I. Background

A compensated attenuator is a simple two-port network providing fixed voltage attenuation over a wide frequency band. Such networks are used where precision measurements voltage are required, particularly when the signal is not sinusoidal. The simplest voltage attenuator is a purely resistive voltage divider with transfer function: $H(j\omega) = \frac{V_2}{V_1} = \frac{R_2}{R_1 + R_2}$. The transfer function of a resistive voltage divider is independent of frequency only if the resistors exhibit ideal behavior and if parasitic capacitances are negligible. Unfortunately, at high frequencies a resistor can exhibit substantial parasitic inductance. This series inductance makes the attenuation factor dependent upon the frequency.

Another problem evident at higher frequencies is that stray (parasitic) capacitance interferes with the function of a resistive voltage attenuator. A simple way to alleviate this problem is to introduce capacitance in parallel to the resistors. Examine the circuit in Figure 1. It should be obvious that this circuit, known as a compensated attenuator, works like a resistive voltage divider at low frequencies and like a capacitive voltage divider at high frequencies. In essence, the capacitors $C_1$ and $C_2$ provide a shunt path for most of the current flow at high frequency, thus overwhelming any series inductance in the resistors as well as any stray capacitance due to the circuit layout, probe configuration, etc.

II. Preparation for laboratory exercise

The compensated attenuator employs pole-zero cancellation to suppress undesirable frequency dependence caused by stray inductance and capacitance. 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.

![Compensated Attenuator Circuit Diagram](image)
A. An instructive way to learn the condition for pole-zero cancellation is to write down the limiting, low- and high-frequency 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 $C_2$. Find this relationship.

B. Now use this relationship in the general expression for $H(s)$ to show that it guarantees pole-zero cancellation, that is, constant $H(j\omega)$.

C. Sketch pole/zero plots for the cases illustrated in Fig. 2, i.e., undershoot, overshoot, and correctly compensated.

![Figure 2](image-url)

Figure 2. Square waves showing (i) proper adjustment, (ii) overshoot and (iii) undershoot on the leading edge of the waveform.

*Bring your work to the lab and show it to the lab TA before you start working.*

### III. Experimental procedure & lab questions

A. Design & build a purely resistive voltage divider (no capacitors) to provide 20(±0.5) dB of attenuation. Limit the resistors to the range from ~2 kΩ to 100 kΩ. Be sure to specify the tolerance values (in percent) for $R_1$ and $R_2$ required to achieve the ±0.5 dB specification. Do not use the scope probes! Instead, connect the input to the signal generator and the output directly to the oscilloscope, making all connections with mini-grabber/BNC
cables. With sinusoidal input, measure attenuation from 100 Hz to 1 MHz. Measure and plot $|H(j\omega)|_{dB}$ & $\angle H(j\omega)$ over this 4 decade frequency range using the log-log paper provided. **Show your plot to the TA before proceeding to part B.**

B. Examine your results. Have you achieved the desired 20 dB attenuation at over the entire frequency band? Determine the influence of stray capacitance by touching the resistor $R_2$ to see if the magnitude of the output signal is affected.

C. Without changing the circuit, apply a square wave signal at ~10 to 100 kHz and notice the significant undershoot of the leading edge of the output wave. Refer to Fig. 2 for a sketch of a square wave showing undershoot. Now add approximately 10-20 pF of capacitance in parallel to the resistor $R_1$ and observe how this capacitance changes the appearance of the output waveform. (It should decrease the undershoot.) Now add additional capacitance, trying to achieve a square wave output. If you add too much capacitance, then the output signal will exhibit overshoot, as shown in Fig. 2. **Obtain several scope traces for use in your lab write-up.**

D. With your new voltage divider network, re-measure the voltage transfer function, $|H(j\omega)|_{dB}$ and $\angle H(j\omega)$, from 100 Hz to 1 MHz as before, using a sine wave input. The attenuation factor should now be much less dependent upon the frequency than it was in part a) above. Why is this so?

To answer this last question, we have to learn something about the input impedance of the oscilloscope and also something about coaxial cable. First, examine the front face of the scope and note the "fine print" located near each of the input bnc plugs. It should say something like "20 pF" and "1 M\(\Omega\)". These values represent the shunt capacitance and resistance of the equivalent input RC networks of the A and B channel amplifiers. The scope capacitance is in parallel with your resistor $R_2$ and thus influences the measured high-frequency attenuation. The cable connecting the circuit to the scope also adds substantial capacitance in parallel to $R_2$.

In section III.C above, when you added the capacitance $C_1$ in parallel to $R_1$, you actually created an attenuator that largely compensated for the input capacitance and resistance of the scope as well as the cable capacitance. With the value of $C_1$ properly adjusted so that the output waveform exhibits neither overshoot nor undershoot, you have achieved cancellation of the pole in $H(s)$ with the zero of the transfer function.
Figure 3. Equivalent circuit for resistive voltage attenuator.

E. Fig. 3 provides a more accurate representation of the network you are investigating. Keeping this circuit in mind, sketch a new equivalent circuit that includes all resistance and capacitance elements influencing attenuator performance. It is essential to account for the capacitance of the cable, which is specified per length and will be approximately 120 pF per meter for the bnc cable you are using. Measure the cable length and use this length to calculate the net contribution to capacitance due to the cable. Add this amount to the scope capacitance for a new estimate, i.e., \( C_2 = C_{\text{scope}} + C_{\text{cable}} \), then re-calculate \( R_2C_2 \). It should be almost equal to \( R_1C_1 \).

F. The probes commonly used with an oscilloscope are in fact accurately calibrated, compensated attenuators matched to the input impedance of the scope. Most such probes have a screw adjustment feature for trimming the capacitor. Use the 1 kHz square wave signal available at the front face of the oscilloscope with a 10\( \times \) probe and trim it (i.e., adjust it) to obtain a square wave showing neither overshoot nor undershoot. At this setting, you have achieved the pole-zero cancellation condition: \( R_2C_2 = R_1C_1 \).

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Lab. technique to remember The probe-trimming procedure described in section III.F above should always be followed before using an oscilloscope to display voltages in high impedance ckt's, i.e., high resistance (>100 k\( \Omega \)) or low capacitance (<100 pF), especially at high frequencies (>100 kHz). Probe trimming facilitates measurement transients, such as the rise time of pulses, by eliminating artifacts of the measurement circuitry.