin sensitivity to 0.5V/Div and the Vout sensitivity to 2V/Div.
- Set the time base to 200uS/Div.
- You should see the input and output voltages appear on the screen. The output should be clipped.

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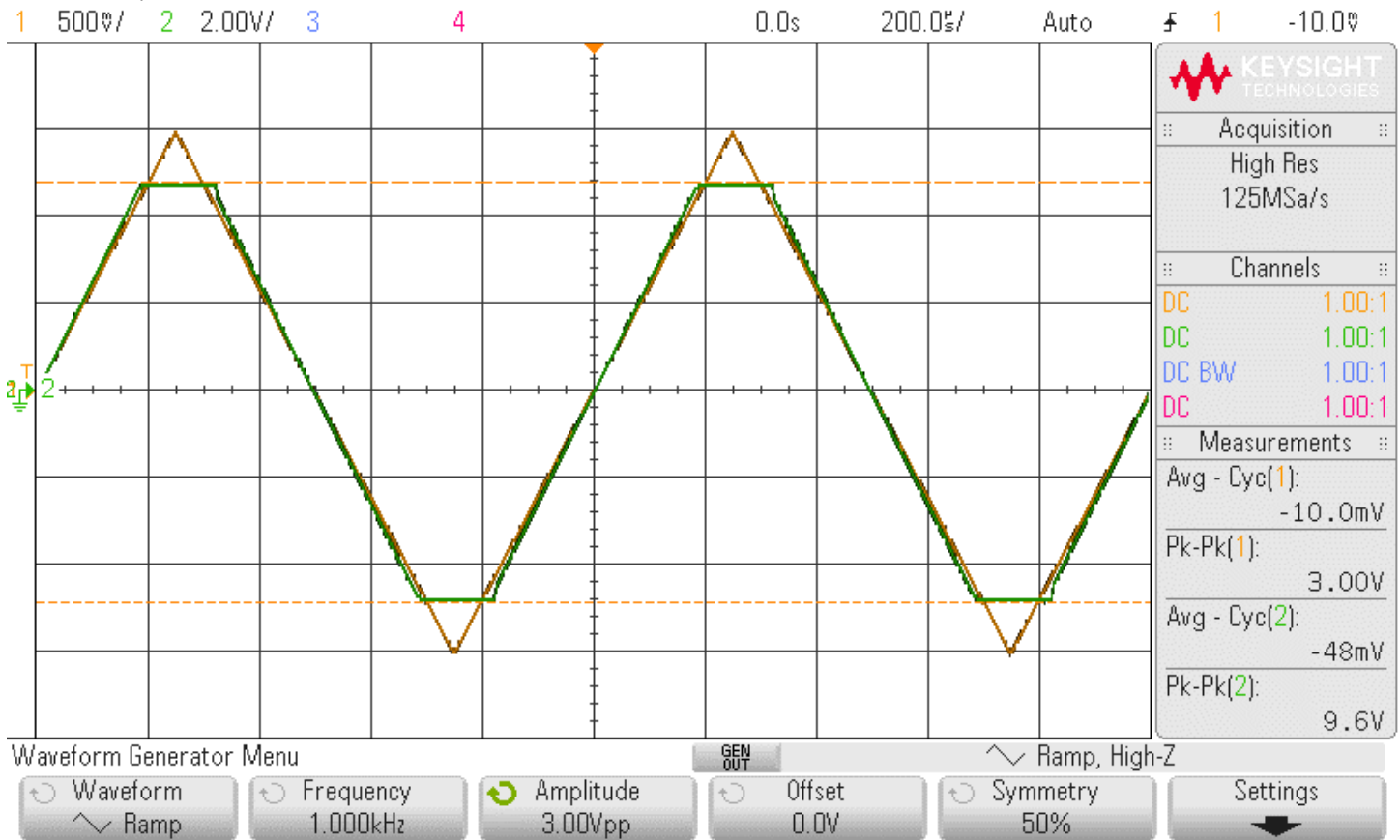

Figure 3: Triangle Vin (Yellow) and Vout (Green).

Next we will use the same circuit you built for the previous measurements. You will be adding a load resistor then changing the load resistor during the next experiment. Just add the load resistor from pin 6 to GND on the breadboard.
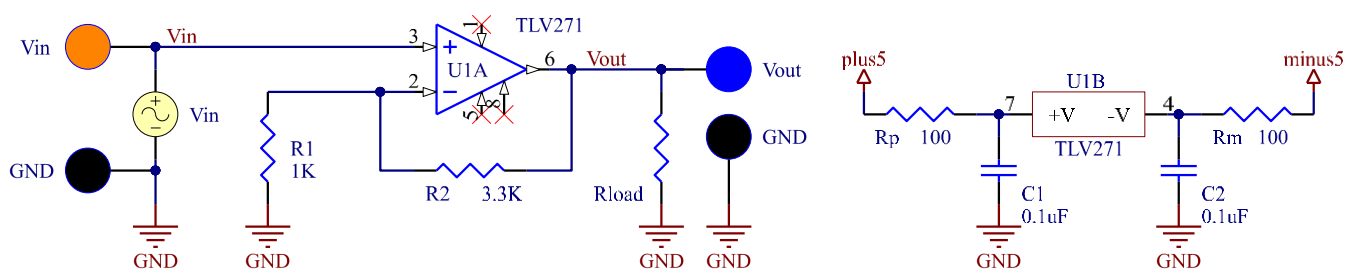

Figure 4: Non-inverting amplifier with gain and variable load resistor.

4. Qualitatively observe the output resistance of the op amp circuit shown in Fig. 4. This circuit is the same one in Figure 1 with the addition of a load resistor. Qualitative means: See if the output voltage changes when the load resistor changes. You will do this by measuring V_{OUT} with the scope.
- Use the Oscilloscope to measure AC voltages and the DMM for DC.
- Use a DC input first and secondly use a 1KHz sine wave input for each R_{LOAD}.
- Use R_{LOAD} as specified in table 2 for each test.
- Use the trigger on CH1 rising edge trigger mode to hold the sine wave still.
- Set V_{IN} to $1V_{DC}$ for the DC input or $2V_{PP}$ for a sine wave input of 1KHz. **NOTE:** Only input the AC or the DC not both at once.
- Measure the real value of R_{LOAD} with the DMM and enter it in the Actual column of Table 2.

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- Measure the voltages at V_{IN} and V_{OUT} as per Table 2 and enter the actual value next to the nominal value into the table. Use the Peak-peak measurement for AC and the DMM for DC measurements.

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Capture V_{OUT} with the AC input for 3.3KΩ and 100Ω R_{LOAD} cases.

R_{LOAD}		DC		1KHz sine wave	
Ideal	Measured	V_{INDC}	V_{OUTDC}	V_{INPP}	V_{OUTPP}
100K Ω	99.17K Ω	1V_{DC} |1.019V	4.363V	2V_{PP} |2.002V	8.28V
3.3K Ω	3.246K Ω	1V_{DC} |1.019V	4.361V	2V_{PP} |2.002V	8.26V
1.0K Ω	997 Ω	1V_{DC} |1.019V	4.247V	2V_{PP} |2.002V	8.30V
100 Ω	99.9 Ω	1V_{DC} |1.019V	1.973V	2V_{PP} |2.002V	3.716V

Table 2. Measured data.

Op-amp output limit explorations: For now assume the op-amp is constrained by either a voltage limit or a current limit. Both limits look like the output voltage is limited when driving a resistor so first we will measure the voltage limit with no load resistor. No load so the op-amp is not delivering any current. Then we will ask for more current than the op-amp can deliver to measure the current limit.

5. Voltage clipping limits: Set V_{IN} to a 3V_{PP}, 1KHz sine wave with no offset. Using the circuit shown in Fig. 1, observe V_{OUT} on the Scope. Use R_{LOAD} = ∞Ω (No Load) . You will use the **scope** to measure the flattened (clipped) voltage levels.

Figure 5: Clipped Vout display Vin Yellow and Vout Green..
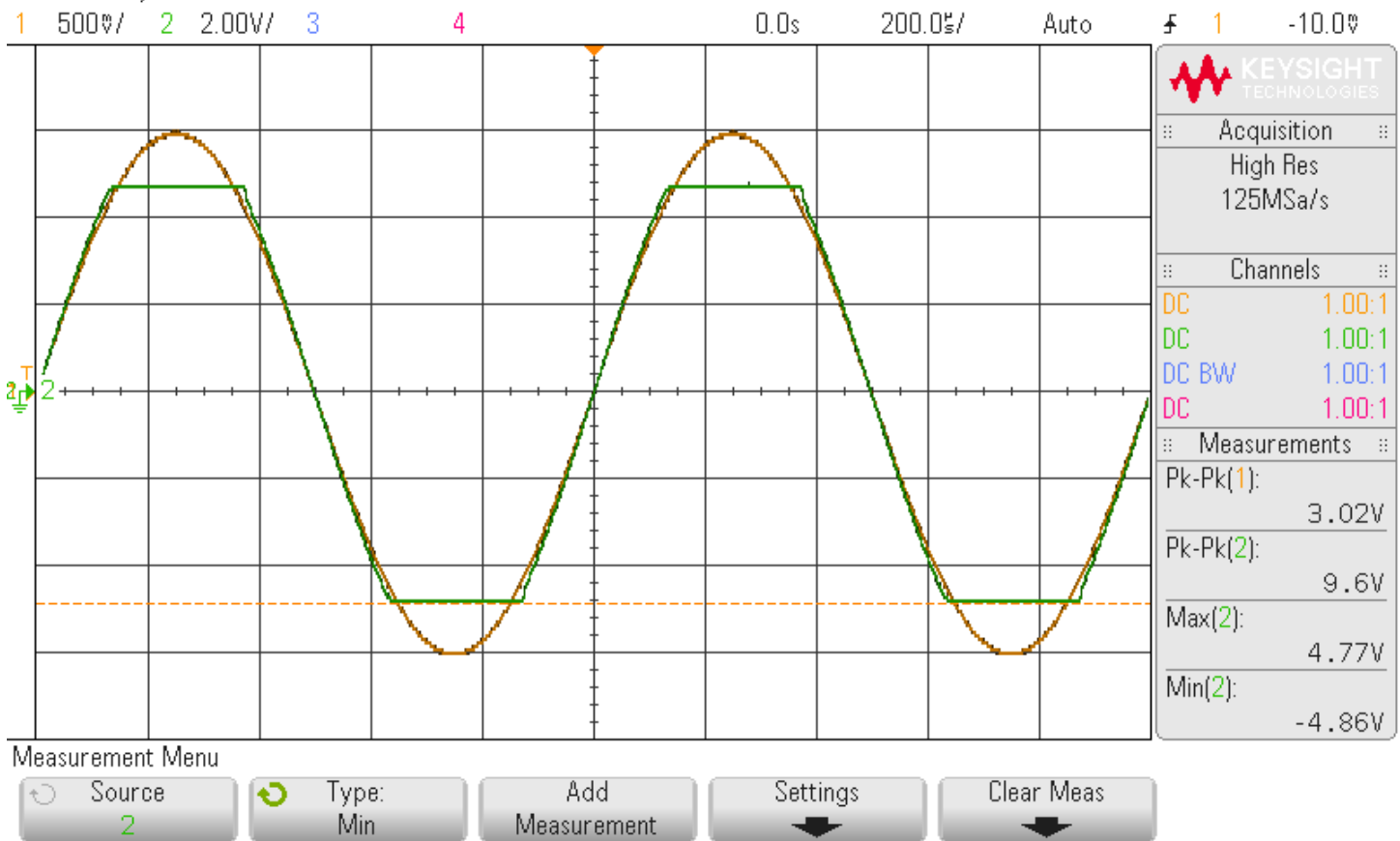
6. I recommend that you use Max and Min measurement with to determine V_{HIGH} and V_{LOW}. Record the positive and negative voltage levels where V_{OUT} flattens out. The levels will be smaller in magnitude than the power supply voltages but close.

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$V_{OutClippedHighNoLoad}$ _____4.753V____ $V_{OutClippedLowNoLoad}$ _____-4.896V____

7. Output current limit: Use the circuit from the Figure 4. Use an R_{LOAD} of 100Ω.

   First put a 2VPP 1KHz sine wave in and look at the output with the scope. It should be clipping at a lower voltage than the voltage limits.

   Next set V_{IN} to -1.0V_{DC}. Use the **DMM** to measure V_{OUTDC}. Copy the theoretical gain calculated above down here.

   $A_{THEORETICAL}$ _____-4.3_____ V/V.

   What should the output voltage be for the 1.0VDC input? ____-4.363V___.

   At what positive and negative voltages should the circuit clip due to no load voltage limit measured above. ($V_{OutClippedXNoLoad}$)? pos ___4.27___V, neg ____-4.29___V.

   Measure the High and Low voltage that you get when driving the 100Ω resistor. Vin = +1V_{DC} or -1V_{DC}.

   $V_{IlimitOutHigh}$ _1.973__V, $V_{IlimitOutLow}$ _-1.935___V.

   Are the measured High and Low voltages lower than the no load clipping limits? ___Yes____

   So is the output voltage limited or current limited with the 100Ω load? _Current__

   Calculate the output currents by dividing the positive then negative $V_{IlimitOutXxxx}$ by R_{LOAD} (100Ω).

   $I_{IlimitOutHigh+}$___19.73__ mA, $I_{IlimitOutLow}$___-19.35__ mA

8. **We are going to build a simple inverting amplifier with low gain.** The schematic is shown in Fig. 6. Determine the theoretical gain (Theory), Vout/Vin, of this circuit. $Gain_{LOW}$ = _____-3.3___. Build this circuit on the breadboard. Since you got the circuit in Figs 1 and 4 running you can skip using the 100Ω current limiting resistors. They were there to prevent the destruction of the op-amp in case the circuit was built wrong. The assumption being you built it correctly and will this time too.
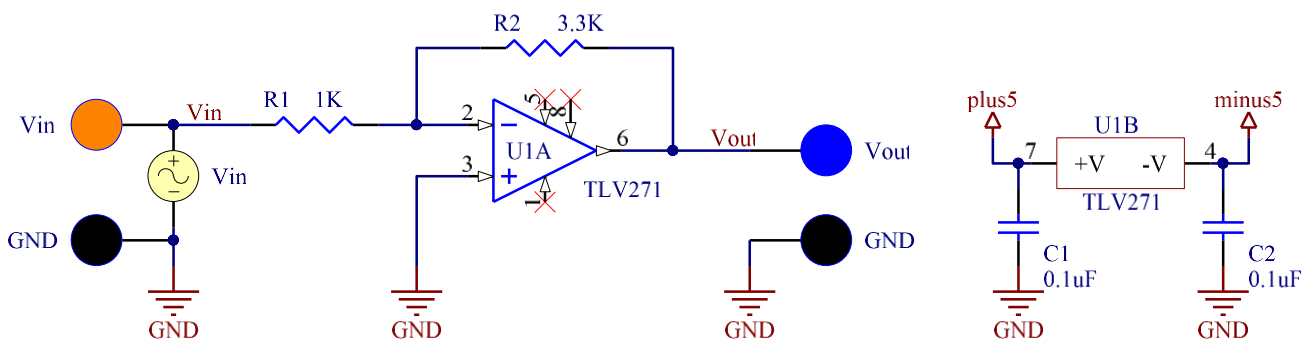

Figure 6: Inverting amplifier with low gain.
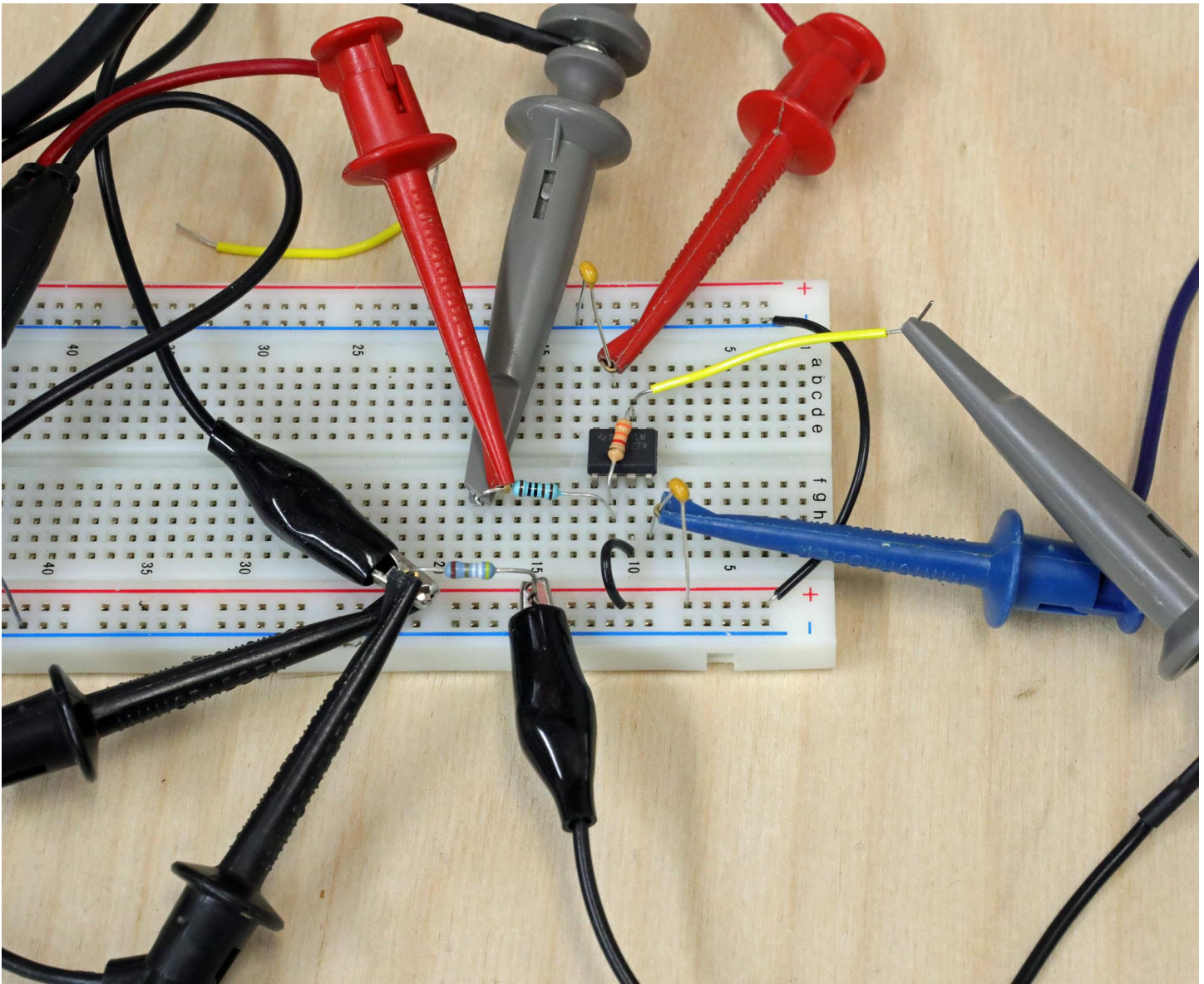
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Figure 7: Inverting amplifier layout example.

- Set the input voltage Vin to 2.0V$_{PP}$ at 200Hz with 0V$_{DC}$ offset.
- What should the theoretical DC output voltage be? _____0_____V$_{DC}$.
- Note the AC input is 2.0V$_{PP}$.
- What should the AC output voltage be? _____-6.6_____V$_{PP}$.
- Monitor the AC output voltage with the scope. (Peak to peak Measurement) Measure the DC output with the DMM.

8. **Measure Vin and V$_{OUT}$.** to make sure the circuit is working as expected. Set the time base to about 1ms/div. Put the measured values in Table 3 for the gain Low row.

Review the theory section of the inverting amplifier. Make sure you understand what virtual ground means. Now connect the CH3 input to pin 3 of the op-amp. Pin 3 is connected directly to ground. The CH3 scope trace should be a straight line at 0V. Change the CH3 sensitivity to 1 mV/div. Is it still a straight line at 0V? For the next measurements. Put the CH4 probe on pin2 of the op-amp. Now measure the Pin2 (2) and pin3 (3) AC and DC voltages only with the scope. Only fill in the -3.3 Gain row right now. NOTE: If the output of the op-amp gets noisy try the X10 probe setting. Don't forget to change the probe setting on the scope too.

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OpAmp	200Hz 1V_P sine wave with 0V_{DC}							
Gain	Vin_{AC}	Vin_{DC}	V_{OUTAC}	V_{OUTDC}	V_{3AC}	V_{3DC}	V_{2AC}	V_{2DC}
LOW (Fig 6)	719.3mV	0.211mV	2.22V	0.866mV	-57.73mV	-400mV	-23.27mV	-0.127mV
HIGH (Fig 8)	Fill in later.							

Table 3:

Change R1 to 100Ω and R2 to 100KΩ as shown in Figure 8. **Note:** The power supply connections are omitted from the figure but please make sure you still connect the power supply to the power pins of the op-amp.
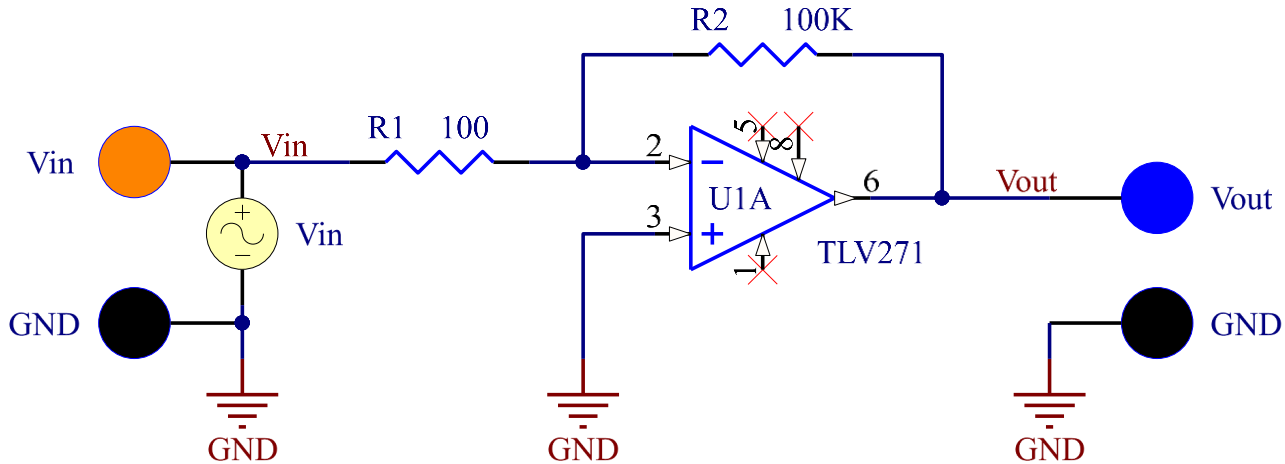

Figure 8: Inverting amplifier with high gain.

What is the theoretical gain, Vout/Vin, of this inverting amplifier? Gain$_{HIGH}$ _____-1000_____.

We want to put about in a 1 mV$_{PP}$ Vin so that Vout will be 1 V$_{PP}$. We can't really do that with the existing signal generators so we need to do something special. We need to divide a 1V$_{PP}$ signal down by about a 1000 using a resistor divider. Fig 14. shows a scheme to do this division. This is usually called an attenuator.
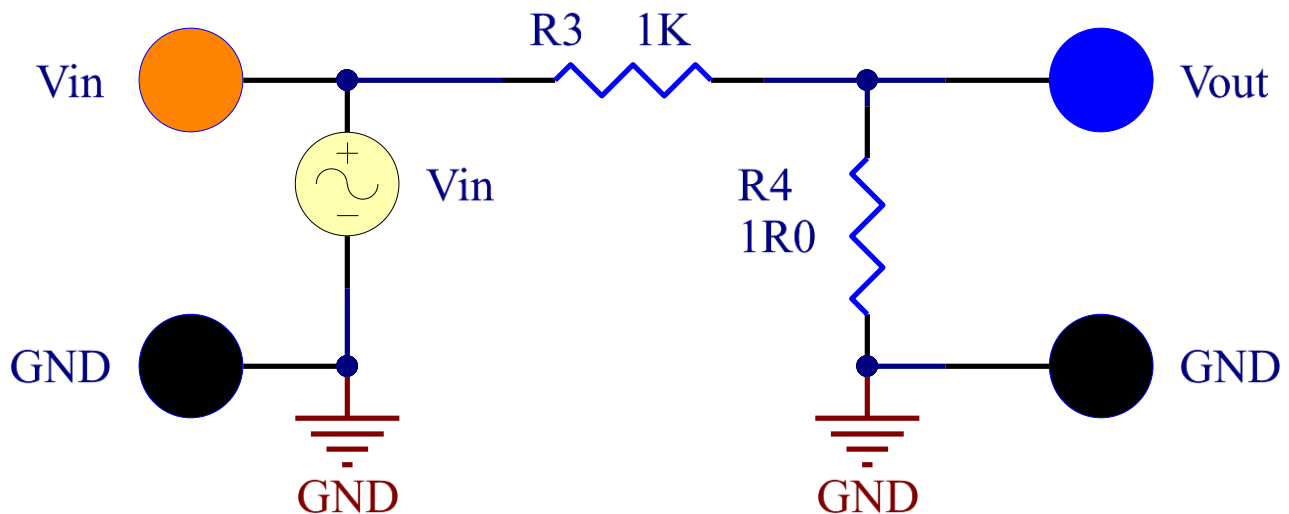

Figure 9: Resistor attenuator to generate a clean very low voltage.

Note the resistor marked 1R0 is a convenient way to list the value as 1Ω. The R takes the place of the decimal point (.). The R is much more visible than the decimal point so the value is clearly indicated this way.

What is the theoretical gain (It will be << 1) ? GAIN$_{RESISTORS}$ = __9.99e-4___

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Note when gain is < 1 we sometimes use attenuation ratio which is the inverse of the gain.
Gain = Vout/Vin and Attenuation ratio is Vin/Vout. Again we usually call this little 2 resistor circuit an attenuator.

Connect in a 5V$_{PP}$ 1KHz sine wave at Vin of the resistor divider. Connect CH1 from Vin to GND and connect CH2 from Vout to GND. Use the X1 setting on the on the probed if you aren't already. Adjust the CH2 sensitivity to 1mV / Div. Use the **Normal** "Acquire" mode.

Ch1 should be a nice clean sine wave. Ch2 looks like (pick 1) Good, Bad or Ugly google the phrase "The good the bad and the ugly".
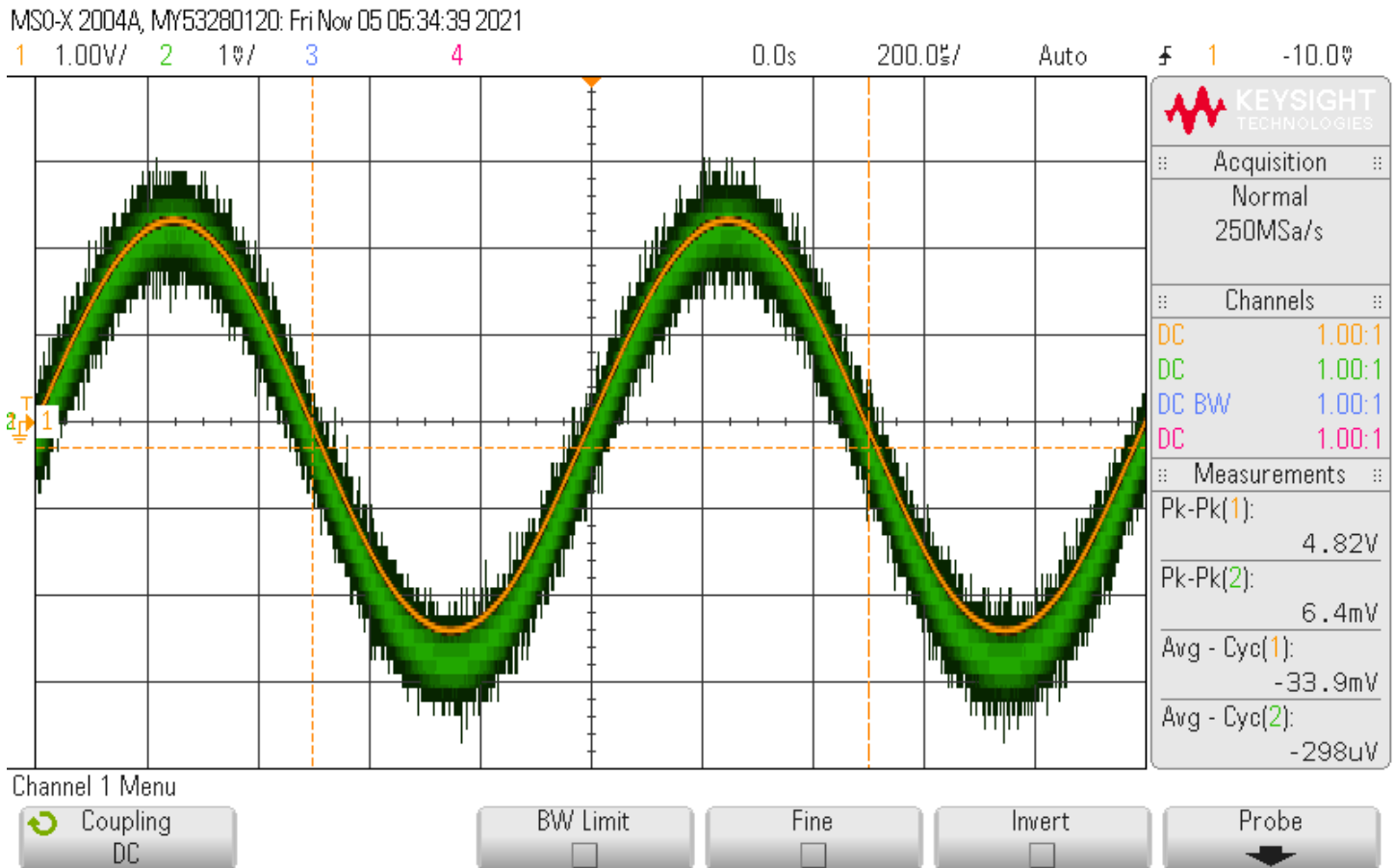

Figure 10: Attenuator signal voltages across each resistor. Yellow R3 and Blue R4.

Now use the **Average** mode of "Acquire" instead of Normal. I used 32 averages and got a pretty good trace. For this to work you need to be triggering on the input so the sine wave is not moving.

What is the approximate size of Vin and ___4.86___ V V$_{OUT}$_____5.9___mV ?

Build the circuit shown in Fig.11. What is the theoretical gain from Vin to Vout? GAIN$_{AMPLIFIER}$ ___1000____

Note the gain is for both AC and DC signals that are at Vin.
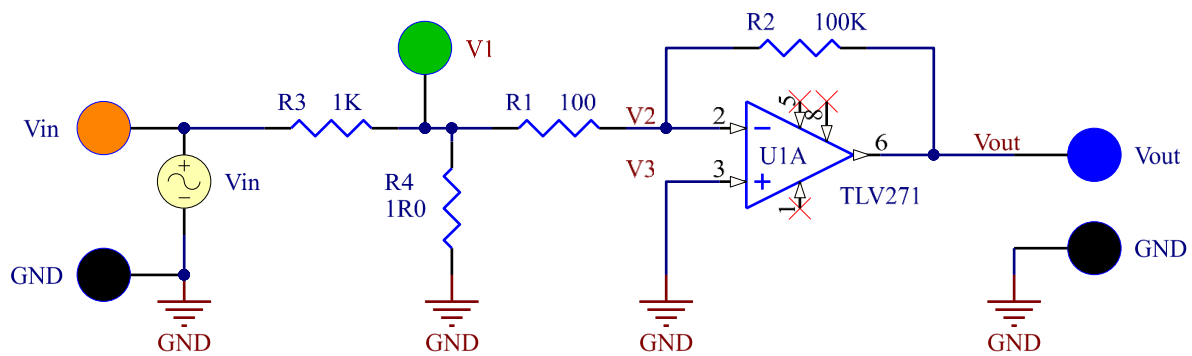
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Figure 11: High gain inverting amplifier with attenuated input signal.
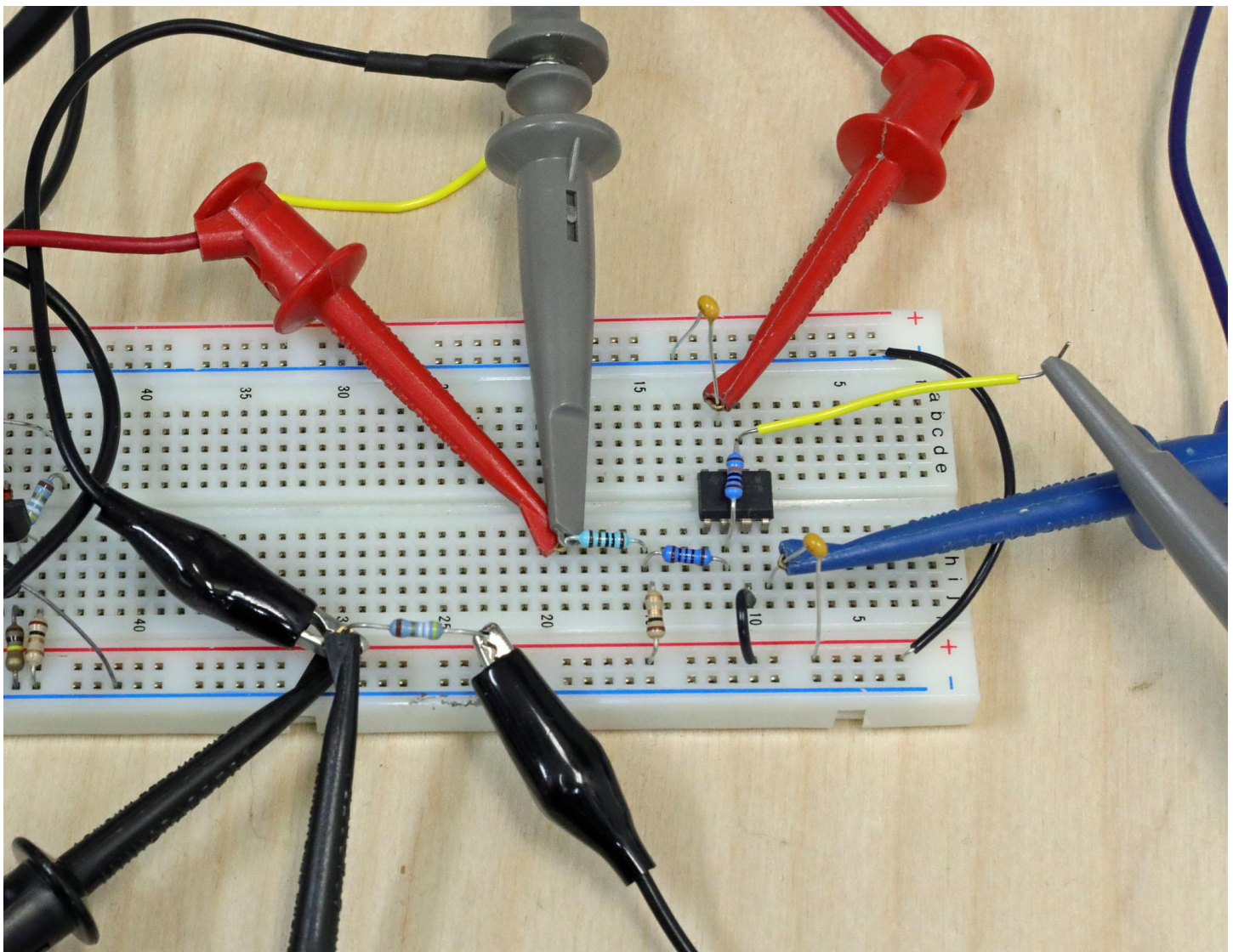

Figure 12: High gain inverting amplifier with attenuator layout example. This is similar to Fig 7 with R1 and R2 changed and R3 and R4 added.

What is the theoretical gain from Vin to V_{OUT}? $GAIN_{ATTEN\_W\_GAIN}$ = ___0.999___

Hint: $GAIN_{ATTEN\_W\_GAIN} = GAIN_{RESISTORS}*GAIN_{AMPLIFIER}$

So anything at Vin should show up at V_{OUT} times $GAIN_{ATTEN\_W\_GAIN}$.

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Set Vin to a 200Hz 5V_{PP} sine wave. Is the output a clean sine wave? _Yes__

Remember Table 3 from above. Here it is again. Copy the values from above for the -3.3 gain row.

OpAmp Gain	200Hz 1V$_P$ sine wave with 0V$_{DC}$							
	Vin$_{AC}$	Vin$_{DC}$	V$_{OUTAC}$	V$_{OUTDC}$	V$_{3AC}$	V$_{3DC}$	V$_{2AC}$	V$_{2DC}$
LOW	-719.32mV	0.024mV	772.81mV	0.866mV	-0.204mV	-0.004mV	-27.58mV	-0.127mV
HIGH	720.62mV	0.533mV	2.22V	1.405mV	1.21mV	0.052mV	20.2mV	1.421mV

Table 3: Again

Copy the info for the LOW gain entries from the previous table. Measure the data for the HIGH gain amplifier
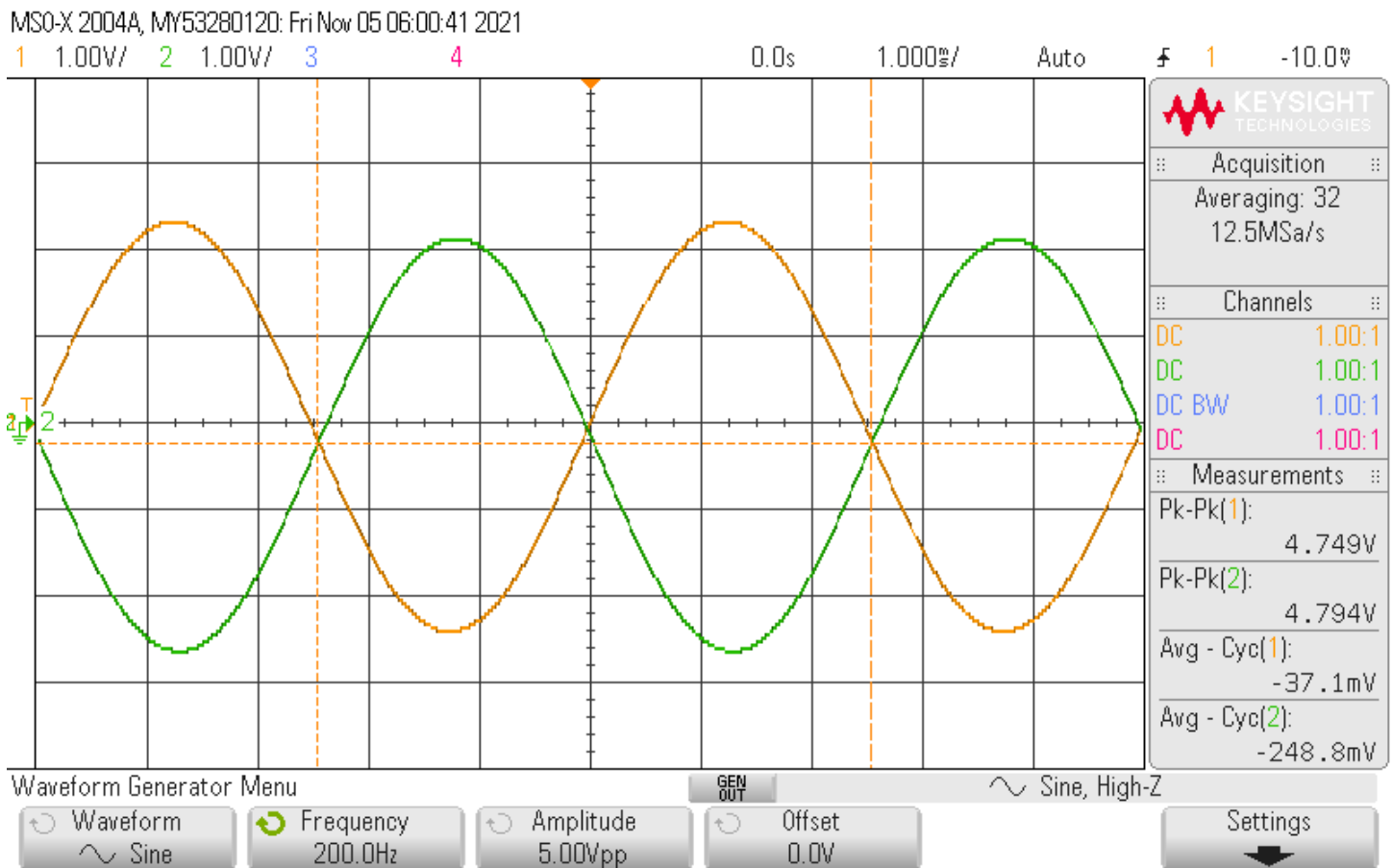Measure Vin and Vout first. Use the scope for AC and the DMM for DC. Then measure V2 and V3 with only the scope.

Figure 13: High Gain amplifier with attenuated input. Vin and Vout.

V$_{INAC}$ and V$_{OUTAC}$ should be about the same voltage. Remember: For V2 and V3 use the 1mV setting for CH3 and CH4 on the scope.

Is there anything suspicious about the waveform of V$_{OUT}$ for the HIGH gain amplifier? Does it look different than it should in theory (Consider both the AC and DC output.)?__Yes__
If yes what is "funny"?

There is probably a DC offset on the Vout signal. Where could that DC output voltage be coming from?

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Is it the DC offset of Vin * GAIN$_{ATTEN\_W\_GAIN}$? Consider that. _No_____
- What is the DCoffset measurement of Vin (Use the DMM)? _0.014mV __
- Vin$_{DC}$ * GAIN$_{ATTEN\_W\_GAIN}$ = _0.014mV_.
- Is that close to the V$_{OUTDC}$? __No____

Is it caused by the DCoffset error of Vin? Consider that the DC at Vin should be 0. ____No___
- DCoffset error of Vin = ____533___mV (measure it with the DVM)
- Is this error * GAIN$_{ATTEN}$ close to the V$_{OUTDC}$? __No___.

Is it coming from the amplifier with a HIGH gain ? Consider that. ___Yes___
- Disconnect Vin from R3, the 1.0K resistor, and ground the R3 input. Use the DMM to measure Vout. What is V$_{OUTDC}$? __1.405mV____
- Is that close to the original V$_{OUTDC}$? __Yes__

You have discovered one of the problems with using op-amp circuits with very high gain. In a real op-amp there is a small amount of dc offset between the In+ and In- terminals. With low gain circuits it doesn't really cause trouble. With high gain circuits it often causes trouble. To see what the DCoffset at the input terminals is you just take the V$_{OUTDC}$ from table 3 and divide it by the gain. So if you got 1V DCoffset with a gain of -1000 the calculated input referred offset is 1V/(-1000) or -1 mV. We call this the input referred offset. What is the input referred offset for your -1000 gain amplifier? ___1.405e-6V _____

Post Lab Questions

1. Plot the transfer function of V$_{OUT}$ versus V$_{IN}$ for the values you obtained in step 3, Table 1. Explain what is happening in the different regions of your plot.
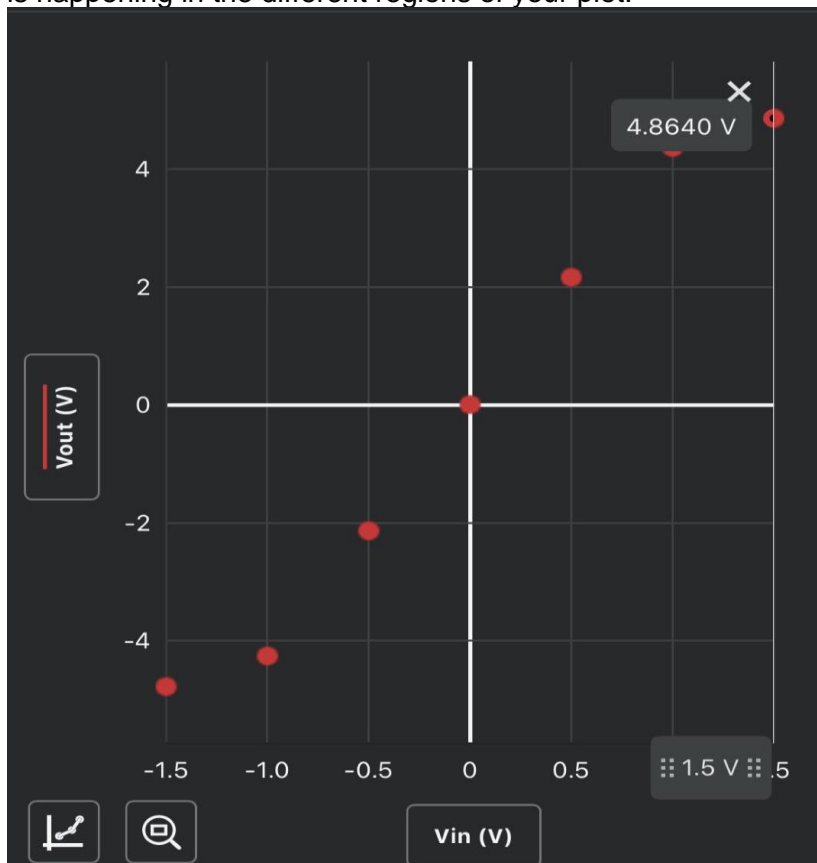
The middle 5 points can form a very smooth straight line, which means the gains for input voltage -0, +-0.5, +-1 are almost the same. The reason +-1.5 cannot from a straight line with other points is the output voltage is limited by the dependent source in the op amp.

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2.   What are all the paths that the current coming out of or going into the output (pin 6) of the TLV271 for the circuit shown in Fig.4?

       The current through R2 going into pin 6 and the current coming out from the op amp.

3.   What is the minimum load resistance (smallest resistive load) you can connect to the output so the current limit is reached just as the voltage clipping limit is reached? Choose the smaller magnitude of the current limits to make this calculation.

       The minimum load resistance should be 220 Ohm.