Lock-In Detection Experiment

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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 noise increases and the signal becomes more attenuated, which improves the margin between the lock-in and the bandpass filter, showing the former is clearly more effective. At high frequencies, our quality decreases, but 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 tiny signal from a very noisy environment, 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 of the correct frequency, the lock-in amplifier gives only a DC signal. This is the trade-off. 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 to remove unnecessary data. 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.

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 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 should form a steady DC signal for a high enough time constant. The lowest time constant that produces output in this form should be used, since anything less will not remove all the noise, and anything higher will remove all meaning from the output and take too long to update.

III. APPARATUS AND EXPERIMENT

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 better.

For this experiment, we use an apparatus consisting of a function generator, an oscilloscope, and a box with other modules. These modules act as independent com-

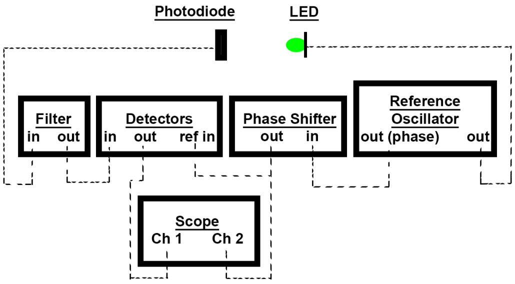

FIG. 1. The experimental setup for the LED as test signal. A function generator could be used in place of the reference oscillator as long as the same input goes to both the LED as well as the reference input of the lock-in detector. A different source or different signal here will corrupt the output irrevocably.

ponents, and are shown as such in Fig. 1. 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 problems with 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 flat DC signal for ease of measurement. We record $V_{rms,signal}$ from this, and turn the reference oscillator off to measure $V_{rms,noise}$. We obtain the signal-to-noise ratio as simply

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

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, similarly 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 or very low. 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 band-pass filter.

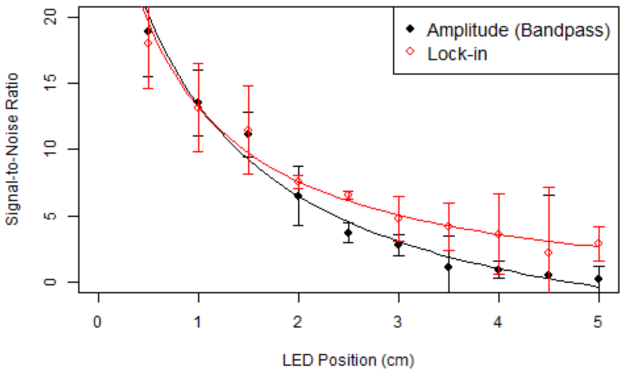

FIG. 2. Data gathered at a fixed frequency of 50 Hz and a changing position using both the lock-in detector and the amplitude detector (bandpass filter).

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. 2. 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 very close to the photodiode, the bandpass filter performs slightly better, but with any distance, it is surpassed by the lock-in.

At higher frequencies, our apparatus loses some effectiveness, causing our data reliability to break down and our correlation coefficient to drop, but this trend still holds. A data-set gathered at 150 Hz is shown in Fig. 3. There is a greater SNR gap at lower positions than in Fig. 2, 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 a standard bandpass filter/amplitude detector, and works best at lower frequencies.

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

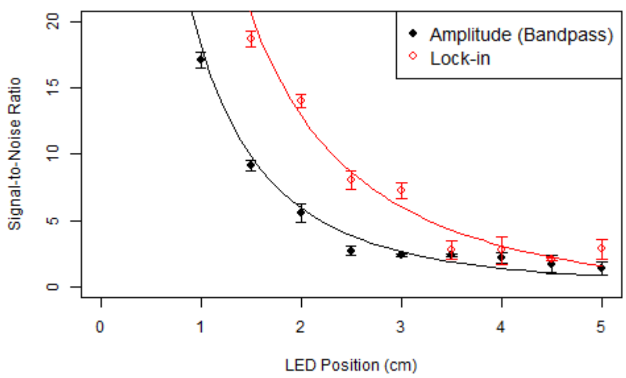

FIG. 3. Data gathered at a fixed frequency of 150 Hz and a changing position using both the lock-in detector and the amplitude detector (bandpass filter).

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

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