Parallel Plate Capacitors

Introduction

Capacitors are a very integral part of electronics. They can be used in many different ways to change an input signal. In this lab, the effects of a capacitor on a square wave signal will be studied using an oscilloscope. A capacitor comprised on two parallel (conducting) plates will then be studied. Lastly, this configuration will be used to determine the dielectric constants of several materials.

Capacitance is defined as the ability for an object to hold (electric) charge or more obvious to the name, the electric charge capacity. It is defined as:

\[ C = \frac{q}{V} \]  

(1)

A simple example of this is to consider two conductive surfaces separated by a distance. If one were to connect one plate to a positive voltage, and the other to (electric) ground, a charge of equal quantity, but opposite polarity would build up on the plates. The capacitance of this type of capacitor was found to be:

\[ C = k\epsilon_0 \frac{A}{d} \]  

(2)

A is the surface area of the plates, \( d \) is the separation of the plates, \( k \) is the dielectric constant, and \( \epsilon_0 \) is the permittivity of vacuum. The dielectric constant is determined by the relative difference in permittivity: \( k = \frac{\epsilon}{\epsilon_0} \). As one can see, the capacitance is based purely on physical parameters. We will verify Eqn. 2 experimentally.

Apparatus

- Oscilloscope
- Power Supply
- Decade Capacitor
- Oscilloscope probe
- Banana-BNC Cables
- Alligator-BNC Cables
- Alligator Clips
- Banana-Banana Cables
- Micrometer
- Dielectric materials

Part I - The Oscilloscope

Fully covering the operation of an oscilloscope will not be possible in the given time for this lab so additional information on how to use the oscilloscope can be found in Appendix A.
which are the sections *Operating Basics*, and *Understanding Oscilloscope Functions* taken from the full manual found [here](#).

The oscilloscope is a very useful piece of equipment for measuring electronic signals (such as the voltage) of electronic devices. The oscilloscope serves to capture signals over a period of time allowing us to observe how they change as a function of time. We will begin by observing an oscillating signal and later on in the lab, capture single ’pulse’ signals.

The oscilloscope used in this lab is shown below.

![Figure 1: Tektronix 4 channel digital oscilloscope](#)

Looking carefully, one can see that the control panel is split into several different regions named *Trigger*, *Vertical*, and *Horizontal*. In addition, note the buttons to the right of the display screen and the embossed line indicating what the button will correspond to for options on the screen. We’ll elaborate on this a bit later. Lastly, note the various buttons on the top which are a mix of additional functions, and running modes.

### Vertical Controls

The vertical controls show 4 channels with knobs for each channel arranged vertically. Below each set of knobs, there is a BNC connection for each channel. In addition to that, the **Math** button allows for certain mathematical operations (addition, subtraction, etc.) of channels 1 and 2.

- **Position** - This adjusts the vertical position of your waveform. Each channel has a dedicated position knob.
- **Menu** - These buttons toggle each channel on the display. This also brings up additional options on the right side of the display screen for each corresponding channel. Note how the colour for each channel is different.

- **Scale** - This changes the vertical scale of each channel. The scale is given as a units per division where a division is one grid length on the screen. Each channel has a dedicated scale knob.

**Horizontal Controls**

The horizontal control changes the time scale in which you can observe your signal. Similar to the vertical controls, the horizontal control has similar **Position, Horiz (Menu)**, and **Scale** controls. In addition, there is a **Set to Zero** button that sets your **Position** to $t_0 = 0$.

**Trigger Controls**

These controls are adjustments for capturing your signal. Without this, the oscilloscope will merely display a signal (in a specific time window). In short, this control is meant to indicate, at a specific signal level, when you want the signal to be captured. An example of when this is very useful is if the channel is trying to measure a sudden increase in voltage. For the most part, we will be using the **Level** knob which indicates at what level you want the signal to be captured.

**Capturing a signal**

Here we will learn how to observe, and capture a signal. The signal used will be a 5 V, 1 KHz square wave. The source terminals are in the lower left of the **Vertical** section on the oscilloscope and is labelled **Probe Comp**.

1.) Turn on the oscilloscope and wait for the Power-Up tests to complete.

2.) For consistency, press the **Default Setup** button. This is equivalent to ‘factory default’ on many other electronics.

3.) Ensure Channel 1 is displayed on the screen (should be on by default).

4.) Connect the Banana-BNC connector on Channel 1.

5.) Connect the probe end to the top terminal of **Probe Comp**. No need to connect the ground alligator clip to the ground terminal (it is a common ground). For reference, this is the circuit that is created:
6.) On the right hand of the screen, there are several settings for the channel. Ensure that the Coupling is DC, BW (Bandwidth) Limit is Off, Volts/Div is Coarse, Probe Voltage is 1X, and Invert is Off. If you need to change any of these settings, use the buttons to the right of the screen to bring up sub-menus. In the sub-menu, you can cycle through settings using the buttons on the right side of the screen.

7.) Adjust the Vertical Scale knob for Channel 1 to 1 V in the lower left hand corner. This value is the volts/div.

8.) Adjust the Vertical Position knob for Channel 1 such that the square wave is fully shown on the display. Note the arrow on the left side of the grid with the number '1' above it. This indicates the horizontal axis. Observe what happens when you move the position well above or below the display.

9.) At this point in time, you should see something reminiscent of a square wave. The trigger level needs to be adjusted such that the square wave can be captured. The signal is captured when the voltage of the input exceeds the trigger level. When this occurs, that event is set to \( t = 0 \).

10.) Adjust the Trigger Level knob and set the trigger level above 0 V. There is an arrow on the right side of the grid for visual representation of the level. The numerical value is found in the lower right hand corner. Explain what happens when you increase the trigger level to \( > 5 \) V. Additionally observe what changes at the top of the display when you do this.

11.) Set the trigger to a level such that you’ve captured the square wave. Adjust the Horizontal Scale knob such that you can observe a few periods. For familiarity, adjust the Horizontal Position knob and observe what happens.

12.) Using all that you’ve learned, verify that the square wave is indeed 5 V with a frequency of 1 kHz.

Part II - Capacitors
A good use of an oscilloscope is to study the properties of capacitors as they are used in many situations that are not necessarily in steady state. We start by observing what happens when we connect a capacitor to a square wave.
1.) Connect the Alligator-Banana cables to the Probe Comp terminals. **Note:** The alligator clips might be a bit tricky to position correctly on the Probe Comp terminals.

2.) Using a decade capacitor \((C_1)\), the square wave source, and the oscilloscope, connect the following circuit:

![Circuit Diagram](image)

3.) Adjust the oscilloscope such that the signal is being captured, and at a good resolution (scale). Make sure to have at least 1 period of oscillation showing.

4.) On the decade capacitor box, turn the 10X pF knob and observe what happens when you change the capacitance higher or lower.

5.) Using your knowledge of capacitors, explain what you are observing. **(Hint: consider the capacitance relationship** \(C = \frac{q(t)}{V(t)}\)**

**Part III - Parallel Plate Capacitors**

Using what you understand of capacitors, we will further extend this knowledge to a parallel plate capacitor. Here, we use a capacitor charge/discharge circuit comprised of a power supply, switches, and a load (resistor).

1.) Determine the area of the capacitor plates by measuring the diameter.

2.) Record the value of the resistor.

3.) Turn the knob on the back of the parallel plate capacitor to close the plates completely. Make note of the ‘zero’ value on the vernier.

4.) Turn the knob the opposite direction such that the plates are separated by 0.2 mm.

5.) Connect the charge/discharge circuit shown below:
6.) The charge/discharge circuit switches between charging and discharging the capacitor depending on which way the switch is flipped. Using what you’ve observed in Part II, sketch what you would expect to see the voltage across the capacitor to be when it is charging. Assume the capacitor starts discharged ($V = 0V$).

7.) Sketch what you expect to see the voltage across the resistor to be when the capacitor is discharging (switch flipped).

8.) Ensure the switch is in the charging configuration.

9.) Turn on the power supply and set it to 10 - 20 V. You will also need to turn the current knob up such that it’s not completely off. Record the voltage and explain why the current reads (nearly) zero.

10.) Based on the voltage you set, configure *Vertical Scale* on the oscilloscope to a reasonable range such that you are able to see both $V_{max}$ and $V = 0$.

11.) Set the trigger voltage to a non-zero value. Is there a limit to what you should set this value to be? *(Hint: Recall the trigger portion of Part I)*

12.) In the top right corner, press *Single* to change the trigger mode to single capture. This way, the oscilloscope knows that you do not want to continue to scan after the capture. Notice at the top of the screen what changed when you did this.

13.) Flip the switch to discharge the capacitor. What do you observe on the oscilloscope screen? You may have to change some settings on the oscilloscope and repeat charging/discharging the capacitor to obtain a good output. To do this, revert the switch back to charging, press *Single* again to prepare for a new capture.

14.) If you are satisfied with your capture, proceed to save the data following these instructions:

(a) Plug in a USB drive. The oscilloscope should verify that the USB is compatible. If not, see your TA for further instructions.
(b) Press **Save/Recall** to verify the first menu options is Action: Save All and PRINT Button: Saves All to Files. If you need to change any of these settings, use the buttons to the right of the screen to bring up sub-menus. In the sub-menu, you can cycle through settings using the buttons on the right side of the screen.

(c) Press **Save** *(this is a different button from Save/Recall)* to save all the output to the USB. Each time you save, a new folder will be created. Note that only the displayed window data is saved so make sure you have the as much of the discharge captured.

15.) Record the plate separation of capacitor that corresponds to each set of data.

16.) Repeat the measurement for increasing plate separation in increments of 0.2 mm up to 2.0 mm.

17.) Does increasing/decreasing the source voltage change your results? Explain your answer.

**Part IV - Determining The Dielectric Constant of Materials**

Using the method used in the previous part, we can determine the dielectric constants of various materials.

1.) Obtain six sheets of all of the same material.

2.) Using a micrometer, measure the thickness of a single sheet of the material.

3.) Using the same circuit configuration, place one sheet of material between the capacitor plates and close the plates on it until it is snug.

4.) Take a measurement of the voltage discharge across the capacitor as you did in the previous section.

5.) Save the data and record the plate separation as a multiple of the material thickness.

6.) Repeat this for multiple layers of the material.

7.) Repeat this whole process using a different material.

**Part V - Analysis**

1.) Derive the equation for the voltage of a discharging capacitor $C$ connected to a resistor $R$ as shown below. This is effectively the discharging circuit used in Part III. **Hint:** Use Kirchoff’s Current Law, Ohm’s Law, and the definition of Electric Current: $I = \frac{dQ}{dt}$
2.) Using the data obtained for Part III, plot your results on a C vs. $\frac{1}{d}$ graph. Several steps are needed to achieve this.

(a) Load a single set of data in a plotting program such as Microsoft Excel. It is in CSV (comma separated value) format.

(b) Generate a scatter plot of said set of data. Make sure the units for the plot are the necessary SI units.

(c) Apply an appropriate fit to the data across an appropriate range. **Hint: consider the equation derived above.**

(d) Ensure that your fit has an $R^2$ close to 1 (ie $>0.995$).

(e) From this fit, the capacitance for each distance can be calculated.

(f) Plot these values with their corresponding $\frac{1}{d}$ values.

3.) From the C vs. $\frac{1}{d}$ graph, determine the slope and compare it to what you would expect.

4.) On the same plot, add the results from Part IV - determining the dielectric of the materials.

5.) Using the slope, determine the dielectric constant, $k = \frac{\varepsilon}{\varepsilon_0}$.

6.) Based on your results, provide a best guess as to what the sheets were made of.

7.) Discuss any factors that could contribute to the error in these measurements.

**Last Few Steps**

1.) Ensure that all your data is saved. It’s often a good idea to have a backup beyond your USB stick.

2.) Tidy up your work station, turn off the oscilloscope, turn off the power supply (after setting values to 0), unplug all the components, and return the dielectric sheets.