Assignment 14
(Due Monday 5 December)

Lock-in detection

A lock-in amplifier makes use of both frequency and phase to extract signals that are accompanied by noise and other unwanted background disturbances. A signal can often be recovered even when the absolute noise level is many orders of magnitude larger.

An experiment is driven at a known fixed frequency (ω). The measured output of the experiment will have this frequency impressed on it, although its amplitude may be very small. This output signal (V_{sig}) is multiplied with a clean sinusoidal reference waveform (V_{ref}) at the same frequency:

$$V_{sig} \sin(\omega t) V_{ref} \sin(\omega t + \phi)$$

where ϕ is the fixed phase difference between the two sinusoidal signals. Trigonometric manipulation gives:

$$\frac{1}{2} V_{sig} V_{ref} \cos(\phi) + \frac{1}{2} V_{sig} V_{ref} \cos(2\omega t - \phi)$$

Sending this through a low-pass filter leaves only the DC component, since the phase difference is not a function of time:

$$\frac{1}{2} V_{sig} V_{ref} \cos(\phi)$$

This DC signal is proportional to the amplitude of the desired signal (V_{Sig}). It is maximized when ϕ is a multiple of π and vanishes when ϕ is a multiple of $\pi/2$.

This VI illustrates lock-in detection by simulating an experiment with an adjustable amount of random noise.

VI construction

Begin by creating a While Loop with a simple Boolean control on the conditional stop terminal. Place four DBL controls on the Front panel for Frequency (Hz), Amplitude (V), Offset (V), and Noise Amplitude (V). Use vertical sliders for the Amplitude and Offset, with ranges of 0—5 and ± 5, respectively (example Front Panel shown below). Make the digital displays of both visible. Check that all the corresponding icons are inside the loop in the Block Diagram. All the controls and indicators of this VI should be inside the While Loop so they can update during operation.
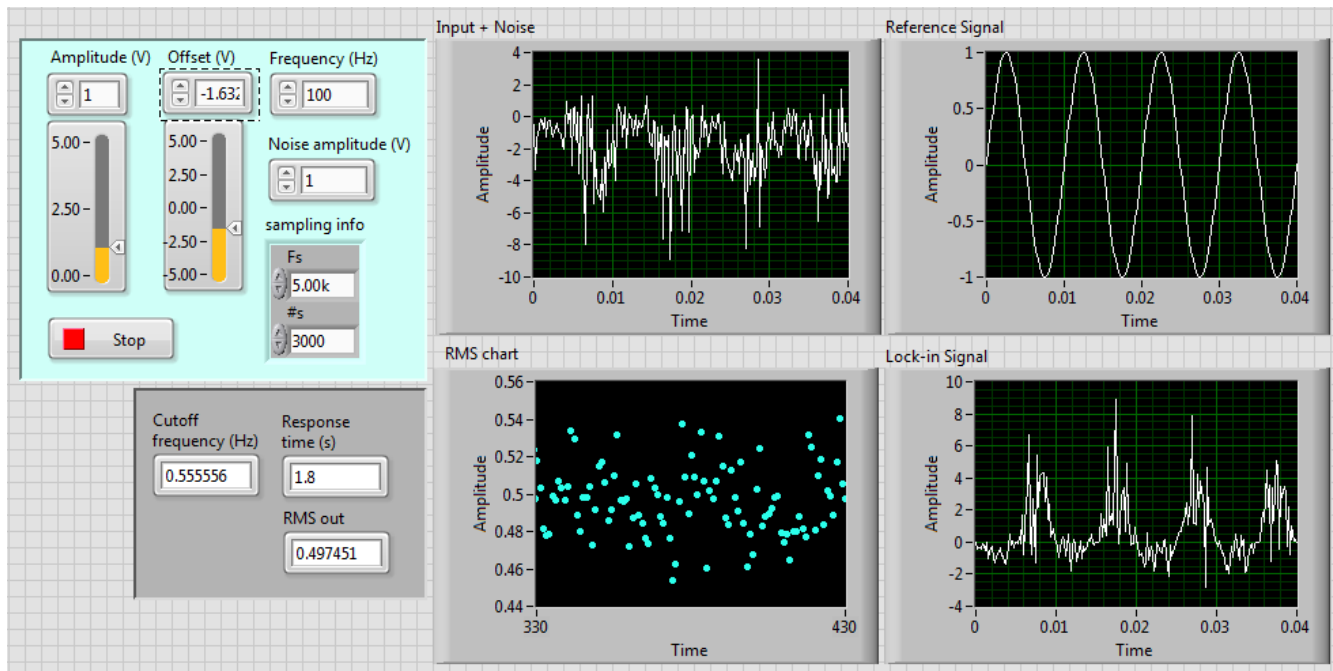
From the Waveform Generation sub-palette, arrange two copies of Sine Waveform.vi vertically inside the loop. One will generate a signal waveform and the second is for the reference waveform. Connect the Frequency, Offset, and Amplitude controls to the signal waveform generator. Connect only the Frequency control to the reference generator. The phase for both should be left at the default value of zero to maximize the detected signal.

Right-click on the **Sampling Info** terminal of one of the generators and create a control. Wire this cluster in parallel to the other Sine generator. Unbundle the cluster to reveal the sampling frequency (**Fs**) and number of samples (**#s**). This information is used to control the rate at which the loop executes, which determines the signal integration time. This time is given by #s/Fs, which is in seconds. Multiply this value by 1000 to generate the time in ms and connect it to Wait Until Next ms Multiple.vi.

Simulated noise is introduced with the Gaussian White Noise Waveform.vi, located in the Waveform Generation sub-palette. Wire the same Sampling Info cluster to the appropriate terminal and multiply its signal out by the Noise Amplitude control. Add 1 to this signal (the increment function makes this easy) and then multiply it with the signal waveform. Create a Waveform Graph on the Front Panel to display the resulting signal; label it "Input + Noise". Take this same signal (Input + Noise) and multiply it with the reference waveform. Display this on a second Waveform Graph and label it "Lock-in Signal". A third Waveform Graph should show the reference signal.

The next step is to add a low-pass filter to produce a slowly varying output that is proportional to the detected signal. There are a variety of ways to accomplish this. A simple way is with the Express VI named Filter.vi. Place it in the Block Diagram and use the default values; be sure it is configured for low-pass operation. Its cutoff frequency will be set in the program. The filtered signal is sent to Basic Averaged DC-RMS.vi found on the Waveform Measurements sub-palette. Display the RMS data using a chart and numerical indicator (it may render as a 1-D array, so take the first element).

The cutoff frequency (f_c) of the filter should be as close to DC (0 Hz) as practical, but it cannot be chosen arbitrarily. The lower limit is set by the Nyquist sampling requirement. If f_c is too large, however, noise is introduced unnecessarily. A good choice is $f_c = 1/(3T)$, where T is the loop wait time in seconds. Display f_c on the Front Panel and also its reciprocal, which is the response time of the lock-in detector.

As the noise increases, a longer integration time is necessary to retrieve a useful lock-in signal. The integration time is controlled by the number of sample points, i.e. the parameter labeled **#s** in the Sampling Info cluster. When the number of sample points becomes very large, however, the waveform graphs get over-crowded with data. To make a lengthy waveform readable, the time axis of each graph can be clamped to show a fixed number of points; a good choice is the first 200 points of each waveform. Create a Property Node for each Waveform Graph and select X scale: Range: Maximum. You should now have three Property Nodes. Place Get Waveform Components.vi on the Block Diagram and wire the reference waveform to its input terminal. Right-click and select the **dt** component. Multiply **dt** by 200 and wire this to the input of each Property Node (configure them for Write). Go to the Front Panel and disable autoscale on the x-axis for each of the waveform graphs.

The remaining step is to clear the chart history each time the VI is started. Create a Property Node for History Data, set it to write an empty array constant, and use the error cluster to execute it before starting the While Loop. It is not necessary to clear the graphs.

Note: You may experience erratic displays because of data flow ambiguities in the Block Diagram. Use the error cluster to fix this. There are error cluster input/output terminals on the Property nodes. The arithmetic operators also have error terminals when they operate on waveforms. You can use these error terminals to your advantage to enforce the flow of data if needed.

Testing

The lock-in operating frequency and sampling rate (**Fs**) should remain fixed. Values of 100 Hz and 5000 samples/sec, respectively, are good choices but feel free to experiment. Set the amplitude, offset, and noise to 1, 0, and 0, respectively. The number of samples (**#s**) determines how long data is collected. The more samples, the better the accuracy but the measurement will take more time. With zero noise, confirm that the lock-in rms output is very close to 0.5. The presence of a DC offset should not affect this.

Now add noise to the system. When the noise level is 0.1 (signal-to-noise = 10:1), a sinusoidal signal can still be observed on the time trace. Depending on the sample size (integration time), lock-in detection can easily recover the rms level with an error of less than 1%. Increase the noise to 1 and larger. Although the sinusoidal signal waveform cannot be recognized on the time trace, values close to the correct rms level (0.5) emerge at the lock-in output. This demonstrates how phase-sensitive detection can recover signals that are buried deep in the noise. Observe that as the integration time increases, the response of the lock-in slows down. Slower response is the trade-off for measurement accuracy.

Demonstrate the VI for the instructor before class. It will be modified to interface with an LED source and photodiode detector on the Elvis board.