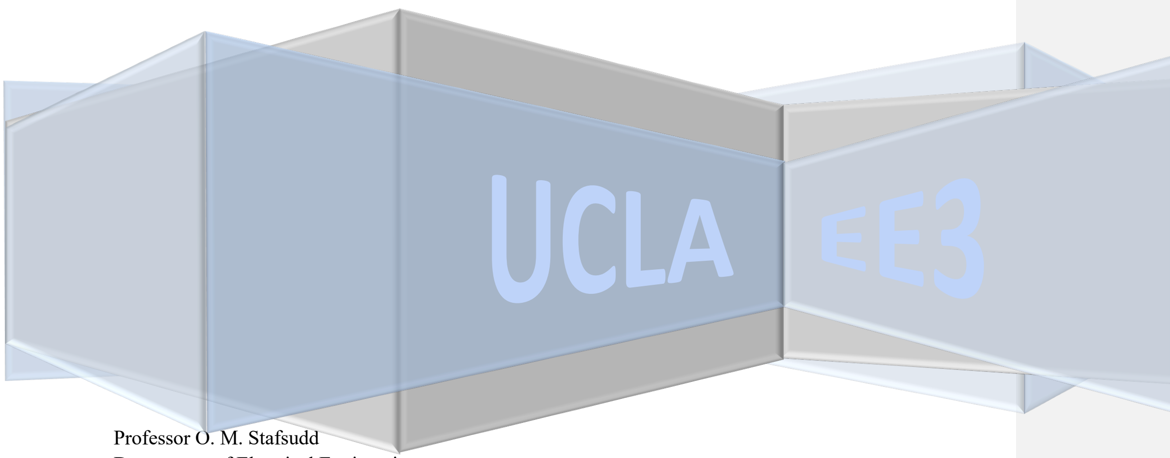
EE3 Introduction to Electrical Engineering

LABORATORY MANUAL



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Department of Electrical Engineering
October 2013
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Rev. October 2019 (version 1.10; Dr. Dennis M. Briggs)
Rev. September 2020 (version 1.11; Dr. Dennis M. Briggs)

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Dr. Michael Briggs is thanked for his generous insight into the changes that needed to be made to improve the program based on his experience with the previous EE3.

Previous students of EE3 gave us many suggestions that we have attempted to include in the re-design of this important "Introduction to Electrical Engineering."

Finally, I thank the Elenco Corporation for the generous use of their copyrighted materials.

-Prof Oscar Stafsudd, 2012

Student Albert Liu contributed much to Version 1.9, both in providing constructive ideas and in seeing that the changes were implemented.

-Dr. Michael Briggs, 2015

TA Xin Li has contributed much to Version 1.10.1, especially in Lab Experiments 2 and 3.

-Dr. Michael Briggs, 2019

Student Arhison Bharathan contributed much to Version 1.11.

-Dr. Michael Briggs, 2020

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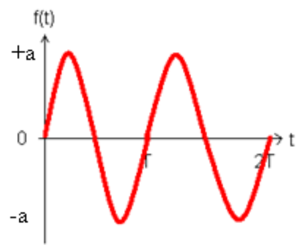
Week 2: Oscilloscopes and Function Generators

RMS of a periodic signal is calculated by first squaring the waveform, then taking its mean over its period, T, then taking the square root. Its definition using the calculus is

$$\text{RMS} = \sqrt{\frac{1}{T}\int_0^T f^2(t)\,dt}$$

As an example, we will derive the equation for RMS/Vpp for a sine wave. You will be asked to derive the equation for square waves and triangular waves in the pre-lab.



First, $f(t) = a\sin\left(\frac{2\pi t}{T}\right) \rightarrow RMS = \sqrt{\frac{1}{T}\int_0^T \mathrm{a}^2 \sin^2\left(\frac{2\pi t}{T}\right) dt}$

Using the definition of $\sin^2(\theta) = \frac{1-\cos(2\theta)}{2}$, $RMS = \sqrt{\frac{a^2}{T}\int_0^T \frac{1-\cos\left(\frac{4\pi t}{T}\right)}{2} dt}$

Taking the integral, $RMS = \sqrt{\frac{a^2}{T}\left[\frac{1}{2}t - \frac{\frac{1}{2}\mathrm{T}}{4\pi}\sin\left(\frac{4\pi t}{T}\right)\right]_0^T}$

Evaluating, we get $RMS = \sqrt{\frac{a^2}{T}\left[\frac{1}{2}T\right]}$ (Note that at t = 0 and T, $\sin\left(\frac{4\pi t}{T}\right) = 0$)

Therefore, $RMS = \frac{a}{\sqrt{2}}$, and since $Vpp = 2a$, then $\frac{\boldsymbol{RMS}}{\boldsymbol{Vpp}} = \frac{\mathbf{1}}{\mathbf{2\sqrt{2}}}$

It may for the purposes of your lab helpful to think of RMS in terms of Vpp, like so:

$$RMS = \frac{Vpp}{2\sqrt{2}}$$

Week 2 Prelab

Calculate the ratio RMS/Vpp for the following signals. Show all your work!

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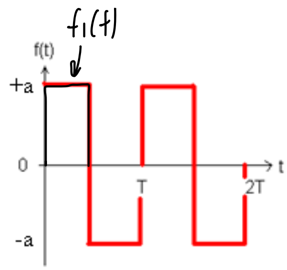
1. Square Wave: RMS / Vpp = ?

$$RMS = \sqrt{\frac{1}{T}\int_0^T f^2(t)\,dt}$$



$$f(t) = \begin{cases} a, & 0 \le t < \frac{T}{2} \\ -a, & \frac{T}{2} \le t < T \end{cases}$$

$$RMS = \sqrt{\frac{1}{T}\left[\int_0^{T/2} a^2\,dt + \int_{T/2}^{T} a^2\,dt\right]}$$

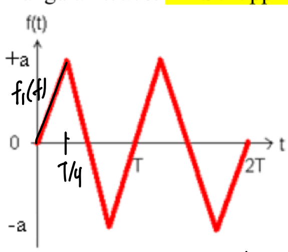
$$= \sqrt{\frac{1}{T}\left[a^2(T/2) + a^2(T - T/2)\right]}$$

$$= \sqrt{\frac{1}{\cancel{T}}a^2\cancel{T}} = a$$

$RMS = a$ $\quad V_{pp} = 2a$

$$\frac{RMS}{V_{pp}} = \frac{1}{2}$$

2. Triangular Wave: RMS / Vpp = ?



$$\frac{rise}{run} = \frac{a}{T/4} = \frac{4a}{T}$$

find RMS for $f_1(t)$.

$$f_1(t) = \frac{4a}{T}t, \quad 0 \le t < \frac{T}{4}$$

$$RMS = \sqrt{\frac{1}{T/4}\int_0^{T/4}\left(\frac{4a}{T}t\right)^2 dt}$$

$$= \sqrt{\frac{4}{T}\cdot\frac{16a^2}{T^2}\left[\frac{t^3}{3}\Big|_0^{T/4}\right]}$$

$$= \sqrt{\frac{4}{\cancel{T}}\cdot\frac{16a^2}{\cancel{T^2}}\cdot\frac{\cancel{T^3}}{192}} = \sqrt{\frac{64}{192}a^2} = \frac{1}{\sqrt{3}}a$$

using symmetry, $\Rightarrow$ $RMS = \frac{1}{\sqrt{3}}a$ $\quad V_{pp} = 2a$ $\quad \frac{RMS}{V_{pp}} = \frac{1}{2\sqrt{3}}$

Vpp = peak-to-peak

For question 5, consider that you are using a laboratory oscilloscope and laboratory function generator. This questions is not applicable to the AD2 but answer it anyway).

3. If you see a difference by a factor of 10 between the oscilloscope reading and the function generator setting, where is the first place that you should look? Watch the Probe Setting video (https://youtu.be/dtSuTHIviSo) for the answer.

   Look at the channel's probe attenuation (device making the actual measurements, a wire). Press Probe and set it from 10:1 to 1:1.

4. If you see a difference by a factor of 2 between the oscilloscope reading and the function generator setting, where is the first place that you should look? Watch the Function Generator Output Impedance video (https://youtu.be/-8Dv1oOjD9w) for the answer.

   There is a gain of 2 difference from what you expect and what you are reading from the oscilloscope. Check output impedance, change what the oscilloscope thinks the load is.

5. Why would you ever want to use AC coupling on an oscilloscope? Watch the AC Coupling video (https://youtu.be/1q-RBjt2WRI) for the answer.

   You would want to use AC coupling if you want to see the noise of your DC value coming from the power supply, how the signal is not perfectly captured but fluctuates. You can only see it if you AC couple the signal so all of the DC is blocked, lowering the sensitivity.

6. Watch the 7-minute triggering video

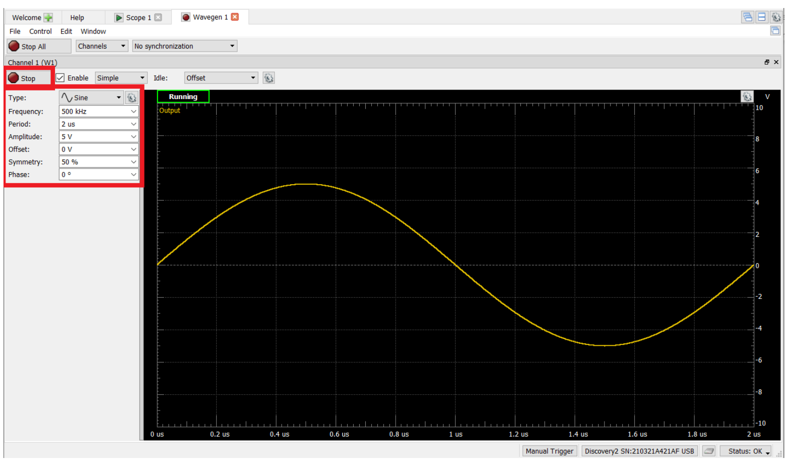
Week 2 Prelab End

Time Dependent Measurements

This week's experiments will give you the opportunity to learn the basic operations of an oscilloscope and a function generator.

Setting up the Oscilloscope and Function Generator

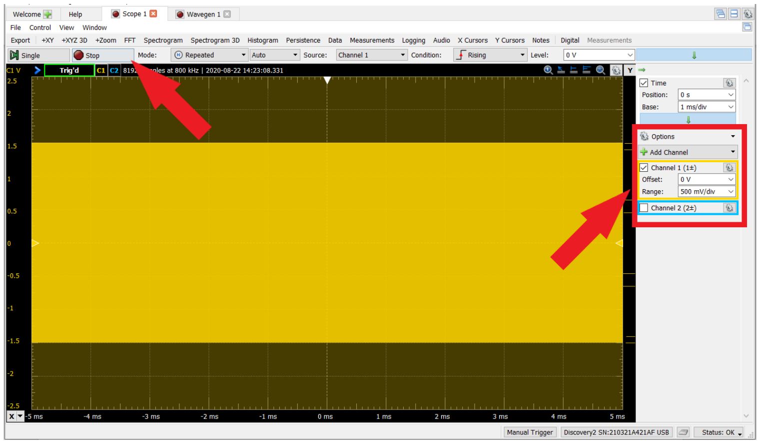
1. In the WaveForms software, start the Scope and Wavegen applications from the Welcome tab. These will be your oscilloscope and function generator respectively.
2. Using your breadboard, connect Function Generator Channel 1 (W1, solid yellow) to Oscilloscope Channel 1 (1+, solid orange). Then connect GND (solid black) to Oscilloscope Channel 1 (1−, Orange/White Stripe).
3. In the function generator, specify a Sine output at Channel 1. Set the frequency to 500 kHz and amplitude to 5 V and click Start.



Wavegen Tab / Function Generator (After Step 3)

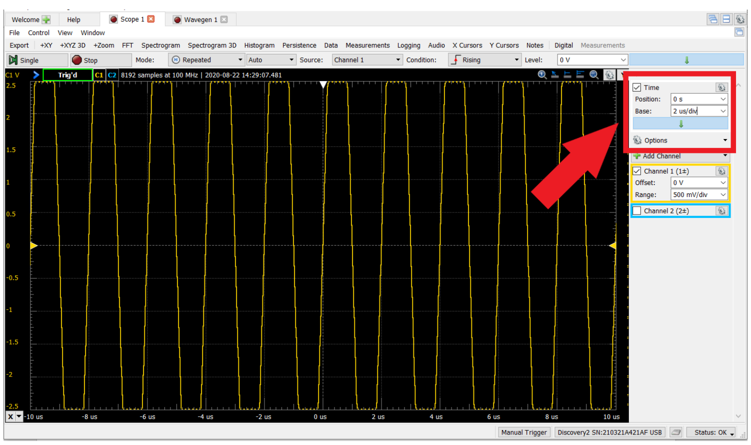
4. You will now learn to display the input signal to your oscilloscope using the three basic settings: Horizontal control, Vertical control, and Triggering.

5. In the Scope tab, enable *only* Channel 1 and click Start. You should see the following:



Horizontally and Vertically Incorrect Display (After Step 5)

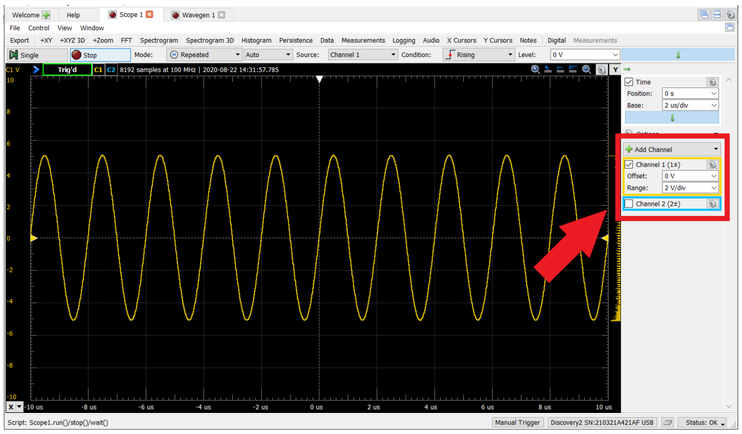
6. We will first adjust the Horizontal setting. Using the **Time** section on the right, change the Base to "2 us/div." You should see the following:



Horizontally Correct, Vertically Incorrect Display

Know that this setting can go by many names: Horizontal, Sweep, or Base. It is measured in seconds per division.

7. Now we will adjust the Vertical axis. Set the Range option on the right to "2 V/div." A sinusoid should now be visible on the display:



Horizontally and Vertically Correct

To check that the waveform we see makes sense, let's do two quick calculations.

a. On the horizontal axis, we see that 1 period of the Sine fits in 1 division. Given that our Horizontal setting is "2 us/div," we can easily find the signal's period:

$$1 \text{ period } \times \frac{1 \text{ division}}{1 \text{ period}} \times 2\ \mu\text{s/div} = 2\ \mu\text{s}$$

Taking the reciprocal of period to get frequency,

$$\frac{1}{2\ \mu\text{s}} = 500 \text{ kHz}$$

The oscilloscope shows a 500 kHz sine as expected.

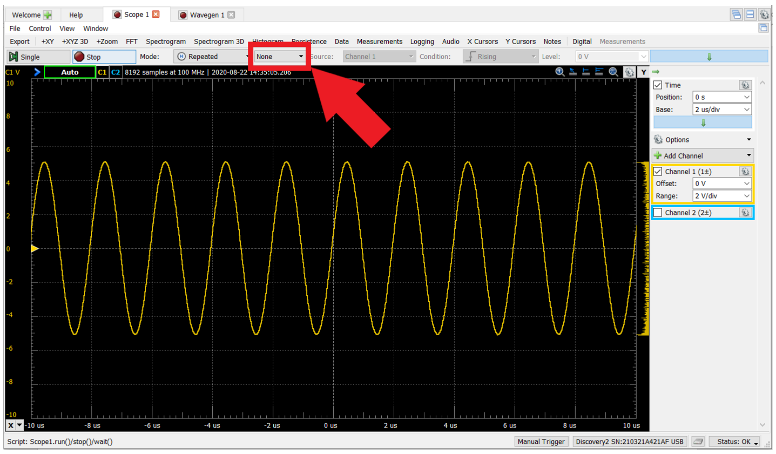
b. On the vertical axis, we see that the top of the Sine is 2.5 divisions above 0 V. Given our Vertical setting is "2 V/div," we can easily show:

$$2.5\ divisions\ \times 2\ V/div\ = 5 \text{ V}$$

The sine has an amplitude of 5 V as expected.

8. Finally, we cover triggering. If you have not already, watch the 7-minute triggering video. Up until now, the waveform has appeared correctly without adjusting the trigger settings.

This is because the AD2's triggering feature is automatically set. To demonstrate what happens when you trigger is set incorrectly, select triggering to be None:



You should see that the waveform appears jittery. You will understand why you'd expect this in the next section. Note that in this class, the Trigger will typically be set to Normal or Auto.

9. [BONUS FEATURE] Along with displaying a signal with respect to time, the AD2 oscilloscope (as with any modern oscilloscope) can perform a variety of measurements on the signal. For example, we can measure the RMS voltage of a waveform. To do this, select the Measurements option at the top of the oscilloscope window to bring up the Measurements window. From here click Add > Defined Measurement. In the window, pick Channel 1 on the left and add the DC RMS[1] measurement option from the Vertical dropdown menu. You can now view the DC RMS measurement in the Measurement window. Take note of all the other measurements you can make in both the Vertical and Horizontal sections.

[1] The AD2 oscilloscope can measure AC RMS as well. This operation simply removes the DC component of the signal before calculating the RMS voltage.

Understanding Triggering

If you have not done so already, watch the 7-minute triggering video.

As you saw, an oscilloscope uses triggering to determine where in the time domain to display a signal it sees at the input. By adjusting the trigger settings, a user can specify features of the input that the oscilloscope can trigger on. When the oscilloscope recognizes such a feature, it uses that feature's point in time to position the signal on the horizontal axis.

Setup:

Like the previous exercise, open the Waveforms software and select the Scope and Wavegen applications from the Welcome tab. To continue our investigation of triggering, you will connect Channel 1 of the oscilloscope to Channel 1 of the function generator. Also, connect Channel 2 of the oscilloscope to Channel 2 of the function generator.

Edge triggering is a common triggering method you will use on most oscilloscopes. Simply put, this method has the user set a Level for the signal to cross. When this cross occurs, the oscilloscope will use that moment to position to waveform. We will demonstrate this and its implications below:

1. Set the function generator to output a Sine at Channel 1 with frequency 1 kHz and amplitude 5 V. Use the oscilloscope to bring the signal into view.
2. The trigger has a few settings you can adjust. First, let's look at the Condition setting with the options Rising, Falling, or Either. These options describe what slope a signal must have when it crosses the Level to be considered a trigger event (by default the Level is set at 0 V). Set Position to 0 s and switch between Rising and Falling to get a feel for what Condition does:

Note: If you select Either, you will notice that the signal becomes erratic. This is because the Sine function triggers the oscilloscope at two different points in a single period under this setting. The signal will now jump between these positions when displayed.

3. Now we look at the trigger level. First, select Condition to be Rising. Using the Level option or the yellow arrow on the right edge of the oscilloscope screen, adjust the trigger level to be about 3 V. Now in the function generator, vary the amplitude of the Sine wave above and below the trigger level (you may find it helpful to put the Waveforms software in split screen using the button in the top right. The button left of the split screen one will take you back to normal view):

As you saw, reducing the amplitude below the trigger level causes the oscilloscope to lose the trigger (in the top-left, the readout no longer says Trig'd). While for this waveform we can easily correct the trigger settings for work at lower amplitudes, more complicated signals will require other methods to let the oscilloscope trigger correctly. We cover this next.

4. Since we know the frequency of the signal we'd like to view, we can generate another signal of the same frequency and trigger the oscilloscope off that. To demonstrate this, enable Channel 2 of the function generator (click on the Channels button; a pulldown menu appears) and have it output a Pulse at frequency 1 kHz with amplitude 5 V. Wavegen channels 1and 2 must be on the same tab Also, the Synchronized button next to the Channels button must be visible.

Creating a Pulse at Channel 2

Now, on the right of the oscilloscope, enable Channel 2 in the display and bring the signal into view. At the top, select the trigger Source to be Channel 2 and change the trigger level to be around 2.5 V:

Now, disable the Channel 2 view in the oscilloscope. Though you cannot see the waveform, the oscilloscope is still triggering on Channel 2. If you change the Sine's amplitude in

Channel 1, you will see that the oscilloscope stays triggered for all values (the top-left says Trig'd) unlike before.

Beginning the Experiment

Change the mode of the function generator from Sine to Triangle to Square. Note each of these waveforms. The actual voltage levels of a waveform can be measured by double-clicking in the waveform window and using the cursor (double-click again to turn this off). To measure the peak-to-peak voltage (Vpp), add the Peak2Peak measurement to the Measurements window as previously described for the RMS voltage measurement.

In this lab, you will be comparing RMS voltage measurements between the AD2's voltmeter and oscilloscope. Note that the behavior you observe here is analogous to the behavior you would observe between a laboratory DMM[2] and oscilloscope.

Take the following measurements for each frequency and waveform type. Use Vpp = 5 V for all functions (NOTE: You are not setting 5 V as the amplitude!). You may use either triggering method covered thus far. (One way is easier than the other!)

$V_{pp} = 5$

WORK SHEET HERE (100 Hz)				
Ⓐ Waveform (100Hz)	Ⓑ Theoretical Caculation (V_{rms})	© AD2 Scope Measurement (V_{rms})	Ⓓ AD2 Voltmeter Measurement (V_{rms})	Difference (%) $\frac{(Ⓓ - ©)*100}{©}$
Sine	1.768 V	1.768 V	1.768 V	0
Triangle	1.443 V	1.442 V	1.444 V	.139
Square	2.5 V	2.4993 V	2.498 V	.772

² The DMM (Voltmeter in the Welcome screen) reports TRUE RMS and AC RMS. TRUE RMS is equivalent to DC RMS as described in the oscilloscope bonus.

WORK SHEET HERE (1 KHz)				
ⒶWaveform (1KHz)	ⒷTheoretical Caculation (V_{rms})	© AD2 Scope Measurement (V_{rms})	Ⓓ AD2 Voltmeter Measurement (V_{rms})	Difference (%) $\frac{(Ⓓ-©)*100}{©}$
Sine	1.760V	1.7585V	1.728V	1.734
Triangle	1.443V	1.4347V	1.406V	2.000
Square	2.5V	2.5001V	2.292V	8.543

WORK SHEET HERE (25 KHz)				
ⒶWaveform (25KHz)	ⒷTheoretical Calculation (V_{rms})	© AD2 Scope Measurement (V_{rms})	Ⓓ AD2 Voltmeter Measurement (V_{rms})	Difference (%) $\frac{(Ⓓ-©)*100}{©}$
Sine	1.760V	1.8020V	32mV	98.22
Triangle	1.443V	1.4743V	26mV	98.24
Square	2.5V	2.5293V	42mV	98.33

What's your observation regarding the voltmeter/DMM reading's accuracy over different frequencies within the same waveform? Can you guess why that's the case?

ANSWER HERE:

The difference between the AD2 scope measurement and the AD2 voltmeter measurement is larger for significantly higher frequencies (25KHz). The voltmeter can only measure RMS from 4Hz to 2.048 KHz, so it cuts off for higher frequencies.

Does the voltmeter/DMM perform poorer when measuring square or triangular waves over sine waves? Can you guess why that's the case?

ANSWER HERE:

The voltmeter's performance is noticeably worse for square waves and slightly worse for triangular waves over sine waves. This is probably because of the large jumps in voltage over a short period of time. In an ideal graph, these jumps are instantaneous, but they are impossible for the voltmeter to measure. The jumps thus produce some inaccuracy.

Take these questions as a cautionary exercise in knowing what limits your measuring devices have. Here you've seen that DMMs are not suited for use at high frequencies!

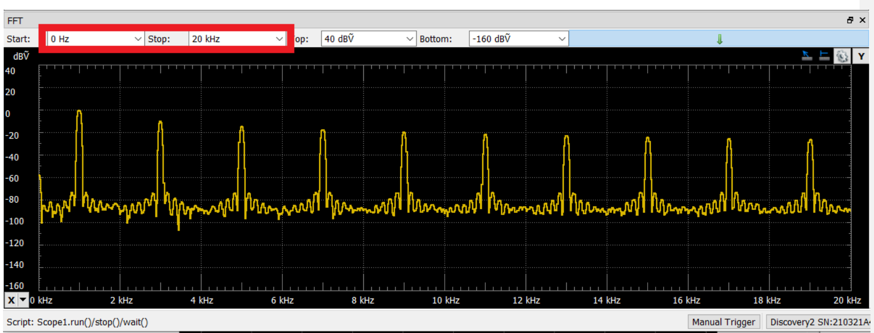
Spectrum Analyzer – Knowing how your input signals are constructed

In this part of the lab you'll be learning how to display and analyze your input signal in the frequency domain, as well as learning how other types of periodic signals (e.g. square waves) are formed from sinusoids with different frequencies.

Setting up your Oscilloscope for Spectrum Analyzing

1. Start the Scope and Wavegen applications as done previously. For this section, only connect Channel 1 of the oscilloscope and function generator.
2. Set the function generator to output a Square wave at frequency 1 kHz and amplitude 1 V. Bring the signal into view in the oscilloscope.
3. At the top of the oscilloscope view, choose the FFT option (Fast-Fourier Transform, a mathematical transform that takes a signal from time domain to frequency domain, more details can be found in course ECE 102 and 113). After choosing this option, you should see something similar to:

4. Adjust the FFT view to Start at 0 Hz and Stop at 20 kHz. Doing this correctly, you will see a representative view of the square wave's spectrum. If you do not see a spectrum as detailed as what is shown, increase the Time Base.



The nature of square waves – Limits in measuring systems

Square wave response requires a higher frequency response from the measuring system than sinusoidal waves. As you can see in the spectrum analyzer experiment, square waves can be thought of as being formed from a fundamental sinusoidal wave whose period is the same as the square wave plus higher frequency components (all odd integer multiples, or harmonics, of the fundamental frequency) to make up the sharp rise and flat top associated with the square wave.

Therefore, as your measuring system goes to its high frequency limit, the sharp rise and fall of the square wave will be lost due to the lack of these higher frequency components being accurately displayed. This is known as the Gibbs phenomenon, which you will have a chance to look at later.

A closer look at the spectrum of a square wave

In this part of the experiment we will be comparing the frequency components of a square wave to their amplitudes in theory. That is, only odd harmonics should appear (1 kHz, 3 kHz, 5 kHz, etc.) and the ratio of the various harmonic amplitudes to that of the fundamental should be 1/N where N is the harmonic (1: 1/3: 1/5: 1/7: … etc.)

Note: the spectrum analyzer displays the data in logarithmic manner, called dB (decibel) defined as a ratio of powers:

$$dB = 10 * log\left(\frac{Power_{test}}{Power_{reference}}\right) = 20 * log(\frac{V_{test}}{V_{reference}})$$

The logarithm display gives greater detail over a wide dynamic range and is therefore commonly used in engineering.

In the following experiment we will be taking the first harmonic (the first peak, AKA the *fundamental harmonic*) as the reference voltage and try to use the magnitude of the first 10 harmonics as the test voltages, in order to compare them with the first harmonic. (Think: first harmonic is at the first peak; is it also true that second harmonic is where the second peak is?). You can use the cursor functionality in the oscilloscope to help you read the difference in dB scale between the first peak and every other peak.

1. Double-click in the FFT window to bring up the measurement cursor.
2. Single-click the fundamental peak to set the first measurement position.
3. Place the cursor over each proceeding peak to measure the change (Δ) in dB.

WORK SHEET HERE (SQUARE WAVE ANALYSIS)		
N^{th} Harmonic	Measured value in dB: $20 * log\left(\frac{V_{Nth\ harm.}}{V_{1st\ harm.}}\right)$	Theoretical value in dB: • $20 * log\ (1/n)$, n=odd; • $-\infty$, n=even.
1	0	0
2	-91.75137	$-\infty$
3	-9.55079	-9.542
4	-92.81111	$-\infty$
5	-13.98012	-13.979
6	-89.50152	$-\infty$
7	-16.91809	-16.902
8	-95.83341	$-\infty$
9	-18.69144	-19.085
10	-97.98786	$-\infty$

End of Lab 2.