A problem seen at high frequencies is that stray (parasitic) capacitance effects with the overall response of a resistive voltage divider. The simplest way to correct for this problem is to introduce capacitors in parallel to the resistors. Consider the divider circuit in Figure 3. Capacitor $C_2$, which is across the output $V_2$, can be thought of as any stray parasitic capacitance at the output of the divider that might be part of the system. We can see that this circuit, known as a frequency compensated divider, works like a resistive voltage divider at dc or low frequencies and like a capacitive voltage divider at high frequencies. Voltage dividers can be constructed from reactive components just as they can be constructed from resistors. Also, as with resistor dividers, the divider ratio of a capacitive voltage divider is not affected by changes in the signal frequency even though the capacitor reactance is frequency dependent.

The divider ratio is $V_2/V_S = X_{C_2}/(X_{C_1} + X_{C_2})$. The capacitive reactance $X_C$ is proportional to $1/C$ so $V_2/V_S = C_1/(C_1 + C_2)$ is similar to the formula for the resistor divider. For the simple case where $R_1 = R_2$ we have a divider ratio of $1/2$ for the resistors. To have the same $1/2$ divider ratio for the capacitors, then $C_1$ must be equal to $C_2$.

The compensated divider employs pole-zero cancellation to suppress undesired frequency dependence caused by any stray capacitance on the output side of the network. If the resistor and capacitor values are adjusted so that the pole and the zero of $H(s)$ are superimposed, $|H(j\omega)|$ becomes independent of frequency.

An instructive way to learn about the conditions for pole-zero cancellation is to write down the low and high frequency limiting expressions for $|H(j\omega)|$ and then to set them equal to each other. The result is a simple relationship between $R_1$, $R_2$, $C_1$, and $C_2$.

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**Objective:**

The goal of this lab activity is to examine the issue of capacitive loading of resistive voltage dividers and the resulting effects on frequency response.

**Background:**

A frequency compensated voltage divider or attenuator is a simple two-port RC network providing a fixed voltage division ratio or attenuation over a wide frequency range and not just at dc. Such networks are used where the part of the circuit loading the voltage divider output is capacitive. This is particularly important when the signal has a wide bandwidth—that is, it is not sinusoidal. The simplest voltage attenuator is a purely resistive voltage divider with transfer function: $H(j\omega) = V_2/V_1 = R_2/(R_1 + R_2)$ where the input is $V_1 = V_1 + V_2$, and the output is $V_2$, as in Figure 2. The transfer function of a resistive voltage divider is independent of frequency only if the resistors are ideal and any parasitic capacitances associated with the circuit are negligibly small.

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**Figure 1. A schematic of the ADALM1000.**

**Figure 2. A simple resistor voltage divider.**

**Figure 3. A frequency compensated divider.**
Experiment to Compensate for the Input Capacitance of the ALM1000

Materials:
- One ADALM1000 hardware module
- One 1 MΩ resistor
- One capacitor, value to be determined

Directions:
Referring back to Figure 3, we can consider R2 to represent the 1 MΩ input resistance of the ALM1000 channels when in Hi-Z mode. Likewise, C2 can be considered to represent the stray parasitic capacitance of the inputs. The resistor and capacitor inside the green box shown in Figure 5. Use another 1 MΩ as R1 to make a ½ divider ratio. Start without including C1 to measure the effect on the frequency response due to C2.

Open the Bode Plotting window. You can disable the time plot if you would like while generating the frequency response curves. Set the AWG A Min value to 1.082 and the Max value to 3.92 (1 V rms or 0 dBV). Check that the shape has been changed to Sine. Set the start frequency to 100 and the stop frequency to 20,000. Select CH-A as the sweep source. Under Curves, select the CA-dBV, CB-dBV, and CA-db – CB-db traces to be displayed. Under the FFT window, using the Flat-Top window option works the best. Set the number of sweep point to 300 and single sweep. Hit the Run button.

You should now have the gain (attenuation) ratio vs. frequency response for the uncompensated divider. From the –3 dB point of the gain plot, estimate the RC time constant and the value of C2. How do these values compare to what you calculated using the time domain response? Based on your best estimates for the value of C2, calculate a value for C1 that will exactly compensate for C2. The value you come up with will probably not be close to a standard capacitor value. Find a parallel combination (or series combination) of two or more capacitors that closely adds up to the required value for C1.

Add your new C1 combination across R1 on the breadboard.

Repeat the time domain and frequency domain tests on this new circuit. Does the time domain response of the output of the divider now more closely resemble the blue waveform of (a) in Figure 4? If not, why not? Compare the frequency response of the circuit before and after C1 is added. What is the –3 dB frequency now?

Capacitor Divider Path Response:
Let’s now take a look at just the capacitor divider path. Disconnect R1 from the end of C1 and connect it to the 2.5 V fixed supply as shown in Figure 7. The path through just C1 blocks the dc path from Channel A. Connecting R1 to the fixed 2.5 V supply restores the dc voltage level at the Channel B input.

Using Your Divider to Measure a 9 V Battery:
We will now use the voltage divider to measure voltages larger than the 0 V to 5 V allowed by the ALM1000 hardware. But first we need to calibrate the divider offset and gain.

Disconnect the end of R1 and C1 from Channel A, as shown in Figure 5, and connect them to ground. Set the value for the Channel B gain to 2.0, the approximate divider ratio, for the moment. While monitoring the dc average of Channel B, adjust the value entered in the Channel B offset entry window.

Now reconnect R1/C1 back to the Channel A output. The Channel A and B waveforms should now more closely align on top of each other. Adjust the gain value up or down slightly as needed such that the flat portions of the

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**Figure 4.** The edges of a square (a) with proper adjustment, (b) under compensation, and (c) over compensation.

**Figure 5.** Voltage divider setup.

**Figure 6.** A voltage divider plot.

**Figure 7.** A just capacitor divider path.
top and bottom of the square waves are right on top of each other. You might need to tweak the offset slightly as well to get perfect alignment. The software is now calibrated to the voltage divider.

Disconnect R1/C1 from Channel A. Connect the negative (–) terminal of the 9 V battery to ground and connect the positive (+) terminal to R1/C1. The dc average read by Channel B should now be the dc voltage of the 9 V battery. You will need to change the Channel B vertical range to 1 V/div and the position to 5.0 to see the 9 volts on the scope grid.

Oscilloscope Probes:

A 10× passive oscilloscope probe uses a series resistor (9 MΩ) to provide a 10:1 attenuation when it is used with the 1 MΩ input impedance of the scope itself. A 1 MΩ impedance is standard for most oscilloscope inputs. This enables scope probes to be interchanged between oscilloscopes from different manufacturers. Figure 7 is the schematic for a typical 10× probe. 10× oscilloscope probes also allow some amount of frequency compensation to allow for variations in the scope channel input capacitance. A capacitor divider network is designed into the probe as shown. The adjustable capacitor connected to ground can then be used to equalize the frequency response of the probe.

\[
\begin{align*}
\text{C1} & \quad \text{9 MΩ} \\
\text{C} & \quad \text{Compensation Adjustment} \\
\text{Ground} & \quad 1 \text{ MΩ} \\
\text{C2} & 
\end{align*}
\]

Figure 8. A typical oscilloscope probe schematic.

The input channels of the ALM1000 have a 1 MΩ input resistance but the input capacitance is much larger than the roughly 10 pF to 50 pF adjustment range of most 10× probes. The capacitor in parallel with the 9 MΩ resistor is typically 10 pF and the parallel combination of the scope input capacitance and the adjustable compensation capacitor in the probe needs to be close to 90 pF. This means that if a standard probe were connected directly to the ALM1000 input, then it is not possible to compensate the frequency response.

A unity-gain buffer amplifier (such as AD8541 or AD8542) can be inserted between the probe circuit and the ALM1000 input, as shown in Figure 9. R1 and C1 complete the resistor/capacitor divider circuit of the 10× probe.

\[
\begin{align*}
\text{Inside 10× Probe} & \quad \text{9 MΩ} \\
\text{C} & \quad \text{Compensation Adjustment} \\
\text{R1} & \quad 1 \text{ MΩ} \\
\text{Inside Scope} & \quad \text{C2} \\
\text{Unity-Gain Buffer} & \quad \text{AD8541} \\
\text{ALM1000 Input} & \quad \text{5 V} \\
\text{S1} & \quad \text{Rm} \\
\text{R2} & \quad 32 \text{ pF} \\
\text{C3} & 
\end{align*}
\]

Figure 9. The insert of a unity-gain buffer to lower input capacitance.

With resistor R1 connected to ground, only positive voltages can be measured. If R1 is connected to 2.5 V, the middle of the 0 V to 5 V input range of the amplifier, an offset is injected and both positive and negative voltages can be measured.

Questions:

Considering the typical probe schematic presented in Figure 8, determine how the adjustable capacitor value can be computed to compensate the frequency response.

You can find the answers at the StudentZone blog.

Notes:

As in all the ALM labs, we use the following terminology when referring to the connections to the ALM1000 connector and configuring the hardware. The green shaded rectangles indicate connections to the ADALM1000 analog I/O connector. The analog I/O channel pins are referred to as CA and CB. When configured to force voltage/measure current, -V is added (as in CA-V) or when configured to force current/measure voltage, -I is added (as in CA-I). When a channel is configured in the high impedance mode to only measure voltage, -H is added (as in CA-H).

Scope traces are similarly referred to by channel and voltage/current, such as CA-V and CB-V for the voltage waveforms, and CA-I and CB-I for the current waveforms.

We are using the ALICE Rev 1.1 software for those examples here.


The ALICE Desktop software provides the following functions:

- A 2-channel oscilloscope for time domain display and analysis of voltage and current waveforms.
- The 2-channel arbitrary waveform generator (AWG) controls.
- The X and Y display for plotting captured voltage and current vs. voltage and current data, as well as voltage waveform histograms.
- The 2-channel spectrum analyzer for frequency domain display and analysis of voltage waveforms.
- The Bode plotter and network analyzer with built-in sweep generator.
- An impedance analyzer for analyzing complex RLC networks and as an RLC meter and vector voltmeter.
- A dc ohmmeter measures unknown resistance with respect to known external resistor or known internal 50 Ω.
- Board self-calibration using the AD584 precision 2.5 V reference from the ADALP2000 analog parts kit.
- ALICE M1K voltmeter.
- ALICE M1K meter source.
- ALICE M1K desktop tool.

For more information, please look here.

Note: You need to have the ADALM1000 connected to your PC to use the software.
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