# Signal Capture and Analysis

Introduction

The purpose of this lab is to capture waveforms with a digital oscilloscope and analyze the captured signals using numerical analysis software and spreadsheets.

You're already familiar with measurements of deterministic signals such as sine and square waves. However, some signals are unpredictable (random) and we cannot describe them as voltages or currents as functions of time. Typical examples include noise or speech waveforms.

However, we can describe their statistics, which are summaries of some relevant feature of the signal such as the fraction of time it has a certain voltage (the "probability density") or the amount of power the signal contains at certain frequencies (the "power spectrum").

In this lab we will study two deterministic and one random signal and measure some of their statistics including the probability density.

You will measure the statistics of the three waveforms that can be generated by the lab's waveform generator: a square wave, a sine wave, and Gaussian noise:
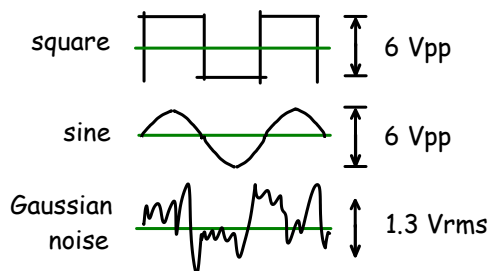
You will capture these waveforms with a digital oscilloscope. Then you will use Octave[1] to compute histograms that estimate the probability density functions of the waveforms. The histogram data will be imported into a spreadsheet that you will use to plot the histograms, compute the RMS powers from the probabilities and compare them to the powers measured using an RMS voltmeter and the oscilloscope's measurement function.

Software

Numerical Analysis Software

Numerical analysis software allows us to carry out a much wider range of analyses than can be done by an oscilloscope.

For this lab you will use Octave. Many other software packages, both commercial and open-source, are also available. Some of the most popular include Matlab (largely Octave-compatible), Mathematica, Maple, MathCAD, and R[2].

All of these programs have high-level language features such as support for working with complex vectors and matrices. These allow us to analyze signals using little or no programming.

Spreadsheets

You are probably already familiar with spreadsheets from previous courses. They are useful for manipulating and presenting limited amounts of data and for formatting numerical data for reports.

For this lab you can use Microsoft Excel or LibreOffice Calc.

CSV Files

Text files contain printable characters that form readable text. On the other hand, "binary" files contain data in formats that are only meant to be read and written by software.

A common text file format for exchanging numerical data between programs is called comma-separated values (CSV). Each line of the file corresponds to one row of a matrix or table and the values for each column are separated by commas.

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[1]You should also be able to use Matlab with some minor changes to the commands.

[2]See Wikipedia for a more complete list.
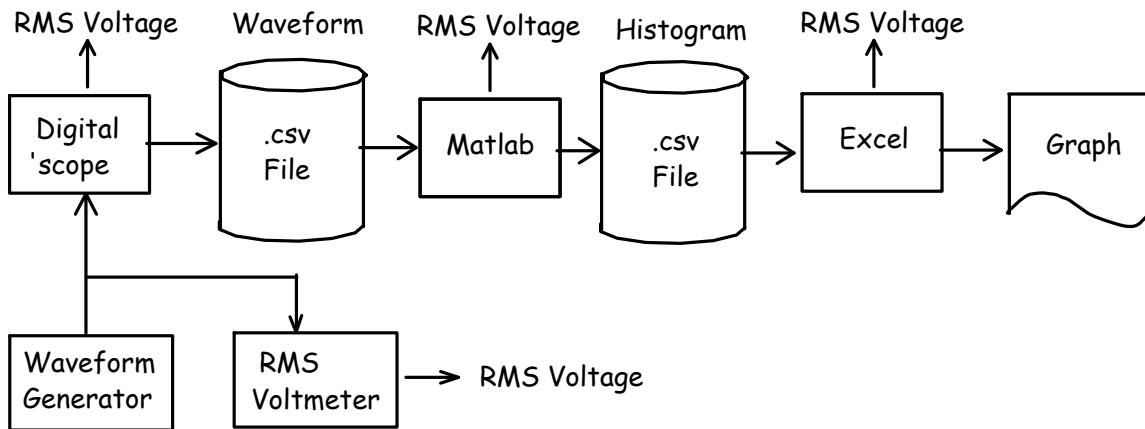
Here's an example of a CSV file with data that could be used to fill a table consisting of four columns and three rows:

```
2.6,2.6, 1.3, .006
9.7, 1.734e-2, 1.1, 3
-0.3, .87, 0.45, 22
```

Strings can also be included in CSV files by quoting them although in this lab we will restrict ourselves to CSV files with numerical values.

AC and DC Measurements

We sometimes wish to measure the constant and time-varying components of a signal separately. Often this is to allow measurement of time-varying signals superimposed on much larger constant voltages.

The constant voltage is the average or "DC" voltage. Most DMMs and 'scopes, have an "AC" (alternating current) setting that removes the DC component by connecting the input through a capacitor.

The voltage readings you obtain will therefore depend on the input coupling you use. With DC coupling the RMS voltage measured by a 'scope or DMM will be the sum of the AC (time-varying) and DC (constant) powers. But when set to AC coupling only the AC component will be measured.

Procedure

Waveform Capture

As shown below, connect the output of the waveform generator to both Channel 1 of the 'scope and the voltmeter so you can view the waveform and measure its voltage on the DMM simultaneously. The 'scope will sample the input signal and digitize it (convert it to a number). The RMS voltmeter will allow you to measure the RMS voltage independently of the 'scope.

Note that the multimeters in the lab are are RMS-responding. Some DMMs are average-responding and only measure the average value of a signal. For these DMMs the voltage reading only corresponds to the RMS voltage when the signal is a sine wave.

Set up the waveform generator for a square-wave output at a 1 kHz frequency with a 6 Vpp level and +1 V offset.

Set up the 'scope's channel 1 for DC coupling with the appropriate scale factor for your probe (typically 10X).

Use the 'scope's Measurement menu to add frequency and Vrms (RMS), Vavg (average) and Vamp (peak-to-peak amplitude) voltage measurements to the display. Don't use the "all measurements" feature – add specific measurements instead.

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Use the Acquire menu to set the memory Depth to 140 kSamples. Use the Scale control in the Horizontal controls section for a sampling rate of 1 MHz. These values will be visible in the status line at the top of the display.

Press the Horizontal scale knob to switch to delayed trigger mode. This will show a portion of the captured samples. Adjust the horizontal scale so you can view a few cycles of the square wave:
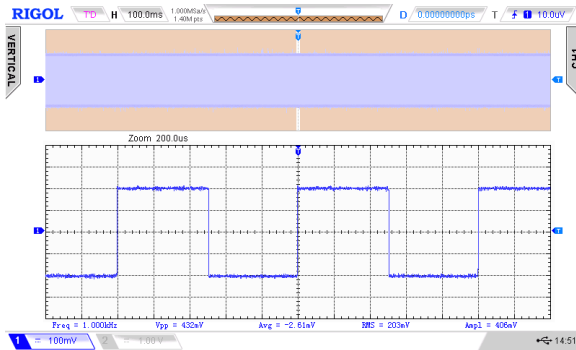
Use the DMM to measure the DC and AC voltage. They should match the values shown on the 'scope.

For practical reasons the measurements are made on the displayed waveform rather than all the stored samples. If the displayed waveform is not representative of the whole waveform then the measurement will not be either. To get an accurate measurement you should adjust the horizontal scale to obtain a representative waveform (e.g. an integral number of cycles of a periodic waveform or a large-enough number of samples of a random waveform). Also, note that reducing the sample rate so much that each time point contains multiple values will also give incorrect measurement values.

Plug a flash drive into the USB connector on the front of the 'scope. A USB icon (⟨USB⟩) should appear on the bottom right of the screen. Press the printer icon (⟨printer⟩) on the top right of the panel to capture an image of the display. The image file name will be displayed briefly.

Use the Storage menu to save the captured data to your flash drive. Under "Storage" select CSV for the file type, Channel 1 for the source, "Maximum" for the Data Depth and disable Parameter Save.

Press Save to select the folder (directory) and file name under which to save the file. If you wish, you can create a new folder on the flash drive and a new file name.

Record the date and time, the type of waveform, the voltage shown on the DMM, the three measurement values on the 'scope and the names of the image and waveform capture files. You will need this information for your report.

Change the signal generator to a sine-wave output, a (peak-to-peak) voltage of 6 V and zero DC offset.

Repeat the steps above, saving image and waveform capture files and recording the various instrument readings.

Now configure the waveform generator for (Gaussian) noise output with a level of 1.3 Vrms and zero offset. Again, save the image and waveform capture files to your flash drive and record the same information as before.

You should now have three sets of voltage readings, three display files and three waveform files.

The rest of the lab can be done without test equipment but you should try to do as much of it as possible during the lab session in case you need to repeat some of your measurements.

Import Samples into

Run Octave (GUI). Use the File Browser to change to the directory where you have copied the files for this lab (e.g. a folder on your flash drive or `H:` network drive).

Edit the file (e.g. using Notepad++ or Octave's file editor) and remove any header lines at the beginning of the file.

The CSV file saved by the 'scope should consist of rows with the sample number and the voltage as shown below:

```
0,-1.520000e+00,
1,-1.760000e+00,
2,-2.040000e+00,
3,-2.240000e+00,
```

You can read the waveform data from the CSV waveform sample file using the commands:

```
s=csvread('Newfile1.csv');
s=s(:,2);
```

which will read the CSV file and extract the second column (the sample values). You may have to prefix the file name with the drive letter and folder name.

Plot[3] the first 2000 samples of the waveform to make sure you captured and have read the waveform correctly:

```
plot(s(1:2000))
```

Use the Copy button or use the Windows 'Snipping' tool to save this plot to an image file (e.g. `.png` format) so that you can include it your report later.

Compute the mean and RMS values of the captured waveform and record the results for your report:

```
mean(s)
std(s)
```

Compute the Histogram

A histogram is a graph that shows on the y-axis the number of times the value on the x-axis appears in a set of values. For example a histogram of BCIT student ages would show the number of 18-year old students as the y-value for the x-value 18. If we scale the histogram values so that their sum is 1 then the histogram becomes an estimate of the probability density.

Histogram values represent counts so if the input variable is continuous we must assign the input values into discrete categories called "bins".

In our case the binning is done by the 'scope's 8-bit A/D converter which quantizes the input signal into $2^8 = 256$ discrete voltage levels.

The measured voltages can only have certain specific values separated by steps equal to the quantization step size. For example if the input voltage was 1.63 volts and the step size was 0.08 volts, the 'scope might measure this as 1.60 or 1.68 volts.

When computing the histogram of the signal we should use a bin width equal to the step size to make sure we include exactly one voltage range per bin.

We can find the step size by examining the voltage levels measured by the 'scope. The Matlab function `unique()` returns a sorted list of the unique values in the input. Assuming we have at least two values separated by the step size we can find the step size as the minimum difference between successive unique values:

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[3]The first plot could take a couple of minutes to be displayed. To avoid this delay first run the Octave command `graphics_toolkit('gnuplot')`.

```
ssize=min(diff(unique(s)))
```

where the sequence of unique, diff and min operations compute the minimum difference between successive unique measured voltages.

The step size can then be used to compute the number of histogram bins we should use:

```
nbin=(max(s)-min(s))/ssize + 1
```

Compute a histogram of the voltage waveform using the `hist()` function:

```
[n,v]=hist(s,nbin);
```

which will return a vector `n` with the number of samples values in each histogram bin and a vector `v` with the voltages at the midpoints of each bin.

We can then export the histogram to a CSV file by opening a file for writing:

```
fo=fopen('lab4square.csv','w')
```

and writing the values to the file as strings separated by commas, two per line:

```
fprintf(fo,'%f, %d\n',[v;n])
```

and closing the file:

```
fclose(fo)
```

Repeat for the sine wave and Gaussian noise capture files, saving them to different CSV files and recording your results for the mean and standard deviation (rms voltage). You can use the cursor keys and/or the command history window to repeat previous commands and minimize typing.

Compute RMS Voltage

The RMS (root mean square) voltage of a signal is defined as the square root of the mean (average) of the square of the voltage. In cases where different voltages have different probabilities we must scale each voltage (or its corresponding power) by the probability of that power and then compute the sum. For example, if 20% of the values had a power of 0.3W and 80% had a power of 0.2W then the average power would be $0.2 \times 0.3 + 0.8 \times 0.2 = 0.06 + 0.16 = 0.22$.

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We can use a spreadsheet to do this calculation on the histogram values stored in the CSV file.

Run Excel or LibreOffice Calc. Open the CSV file (File->Open) which will result in a spreadsheet with two columns, the first with the bin counts and the second with the bin voltages. *Note: Immediately save the file in `.xlsx` format or you will lose all your work when you exit the program!*

Enter a formula at the bottom of the first column to compute the total number of samples (this should be 140,000). Add additional cells with formulas that divide by this value to convert the bin counts to probabilities[4]. These should sum to 1. Then add additional cells that compute the square of each bin voltage multiplied by the probability of that voltage. Compute the sum of these scaled squared voltages. This is the mean square voltage. Finally, compute the square root of the mean square voltage. This is the RMS voltage of the waveform.

Here is an example showing the spreadsheet columns containing bin voltages, bin counts, bin probabilities and scaled squared voltages. The bottom row contains sums of the bin counts, probabilities, and the mean-square and RMS voltages.


Repeat using the histogram bin counts for the sine and Gaussian noise waveforms, importing their data into different sheets of the same document (Data->From Text/CSV or Import->Sheet from File). Compare your results to the values read from the 'scope and DMM.

Plot Histograms

Create three line graphs (charts) with curves showing the values of the three histograms. Use Insert->Chart, set the chart type to an XY Line graph and use the voltages as the X values and the histogram sample counts as the Y values. Add an accurate title, sub-title and X and Y axis labels. Adjust the chart properties so it is formatted as shown below:

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[4]To insert a reference to an absolute rather than relative cell, prefix the cell and/or row with a dollar sign ($). For example, A101.
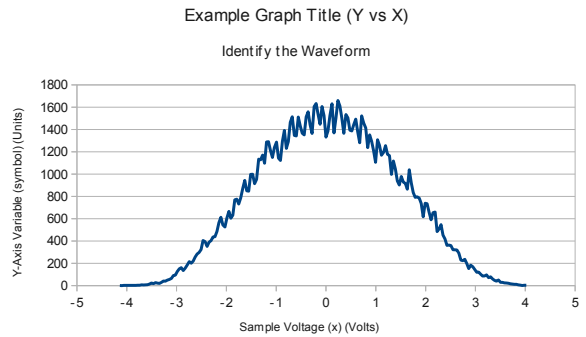
Signal Bandwidth and Voltage Measurement

You may find that the power of the noise measured by the DMM does not match the power measured by the 'scope. This is because the noise power is distributed over a frequency range (bandwidth) of many tens of MHz while the DMM only responds to signals at low (audio) frequencies [5]. This means the DMM's input circuits "smooth out" the signal and the DMM measures a smaller voltage than is present at the input. For example, the following graph shows a noise signal before and after low-pass filtering:
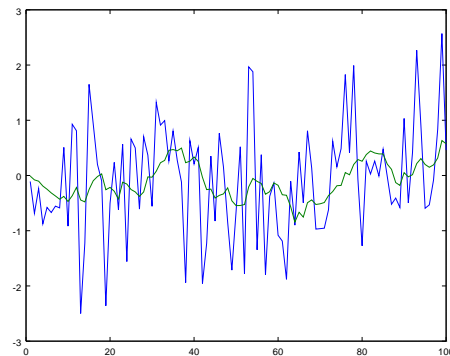
It's clear that the power of the low-pass filtered version is significantly less than the unfiltered signal.

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[5]The DMM frequency response specifications are in the Specifications chapter in the manual available on the course web site.

On the other hand, the bandwidth of the 'scope (also many tens of MHz) is close to the bandwidth of the noise so the 'scope measurement is closer to the actual value.

Pre-Lab Report

Submit a report containing the student and lab identification as described in the course information handout and the answers to the following questions:

(1) If a waveform's peak-to-peak voltage is $3x$ (where x is a variable) and its DC value is 0 V, what are the average and RMS voltages of (a) a square wave and (b) a sine wave?

(2) A sine wave of 2 V peak-peak is superimposed on a DC voltage of 1 V. What DC and AC voltages will be measured by a DMM? If a 'scope is set for DC coupling, what will be the average, peak-peak and RMS voltage measurements?

(3) A signal switches randomly between two levels, +1 V and +3 V. The level is +1 V 30% of time and +3V 70% of the time. (a) What is the average voltage? (b) What is the *RMS* voltage? (c) Draw the probability density function (you can draw arrows (impulses) whose heights correspond to the probability of a particular voltage).

(4) Over what range of frequencies is the accuracy of the BK Precision Model 2831E DMM specified *for AC voltage measurements*?

(5) (a) If the 'scope had an 8-bit A/D converter, how many different voltage levels can it resolve? (b) If the display was set to ± 10 V, approximately what minimum voltage difference would you expect to see between the sampled voltages? (c) If the maximum input voltage was 2 V and the minimum was -2 V, how many bins would be used for the histogram?

Lab Report

Upload three files to the dropbox folder for this lab:

1. the histogram CSV file for the sine wave input (only) in CSV (`.csv`) format

2. the Excel (or LibreOffice Calc) spreadsheet file in Excel (`.xls`) format (any version) containing the three sheets and three charts

3. your report in PDF (`.pdf`) format

Your report should include:

- identification information as described in the course information handout,

- plots of the first 2000 samples of each of the three sampled waveforms,

- 'scope screen captures for the three waveforms including the measurement data,

- the histograms for the three waveforms created by your spreadsheet (if possible, use copy and paste, not a screen capture)

- a table comparing the RMS voltages measured by the DMM, the 'scope, Octave (or Matlab) and computed by your spreadsheet from the histogram. Include one row for each waveform.

- a brief explanation for any discrepancies between the results for the different types of measurements