

EE 462G Laboratory #1

Measuring Capacitance

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I. Instructional Objectives

- Introduce lab instrumentation with linear circuit elements
- Introduce lab report format
- Develop and analyze measurement procedures based on two theoretical models
- Introduce automated lab measurement and data analysis

II. Background

A circuit design requires a capacitor. The value of an available capacitor cannot be determined from its markings, so the value must be measured; however a capacitance meter is not available. The only available resources are different valued resistors, a variable frequency signal generator, a digital multi-meter (DMM), and an oscilloscope. Two possible ways of measuring the capacitor's value are described in the following paragraphs. For this experiment, the student needs to select resistors and frequencies that are *convenient* and *feasible* for the required measurements and instrumentation. Be sure to use the digital multi-meter (DMM) to measure and record the actual resistance values used in each measurement procedure.

III. Pre-Laboratory Exercise

Step Response Model

1. For a series circuit consisting of a voltage source $v(t)$, resistor R , and capacitor C , **derive (show all steps)** the complete solution for the capacitor voltage $v_c(t)$ when the source is a step with amplitude A and the initial capacitor voltage is 0.
2. Assume the source $v(t)$ is a function generator, where the source voltage can only be measured after the $50\ \Omega$ internal resistance. See **Fig. 1**.
 - a) Find the step response of amplitude A in terms of R and C for $v_c(t)$. (Hint: this should look very similar to the answer to problem 1).
 - b) Find the voltage measured at the output of the function generator, $v_m(t)$, as shown in **Fig. 1**. (Hint: Use the solution to part A to find $R*i_c(t) = RC*dv_c/dt$ and KVL).

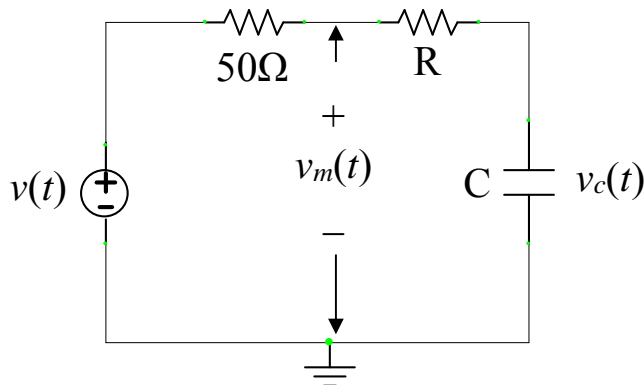


Figure 1. Test Circuit accounting for output impedance of function generator.

3. For the step response model derived in Problem 1, determine the value of C if $R = 200\Omega$, $A = 5$ volts, and the step response is approximately 3.2 volts at $t = 10\text{ms}$ (assume input step turns on at $t = 0$).
4. Describe an experimental procedure that uses ideas from the model of Problem 1 along with a known resistor value, a periodic function generator, and an oscilloscope to estimate a capacitor value. This description must include:
 - Circuit diagram
 - General function generator settings
 - Placement of oscilloscope probes (label positive and common ground connections)
 - A graph of what you would expect to see on the scope (including both $v_c(t)$ and $v_m(t)$) and any pertinent measurements.
 - Formula or procedure used to estimate capacitor value

Frequency Response Model:

5. For a series circuit consisting of a voltage source $v(t)$, resistor R , and capacitor C :
 - a) Derive the transfer function $H(f)$ with input $v(t)$ and output $v_c(t)$.
 - b) Write an explicit equation for the magnitude of the transfer function.
 - c) Write an explicit equation for the phase of the transfer function.
6. Repeat Problem 5 for the circuit of **Fig. 1**, and find transfer function from input $v_m(t)$ to output $v_c(t)$. (Note: If you did the derivation correctly the 50Ω resistor does not affect this transfer function. Therefore, if the phase difference and magnitude scaling between v_m and v_c are measured directly, and the 50Ω internal impedance will not have to be accounted for even when small resistors values are used).
7. For the frequency response model derived in Problem 5, determine the value of C , given $v(t)$ is a 4 volt peak-to-peak sinusoid at frequency $f = 1.5\text{kHz}$, $R = 200\Omega$, and the amplitude of the sinusoidal voltage across the capacitor voltage $v_c(t)$ is 2.8 volts peak-to-peak.
8. For the frequency response model derived in Problem 5, determine the value of C , given $v(t)$ is a sinusoid at frequency $f = 4\text{kHz}$, $R = 6\text{k}\Omega$, and the phase between $v(t)$ and capacitor voltage $v_c(t)$ is 45° ($\pi/4$ radians).

9. Describe an experimental procedure that uses ideas from the frequency model along with a known resistor value, a periodic function generator, and a 2-channel oscilloscope to estimate a capacitor value.

Automated Measurement and Data Analysis Method

10. Assume that data was automatically collected from a first-order low-pass filter (as shown in Fig. 2 at several frequency points list below in Table 1.

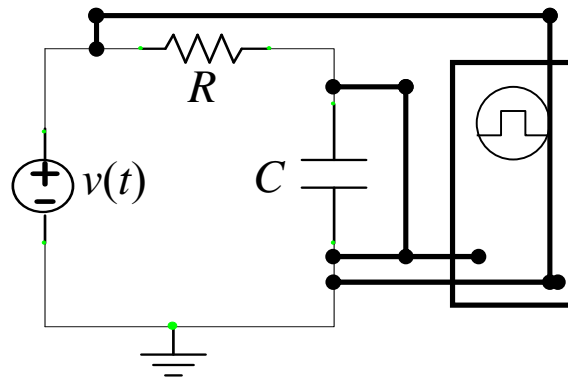


Figure 2. Circuit B measurement for frequency response model.

Table 1. Measurements on a Low-Pass Filter Circuit

Frequency (Hertz)	Peak-to-Peak Input (Voltage)	Peak-to-Peak Output (Voltage)	Phase of Output - Input (Degrees)
120	4.1202	3.7137	-23.7380
160	4.0984	3.6122	-27.6350
200	4.0939	3.4766	-32.5860
240	4.0995	3.3042	-37.1420
280	4.1080	3.1847	-38.8100
320	4.0994	3.0345	-41.8310
360	4.0994	2.8817	-45.8470
400	4.0833	2.7716	-47.4650
440	4.0875	2.5484	-52.3820

Write a Matlab script file to find the 3dB cut-off frequency that results in the best-fitting transfer function for the above data in a mean squared error sense. Fit using magnitude and phase separately (in the same script), print out the code, and write the resulting magnitude and phase fit cutoff frequencies on the page.

The script must be commented in such a way as to allow someone to understand how the code works quickly and without in depth analysis of individual commands.

(Hint - generate a range of values to compare with the input values by using the single pole transfer function, input frequency readings, and looping through a set of "good guess" cutoff frequencies. Record the sum of the square of the difference, and use this to determine where the least difference occurs).

IV. Laboratory Exercise

1. To use the **step response model** in the capacitor measurement, build the Circuit A shown in **Fig. 3**. How to choose the resistor and capacitor values? Considering the coaxial cable resistance of 50Ω , you may choose a large resistance of $>1k\Omega$. If the resistance and capacitance values are too large, the time constant RC is much larger than the period of the square wave, you cannot observe the charging effect. First you calculate the time constant of RC and then make the period of your square wave several times larger than the RC time constant. Use a 0 to 5V square wave input (function generator and voltage offset setting so that the wave starts at 0 volts) and use the oscilloscope to measure the voltage waveform across the capacitor.
2. You may do experiments in one of the following three ways: (1) using Agilent function generator and Tektronix Oscilloscope, but later you do frequency response manually; (2) using Agilent function generator and your Analog Discovery as the oscilloscope; (3) using Analog Discovery's function generator and oscilloscope. Enter on your **data sheet** the critical time and amplitude points for 4 different values of R (measure the resistance values with the DMM). Use the waveform save feature on the scope to record **ONE** of the capacitor voltage waveforms from the 4 trials that you used to obtain the time and amplitude point measurement. Proper use of the horizontal and vertical cursors can be helpful in making this measurement. The waveform should be presented as a figure in the **results section** and just sketched in the **data sheet**. Compute the mean and 95% confidence limits over the capacitor values determined from each trial and present this in the **results section** also. In the **procedure section**, address/include the following:
 - a. Introduce your procedure by stating what it should accomplish. Describe the quantities you want to measure and their relationship to what you ultimately want to find (i.e. capacitor estimate). Identify the independent and dependent variables over the set of trials.
 - b. Describe the set up (equipment and supplies used and configured). Include a description of probe placement, and grounding issues associated with your circuit if appropriate. (Where are the grounds for the oscilloscope and signal generator this circuit, and why should they be there?) Draw a circuit diagram including probe locations and grounding connections.
 - c. Describe formulae used on the measured data to estimate final results, if applicable.
 - d. For this experiment you must select a square wave frequency and resistor values. So describe the critical issues in selecting a square wave frequency for the experimental measurement and indicate how you determined the specific square wave frequencies used in your measurements. Likewise, describe how you determined the resistor values you used.

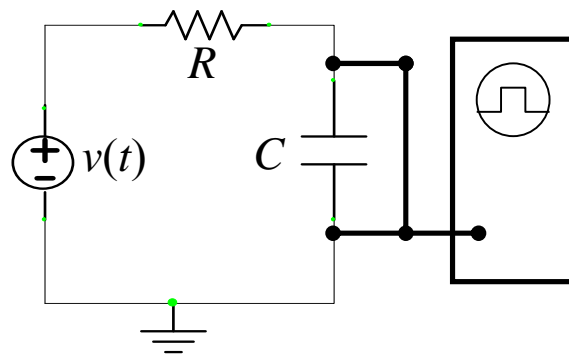


Figure 3. Circuit A measurement for step response model.

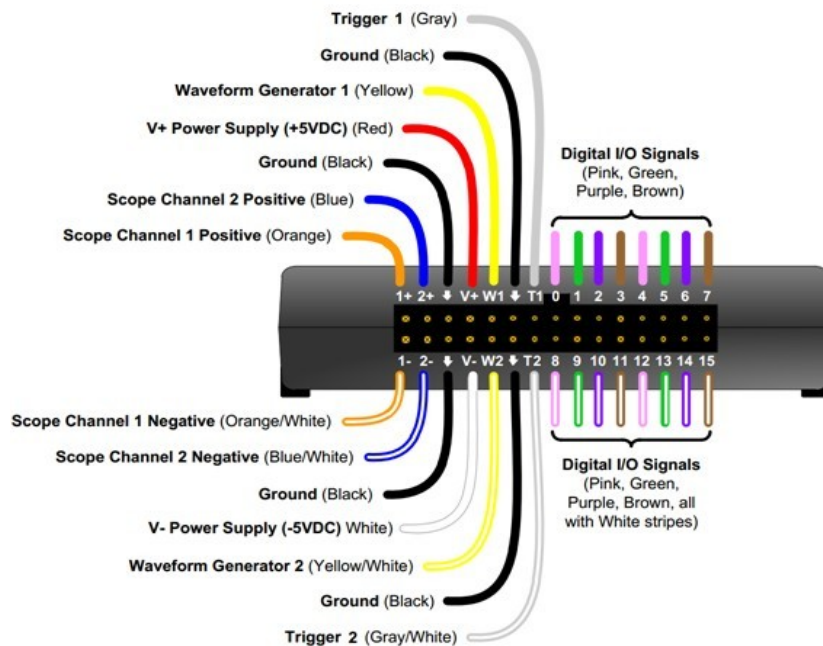
For each resistor, create an ASCII file (you can use Notepad, MS word with the save as TEXT file option, or even Matlab's editor to do this) with a list of frequency values in Hz (separated by carriage returns), where the frequencies span a range that includes the cutoff frequency of low-pass circuit. Start about a decade before and go to about a decade after the frequency cut-off (the frequencies do not have to be uniformly spaced, however, you should make them more dense around the expected cut-off value). Do not use more than 20 points as it may take too long to finish. Then run your Matlab script to estimate the cutoff frequency based on the magnitude and phase of your measured transfer function (don't forget to update the resistor values and file names). Run this program several times making adjustments on the cut-off frequency range value or increments as needed until you are satisfied with the results. You may notice frequencies at which bad measurements occurred (they will typically have number way out of range, like 99999999 for a phase angle). You can delete these lines from the text file before processing with the curve fit program. Record the results (printouts of the table values, with estimates of center frequency, and capacitor values written on your data sheet) from each trial in your datasheet. Present the tables of measured frequencies in **results section and data sheet** (you should have table for the 4 different values of R clearly labeled). For the **results section** of your final report, also compute the mean and 95% confidence limits over all your best-fit transfer function magnitude capacitor estimates, and the same for all your best-fit transfer function angle estimates. Then combine the estimate from both magnitude and phase estimates to compute the mean and 95% confidence limits of that. In the **procedure section**, address/include the following:

- a. Describe the quantities you want to measure and/or the relationship you want to find. Identify independent and dependent variables.
- b. Describe the set up (equipment and supplies used and configured). Include a description of probe placement, and grounding issues associated with your circuit if appropriate. (Where are the grounds for the oscilloscope and signal generator this circuit, and why should they be there?) Add proper ground symbols to your circuit and measurement equipment.
- c. Indicate the name of the program used to apply multiple frequency values and how you determined the frequency for each resistor.
- d. Describe program used on the measured data to estimate final results. Include the script or sample script as an appendix.

The **discussion section** should explain the results relative to the theory. You should be as quantitative as possible here. If you are comparing measurements, don't say "the measurement were about the same." Indicate differences numerically. Also indicate whether the capacitor values estimated by the different methods were significantly different. If so, try to explain why the difference existed and suggest which values are probably more accurate. The different method were the step response estimates, the frequency response estimate with transfer function magnitude, with transfer function angle, and combined transfer function magnitude and phase. If variations were within the confidence limits of the estimates from different methods you can attribute that to experimental error. However, even if they are within the range and you feel something went wrong in the experiment resulting in too high of a variance because of a mistake or malfunctioned piece of equipment, you should indicate this. If differences between methods were outside each other's confidence range consider contributions from mistakes in your implementation of the procedures, faulty connections, components, equipment, or a limitation of the theory used to develop the estimation process. Comment on the difficulty or efficiency of each measurement procedure.

In the **conclusion section** summarize what was accomplished in your experiment and discuss how well the lab exercise met the lab objectives.

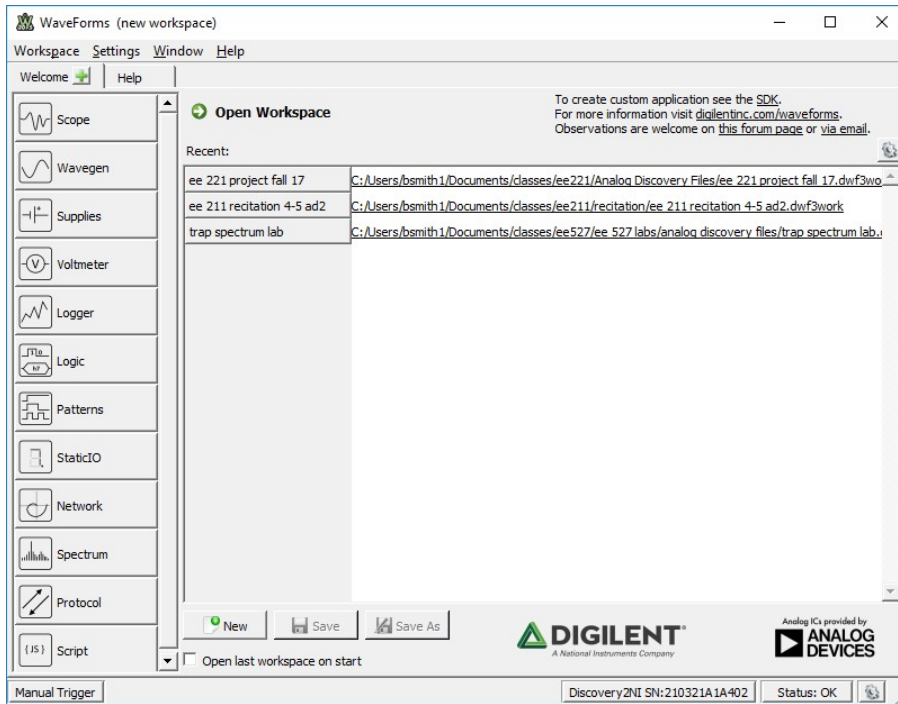
Analog Discovery 2 guide¹:



pinouts for the AD2

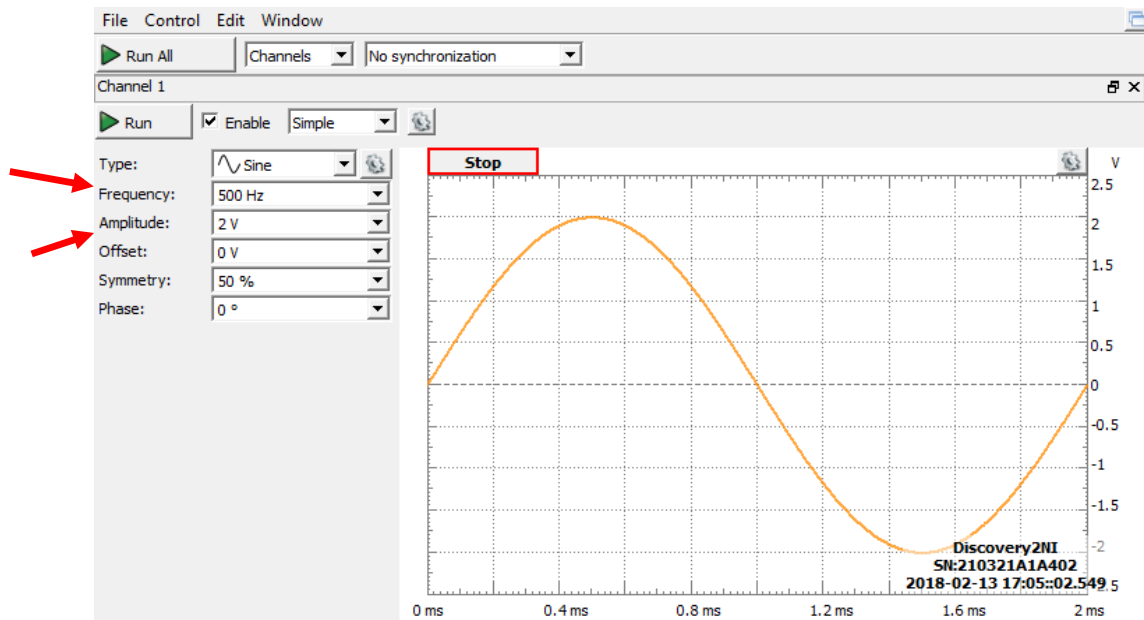
When you open the Waveforms app, it should look something like this:

¹ EE211 recitation by Dr Smith

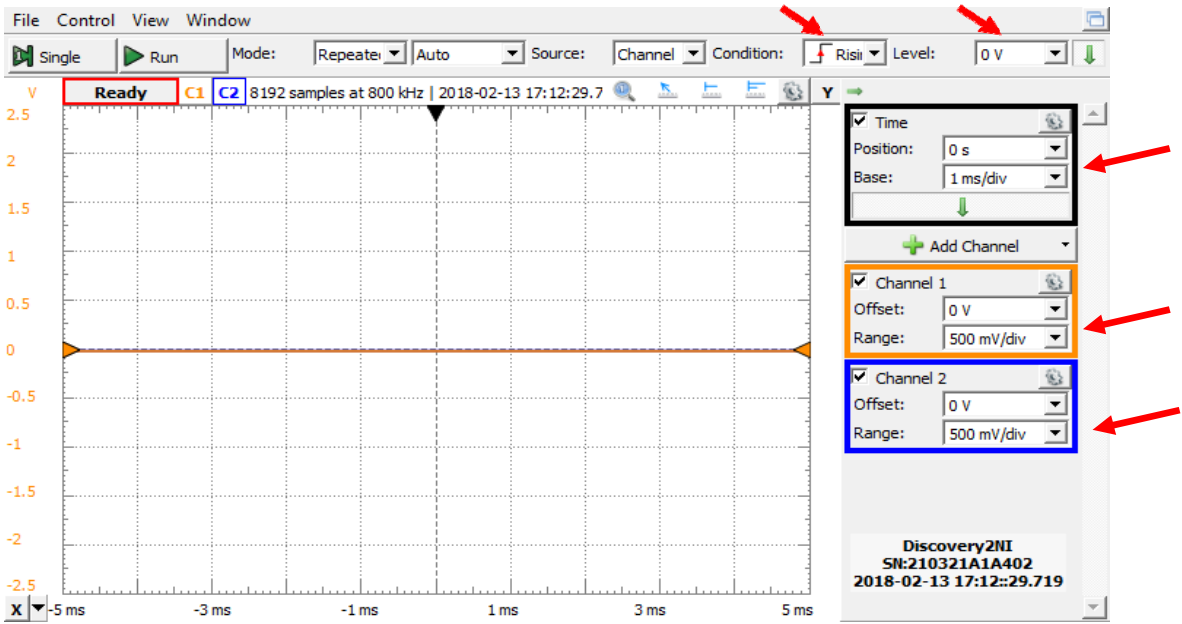


Start the instruments by clicking the button on the left or using the “Welcome +” button.

Wavagen:



Scope:



Voltmeter:

	Channel 1	Channel 2
DC		
True RMS		
AC RMS		