Lock-In Detection Experiment

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I. INTRODUCTION

The lock-in amplifier is an instrument invented in the 1930s which is capable of parsing out a signal from a very noisy environment, if the reference wave is known [1]. This device was later commercialized, and can be found commonly in other experiments, as either a black box or something easily constructed. 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. This restricts its use cases, but in cases where it can be used, it meets or outperforms other detectors such as a simple bandpass filter.

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.

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 by multiplying this 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 [2].

The output from the lock-in detector will then have a non-sinusoidal appearance, but the V_{rms} will be the correct signal amplitude. This signal can then be compared to the nonzero noise, which is measured by turning the LED off and measuring the photodiode input from background effects, which could be due to the instrument itself, excess light in the room, or any other cause of systematic error. We then calculate a signal-to-noise ratio as simply

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

This signal/noise ratio is what we will use to compare the lock-in amplifier to other types of detectors, such as a simple bandpass filter and amplitude detector.

The output from either detector will be put through a low-pass filter/amplifier to turn it back into a sine wave with twice the frequency of the reference, allowing us to plot this against the reference for phase comparison. We adjust the phase-shifter until our output is maximized, so we know it is perfectly in phase.

III. APPARATUS AND EXPERIMENT

For this experiment, we use an apparatus consisting of a function generator, an oscilloscope, and a box with modules for noise generation, detection, and others shown in Fig. 1. We initially use only the box and

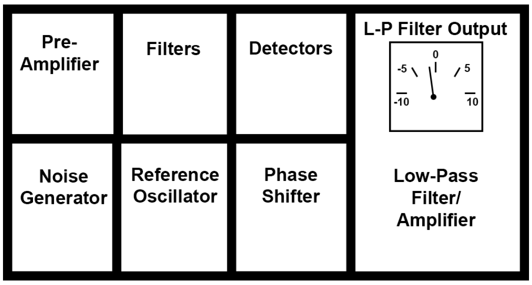

FIG. 1. The main apparatus. This box contains seven modules, each of which is used in conjunction with others in different ways depending on the part of the experiment.

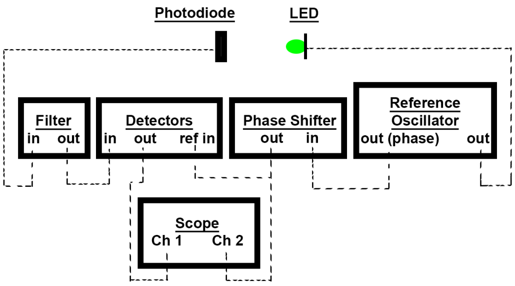

FIG. 2. The experimental setup for the LED as test signal. A function generator could be used in place of the reference oscillator as long as the same input goes to both the LED as well as the reference input of the lock-in detector. A different source or different signal here will corrupt the output irrevocably.

the scope, generating a test signal to compare outputs and verify functionality of the different modules. After this cycle of learning and testing, we include an LED and a photodiode in the setup, as shown in Fig. 2, and modulate the LED to create the test signal. In this case, the noise generator module is replaced by real noise 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 sinusoid 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 then 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 signal-to-noise 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. 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 poorly.

IV. ANALYSIS AND DISCUSSION

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V. CONCLUSIONS

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[1] Zurich Instruments, *Principles of lock-in detection and the state of the art* (Zurich, Switzerland, 11/2016).
[2] Jadranka Buturovic-Ponikvar, *The theory of lock-in detection* (University of Ljubljana Faculty of Mathematics and Physics, Slovenia).
[3] TeachSpin Instruction Manuals, *Signal Processor/Lock-In Amplifier (SPLIA1-A) Ver 2.2* (9/10/2009).