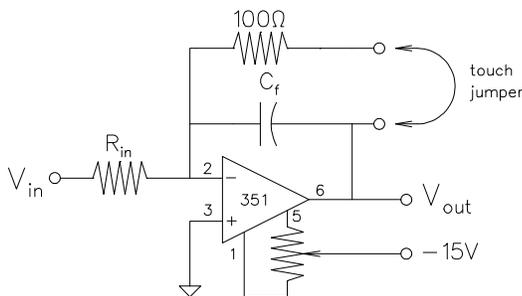


Experiment 4

Advanced op-amp designs

4.1 Op-amp integrator

The purpose of this section is to wire up and analyze an analog integrator, using a carefully balanced op-amp and a low-leakage quality capacitor. We will observe the circuit response to both dc input signals and to the ac waveforms generated by the FG.



Using a capacitor as the feedback element in the inverting amplifier circuit, wire up the op-amp integrator.

Use a $1\ \mu\text{F}$ low-leakage capacitor (10% tolerance or better), $R_{\text{in}} = 1\ \text{M}\Omega$, and set $V_{\text{in}} = 100\ \text{mV}$.

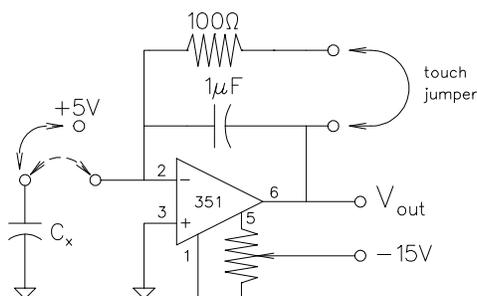


Measure the times required for the output to change by 1V, 3V, 5V, and 8V. Begin the timing when the touch jumper is removed. Use the jumper to discharge the integrating capacitor, *i.e.* to restart the integrator. Repeat 1V measurement at least 3 times, estimate the precision of your measurements (standard deviation).

The above measurements require that the op-amp be well-balanced. To test, restart the integrator, and quickly remove V_{in} when $V_{\text{out}} \simeq 1\text{V}$. Does V_{out} remain constant after that? If not, re-balance the op-amp.



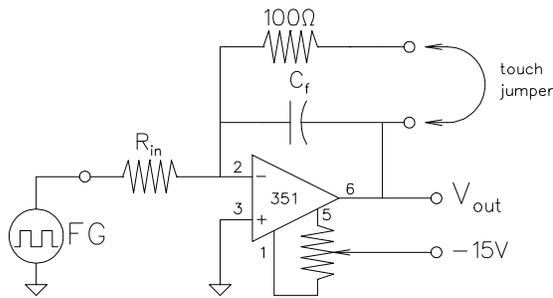
Connect the input to ground, reset the integrator, and observe V_{out} on the most sensitive DMM scale. Record your observations.



Modify the circuit as shown, turning it into a charge-to-voltage converter. The circuit will be used to measure the capacitance of another capacitor, C_x .

Discharge C_f ($1\ \mu\text{F}$), disconnect the touch jumper, then carefully move the input jumper from +5V to the negative input of the op-amp, and observe changes in V_{out} . Repeat several times.

- ❓ Compare the measured value of the ratio C_f/C_x with that obtained by a direct reading of the capacitance meter.



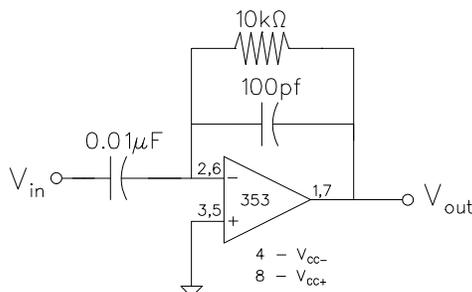
Use FG to provide a square-wave input to the integrator. Use $R_{in} = 1 \text{ M}\Omega$ and set the frequency to about 1 kHz. Choose the C_f value appropriate for this frequency. Monitor both the input and the output with the scope. Make sure you adjust FG to have a zero DC offset. Alternatively, you may want to use a small capacitor ($\approx 1 \mu\text{F}$) in series with FG, to remove the dc component from the input.

- ⚠️ Sketch and explain the observed waveforms.

4.2 Op-amp differentiator

By interchanging the resistor and capacitor of the op-amp integrator, we obtain an op-amp differentiator. We will analyze its response to various waveforms of the FG.

Do not remove the circuit of the previous section; you may want to re-use it in Section 4.3.



Wire up an op-amp differentiator as shown. In a dual-353 package you may choose either of the two op-amps (pins 2,3,1 or 6,5,7). The 100 pF capacitor is included to provide noise stability. For this circuit,

$$V_{out} = -RC \frac{dV_{in}}{dt}$$

Set the FG to 5V peak-to-peak 1 kHz triangular wave and connect it as V_{in} .

- ⚠️ Sketch the input and output waveforms, including the proper scales. Make sure your scope is on a calibrated setting.

Calculate and record the slope of the input triangular wave. Also, record the amplitude of the square wave at the output.

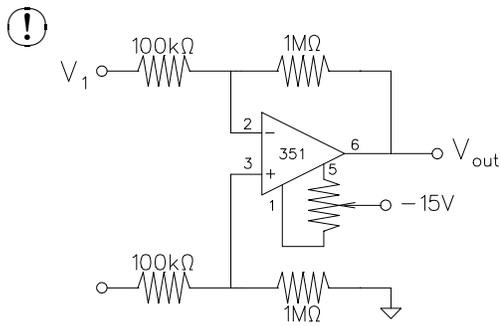
- ❓ Calculate the expected theoretical value for the differentiator output and compare it to the experimental value.

- ⚠️ Change the FG to square wave setting. Sketch the observed waveforms.

4.3 Difference amplifier

The purpose of this section is to introduce precision amplifiers and to learn to distinguish differential and common mode signals.

Ref: Simpson, Ch. 9–10, esp. Sec. 9.8.7, 10.4; Faissler, Ch. 31 (review); Malmstadt *et al.*, Ch. 8.1.



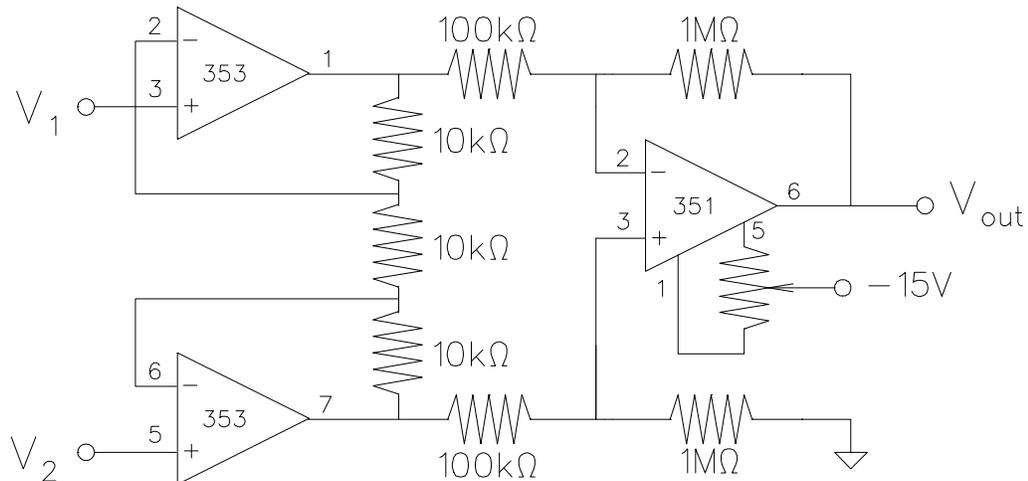
Wire up the difference amplifier as shown: Balance the op-amp by connecting both V_1 and V_2 to ground and adjusting the offset potentiometer until $V_{\text{out}} = 0$. Leaving V_2 grounded, vary V_1 (several values between $+1\text{V}$ and -1V) and measure V_{out} .

- ?** Calculate the average gain of the amplifier. In this measurement, which components determine the gain of the amplifier? How does the measured value compare with the theoretical one?
- !** Connect V_2 to a constant $+1\text{V}$ source and repeat the above two steps.
- !** Connect *both* V_1 and V_2 to the same variable voltage source; measure V_{out} for several values of $V_1 = V_2$ between $+1\text{V}$ and -1V .
- ?** Plot V_{out} vs. V_1 and determine the value of the **common mode gain** from the plot.
- ?** Interpret your data in terms of the imbalance of the resistance ratios of the two pairs of resistors determining the gain, for the inverting and for the non-inverting input. Which pair has the higher gain and by how much? How could this common mode gain be reduced?
- ?** Calculate the **common-mode rejection ratio** (CMRR) for your difference amplifier. Calculate the maximum common-mode signal the amplifier can accept if a 100 mV signal is to be amplified with an error of less than 0.1% .

4.4 Instrumentation amplifier

The purpose of this section is to combine the advantages of a difference input with the high input resistance of the voltage follower in a complete instrumentation amplifier.

- ⓘ Wire up the instrumentation amplifier as shown (add the input voltage followers to the existing circuit).

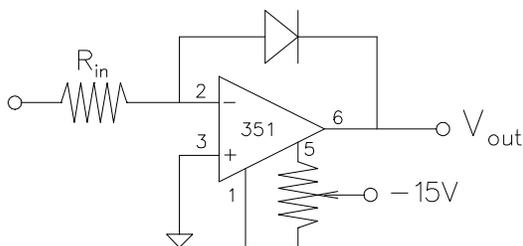


Check the offset of the instrumentation amplifier and adjust the difference amplifier offset potentiometer if needed. Measure V_{out} for various values of V_1 and V_2 so that you will be able to determine the difference gain and the common mode rejection ratio of the instrumentation amplifier. Be sure you have taken sufficient data to perform your calculations.

- ❓ Describe the reasoning you used in selecting the values for V_1 and V_2 . From these data, determine the gain and the CMRR. Explain your interpretation of the data. Compare your results with the expected values.

4.5 Logarithmic amplifier

Using a non-linear feedback element with an op-amp (e.g. a pn-junction diode) produces startlingly different transfer functions. Logarithmic amplifiers serve as the basis for circuits such as analog multipliers studied in Section 4.6.



Carefully balance a 351 op-amp. Then wire the logarithmic amplifier (log amp), using a signal diode as the feedback element.

- ⓘ Measure V_{out} as a function of V_{in} and R_{in} :

V_{in}	R_{in}	I_{in}	V_{out}
10.0mV	1M Ω		
10.0mV	100k Ω		
100.0mV	100k Ω		
1.0V	100k Ω		
10.0V	100k Ω		
10.0V	10k Ω		

? Plot $\log I_{in}$ vs. V_{out} .

For all but very small forward bias voltages, the current through a diode varies exponentially with the applied voltage:

$$I \simeq I_i e^{eV/\eta kT}$$

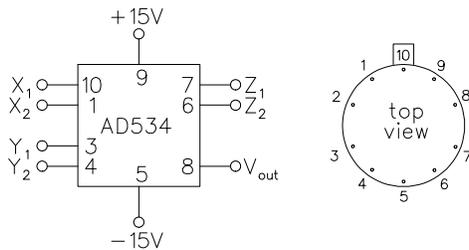
where η is an empirical parameter (~ 2 for Si, 1 for Ge diodes), and I_i is the intrinsic current at zero bias.

Apply circuit analysis (Simpson, Sec. 9.7) to your logarithmic amplifier and verify that the same relationship holds for the measured I_{in} and V_{out} .

Fit your data to the above equation and determine the parameters η and I_i for your diode. Can you tell if this is a Si or a Ge diode?

4.6 Analog multiplier

Combining log amps with adding amps allows one to build analog multipliers and other components of analog computers (for a review, see Faissler, Ch. 30). Here we examine the transfer functions of one such commercial device, AD534.



AD534 is internally trimmed and does not require external trimmer potentiometers. Its pinout is shown on the left.

! For multiplication, use the fixed +10V supply from the job board as the X_1 input and use several fixed voltages from the reference job board as the Y_1 input (+10V, -10V, -1V, +1V). Connect the Z_1 input to the output. Connect the X_2 , Y_2 , and Z_2 inputs to common. Test the multiplier in all four quadrants by applying voltages of both polarities in the range of ± 10 V. The multiplier transfer function should be $V_{out} = (V_x \times V_y)/10$. Include in your data set (X_1, Y_1) values of (+10, 0), (0, 0), and (0, +10).

? Offsets modify the multiplier equation:

$$V_{out} = V_{out}^{(0)} + 0.1 \times [V_x - V_x^{(0)}] \times [V_y - V_y^{(0)}]$$

where $V_x^{(0)}$, $V_y^{(0)}$, and $V_{out}^{(0)}$ are the X , Y , and output offsets, respectively. Use your data to evaluate each of the offsets. Explain how magnitude of offset-induced errors changes with X and Y input levels.

- ⓘ To obtain an output voltage proportional to the square of an input voltage, connect both X_1 and Y_1 inputs to the same voltage source and the X_2 and Y_2 inputs to common. The Z_1 input remains connected to the output. Test the circuit over a $\pm 10\text{V}$ range of voltages and compare to the expected $V_{\text{out}} = 0.1 \times V_{\text{in}}^2$.
- ⓘ The “squared voltage” output can be plotted against the input with the xy -mode of the oscilloscope. Substitute the output of the FG set in the sine wave mode as the source in the squaring circuit wired above. Connect the multiplier output to the vertical scope input and the FG output to the horizontal. Use a 10 Hz sine wave signal. Sketch the resulting display.
- ⓘ Now use the dual-trace mode to observe the waveforms of the input and output signals. Sketch a representative display and indicate the position of OV for each waveform.
- ❓ Explain the relationship of the frequencies and the DC components of the input and output waveforms.

Optional: analog division

- ⓘ To obtain division, connect the multiplier output to the Y_2 input. Now Z_1 is no longer connected to the output, and Z_2 is no longer grounded. In this configuration:

$$V_{\text{out}} = 10 \times \frac{V(Z_2) - V(Z_1)}{V(X_1) - V(X_2)} + V(Y_1)$$

Measure V_{out} for several values of $V(Z_2) - V(Z_1)$ and $V(X_1) - V(X_2)$. For simplicity, you may want to ground Z_1 , X_2 , and Y_1 . Make sure you keep $V(X_1) - V(X_2)$ positive (see the spec sheets of AD534).

- ❓ The output limits of AD534 are $\pm 11\text{V}$. Calculate and plot the minimum value for $V(X_1) - V(X_2)$ as a function of $V(Z_2) - V(Z_1)$ over the $V(Z)$ range of $\pm 10\text{V}$.