Lock-In Detection Experiment

Kevin Robb, Seth Pickle
University of Oklahoma,
Homer L. Dodge Department of Physics and Astronomy
440 W. Brooks St, Norman, Oklahoma, USA 73019
email address: kevin.robb@ou.edu
(Dated: October 24, 2019)

This experiment tests and verifies the effectiveness of a lock-in detector in various circumstances, and compares its produced signal-to-noise ratio with a classical bandpass filter. When increasing the distance the signal must travel before reaching the detector, the signal that reaches the detector is more attenuated, and the noise is a higher portion of the received signal, so it has a greater effect. As the received signal becomes more cluttered with noise and has a less prevalent true signal, the lock-in becomes noticeably more effective than a bandpass filter at isolating the true signal amplitude. The apparatus and detectors perform well at 5 to 50 Hz, but as the frequency increases to the order of 100 Hz, the quality of the output decreases; however, even at these higher frequencies, the trend is the same.

I. INTRODUCTION

The lock-in amplifier is an instrument invented in the 1930s which is capable of parsing out even a signal on the order of mV from an environment with noise that is orders of magnitude higher, if the reference wave is known [1]. It is called a lock-in detector because it "locks in" to the phase of the reference oscillator, also earning it the title of "phase-sensitive" detector. This device was later commercialized, and can be found commonly in other experiments, as either a black box or something easily constructed. Some applications of lock-in detectors include measuring the response of a driven system, measuring Mie scattering through a liquid medium, or isolating signals with high noise or attenuation [2].

Lock-in detection controls for frequency as well as phase, making it a very effective way of measuring signal, but as mentioned, it can only be used when the reference waveform is known. Where a bandpass filter outputs a sinusoid with the frequency and amplitude from the signal, the lock-in amplifier gives only a DC line at the detected amplitude. This is the trade-off; if the user only needs the amplitude, as is often the case, the lock-in detector gives the best result. If, however, the user does want the output waveform intact or if they do not have a reference waveform to feed to the input of the detector, they cannot use the lock-in. A lock-in will allow more accuracy in the amplitude reading and less signal attenuation at the cost of losing the actual waveform [3]. The output from a bandpass can be sent through a lock-in, which we do in our experiment, but most lock-in detectors will have a built-in bandpass filter as a preliminary step to select a frequency range around what we expect, in this case around the reference. A strength of the lock-in detector is that it can be used even when the signal of interest is much smaller than the noise present, a situation which would cause trouble for more classical detectors.

The goal of this experiment is to test, understand, and apply the lock-in amplifier, and compare its produced signal-to-noise ratio with that of a regular bandpass filter. We will measure this ratio at a range of frequencies to test performance of each detector at high, mid, and low frequencies. These results will tell us the circumstances in which lock-in detection is superior to other detection methods, and to what extent it is more effective.

II. THEORY AND BACKGROUND

The lock-in detector functions by comparing the input signal to the reference wave. This comparison is done by multiplying our phase-shifted reference oscillator with the signal received from the input source. In our case, the reference oscillator modulates an LED, and our noisy input signal comes from a photodiode. The photodiode's input will contain random noise averaging to zero as well as background noise with a nonzero contribution to the root-mean-squared voltage, V_{rms}, of the input signal. The noise in these cases does not have a definite frequency or phase, so the lock-in detector can account for both of these to isolate the true signal amplitude; this is done by multiplying the signal by the reference, and integrating over a "time constant" longer than the reference period of oscillation. This integration will perform the inner product of the input and reference functions, eliminating all terms that do not match the frequency and phase [4]. This works because the inner product of orthogonal functions is zero, and any two sinusoidal functions with different frequencies or phase are orthogonal. The reference oscillation and noise are uncorrelated, so this condition is satisfied and when multiplied the result will be zero. The output of this inner product is averaged by a low-pass filter and

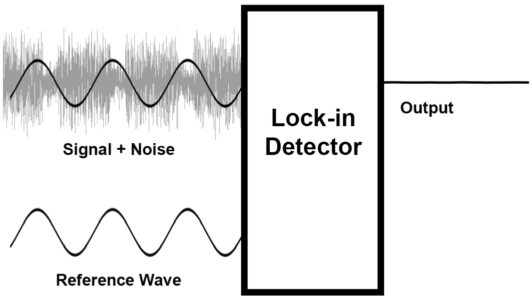

FIG. 1. The basic structure of inputs and output of a lock-in detector. The signal is modulated by the reference wave, and filled with noise before reaching the lock-in, where it is separated and the root-mean-squared voltage of the signal is output as a DC signal (the flat line to the right.

should form a steady DC signal for a high enough time constant, as shown in Fig. 1. The time constant should be set to its lowest value (making the output from the lock-in a waveform with twice the reference frequency), and increased until the output is just a horizontal line. A lower time constant will not remove all the noise, and a higher time constant will take unnecessarily long to update, and could miss information with quick pulses.

When the output is a DC signal, we can measure it's root-mean-squared voltage, $V_{rms,signal}$, which includes the true input signal plus some noise. We can turn off the reference oscillator, and therefore the LED and the true signal, to measure the root-mean-squared voltage with only noise present ($V_{rms,noise}$). This is described further in section III. We can then calculate a signal-to-noise ratio (SNR) as

$$SNR = \frac{V_{rms,signal}}{V_{rms,noise}} \ . \tag{1}$$

We expect that the lock-in detector, being more effective than the bandpass filter/amplitude detector, will have a consistently higher SNR, since the noise will be better pared from the $V_{rms,signal}$ before it reaches the output. The noise should be inherent in the environment through which the signal travels, and therefore not depend on the source of the signal itself. As such, if we move the LED progressively further from the photodiode, as described in section III, the signal received should fall off as $1/r^2$, where r is the distance it travels. We can conclude that

$$SNR \propto \frac{1/r^2}{1} = \frac{1}{r^2} \ . \tag{2}$$

Thus we can plot SNR for each detector at varying positions, and create a fitting function

$$SNR \propto \frac{s}{(r-h)^2} + v \ . \tag{3}$$

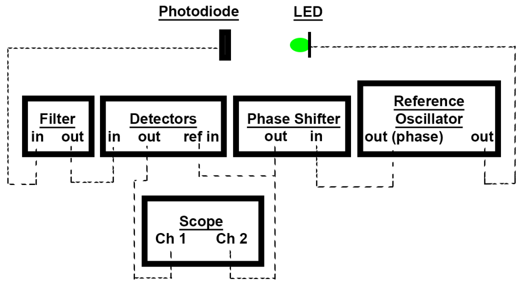

FIG. 2. The experimental setup for the LED as test signal. The "Detectors" module contains a lock-in detector and an amplitude detector, with a switch to select which one is active. A function generator could be used in place of the reference oscillator as long as the same input goes to both the LED as well as the reference input of the lock-in detector. A different source or different signal here will corrupt the output irrevocably.

where v is a vertical shifting parameter, h is a horizontal shifting parameter, and s is a vertical scaling factor. We ignore constant factors in Eq. (2) and Eq. (3), which is fine since the SNR values will be compared to only other SNR values. SNR is unit-less, so assume that s in Eq. (3) is in units of cm^2 to cancel the cm^2 in the denominator.

III. APPARATUS AND EXPERIMENT

For this experiment, we use an apparatus consisting of a function generator, an oscilloscope, and a box with other modules that act as independent components, shown as such in Fig. 2. We include an LED and a photodiode in the setup, and modulate the LED to create the test signal. In this case, noise is introduced by the environment, such as ambient light in the room or systematic effects of the photodiode.

We use the lock-in detector and phase-shifter together to maximize the V_{rms} output to the scope, and send this through the low-pass filter/amplifier to convert it into a DC signal for ease of measurement. We record $V_{rms,signal}$ from this, and turn the reference oscillator off to measure $V_{rms,noise}$. $V_{rms,signal}$ will contain both the true signal and the noise, since we can disable the signal part to measure the noise alone ($V_{rms,noise}$) but cannot do the opposite. We obtain the signal-to-noise ratio simply using Eq. (1). For each position of the LED, this ratio is obtained from the lock-in detector and from the bandpass filter with the amplitude detector. We plot these two on the same graph to compare the SNR for varying distances between the photodiode and LED, which corresponds to increasing noise and increasing signal attenuation.

After modulating position, we fix a position at a reasonable point (for our setup, 2 cm between the LED and photodiode), and alter the reference frequency, calculating the signal-to-noise for both detectors at each frequency. This allows us to similarly compare the two detection strategies, observing trends in effectiveness as frequency becomes very high ($\approx$ 150 Hz) or very low ($\approx$ 5 Hz). We do not expect changes in frequency to have much effect on the functionality of the lock-in detector itself, so we hope to verify this with our measurements and analysis. Frequency changes more test the limits of our apparatus than these types of detectors in general. These two methods, altering position or frequency, allow us to construct a range in which the lock-in detector performs best and in which the lock-in performs on par with or poorly in comparison to a bandpass filter.

IV. ANALYSIS AND DISCUSSION

We determined 50 Hz to be a good middle ground frequency for our input/reference signal. Our observations at this frequency are shown in Fig. 3. We see that for our range in position, moving the LED away from the photodiode increases the relative effectiveness of the lock-in detector in isolating the true signal and stripping out noise. When the LED is within 1 cm of the photodiode, the bandpass filter tends to perform slightly better, but with any greater distance, it is surpassed in performance by the lock-in.

At higher frequencies, our apparatus loses some effectiveness, causing our data reliability to break down and our residual standard error to rise, but this trend still holds. A data-set gathered at 150 Hz is shown in Fig. 4. There is a greater SNR gap at lower positions than in Fig. 3, but at mid and far positions, it looks about the same.

We can see from our data that the lock-in detector performs noticeably better than the standard bandpass filter/amplitude detector at most distances, and works better at frequencies in the 5–50 Hz range than the 50–150 Hz range.

V. CONCLUSIONS

We have gathered data-sets using both a lock-in detector and a bandpass filter in various circumstances, and compared their produced signal-to-noise ratios. From our data, which agrees with the theory on the subject, we can conclude that in a standard frequency range appropriate for our apparatus, the lock-in outperforms the other detector. As noise and attenuation increase, whether artificially or by increasing the LED's distance from the photodiode, the gap between the two

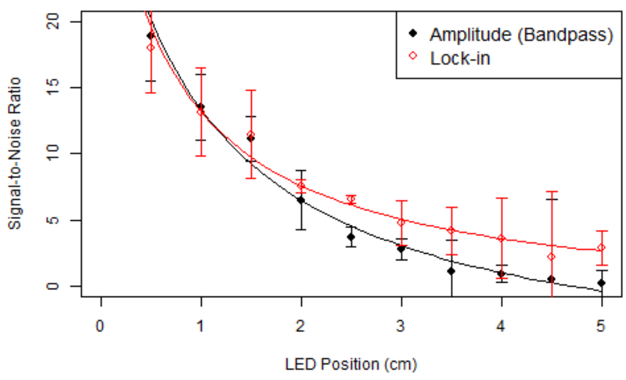

FIG. 3. Data gathered at a fixed frequency of 50 Hz and a changing position using both the lock-in detector and the amplitude detector (bandpass filter). The fitting function is described in Eq. (3), with the amplitude detector's fitting parameters $s = 41 \pm 8$, $h = -1.0 \pm 0.2$, and $v = -7 \pm 1$, and the lock-in's fitting parameters $s = 25 \pm 5$, $h = -0.7 \pm 0.1$, and $v = -2 \pm 1$. These fits have residual standard errors of 0.9783 and 0.9464, respectively. The V_{rms} fluctuated on the scope, so each data point was taken as the average value, with a recorded error for each point reflecting its most significant digit that was unstable. The error bars for SNR on the plot are simply the error in $V_{rms,signal}$ divided by the error in $V_{rms,noise}$.

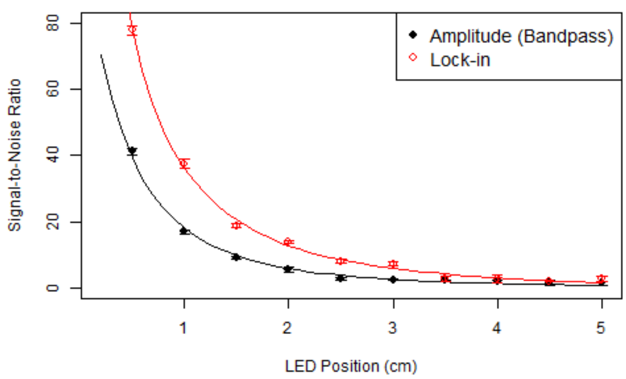

FIG. 4. Data gathered at a fixed frequency of 150 Hz and a changing position using both the lock-in detector and the amplitude detector (bandpass filter). The fitting function is described in Eq. (3), with the amplitude detector's fitting parameters $s = 190 \pm 30$, $h = -1.20 \pm 0.06$ cm, and $v = 0.0 \pm 0.5$, and the lock-in's fitting parameters $s = 98 \pm 6$, $h = -0.61 \pm 0.02$ cm, and $v = -1.5 \pm 0.6$. These fits have residual standard errors of 1.042 and 1.223, respectively. Error bars have the same meaning as in Fig. 3, but appear smaller because the vertical scale is different.

detectors' signal-to-noise ratios only increases, favoring the lock-in. At the higher frequency, our quality decreases, but the trend is the same.

[1] Zurich Instruments, *Principles of lock-in detection and the state of the art* (Zurich, Switzerland, 11/2016).
[2] Jessie Petricka, *An Introduction to the Lock-In Amplifier and a Mie Scattering Experiment* (Gustavus Adolphus College, St Peter, MN, United States, 2015).
[3] TeachSpin Instruction Manuals, *Signal Processor/Lock-In Amplifier (SPLIA1-A) Ver 2.2* (9/10/2009).
[4] Jadranka Buturovic-Ponikvar, *The theory of lock-in detection* (University of Ljubljana Faculty of Mathematics and Physics, Slovenia, 2013).