

Experiment 4

Steady-State, Zero-State and Zero-Input Response of a Second-Order Linear Circuit

Systems and Signals Laboratory

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Contents:

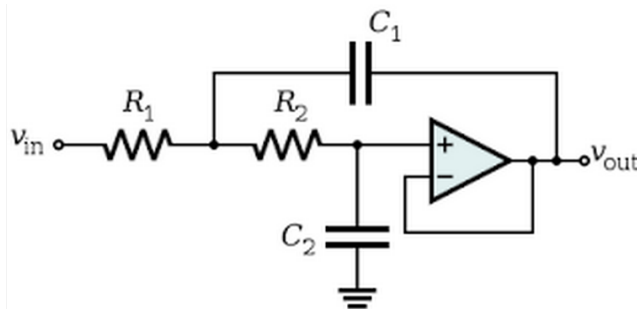
- Pre-lab
- Lab activities: Build and measure the steady-state, zero-state and zero-input response of a second-order active linear circuit.
- Post-lab
- Links to resources and data sheets:
 - [The LF351 op amp data sheet](#)
 - [The 1N4148 switching diode data sheet](#)
 - [WaveForms software download and tutorials](#)
 - WaveForms configuration file: [experiment4](#)
 - [Plotting imported scope traces](#)

Electronic components required for this experiment

- LF351 operational amplifier (1)
- 43k Ω (1/4 Watt, 5%) resistor (1)
- 100k Ω pot
- 150pF (Polypropylene, 1%) capacitor (1)
- 1nF (Polypropylene, 1%) capacitor (1)
- 1N4148 fast switching diode (2)

1. Pre-lab

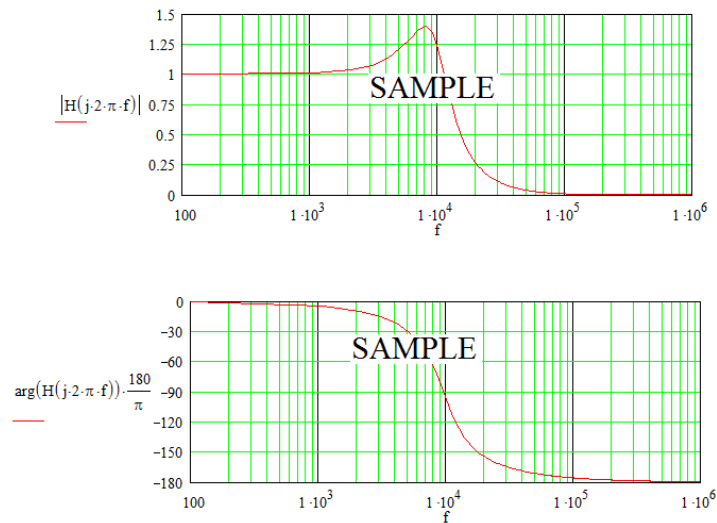
- a. Show that the following second-order active Sallen-Key circuit



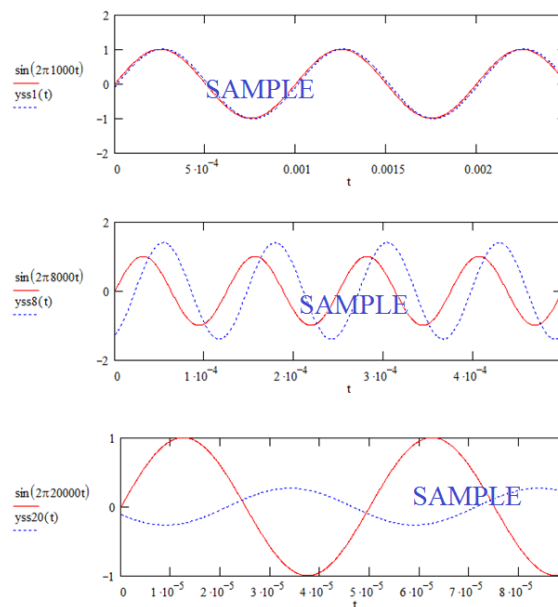
has the transfer function:

$$H(s) = \frac{V_o(s)}{V_{in}(s)} = \frac{\frac{1}{R_1 R_2 C_1 C_2}}{s^2 + \left(\frac{1}{R_1 C_1} + \frac{1}{R_2 C_1} \right) s + \frac{1}{R_1 R_2 C_1 C_2}}$$

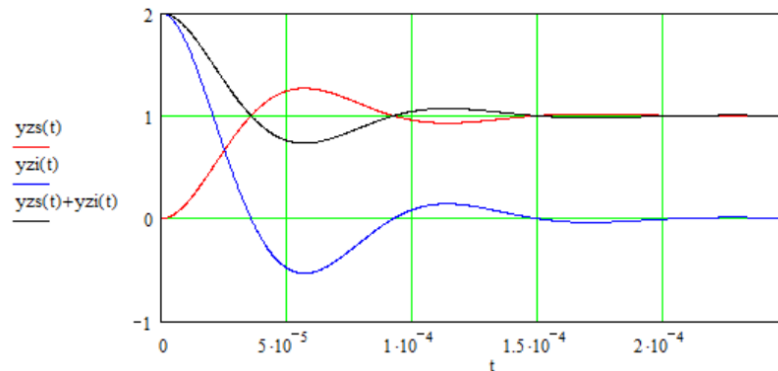
- b. Assume that $R_1 = R_2 = 43,000\Omega$, $C_1 = 1\text{nF}$ and $C_2 = 150\text{pF}$. Use Mathcad to generate the following magnitude and phase plots for the above circuit.



- c. Use Mathcad to compute and plot the steady-state response of the above circuit to a sinusoidal input of 1V amplitude and frequencies: 1kHz, 8kHz and 20kHz. Your plots should look similar to the following plots.



- d. Use Mathcad to solve for and plot the zero-state, zero-input and complete response for the above circuit. Assume $v_{in}(t) = u(t)$ and $v_o(0^-) = 2\text{V}$ and $\dot{v}_o(0^-) = 0\text{V/sec}$. [Challenge exercise: Assume $v_o(0^-) = 2\text{V}$. Analyze the circuit to determine $v_o(0^+)$ and $\dot{v}_o(0^+)$]. Your plots should look similar to the following plot.



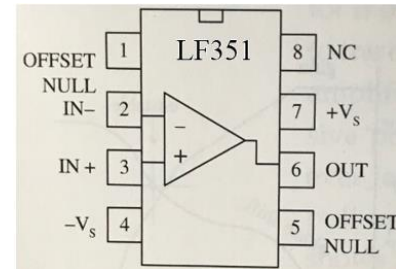
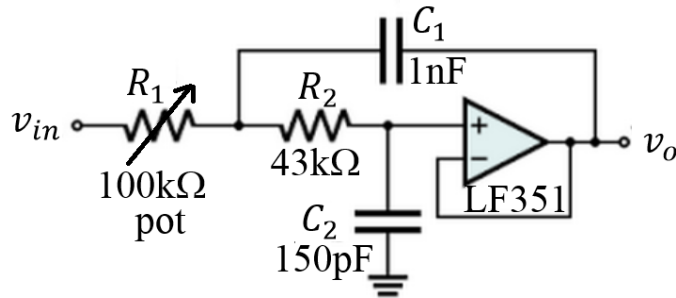
- e. Estimate (via simulation) the value of R_1 (keeping all other component values unchanged) that leads to a critically-damped zero-state response to the input $u(t)$.
- f. In Lab 0 you were asked to install software packages on your laptop including “WaveForms” (user interface for AnalogDiscovery2) and “Jing” (screen capture). Make sure to install these software packages before the lab session. Refer to the course web site for the download links.
- g. Search your laptop for the folder that contains the settings file (for WaveForms) “default.dwf3work” and then download the “[experiment4](#)” configuration file and place it in that folder.
- h. Turn in your pre-lab assignment to your lab instructor at the next lab session.

It is important to read the following section (as part of the pre-lab assignment) in order to familiarize yourself with the upcoming lab activity.

2. Lab activity

Make actual measurements of all resistor and capacitor values that you use in the following circuit and use them in your post-lab to report relative errors between the ideal circuit output and the actual circuit output. Make sure to take photographs of all circuits that you build in this lab session. Also, you are to save all scope trace images. You will be using these photos/images in your lab report.

- a. Use an LF351 op amp and the indicated components to build the following second-order active linear circuit.



- b. Apply a 2V_{pp} 1kHz sine wave as the input to your circuit and also display the waveform on CH1 of the scope (use a BNC splitter adaptor). Connect the output of the circuit to CH2 of the scope. Adjust the scope's horizontal scale so that it displays (approximately) two full periods of the input waveform. Set the vertical scale of CH1 and CH2 to 500mV/div. Set the scope so that it displays (in the measurements bar, at the bottom of the screen) the frequency and V_{max} of the input and output waveforms and the phase difference. You need these measurements for your lab report. Save the scope's display image.

Repeat the above step for the following frequencies: 8kHz, 12kHz and 20KHz.

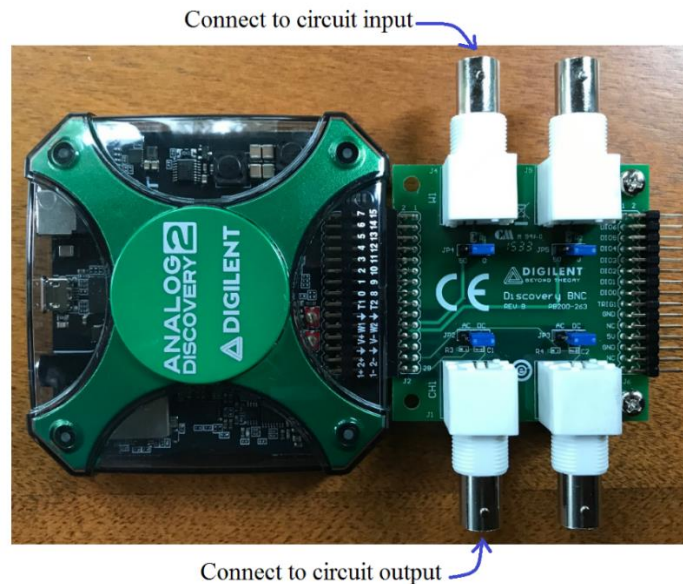
The following figure shows a sample scope capture for the case of 8kHz input frequency.



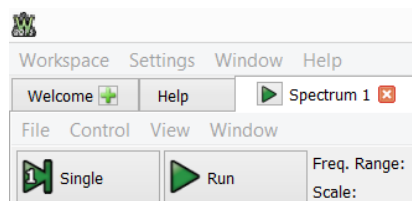
Your scope display capture must have the following measurements

- c. Use the AnalogDiscovery2 (AD2) and the WaveForms software to generate the frequency response of your circuit. Use a BNC-to-hook clip cable to connect the input of the circuit to the W1 connector of the AD2 (refer to the figure below). Connect the output of the circuit to CH1 (scope input 1) of the AD2. Connect the AD2 module to your laptop

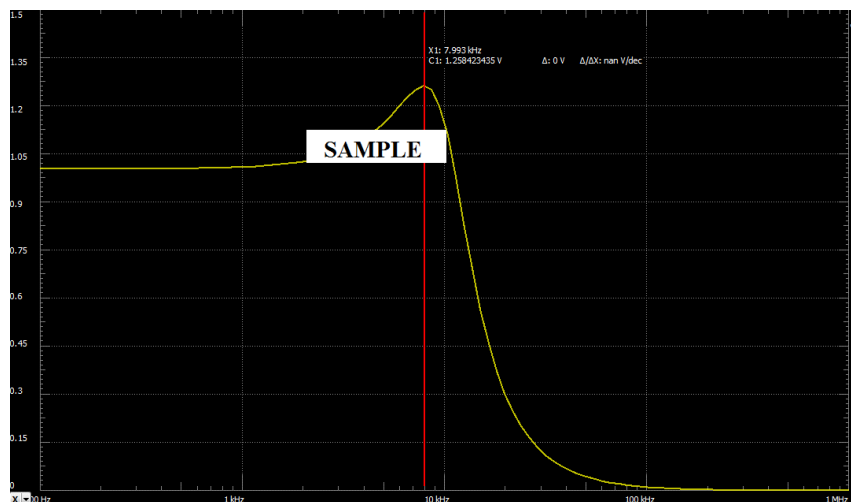
(via the supplied USB cable) and run the WaveForms software. Choose “experiment4” when prompted.



Click on the “Run” icon to generate the magnitude response plot. The “experiment4” configuration file that you used configures WaveForms to generate a magnitude frequency response plot with logarithmically scaled frequencies between 100Hz and 1MHz.

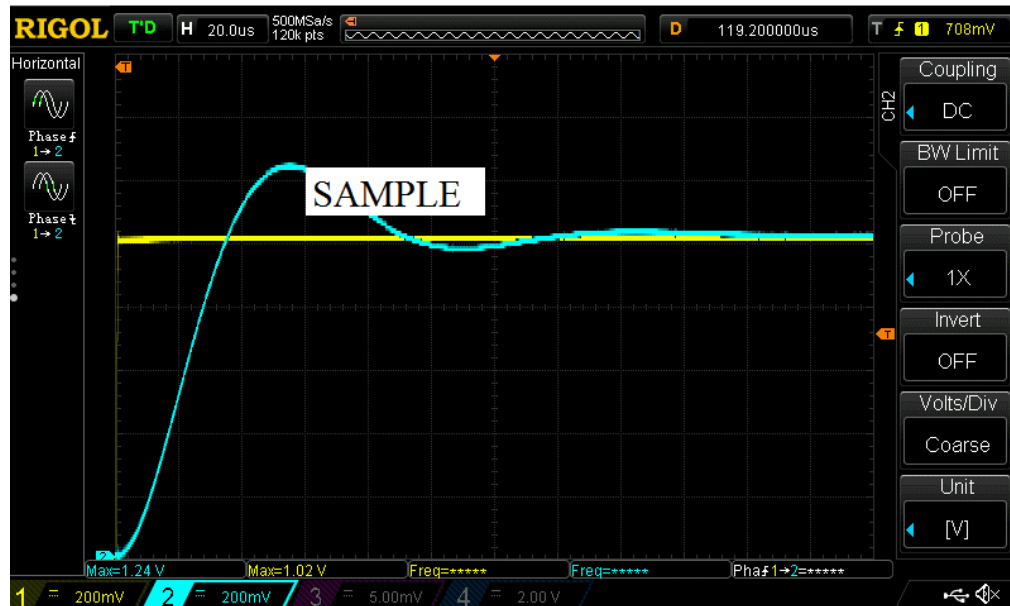


Use the vertical marker to determine the frequency and gain at the trace peak. Use Jing to capture and save the plot (a sample is shown below).

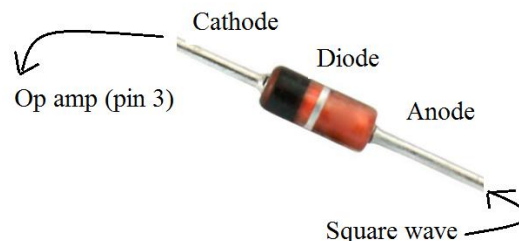


Disconnect the AD2 and give it back to your lab instructor. Reconnect the RIGOL waveform generator and RIGOL scope to your circuit as in Step b.

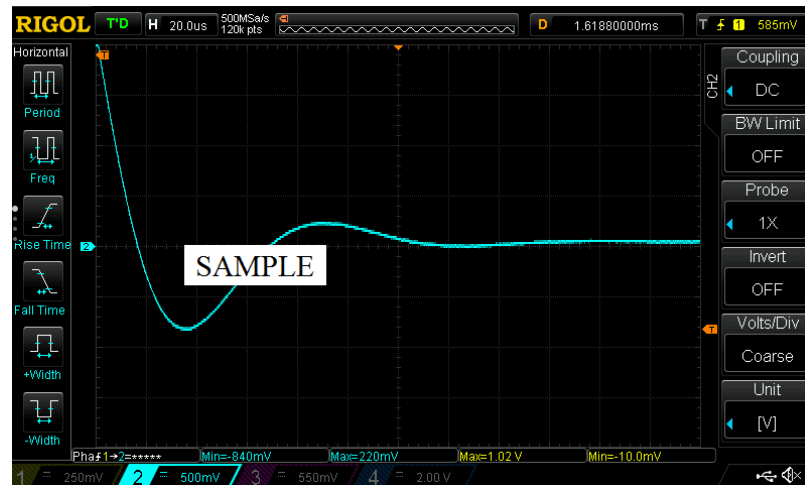
- d. In this step you will determine the zero-state response of your circuit to a unit-step input. Set the RIGOL waveform generator signal to a (50% duty cycle) 2kHz square wave with the “HiLevel” set to 1 Volt and the “LoLevel” set to 0Volt. Essentially, the input is a repeating sequence of step functions. The 2kHz frequency allows the response to settle down to its steady-state value before the next step appears. This input signal will allow the scope to display the desired step-response of the circuit. Set the CH1 and CH2 of the scope to 200mV/div and set the time scale to 20 μ sec/div. Also, offset both waves on the scope so that the traces start at the lower left point of the display. As configured earlier, the scope will display the Vmax of both signals in the bottom measurement bar. Estimate the time it takes for the output to reach DC steady-state. The scope waveforms should look similar to the ones in the following figure.



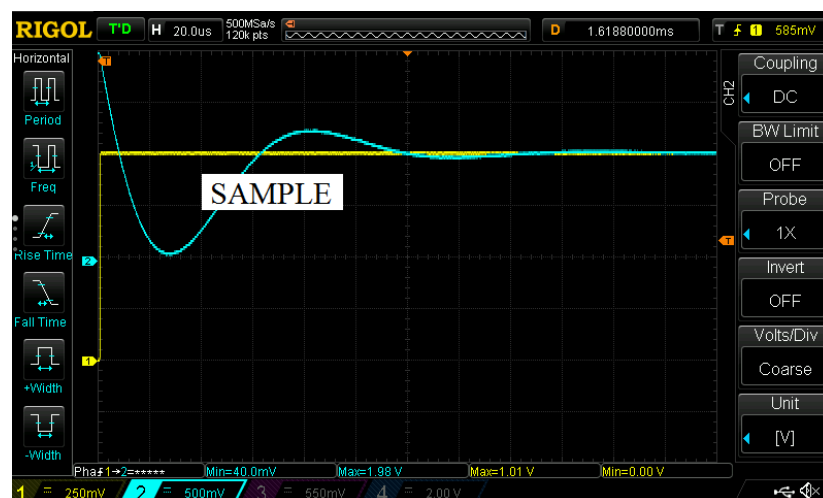
- e. In this step you will determine the zero-input response of the circuit with $v_o(0) = 2$ Volt. Disconnect the square wave from the input of the circuit. Ground the input of the circuit. Connect the (2kHz) square wave to the anode terminal of a (1N4148) silicon switching diode, and connect the cathode terminal of the diode to the positive input terminal of the op amp (pin 3).



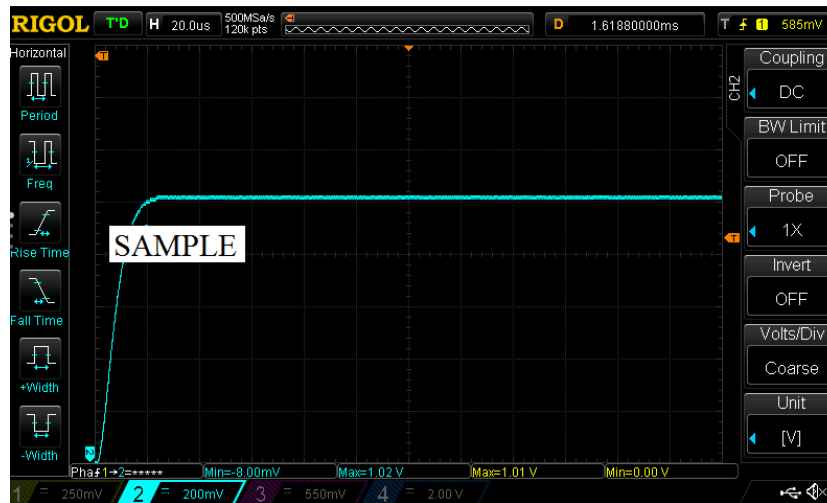
Set the “HiLevel” of the square wave to 2.5Volt and set the “LoLevel” to -2Volt. This basically charges C_2 [and hence sets $v_o(0)$] to 2Volt, and then disconnects (opens) the charging source. Recall that the forward-biased diode has about 0.5 to 0.7Volt voltage drop. Adjust the scope settings so that you display the response as shown below. If necessary, set the scope trigger to CH2. Estimate the slope of $v_o(0)$ [i.e., measure $\dot{v}_o(0)$] in Volts/sec from the plot Save the scope’s display image.



- f. In this step you will generate the complete response (zero-input + zero-state) for your circuit, with $v_{in}(t) = u(t)$ and $v_o(0) = 2\text{Volt}$. With the square wave on CH1 of the waveform generator still connected to pin 3 of the op amp, un-ground the input of the circuit and connect it to CH2 of the waveform generator. Set the signal on CH2 of the generator (as in Step d) to a (50% duty cycle) 2kHz square wave with a “HiLevel” set to 1Volt and a “LoLevel” set to 0Volt. Also, you need to align the phase of both square waves and to set the start phase of the signal on CH2 of the waveform generator to 180 degrees (why? Discuss in your report). Keep the output of the circuit connected to CH2 of the scope and connect the signal generated on CH2 of the waveform generator to CH1 of the scope. Adjust the scope settings so as to display the waveforms as shown below. Save the scope’s display image.



- g. Press the “Storage” button of the scope in order to save the trace data of CH1 and CH2 (as a .CSV file on your thumb memory drive. Make sure you check next to CH1 and CH2 in the “Storage Channel” sub-menu to select the channels). You will import this data to Mathcad (recall Experiment 0 where you used the worksheet “[Plotting imported scope traces](#)” to accomplish such task) and use it in your lab report to compare it to the theoretical complete response.
- h. Finally, you will experiment with the effect of varying the input resistance (the 100k Ω pot) on the behavior of your circuit. Disconnect the signal feeding to the diode and remove the diode. This essentially eliminated the 2V initial condition on the output. Vary the pot so that the response becomes critically damped. Measure and record the resistance of the pot. In your report, you are to compare this experimental value to the one you obtained via simulation in the Pre-lab (Step e). The following figure shows a critically damped circuit output.



As you disassemble your circuit, and in case you forgot to measure element values, carefully measure and record the actual resistor, pot and capacitors value.

3. Post-lab

Write your lab report according to the required format. Analyze and discuss, in details, all results obtained from your pre-lab and your lab activity. Compare the theoretical and experimental responses of your circuit. Report the absolute relative errors (in percent) for all experimental measurement whenever the true value is known.

Use the measured component values to repeat Steps b, c and d of the Pre-lab activity. Generate plots that compares the exact to the actual circuit behavior.