**Lab 7: RC Circuit, Transient and Frequency Responses**

**Background knowledge: the RC circuit**

In this lab, you will investigate a first-order RC circuit, particularly its transient response and frequency response. The knowledge and skills you learn in this lab will prepare you to work on the next project.

An RC circuit (a resistor in series with a capacitor) is a fundamental AC circuit. The input voltage Vin is a periodic AC signal, and is applied across the two input terminals spanning across both the resistor and the capacitor. In the following example, the output voltage Vout is taken across the capacitor.

Diagram, box and whisker chart

Description automatically generated

The RC circuit has several important characteristics.

The first circuit characteristic is the RC circuit’s **transient response**. The capacitor takes time to charge up to a voltage, and also takes time to discharge from a voltage, so the output voltage taken across the capacitor will be delayed for some time when compared with the input voltage. The delay time, signified by the **RC time constant**, is the product of the resistance R and the capacitance C.

The second circuit characteristic is the RC circuit’s **frequency response**. When the input AC signal changes very fast (i.e., at high frequencies), the output voltage will not be able to keep up with the fast-changing pace of the input voltage, since it takes time for the capacitor to charge and discharge. This causes so much delaying of the output voltage that eventually, the output voltage will be significantly diminished when frequency of the input voltage becomes very high. Therefore, for the RC circuit where the output voltage is taken across the capacitor, the output voltage will barely change when the input voltage has a very high frequency. This type of RC circuit is called a **low-pass filter (LPF)** because it filters out the high frequency input signals. In contrast, when the output voltage is taken across the resistor of an RC circuit, it is a high-pass filter (HPF).

The frequency response of an RC circuit is signified by its **corner frequency** (or cutoff frequency), which is the reciprocal of the product of 2π and the RC time constant. When the input frequency is at this corner frequency, half of the input signal’s power is attenuated by the LPF, so the power of the output signal is only half of that of the input signal. The corner frequency formula can be readily derived based on the description above, using the voltage division of the RC circuit.

Both the time delay and the frequency filtering properties of the RC circuit will be investigated in this lab. You will also learn some useful features of the scope, such as using the cursors to accurately measure the waveform properties.

**Part 1: Exploring an RC circuit – transient response**

1. Build the following RC circuit using R1 = 1.5k resistor, and C1 = 0.01 uF capacitor. The Vin and the Vout terminals must share a common ground node. Use a DMM to measure the resistor value and the capacitor value, and record them.

Diagram, schematic

Description automatically generated

|  |  |
| --- | --- |
| R1 measured value (kOhm) |  |
| C1 measured value (uF) |  |

1. Use the function generator Ch-1 to produce an input voltage Vin. It should be a square wave, with1 kHz frequency, 2 Vpp, and 0Vdc offset. Connect the function generator’s Ch-1 to the two input terminals of the RC circuit on the breadboard. Use the generic BNC-alligator/minigrabber probe to make this connection.
2. Then use the scope’s Ch-1 to measure Vin across the input terminals. Use the scope’s Ch-2 to measure Vout across the output terminals. It is crucial that the **black clips of the scope’s probes are always connected to the designated common ground node** of Vin and Vout. Otherwise you may risk forcing a high current through the scope and damage it.
3. As soon as you turn on the function generator’s Ch-1, and the scope’s two channels, you should see the Ch-1 input square wave, and the Ch-2 output signal wave (which is close to being a square wave, but less square looking). To overlay the two waveforms for better comparison, use the vertical position knob. Push Ch-1 button on the scope to select Ch-1, and then adjust the vertical position knob to center the Ch-1 waveform. Do the same for the Ch-2 waveform. Use the vertical scale knob to expand the two signals so you can see them better. You should see something like this:

Graphical user interface

Description automatically generated

1. **Save an image of the input and output waveforms.** How do the two signals compare?
2. Now gradually increase the frequency of Vin. What happens to Vout? **Why does Vout lag more and more behind Vin as you increase the frequency of Vin?**
3. Set Vin to some higher frequency such that the scope display looks like the following:

**A picture containing rectangle

Description automatically generated**

**Record the waveforms with input voltage at high frequency (e.g., 5kHz).**

1. Now accurately measure the time constant τ of the RC circuit with the scope’s cursor function. Press the **Cursor** button on your scope, and set the mode to **Manual**. Press “Select” to be “│ │”, and “Source” to be Ch-2. Press Cursor A, and use the menu select dial (near a small clockwise arrow) to move the vertical line of Cursor A. Record the position of Cursor A in us (microseconds). Do the same thing for Cursor B.
2. Record the time it takes the RC circuit’s output signal (which is the Ch-2 signal) to rise from the bottom to the top of the square wave. You should see an image like this. **Record your image.**

Graphical user interface

Description automatically generated with low confidence

Note: In the waveform shown above, the rising time for Ch-2 signal is 76 – (-2) = 78 usec. Assuming it takes 5 RC time constants to fully charge the capacitor (a reasonable assumption), then the RC time constant τ is 1/5 of 78 usec, which is 15.6 usec. This is reasonably close to the theoretical RC time constant of the circuit, which is (1.5kOhm) (0.01uF) = 15 usec.

1. Use the above method to **measure the RC time constant τ of your RC circuit**, and compare it with the theoretical RC time constant of your circuit.

**Part 2: Exploring the RC circuit – frequency response**

1. Switch the input to a sine wave. Overlay the input and output signals. In the following investigation, record the waveforms that you see on the scope.
2. Watch the output as you increase the frequency of the input signal from 0.5 kHz upward. **Record the waveforms that you see on the scope at input frequencies of 0.5kHz, 1kHz, 5kHz, 10kHz, 20kHz, and 30kHz.** What happens to the output signal as the input signal frequency increases? Why does the output voltage diminish when you increase the frequency of the input voltage?

Here are some examples of what some of your images may look like (at 0.5kHz, 5kHz, 20kHz, and 30kHz):

Chart

Description automatically generated

Chart

Description automatically generated

Chart

Description automatically generated

Chart

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1. Record Vpp for the output over an input frequency range of 0.5kHz to ~30kHz (change the increment as needed). When does Vin start to change? How about Vout? Put your data in a table, and then plot the gain (in dB) vs. the input frequency (on a log scale):

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Input frequency (kHz) | Input Vpp | Output Vpp | Gain (Vout/Vin) | Gain (dB) = 20 log (Gain) |
| 0.5 |  |  |  |  |
| 1 |  |  |  |  |
| 2 |  |  |  |  |
| 4 |  |  |  |  |
| 8 |  |  |  |  |
| 12 |  |  |  |  |
| 15 |  |  |  |  |
| 16 |  |  |  |  |
| 18 |  |  |  |  |
| 22 |  |  |  |  |
| 27 |  |  |  |  |
| 32 |  |  |  |  |

1. Explain (1) why does the output signal **amplitude** increasingly becomes **smaller** as you increase the input signal frequency? (2) why the output signal **phase** appears to increasingly **lag** behind the input signal as you increase the input signal frequency?

1. Identify the input signal frequency where the output Vpp is about 70% of the input Vpp. This is called the **cutoff frequency** of the RC filter circuit. At this input signal frequency, the power of the output signal is reduced to half of the power of the input signal. Explain why this is the case.
2. Sweep the output of the function generator (that is, the input to your RC circuit) over a range of frequencies. You may use the first and final frequency values of your table above. Use the sweep function of the function generator to sweep over one second. Describe what you see on the scope.
3. Now sweep over 10 seconds. What do you see? Try different start/stop frequencies, as well as the sweep times. Does the sweeping function give you an overall idea of how the output voltage of the RC circuit changes as the input signal frequency changes?

**Further exploration (not graded)**

For an RC (one R and one C) circuit, if the output voltage is **taken across the resistor** instead of the capacitor, what will be its transient response and frequency response? If we use this circuit as a filter, what would be a proper name for it? How is this RC circuit different from the previous RC circuit? Understanding this circuit will help you with the next project.

**List of items to include in your lab report results section:**

a) Measured R, C values

|  |  |
| --- | --- |
| R1 measured value (kOhm) |  |
| C1 measured value (uF) |  |

e) scope image of an input and an output waveforms, superimposed

i) scope image of the superimposed input and output waveforms, with vertical cursors applied

j) measured RC time constant; compared with theoretical RC time constant

|  |  |
| --- | --- |
| Measured RC constant | Theoretical RC constant |
|  |  |

m) frequency response – data table of input Vpp and output Vpp

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Input frequency (kHz) | Input Vpp | Output Vpp | Gain (Vout/Vin) | Gain (dB) = 20 log (Gain) |
| 0.5 |  |  |  |  |
| 1 |  |  |  |  |
| 2 |  |  |  |  |
| 4 |  |  |  |  |
| 8 |  |  |  |  |
| 12 |  |  |  |  |
| 15 |  |  |  |  |
| 16 |  |  |  |  |
| 18 |  |  |  |  |
| 22 |  |  |  |  |
| 27 |  |  |  |  |
| 32 |  |  |  |  |

Bode plot: Gain (dB) vs. input frequency (on log scale)

n) explanation of frequency response of the RC circuit

o) Corner frequency measured

|  |  |
| --- | --- |
| Corner frequency (Hz) |  |
| Explain why at the cutoff frequency, the output signal power is half of the input signal power |  |