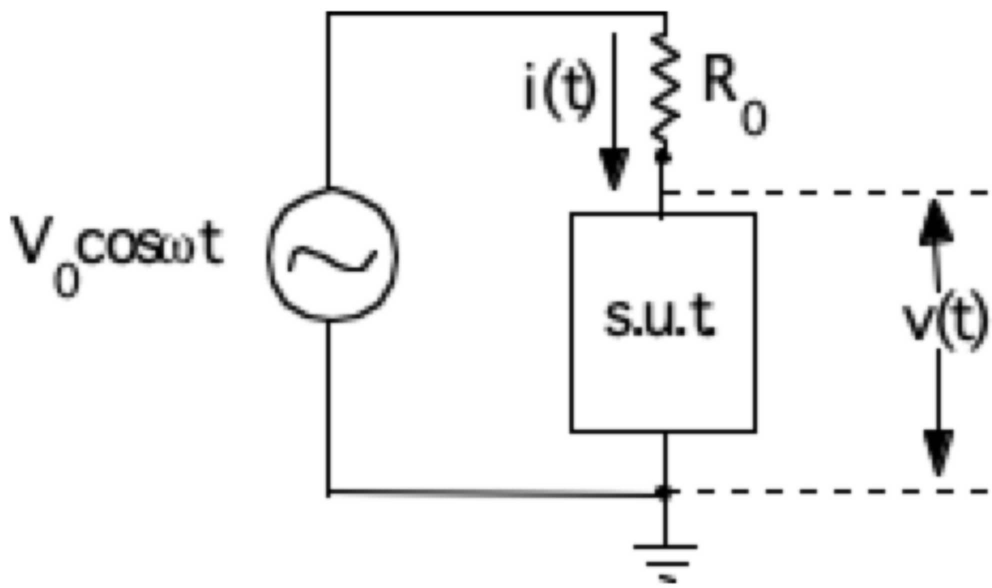
Impedance Spectroscopy - Procedures

Overview

This experiment relies on the ability (1) to inject a precisely regulated amount of (co-)sinusoidally varying current through a system under test and (2) to accurately measure the potential drop across the device even when the response is very weak and contaminated by noise. The latter situation arises because we are sometimes constrained to minimally perturb the system (e.g. human tissue) and thus must severely limit the amplitude of the injected current. Thus we need to "pull" the corresponding potential drop measurement out of a "sea of noise." To do this, we take advantage of the fact that the responding potential drop has a definite frequency and phase relationship with the probing current.

The first major experimental ingredient, a precise current source, may be accomplished in several ways. We start with a poor person's current source: a large resistor R_0 is placed in series with the system under test and a specified (co-)sinusoidally-varying voltage $v_0(t) = V_0 \cos \omega t$ is applied across the series combination using a function generator.



In this setup we assume that the impedance of the system under test (s.u.t.) is much smaller than R0 over the frequency range of interest. Based on this assumption, we then express the current as:

$$i(t) = \frac{V_0}{R_0} cos\omega t$$

Later we plan to add to this experiment a more sophisticated current source that will maintain the desired current regardless of changes of impedance of the system under test with frequency, even if the impedance changes a lot.

The second major experimental ingredient is a method to measure the corresponding potential drop in the presence of significant noise. To do this, we use a method called phase sensitive detection and an instrument called a **lock-in amplifier**. We will present the lock-in amplfier in detail in the Instrumentation document for this lab, which includes this link to the Stanford Instruments provides [primer on lock-ins (https://www.thinksrs.com/downloads/pdfs/applicationnotes/AboutLIAs.pdf)](https://www.thinksrs.com/downloads/pdfs/applicationnotes/AboutLIAs.pdf). If all goes well, this experiment will make a believer out of you that this instrumentation approach can accomplish a remarkable degree of noise reduction!

Of course, there are many other components to the instrumentation for this experiment. In addition to these two main ideas, you will also need to become familiar with the following: using an **LCR meter** to measure electronic component parameters, operating a **function generator** to create sinusoidal signals, optimally using an **oscilloscope** to monitor both probe and response signals (input and output signals), a **period/frequency meter**, and a **precision digital multimeter** to measure RMS voltage variation. You will also need to assemble test components on a **solderless breadboard** and generally configuring a modestly complex instrumentation system using **coaxial cables, BNC adapters, probe clips,** etc.

NOTE: Standard laboratory coax cables are terminated in connectors called BNC connectors. The letters BNC are a historical remnant of the early design of such connectors by Berkeley Nucleonics Corporation. These connectors are designed to allow signals to pass across junctions between cables and instruments with very small disruption of the signal by the junction itself. The connection is established with a simple twist of a "bayonet type" mechanical link. BNC adapters allow multiple cables to come into one junction, provide links to other cable and connector types (e.g. "banana jacks"), create pathways around sharp corners, etc.

Procedure summary

The basic experiment proceeds in four parts:

1. Measure the values of the test components using the LCR meter.
2. Set-up of system under test and familiarization with the lock-in amplifier.
3. Measure potential drop versus frequency using a 10 kΩ resistor as R_0.
4. Measure potential drop versus frequency using a 1MΩ resistor as R_0.

Part 1

You will be given a set of loose components as follows:

- a 10 kΩ current setting resistor R_{0a}
- 1 MΩ resistor as R_{0b}
- two low value resistors to be part of the system under test
- a capacitor that is part of the system under test

The values of the resistors (wth possible exception of the 1MΩ resistors) can be read using the resistor color code. A sequence of four colored stripes at one end of the resistor designates its value and tolerance. Numbers are assigned to the stripes according to the following table:

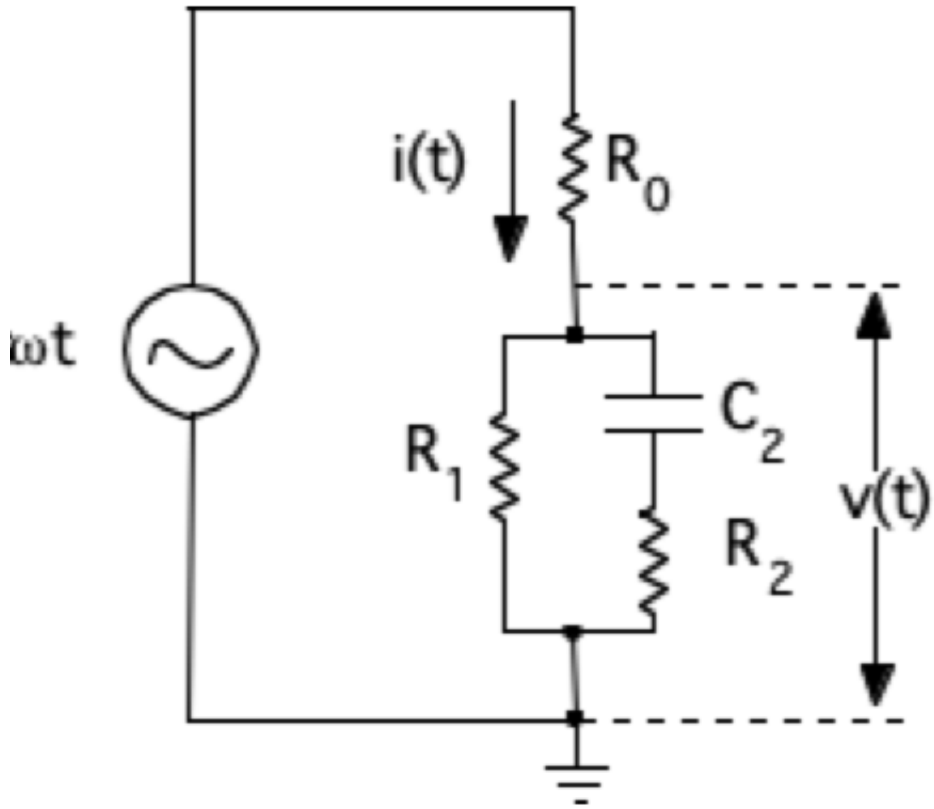
Black	**Brown**	**Red**	**Orange**	**Yellow**	**Green**	**Blue**	**Violet**	**Gray**	**White**
0	1	2	3	4	5	6	7	8	9

The colors red through violet are in the order of the rainbow. A pneumonic for remembering the sequence is "**B**etter **B**eer **R**ates **O**k **Y**et **G**oes **B**elow **V**ery **G**ood **W**ine".

The stripe closest to the end of the resistor establishes the most significant digit, the next stripe establishes the next significant digit, the third stripe designates the number of trailing zeros, and the fourth stripe indicates the tolerance according to: gold = 5%, silver = 10%. Thus a resistor with markings red / red / green / silver would be 2,200,000 Ω (2.2 MΩ) resistor where the value can be vary by ± 10%. Be careful: the color convention is not scientific notation. The third stripe is not the exponent of ten, it is the number of trailing zeros.

Your first task then is to interpret the color codes to establish the nominal values of the resistors. Then you will place each of resistor in turn into the test socket of the LCR meter and measure the corresponding component value resistance. Do this at each of the frequencies available on the LCR meter. Finally, switch the LCR meter into the mode to measure capacitance, place the capacitor in the test socket, and find the value of the capacitor.

The circuit for the system under test is the following. The signal source and current-setting resistor are also shown.



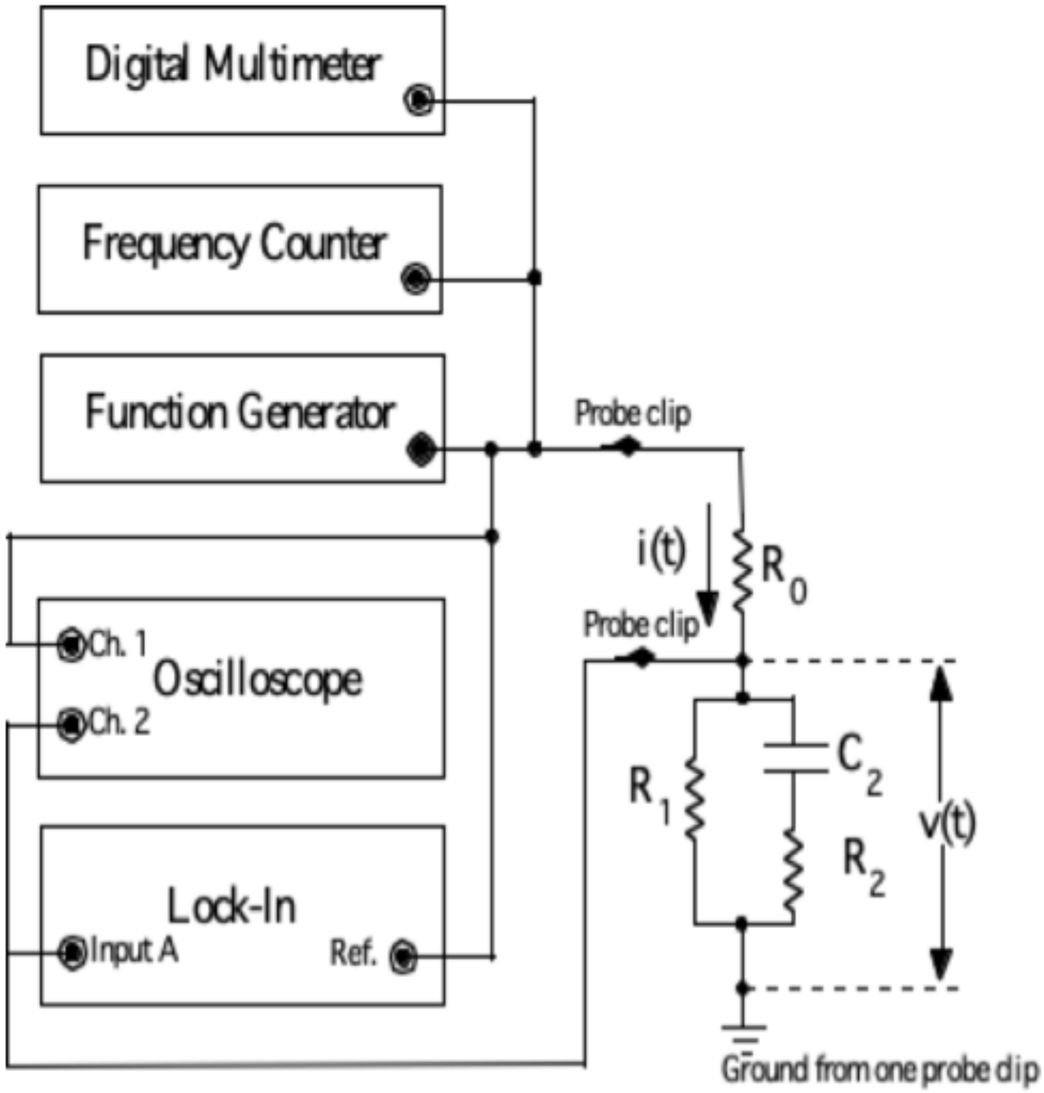
You are provided with components with tape markers indicating which circuit elements they are. Note that you are given two choices for R_0: one is labeled R_{0a} and the other R_{0b}. Place each of component in turn into the test socket of the LCR meter and measure the corresponding component value (R or C) at each of the frequencies available on the LCR meter. For purposes of this experiment, we will average the values of R and C over the frequencies 100 Hz, 1000 Hz, and 10,000 Hz for predicting the impedance of the system under test.

Using the average value, calculate the critical angular frequency $\omega_c = 1/[(R_1 + R_2)C_2]$. Calculate the corresponding value in hertz $f_c = \omega_c/(2\pi)$. This is where "interesting" things should happen to the impedance as a function of frequency in your measurements of part 2.

Part 2

It would be good at this point to lock through the [manual for the Stanford Research Systems model SR530 lock-in: (https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwj4-bSY7-X1AhUTOH0KHTFdCOcQFnoECAkQAQ&url=https%3A%2F%2Fwww.thinksrs.com%2Fdownloa Wc-VB1UWGKNeEGL-1Obk)] You can do this briefly at first and then look at sections more carefully as you use the particular functions.

Check the setup to establish that it is configured according to the diagram below. All instruments should be initially turned "OFF". Note that actual wiring may look different than the diagram (perhaps because instruments are not stacked in the same order) but the that the coaxial cable connections are equivalent: convince yourself of this. Record instrument model numbers. Check the assembly of the components in the proto board to see that the system under test is constructed as shown.



Begin by using resistor $R_{0a} = 10k\Omega$ for the current-setting resistor.

Temporarily disconnect the lock-in from the rest of the instrumentation circuits. Turn on the remaining instruments. On the oscilloscope, set Channel 1 sensitivity to 0.5 volts per division, the time base to 10 ms per division, and the triggering source to Channel 1. Set the function generator frequency to 100 Hz. Make sure the function generator has no DC offset applied to its output. Watching the oscilloscope, adjust the amplitude on the function generator until the voltage swing is 2 volts peak to peak or 1 volt amplitude.

Now look at the digital multimeter. Make sure it is set to measure AC voltage. You should see a value close to 0.707 volts … why? Adjust the amplitude on the function generator until this value is in fact close to 0.707 volts RMS. We are using a digital multimeter that can measure RMS voltage over the entire frequency range of interest in this experiment. (You might find and check the multimeter manual to assure yourself that this is true: less expensive hand-held digital multimeters will NOT accurately measure AC voltage for frequencies above a few hundred hertz.)

With these settings and the choice of R_{1a} the current into the system under test would be 0.1 mA amplitude (0.0707 mA rms). Think about what voltage drop this should cause across the system under test at low frequencies (see the Ideas document). The signal measuring this voltage drop is connected to Channel 2 of the oscilloscope. Adjust the sensitivity to show the voltage drop clearly (i.e. spanning one or two divisions) on the oscilloscope. Convince yourself that the amplitude is what you expect. If it is not, then either check your instrumentation or make sure your understanding of the low-frequency impedance is correct. Also note the relative phase of the signals in channel 1 and 2: at low frequencies, the two signals should be in phase with one another. (How do you determine this?) You should not proceed until you are confident that you are seeing the signal amplitude and phase that you think you should see.

Now it is time to connect the signals to the lock-in and to turn it on. Initially the LED indicating UNLK will be on until the instrument locks to the reference signal, which is supplied by one of the branches of the function-generator output. This should last for a few seconds. Make sure the reference channel is set to trigger from sine waves rather than pulse trains. Also make sure the input filters are all switched "OUT", i.e. not in use. Adjust the sensitivity to have a value just exceeding the expected low-frequency rms voltage across the system under test. (How is this rms voltage related to the amplitude of the signal seen on Ch. 2 of the oscilloscope?)

The twin output displays should be set to $R - \phi$ which will indicate the rms magnitude and phase of the input signal relative to the reference. Note that there are both digital and analog displays. Convince yourself that the display readings are just what you expect for the level of the input signal as seen on the oscilloscope. At low frequency, the phase shift should be close to zero (see the Ideas document).

Part 3

Now you can take the data that will provide the impedance as a function of frequency of the system under test. Starting at low frequencies, use the lock-in to record the rms voltage drop across the system under test as well as the phase. At each frequency, you should also record the rms voltage $V_{0\mathrm{rms}}$of the function generator signal: this should change only slightly across the whole frequency range but you should account for any such slight variation in your impedance calculations. Systematically vary the frequency over a range to explore the entire range of behavior of the system under test: low-frequency behavior, "critical frequency" f_c, and high frequency. This should roughly span frequencies from 0.05 f_c to 20 f_c. You need to think about what strategy for sampling the frequencies would give a good picture of the entire range of impedance behavior.

Once you have the rms voltage drops across the system under test as well as phase shifts, put this data as well as the corresponding function generator rms voltages into a spreadsheet. It is helpful to enter the parameters of the system under test into single cells in the spreadsheet (i.e. have some cells that indicate R_0, R_1, R_2 and C_2. Plot the "raw" rms voltage data as function of frequency on both linear axes and on log-log axes. Notice how the log-log plot accentuates the three regimes of behavior (low frequency, transition, and high-frequency). Mark the location of the critical frequency f_c on your plot.

You should then use a spreadsheet to calculate the impedance by dividing the rms voltage drop by the injected current at each current. Remember that the injected current is calculated by dividing the function generator output rms voltage $V_{0\mathrm{rms}}$by the resistance R_{0a}. Plot the impedance magnitude versus frequency on both linear and log-log plots. Also plot the phase versus frequency, using both linear and log scales for the frequency axis. Again, mark the location of the critical frequency f_c on your plot.

Part 4

Disconnect the signals from the lock-in and replace R0a with R0b, now 1 MΩ. For a 1 volt amplitude function generator signal, this should now give an injected current of only 1 μA. Return the frequency to 100 Hz (the low-frequency end). Look at channel 2 of the oscilloscope with the sensitivity turned up as high as it will go. You will have a hard time seeing any signal: it is likely that the trace will just look like a smear of noise.

Now reconnect signals to the lock-in and change the lock-in sensitivity by a factor of 100 (the factor change in current). You should see an rms voltage reading for the voltage drop across the system under test. Convince yourself that the value is what you would expect.

The key thing to note is that even though the oscilloscope is not able to measure the signal, the lock-in gives a clean measurement. This is because the lock-in has an extraordinary capability to filter noise from signals that have a definite frequency relation to the reference signal.

Now repeat all of Part 3 with this new value of R_{0b} and make the same set of plots in your spreadsheet.