# Laboratory 2 (2 days):
# Operational Amplifiers: Integrators, bandwidth & DC biasing

## Overall notes:

- This laboratory has ***two sessions*** allocated for completion.
  - 1st Lab session: Pre-Lab Exercise 1 and Exercise 1. Exercise 2 is optional.
  - 2nd Lab session: Pre-Lab Exercise 2 and Exercise 3. Exercise 4 is optional.
- You should include screenshots of your results in the report. Oscilloscope plots should include both the input and the output waveforms.
- Screenshots of waveforms can be obtained using the Discovery Board. If you use the benchtop equipment instead, capture an image using your phone and include it in your report.

## Material covered:

- Integrator/Miller Integrator
- Difference Amplifier
- Gain-Bandwidth product
- DC bias voltages
- DC bias currents

## Data Acquisition:

- Discovery Board:
  - Screenshots are available under the Export tab in the upper right corner. Choose the Image tab on the main window to get png images. The png image format is a standard and should open in Windows.
  - Raw data can be obtained as well and used with a numerical tool, such as Excel or Matlab. Some laboratories (including the second session of this lab) will call for further analysis on the raw data.

# Pre-Lab Exercise 1

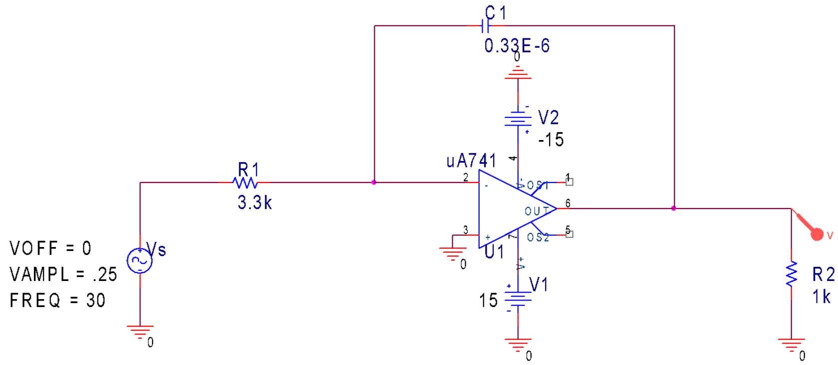



**Figure 1: Integrator**

1. Implement the above circuit in PSpice, using the μA741 amplifier component. Pay attention to the pin numbers for the component, it is consistent with the pin diagrams provided in Laboratory 0. In the above schematic, the amplifier has been vertically 'flipped' for ease of layout. The power supplies are 15 V / –15 V, as shown above. The input signal is a 30 Hz, 0.25 V amplitude sinusoidal voltage (the Vsin component).

2. Run a transient analysis in PSpice and plot a few periods of the output.
   *Is the output behavior consistent with an integrator?*

3. Add an offset voltage, VOFF, of 0.002 V (positive).
   *Why does the output of the integrator change?*

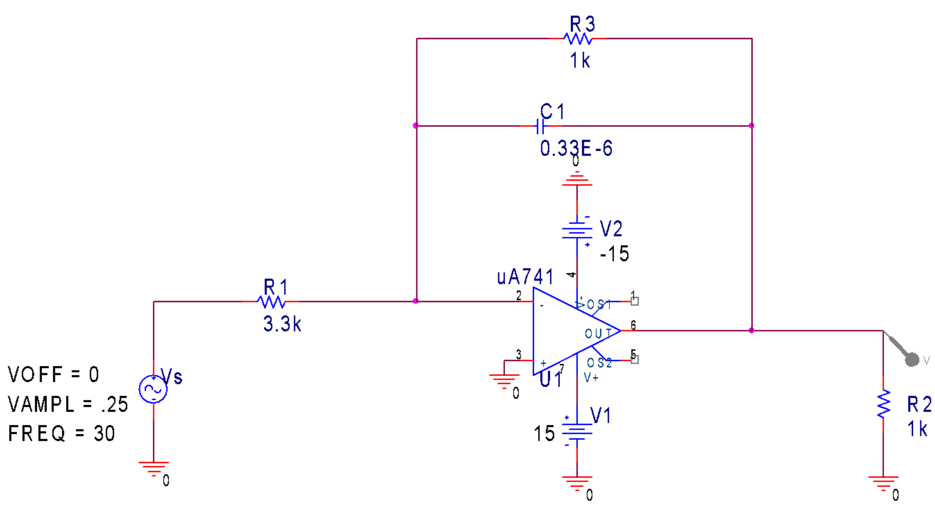



**Figure 2: Op Amp with *R* and *C* feedback**

4. Implement the Miller integrator by adding the 1 kΩ feedback resistor in parallel with the capacitor. Again, run a transient analysis and plot the output.
   *At this frequency (30 Hz), is the PSpice output consistent with an integrator or with an inverter? Does the answer agree with your expectation?*

# Pre-Lab Exercise 2

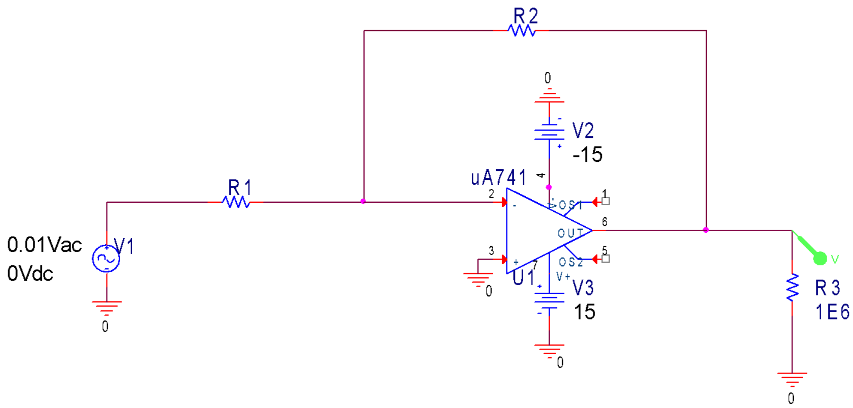



**Figure 3: Op Amp with resistive feedback.**

1. Implement the above circuit in PSpice and perform an AC sweep from 10 Hz to 10 MHz using the resistor combinations given below. For each case, note the cutoff frequency (where the output voltage amplitude is reduced to 70.7% of the passband value, the –3 dB point). Note, the source is the VAC component in PSpice 16.0. Alternatively, you can use the Vsin component in PSpice 16.6. In both cases, you should set the VAC value to 0.01 V so that the output voltage is less than the saturation values.
   a. $R_1$ = 1 kΩ, $R_2$ = 10 kΩ
   b. $R_1$ = 1 kΩ, $R_2$ = 100 kΩ
   c. $R_1$ = 100 Ω, $R_2$ = 100 kΩ (***Note***: $R_1$ has changed)

   *As the amplifier gain increases, what observations can you make with regard to the bandwidth?*

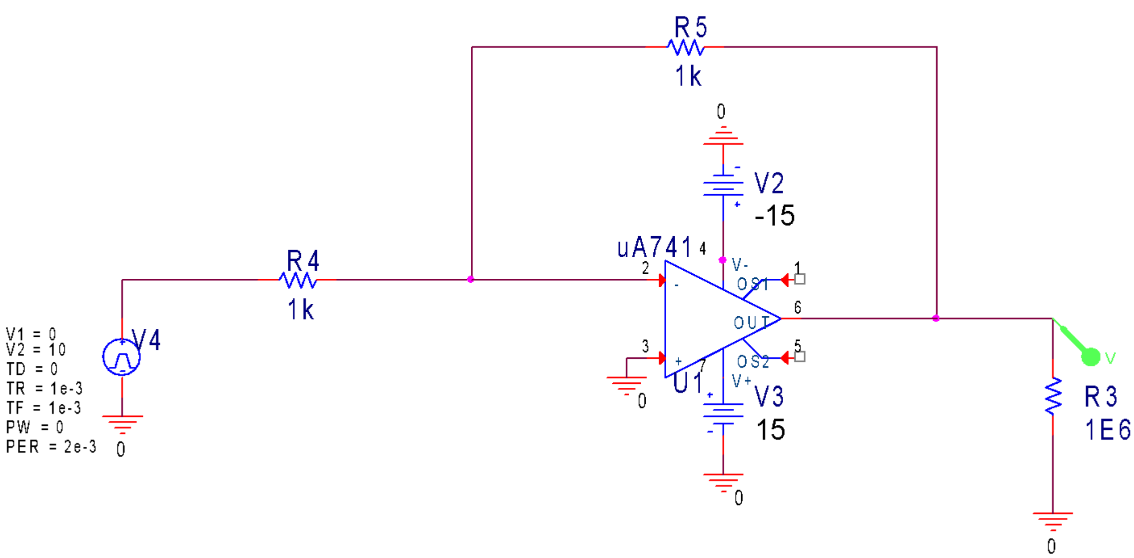



**Figure 4: Op Amp circuit**

2. Implement a triangular wave using the Vpulse component shown in the image above. The above settings for the component produces a triangular wave with a period of 2 ms. Run a transient simulation, plotting about 10 periods.
   *Is the output consistent with theory?*

3. Shorten the period to 20 µs and set the rise and fall times to 10 µs. Again, plot about 10 periods of the output.
   *Ignoring the initial transients, what observations can you make with regard to peak-to-peak value relative to your expectation?*

# Exercise 1: Integrators

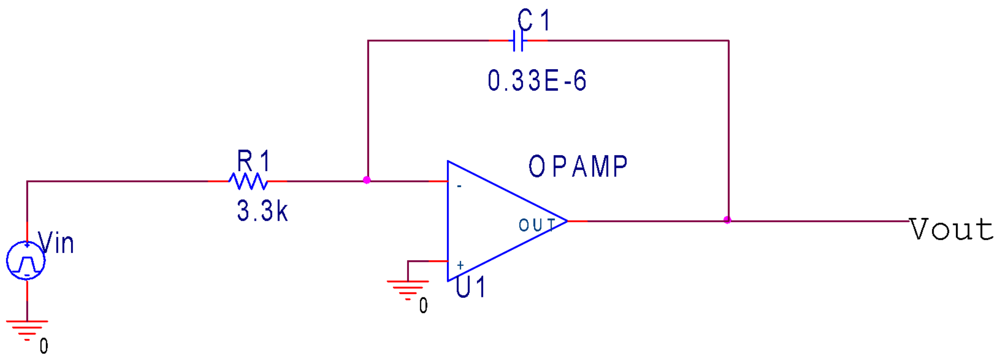



**Figure 5: Integrating Amplifier**

Build the integrating amplifier circuit shown in Figure 5, using the LF351 (or LF353) amplifier chips. Use the E3630A power supply to provide the +15 V and –15 V levels to power the Op Amp. Note that the “common” supply terminal must share a connection with the signal ground. Initially, you can use an open circuit load. Reminder: The power supply connections for the Op Amp are not shown in the above circuit.

1. Set the function generator to produce a 30 Hz square wave with a 4 V (peak-to-peak) signal and 0 V DC offset, Vmax = 2 V and Vmin = –2 V. Verify the voltage levels using the oscilloscope.
   *Question: Qualitatively, what is the integral of a square wave? Does the output ‘look approximately correct’ from a mathematical point of view?*

2. Lower the frequency to 1 Hz.
   *Explain why the output waveform is different.*

3. Increase the frequency to 1 kHz.
   *Explain why the output waveform is different.*

4. At 1 kHz add a DC offset, slowly toggling between 10 mV / –10 mV (waiting to reach steady state before you toggle the offset). If you don’t see any change, increase the values of the DC offset, for example make the DC offset values +25 mV / –25 mV or higher if needed.
   *Again, explain why the output voltage changes.*

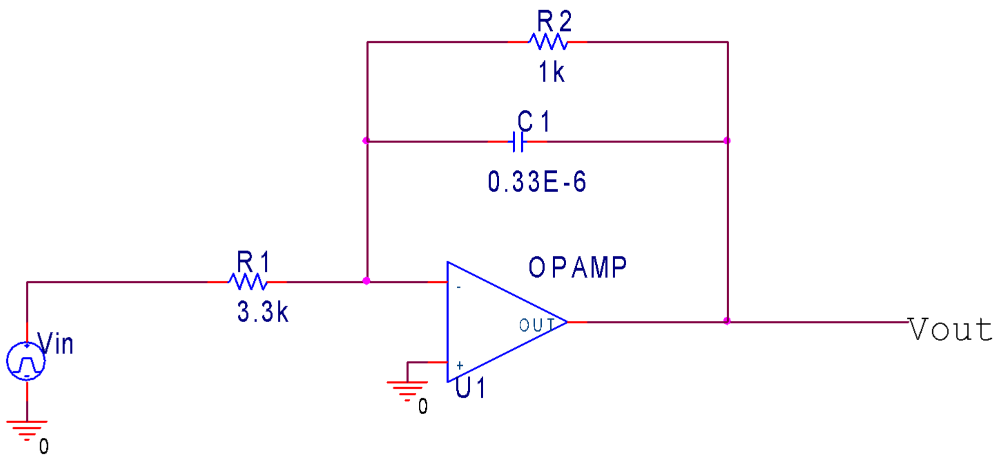



**Figure 6: Integrating amplifier**

Build the Miller Integrator shown in Figure 6, using the LF351 (or LF353) amplifier chips (just add the $R_2$ resistor to your previous circuit). Use the E3630A power supply to provide the +15 V and –15 V levels to power the Op Amp. Set the Waveform Generator output to a 1 V amplitude sinusoidal signal and set the DC offset to zero.

1. Determine the transfer function associated for the above circuit. Sketch the Bode plot of the magnitude for this transfer function. ***Note***: A log-log template is provided on the last page of this document.

2. Identify any poles (one) and zeros (none).

3. Use the Network device on the Discovery Board to experimentally sweep the frequency through the range 10 Hz – 100 kHz. This device is similar to the AC sweep in PSpice and can be used to obtain experimental Bode plots.
   *Question: Is the experimental response consistent with the analytic Bode plot?*

4. Experimentally, locate any poles or zeros. Remember, a single pole can be determined by locating 3 dB points relative to the ideal transfer function.
   *Question: Do experiment and analysis agree?*

# Exercise 2: Common mode gain, Differential gain

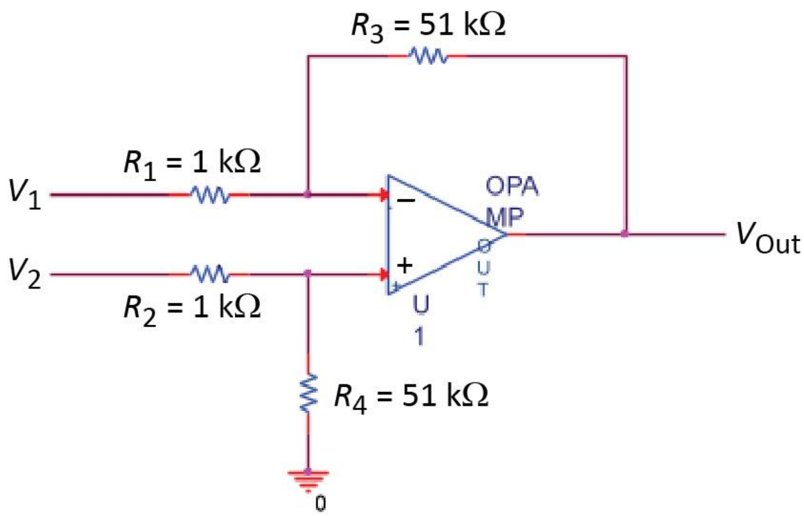



**Figure 7: Difference amplifier**

Use the E3630A power supply to provide the +15 V and –15 V levels to power the Op Amp, using the LF351 or LF353 Op Amp chip. Use the DC (constant) waveform setting.

1. Connect the $V_1$ and $V_2$ inputs to ground (the same ground) and record the output voltage. Consider this output voltage the effective ground for the following parts. In other words, subtract this value from the output voltage in the following parts to determine the actual effective output voltage.

2. Connect the $V_1$ and $V_2$ inputs to 4 V (the same 4 V input) and measure the output voltage.
   *Estimate the common mode gain. Note, statistically, it is possible your common mode gain is zero.*

3. Set $V_1$ to 3.9 V and $V_2$ to 4.1 V. You will need to use both channels on the Waveform generator.
   *Estimate the differential gain. Is it consistent with expectations?*
   *Determine the common mode rejection ratio.*

4. Replace all resistors with resistors having 1 kΩ, and then complete parts 1-3 again with the new 1 kΩ resistors.
   *Why would the results be different?*

# Exercise 3: Gain-bandwidth product and Slew rate

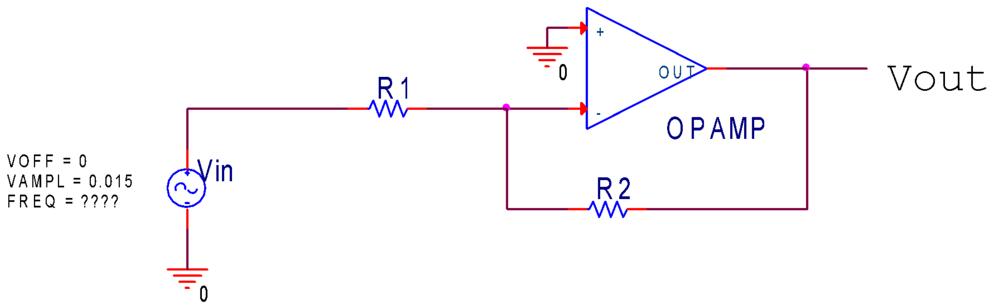



**Figure 8: Inverting Amplifier**

Use the E3630A power supply to provide the +15 V and –15 V levels to power the Op Amp, using the LF351 or LF353 Op Amp chip. Set the function generator to a 0.02 Vpp signal with 0 V offset.

1. On the spec sheet for the Op Amp chip you used, find the Op Amp's Gain-Bandwidth product.

2. For the following resistor values, sweep the frequency from 100 Hz to 1 MHz, recording the output peak-to-peak voltages at intervals. Take enough points to generate Bode plots of the magnitude (which you should include in the report). Experimentally determine the 3 dB cutoff frequency for the low pass filter characteristics of the Op Amp.
   a. $R_1$ = 1 kΩ, $R_2$ = 10 kΩ
   b. $R_1$ = 1 kΩ, $R_2$ = 100 kΩ
   c. $R_1$ = 100 Ω, $R_2$ = 100 kΩ

   *Questions: Are the Bode plots for the above inverter gains consistent with expectations based on the Gain-Bandwidth product?*

3. On the spec sheet for the Op Amp chip you used, find the Op Amp's slew rate.

4. Set $R_1$ = 1 kΩ, $R_2$ = 2 kΩ and the function generator to a 5 V amplitude square wave at 50 kHz and compare the actual output voltage to the expected output voltage. Increase your frequency to 500 kHz and again compare the output voltage to the expected output voltage.

   *Question: When considering the slew rate, are the output voltage waveforms consistent with expectations?*

# Exercise 4: DC bias characteristics of the µA741 Op Amp

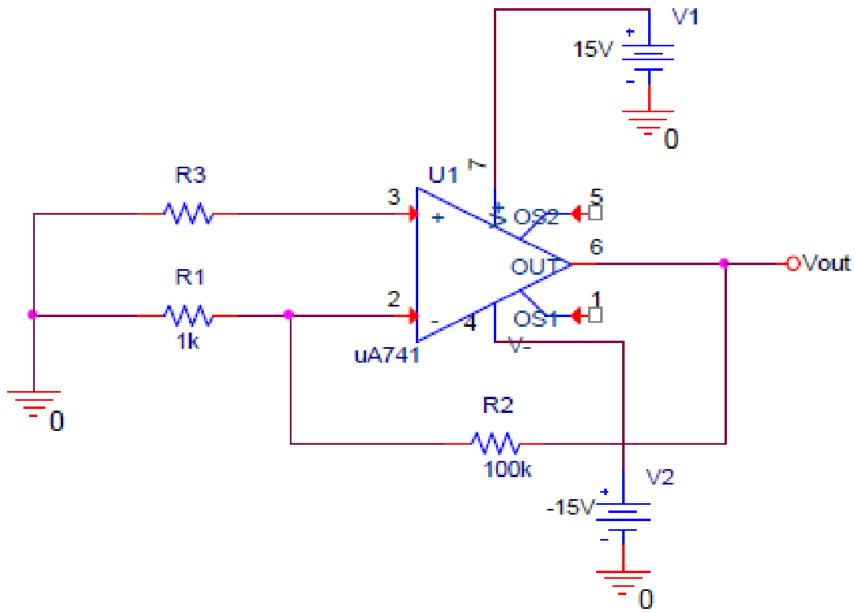



**Figure 9: Set up to measure $I_{B1}$**

Use the E3630A power supply to provide the +15 V and –15 V levels to power the Op Amp, using the µA741 Op Amp chip. This Op Amp typically has larger DC bias effects than the LF351/353 Op Amps. There will be an output voltage due to $V_{OS}$, $I_{B1}$, and $I_{B2}$.

In an ideal case, the output for this Op Amp would be zero.

1. For the above circuit, use superposition to derive the equations expressing Vout for each DC bias component, VDCbias, IB1 (bias current at $V^-$) and IB2 (bias current at $V^+$).

2. Measure $V_{out}$ with these values of $R_3$: 0 Ω, 10 kΩ, 100 kΩ, 680 kΩ, 1 MΩ.
   Note: You will want to use averaging on the Oscilloscope (Mobile Studio, Discovery Board, or Lab equipment). You may need to turn off the trigger. You will need to use a relatively slow sweep rate to avoid a false signal due to 60 Hz pickup (5 ms/div is good.)

3. Use $R_3$ = 0 as the baseline. For each other value of $R_3$, use the change in $V_{out}$ relative to $R_3 = 0$ to estimate $I_{B2}$ (the bias current at the $V^+$ input). Note that the results may indicate that our model isn't perfect. Give these estimates for $I_{B2}$ with sufficient documentation to show how they were calculated.

4. Find the expected value of $I_{BIAS}$ from the data sheets for both the LF351 and the µA741. Compare these to your results and comment on why we didn't use the LF351 for this exercise.

5. Enter the measurement data of Vout as a function of $R_3$ in an Excel Spreadsheet. Analyze the data: Data tab, Data Analysis, Regression.

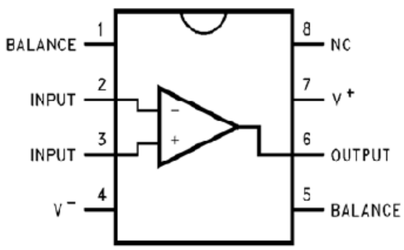
   Note: you might need to include the Add-Ins: 1) click the windows symbol in Excel, 2) At bottom, Excel Options, 3) Click Add-Ins, 4) Analysis ToolPak.

   Run the regression function, Y range should be the Vout, X range is the resistance. Check the Line Fit Plots option. The Coefficients give the intercept and the slope. Assuming the DC offset voltage has a significantly larger contribution than the bias current at the $V^-$ input, the intercept (normalized by the gain of the Op Amp) is an indication of offset voltage that best fits the full set of data. The slope, (normalized by the gain of the Op Amp) is $I_{B2}$. Right click a data point in the plot and "Add Trend Line". Include a table with your data. Include the results of the data analysis using regression. Include the line fit plots.

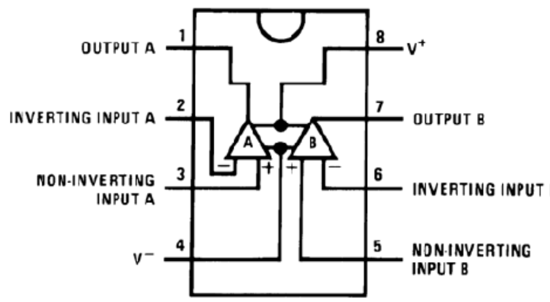
# Appendix

See LF351, LF353 and µA741 datasheets (public information on Internet). Note that µA741 has the same pin-out as LF351.

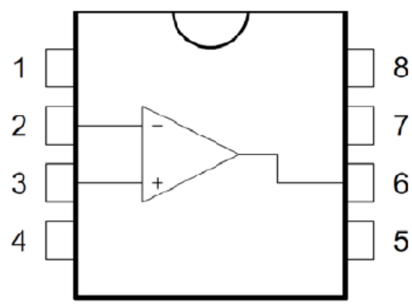
**LF351**




**LF353**




**UA741**




1 - Offset null 1
2 - Inverting input
3 - Non-inverting Input
4 - $V_{CC}^{-}$
5 - Offset null 2
6 - Output
7 - $V_{CC}^{+}$
8 - N.C.