

An Introduction to AC Signals and Their Measurement

1 Objectives

1. To understand the basics of alternating currents in resistive circuits,
2. To learn the operation of a modern digital oscilloscope,
3. To learn to generate AC voltages with a modern digital function generator, and
4. To measure AC voltages, and the amplitude and frequency of a waveform with an oscilloscope and multimeter.

2 Introduction

To date, we have looked at the behavior of constant voltage sources in purely resistive circuits: Ohm's Law, equivalent resistance, and Kirchoff's rules. Of course constant voltages drive constant currents, and these types of systems are known as *Direct Current* or DC systems. DC systems aren't very interesting: you can't do much more than deliver power with DC. You certainly can't do the types of things we really *want* electrical circuits to do, like sample the world, manipulate information, play video games, etc.

Circuits with changing voltages are called generically *Alternating Current*, or AC systems. DC signals are characterized by a single number: the voltage above the ground reference (aka "the voltage"). AC signals, however, don't have this property; they can be literally *anything*. Throughout the rest of the semester, we will spend most of our time studying a particular type of AC signal, the sinusoid or sine wave signal, which isn't quite so wild and unconstrained. We'll do this because of Fourier's Theorem, which tells us that any periodic signal can be decomposed into a sum of sinusoids. Understanding the behavior of pure sinusoids allows us to understand the behavior of significantly more complicated signals with relative ease.

To probe and understand AC signals, we require new tools and techniques beyond DC power supplies and multimeters. There are many tools and devices to generate AC signals, but all of them can be considered as new types of power supplies. In this course, we will be using a fairly simple type called a *function* or *signal generator*.

Similarly, there are many, many different types tools to measure AC signals. We will use two of the most generically useful devices: our trusty multimeters, and a specialized form of voltmeter called an *oscilloscope*. Although we will use them extensively, the multimeter is rather a limited tool for AC measurements: it measures moments of the signal (also known

as descriptive statistics; think “averages”), not the global structure or details of the signal. If you don’t already know what the signal looks like, the measurements out of the multimeter aren’t going to tell you anything useful. That said, if you *do* know what the signal looks like, there are few general purpose tools that will give you more accurate measurements than a good benchtop digital multimeter. In particular, we will be using the multimeter to measure the *frequency* of periodic signals (sinusoids, square waves, etc), as well as the *RMS voltage* or *RMS current* of the signal. The latter is the “root mean square” of the signal: take the signal, *square* it so that it is always positive, take the average or *mean* of that new signal, then take the square *root* of the result. For periodic signals whose averages are zero, the RMS gives a meaningful measurement of the size of the waveform. For a sinusoid in particular, the RMS voltage is $1/\sqrt{2}$ smaller than the amplitude, which itself is half the peak-to-peak voltage (the difference between the maximum and minimum voltage):

$$V_{\text{RMS}} = \frac{1}{\sqrt{2}} V_{\text{amp}} \qquad V_{\text{amp}} = V_{\text{pp}} .$$

From an operating perspective, you should think of oscilloscopes as nothing more than really fancy voltmeters: if you already know how to measure signals with a multimeter, you connect an oscilloscope to the circuit in the same way. On the other hand, oscilloscopes can give you a detailed, visual picture of the entire profile of the signal, not just moment information. Where the multimeter can measure with fantastic accuracy *if* you know the form of the signal, the oscilloscope is the tool that *tells* you what that form is. Inside the shell, a modern digital oscilloscope is usually nothing more than a commodity personal computer with specialized electronic measurement peripherals, a specialized interface, and specialized software to simultaneously measure and display dozens of parameters of the input signals. We’ll touch on a number of those measurements in this lab.

There is another key difference between a multimeter and an oscilloscope that bears mentioning here. Multimeters usually can only measure one signal at a time, while oscilloscopes usually have more (ours can measure four). On the other hand, multimeters have *floating* inputs; that is, they directly measure the voltage difference between the two inputs, which can be connected to *any* two points in the circuit. Oscilloscopes have non-floating inputs: the *reference* or *ground* sides of each channel are tied together, and are tied to the *chassis ground* (also known as *earth ground* or *safety ground*) of the device, which is always connected to the ground lead on the power cord. The grounds of all channels have to be connected to the same point in the circuit, and you are usually forced to make that point the same as the ground terminal of the power supply. To measure the voltage between two arbitrary points using an oscilloscope requires simultaneous measurements on two channels, and a subtraction operation. We’ll show you how to do this later on in this lab.

We will only just barely scratch the outer surface of what these devices can do in this lab; I urge you to read through some of the overviews and tutorials linked in Section 4 before coming to lab, and to keep them handy throughout the rest of the semester.

3 Procedures

In this lab, you will use some equipment you are already familiar with (the Agilent U3401A multimeter) in unfamiliar ways, and some new equipment (the Teledyne Lecroy WaveAce

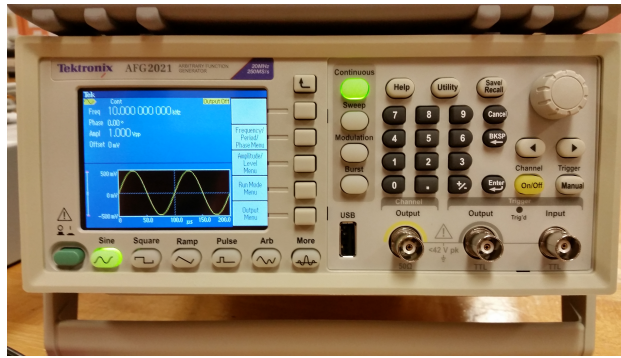


Figure 1: The front panel of the AFG2021 Function Generator.



Figure 2: The front panel of the WaveAce 2014 Digital Oscilloscope.

2014 Digital Oscilloscope and the Tektronix AFG2021 Function Generator). You will also need a resistance board, some BNC-to-banana plug adapters, and the standard banana plug cables.

Remember that the goal of this lab is to learn to use the equipment with proficiency, not to test any hypothesis. While this equipment is relatively simple for modern equipment, these devices are packed with dozens of features, most of which you will never need to use in this course. You would do yourself a favor, and really *read* the documents linked in Section 4. Also, the manuals for the oscilloscopes are available from the CLTs; please request to borrow them if you think it will help. The manual is also linked in Section 4.

3.1 Measure the Resistors

1. Let's start by choosing two resistors on your board, and measuring and recording their resistances with the multimeter.

3.2 Prepare the Function Generator

1. Next, we'll set up the AFG2021 (see Figure 1):
 - (a) Turn on the power by pressing the **[On]** button. Because the AFG2021 is microprocessor controlled, it needs to boot up and run a series of self tests and calibrations. Be patient; it only takes a few seconds.

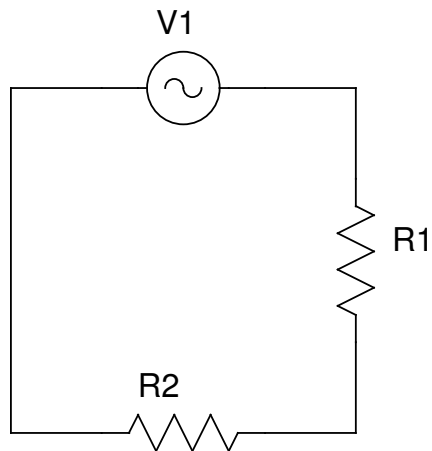


Figure 3: The circuit used for this training exercise. V1 is the function generator (a *voltage* source), while R1 and R2 are resistors. Do not build this circuit until instructed to do so by the instructions!

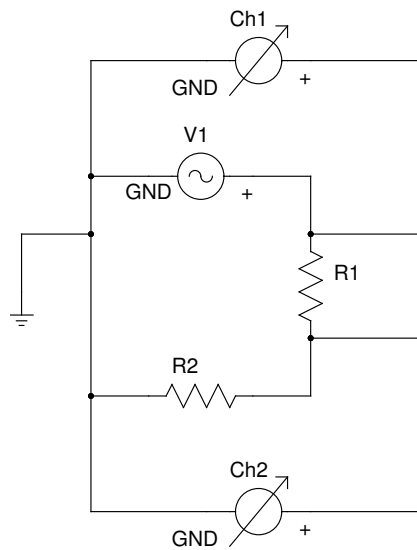


Figure 4: How to measure the voltage across a device with an oscilloscope; see the text in Section 3.4.

- (b) Press the **Sine** button to select a sinusoidal voltage profile, then press **Continuous** to ensure a continuous, non-triggered output waveform.
- (c) Next we have to set the frequency of the generated function; you will need to use the softkeys to the right of the screen, and the keypad. Select the **Frequency,Period,Phase Menu** **Frequency**, enter a frequency on the keypad, and then press the appropriate Unit softkey. For example, to set 9 kHz, press **9** then the **kHz** softkey. For this lab, select a value between 5 kHz and 10 kHz. To return to the main softkeys menu, you need to press the **↑** key to back out one level.
- (d) Since we don't want a signal that is either too big or too small in amplitude, we have to set the amplitude of the signal. Again, we go through the softkeys: select **Amplitude,Level Menu** **Amplitude**, enter a value on the keypad, and select the **Vpp** softkey. For this lab, you should enter $2V_{pp}$; no more, no less please. Again, you will need to press the **↑** key to back out to the main menu.
- (e) Wire the circuit shown in Figure 3. Make sure you connect the circuit to the leftmost Channel connector, not the Trigger Output connector in the middle. If you do, you are going to be very confused as to what is going on . . . You will need to connect a “BNC-to-banana” adapter to the Channel output.
- (f) Now that the circuit and function generator are set up, you need to turn the Channel Output on, or you won't measure any signal. Press the **Channel On/Off** to enable the output; when the button is lit, the output should be enabled.

3.3 Measurements with the Multimeter

1. Power on the multimeter, and set it to measure AC Voltage by pressing the **ACV** button.
2. With an oscillating voltage, of course, there is no sensible “sign” of the voltage - it switches polarity every half cycle. So it doesn't matter which input goes on which side of the device or voltage source.
3. Measure and record the AC Voltage drop across the function generator, and both resistors. Is Kirchoff's Loop rule satisfied here?
4. Compare the multimeter measured voltage (RMS!) across the function generator to the voltage you set (peak-to-peak!). How do they compare?
5. Next, set the multimeter to measure the frequency of the signal by pressing the **Freq** button. Notice that the device screen displays two outputs: the frequency on the main portion of the display, and the voltage in the upper right. Measure as if you were using a multimeter. How many places do you need to measure the frequency? How does the measured frequency compare to the frequency you set on the function generator in the previous section?

3.4 Measurements with the Oscilloscope

As we mentioned before, digital oscilloscopes are both fancy voltmeters, and powerful data processing computers. We'll exercise some of the feature of the “scope” in this section.

1. Let's start with something simple: connect the "GND" (black) side of the output adapter on the function generator to the "GND" side of the oscilloscope's Channel 1 input; see Figure 2.
2. Press the "magical" **AUTO** button. You will hear a number of relays clicking and popping inside the device. When that all stops, you should see a number of cycles of a sinusoidal waveform on the display.
3. Play with the knobs! Start with the **Horizontal** knobs on the upper right. The larger knob affects the "time per division" or the horizontal timescale, while the smaller knob moves the trigger point (and hence the waveforms) left and right on the screen. There are independent **Vertical** knobs for each channel. Again, the larger knob affects the "volts per division" or the vertical timescale, while the smaller knob moves the "ground reference" or "baseline" up and down on the screen. The smaller knobs are continuously variable, while you should feel the detents for the larger knobs. Each "click" of the large knobs changes a horizontal or vertical scale factor, and there is a corresponding scale displayed on the display; find those scale factors, and understand how they relate to changes in the knobs.
4. Now we want to measure something, and there are a number of ways to do that. First, let's use the "measurement" features of the scope. In the **Menu Control** block in the upper half of the controls, press the **Measure** button. A vertical menu will appear on the right side of the display next to the softkeys. You can set up a number of automatic measurements that will be done continuously on a given channel. Play with the options in the menu, until you are simultaneously measuring peak-to-peak voltage, frequency, and period for Channel 1. How do these compare to the output settings on the function generator? To the measurements you made with the multimeter?
5. Let's use the second measurement method built into the scope: cursors. The cursor feature allows you to mark a pair of features on the screen, and measure the horizontal (time) or vertical (voltage) difference between them. This is most useful for non-sinusoidal features, but we'll continue to use the sine wave for pedagogical reasons.
6. Finally, the third measurement method is built into the operator: the Mark I Eyeball. You can make quick measurements in the vertical and horizontal directions by counting the number of grid marks between the features of interest, and multiplying by the scale factor displayed on screen. Try now to measure the period and peak-to-peak voltage "by eye".
7. As we mentioned before, unlike the "floating" inputs of the multimeter (which can directly measure the voltage difference between any two points in the circuit), the inputs on the oscilloscope are tied to each other and to the "earth" or power system ground, so they can't directly measure the voltage difference between any two arbitrary points. What they measure is the difference between the ground reference and any other point in the circuit. It *is* possible to measure the voltage between any two arbitrary points, by using two channels and *subtracting* the measured signals at those

two points.¹ We'll measure the voltage across the two resistors using two reference points. Connect Channels 1 and 2 as shown in Figure 4, and turn on Channel 2 by pressing the **CH 2** button above the second input; it should light up, and a second trace should appear on the display. To measure the voltage profile across Resistor 1, we need to subtract the two measured voltages, since neither end of Resistor 1 is at ground potential. Press the **Math** button, just below and between the large knobs for Channels 2 and 3. Using the softkeys to the right of the display, choose the **Operation** to be **A - B**, set **Source A** to Channel 1, and **Source B** to Channel 2.

8. Using the **Measure** or **Cursors** menus, you can measure the **Math** trace for peak-to-peak voltage, or frequency, etc. Do so now.

Our oscilloscopes are capable of much more than we have covered here; we'll introduce some additional features in the future as we need them.

4 References

In the electronic PDF version of this document, the following list of references links to the online version of the resource:

- The Sparkfun tutorial *How to Use an Oscilloscope*
- Tektronix' *The XYZ's of Oscilloscopes*
- The Teledyne LeCroy *WaveAce 1000/2000 Operator's Manual*
- Teledyne LeCroy Tutorials for the WaveAce Oscilloscopes

¹There is one complication that we won't have to worry about in these labs: signal time delays in the cables connecting the circuit to the oscilloscope. Our signals are slow enough that this isn't going to be a problem, but can be with much higher frequency signals.

Post-Lab Exercises

Unusually, there are no post lab exercises for this lab. Enjoy your spring break!