Experiment 4
The Oscilloscope

1 Motivation

This experiment introduces the digital oscilloscope. The "scope" is an extremely versatile instrument used to observe time-varying electronic signals. You will be using a scope extensively in the remaining laboratory experiments for the semester, so it is important that you understand how the scope works and how to use it to make accurate measurements. A key companion instrument is the arbitrary function generator that you will use to drive time varying voltage and current in AC circuits. You will gain additional experience using the function generator as well. At some point in the next labs you may find yourself asking "I wonder what's going on in this circuit?" Keep the scope in mind, because it can help you diagnose and pinpoint problems, or just give you better insight into a circuit's behavior. You are free to use it anytime.

2 Background

When they were first developed, oscilloscopes were based on cathode ray tube (CRT) technology and analog circuitry. A focused electron beam inside the CRT was steered by electrodes to create a small, moving "spot" on a phosphorous screen. The spot was swept left-to-right across the screen at an adjustable rate while its vertical position was controlled by an input signal voltage. For example, if the input voltage was sinusoidal, the beam's path drew a sinusoidal pattern on the screen. The persistence of the phosphor's glow was adjusted to create a stable image for the eye. Polaroid cameras were used to record a screen image.

Modern digital oscilloscopes use high-speed analog-to-digital (A-to-D) converters to measure input signals at 10^9 samples per second or even faster. The data is stored in memory, and the scope displays a reconstructed waveform image on an LCD screen. "Digital phosphor" oscilloscopes can display multiple recently stored traces at the same time, mimicing useful characteristics of a CRT phosphor screen's adjustable persistence. This allows the user to detect intermittent variations from a typical waveform.

Figure 1: Tektronix DPO/MSO 2000B series digital oscilloscope

This experiment takes you through several exercises that will illustrate the use of the Tektronix MSO 2014B (Fig. 1) available in the 321 laboratory. Learning its basic functions and some of its advanced features will help you efficiently make accurate measurements of time varying quantities.

The most common form of interconnection between the scope and other electronic equipment is a coaxial cable "$\odot$", which has a center conductor and a concentric outer conductor. This is the best way to connect the output of the function generator to the scope. The outer conductor of the "coax" is typically grounded and serves as a shield for the inner conductor. The coaxial cables have bayonet style connectors (BNC) that can transmit signals with a bandwidth of about 10 GHz without significant distortion. For your experiments, you will often convert the BNC to banana connector patch cables to attach to the adjustable resistors, capacitors, etc. This is acceptable for the lower frequencies you will be working with.

Most oscilloscopes have earth ground as the common reference for the input signal ports. The shield (outer circle) of the BNC input connectors are not only connected together, they are also connected to earth ground via the AC power cord, which is typically also connected to the grounds of other instruments like the function generator. This easily forgotten ground connection can lead to confusion and incorrect measurements if you are not careful.

If you want to measure the potential *difference* between two points in a circuit, you must use two separate input channels on the scope (unless one of the two points is ground). Each measurement is referenced to ground, and you then use the scope's math mode to display the potential difference between the two input signals. Other math combinations can be displayed as well.

3 Equipment

For this lab, you will use:

- One Tektronix MSO 2014B Digital Storage Oscilloscope
- One Tektronix P3010 10X scope probe
- One AFG2021 Arbitrary Function Generator
- One 6.3 V transformer (inside a small aluminum box with yellow and white connectors)
- Two ELC variable resistance boxes

4 The Tektronix "Introduction to Oscilloscopes" Lab Experiment

Tektronix has prepared a helpful tutorial that will introduce you to the main features and capabilities of the MSO 2014B. Do all sections of the tutorial (skipping Part 6 of the "Final Exercise"). If you have a lab partner, you both should complete each section of the tutorial. Alternate starting the sections so that you each have first-tries. You will probably need about 1.5 hours to complete the tutorial.

You can print out the tutorial, but just viewing a pdf copy on your computer or other device will be convenient. In either case, record your answers to the tutorial's Exercises in your lab book instead of separate paper. Detailed explanations are not necessary, just adequate notes to track and record your progress through the tutorial.

The tutorial assumes use of a "P2221 1X/10X" passive probe. The probes we have in the 321 laboratory are instead "P3010 10X" (fixed 10X attenuation). Pay attention to how this affects what you see when doing the Trigger Control section of the tutorial.

5 Additional Exercises

The following exercises will help you understand the scope better and give you practice making measurements. As you go through the steps, briefly describe your observations in your lab notebook. Include a few rough sketches of relevant waveforms and circuits where appropriate. As with the tutorial, alternate first-tries with your lab partner so that you each get experience using the scope's capabilities.

As instructed in the tutorial, you can always use "Default Setup", but this clears whatever prior work you may have done to the scope's adjustments. Note that "Default Setup" assumes the scope will be used with a probe, so it enables the "10X" probe attenuation correction setting in the channel menus by default. You need to change this setting to "1X" when you use a scope channel without a probe, otherwise the display will indicate $10\times$ the actual value of the input voltage.

The amplitude displayed on the function generator's screen may not be its actual output voltage. The generator output has $50\,\Omega$ is series internal to the device (to match $50\,\Omega$ coaxial cable transmission lines when working at high frequency). The "impedance" setting in the generator's display menu can be adjusted to compensate for the voltage divider created when the generator is connected to a low impedance circuit. This is for user convenience only. Generally, you should use "high impedance" for this setting and measure the generator's output voltage directly.

1. Using the function generator, produce a sine wave with a frequency 200 Hz and connect it to Channel 1 (CH 1) of the scope. Remember to enable the generator output using the yellow "On/Off" switch. Vary the generator's output amplitude and observe how this appears on the scope's display.
   (a) Set the time base control to 2 ms/division. Using CH 1 as the trigger, create a stable display. Play with the level and slope trigger controls like you did in the tutorial and observe how it differs from triggering using the scope's built-in square wave probe calibrator.
   (b) Investigate the channel coupling setting (AC, DC, or GND): Change the input coupling setting to GND. The signal seems to disappear because GND coupling disconnects the center conductor from the source, which can be useful to identify the ground reference. Adjust the DC offset of the function generator to produce a sine wave that is offset from zero by some amount. Now alternate between AC and DC input coupling. Do you understand what you see in each case?
2. Zero the DC offset in the function generator output and connect the 6.3 V transformer to CH 2 using one of the yellow and black connectors.

   WARNING: Do not use the 6.3 V transformer with the cover removed! There are "live" 120 V AC terminals inside when it is plugged into an outlet. **NEVER** touch exposed 120 V AC connections in **ANY** circuit!

   You now have two independent signals. Practice toggling the display for CH 1 alone, CH 2 alone, and both channels simultaneously. Change the trigger source (CH 1, CH 2, and AC LINE) to make each channel stable in turn. Why is only one channel stable at a time? Why is the transformer waveform stable with the AC LINE trigger source but not the function generator signal?
3. Set up measurements of the AMPLITUDE and RMS AMPLITUDE for each channel using the scope's menus. Do these have their expected values? The scope can display four

measurements. Remove AMPLITUDE and add FREQUENCY for each channel.

4. The impedance of the scope's inputs is $1\,\text{M}\Omega$, rather low for making non-interfering measurements at arbitrary points in a circuit. When you attach a 10X scope probe, the input impedance increases to $10\,\text{M}\Omega$. In this exercise you will observe the impact of the probe's finite impedance by building a divide-by-two divider circuit using two ECL adjustable resistor boxes like you studied in *Lab 1: DC Instruments and Measurements*. Unlike Lab 1, use the function generator as the voltage source. Use a BNC "tee" adapter to make a parallel connection from the function generator to the resistor network. You will need to add a BNC-to-banana adapter on one branch of the BNC tee to connect patch cables from the generator to the resistor network. Use the other branch of the tee to maintain a coaxial connection from the generator to the scope. Connect a probe to CH 3 on the scope and attach the probe tip to the midpoint between the resistors to measure the divider output. Use a banana plug post with small tab to make a secure connection between the tip and the resistor box terminal. The scope automatically detects that the probe is connected (via the wire sticking out of the end of the BNC connector) and turns on the "10X" attenuation correction for CH 3 (if not already set). This setting will return to its previous value when the probe is removed.
5. With the function generator set to $1\,\text{kHz}$ and $10\,\text{V}$ peak-to-peak, measure the input voltage and the divider voltage for resistor settings of $100\,\text{k}\Omega$, $1\,\text{M}\Omega$, $5\,\text{M}\Omega$, and $10\,\text{M}\Omega$ You are likely to notice that the probe waveform has a low frequency modulation when R is large. This is 60 Hz pickup from the 120 V AC line. Ask your instructor to show you how to reduce the modulation and explain why it is there. Tabulate and plot your voltage divider measurements. Considering your work in Lab 1, are your measurements consistent with the scope-probe having a finite input impedance of around $10\,\text{M}\Omega$? Remember, the scope functions as a voltmeter that has finite impedance.
6. Set the resistors to $10\,\text{M}\Omega$. Note that there is a substantial phase shift in the two waveforms, with the signal at the divider midpoint delayed relative to the function generator. Use the scope's cursors to measure the time delay between the maximum amplitudes of the two waveforms and convert the delay to phase shift, ϕ, in degrees or radians. Remember, there are 360° or 2π radians in one period, $T = 1/f = 2\pi/\omega$. You can also measure the time delay by placing the cursors at the zero-crossings of the two waveforms, which is usually more precise if you make sure the ground references are on a major division of the screen grid. The cause of this delay is small "stray" capacitance of order $\sim 10\,\text{pF}$ that is unavoidable in any real component like the resistor boxes. The stray capacitance, C_s, combines with the box's large resistance, R, to create a filter with corner frequency $\omega_c = 1/RC_s$. The phase shift associated with the filter is $\phi = \tan^{-1}(-\omega/\omega_c) = \tan^{-1}(-2\pi f RC_s)$. Estimate C_s using your measured phase shift.
7. A useful capability of the scope not described in the Tektronix tutorial is "X-Y" measurements, where the vertical and horizontal position of the pseudo electron beam is controlled by two input signals. (Normally the horizontal sweep is time-based via a clock in the scope.) This exercise will demonstrate X-Y measurement capability by creating Lissajous figures (Fig. 2). This is a useful way to measure the ratio of frequencies in two AC signals.
   (a) Input the function generator and the 6.3 V transformer (using one of the yellow and black connectors) signals in scope channels 1 and 2. Set the function generator to make a 60.0 Hz sine wave with 10.0 V peak-to-peak amplitude. Press "Autoset" and let the scope choose appropriate vertical scales for the two signals. Do the vertical scales chosen by the scope make sense to you? Watch the display carefully for several seconds and keep in mind the behavior of the two waveforms as you complete the steps below.
   (b) To enable X-Y mode, press "Acquire" in the horizontal control area of the scope's front

panel. This will bring up a menu that includes "XY Display" as an option. Press this option, then in the following menu select "Triggered XY". (The other option is normal time-based horizontal sweep.)

(c) The display will show a square measurement region. You should see a pattern that slowly oscillates between circular and linear shapes. You may need to use the ground reference controls to center the pattern on the primary crosshairs, like shown in Fig. 2. This is the fundamental Lissajous figure in which the two signals have nearly the same frequency. Keep in mind that the X (or Y) position is controlled by the transformer's wave and the Y (or X) position is controlled by the function generator's waveform. What would you expect to see if the two frequencies are exactly equal and in-phase? How about exactly 90° out-of-phase?

(d) To make the oscillation beat a little faster, change the function generator frequency to 60.1 Hz. Do you see why this method is effective for comparing the frequencies of two signals?

(e) Change the function generator to 120.0 Hz and observe how the pattern changes. Repeat this for multiples of 60.0 Hz, including fractions 20.0 Hz and 30.0 Hz. Each of these patterns is a distinct Lissajous figure that carries information about the relative frequency and amplitudes of the two signals. Increase and decrease the output voltage of the function generator and observe how the pattern changes. Make simple sketches with annotations in your lab notebook of several of the patterns you created.

(f) Change the function generator to arbitrary frequencies between 60-120 Hz to see what happens when the two signals have frequencies far from integer multiples.

(g) Explore using other types of waves that the function generator can make (square wave, triangle wave, etc.). They will be particularly instructive if you again use multiples of 60.0 Hz.

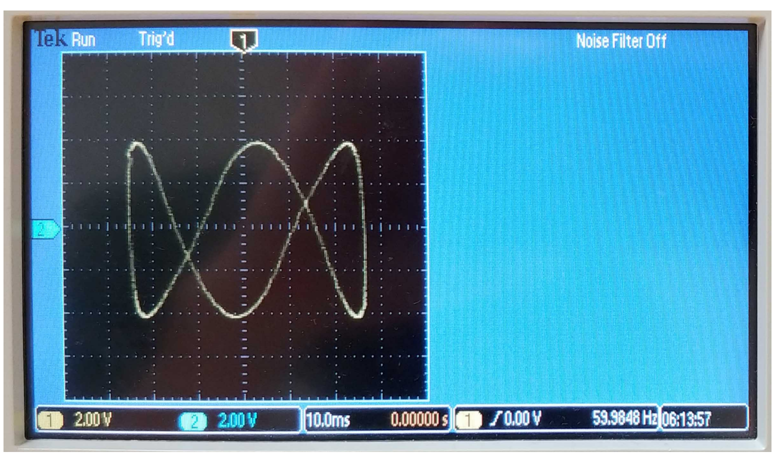

Figure 2: Example Lissajous figure using the oscilloscope's X-Y measurement mode