Application of the Lock-In Amplifier

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(Dated: May 19, 2013)

Abstract

Detecting periodic signals in the presence of large amounts of noise can be achieved using a lock-in amplifier. The following discussion covers the configuration, operation, and concepts behind a lock-in amplifier used in conjunction with photo-transistor detecting the output of a small LED in a noisy environment, as well as potential issues one my encounter during the process.

I. INTRODUCTION

Detecting the existence of a signal in large amounts of noise can be performed using a Lock-In amplifier. Detecting a signal with a photo-transistor in a well lit room is the perfect situation to test the abilities of a Lock-In circuit, as it offers plenty of sources of noise and unwanted signals for the photo-diode to pick up and the lock-in amplifier to subsequently remove.

The photodetector circuit used in this exercise does not differentiate environmental noise and the signal you intend to look at whatsoever, so the output signals needs to be processed to eliminate unwanted information. One could simply filter out frequencies around the desired frequency to remove a large amount of noise, but the signal still remains susceptible to continuous sources of light and other interference. Using a Lock-In amplifier in conjunction with our photodetector circuit, all environmental noise except is ignored and the voltage output indicates a detection only when the reference frequency is present in the signal, even when it is buried deep within noise.

Lock-In amplifiers output a voltage when it detects a particular frequency within its input signal. The output voltage is proportional to the amplitude of the desired frequency present in the signal[2]. The frequency the lock-in searches for is determined by the reference signal, which should be provided directly to the lock-in directly with little environmental noise (for example, over a BNC cable directly from the function generator). The lock-in amp makes the detection by taking the time average of the reference and signal, which, when two sinusoidal signals of the same frequencies exist, are picked out of the rest of the signal due to the orthogonality of all other frequencies and the reference frequency. Commonly in lock-in amplifier configurations, the reference signal is also driving some kind of emitter that is to be detected. In this case, an LED was driven using a function generator that also provided the reference signal for our lock-in detector.

II. ORTHOGONALITY

When two functions, $A(x)$ and $B(x)$ are classified as orthogonal when $\int_0^L A(x)B(x)dx = 0$ where the period is $0 \leq x \leq L$. If these functions, $A(x)$ and $B(x)$, are sinusoidal however, they exhibit a special behavior that can be utilized as the functioning mechanism behind a lock-in amplifier.

$$\int_0^L \sin\frac{n\pi x}{L}\sin\frac{m\pi x}{L}dx = \begin{cases} \frac{L}{2} & n \neq m \\ 0 & n = m \end{cases} \tag{1}$$

In this case, we are purely considering orthogonality from a mathematical viewpoint[1]. In terms of our lock-in amplifier, the time average of two sinusoidal functions of the same frequency result in a value where the time average of two sinusoidal functions with different frequencies will result in zero.

The Lock-In amplifier mixes the measured signal and the reference signal and takes the time average. If the measured signal contains any frequencies that match the reference signal, this time average will result in a measured value. Due to the super-position principal, if the measured signal contains a large amount of noise as well as a signal of the correct frequency, then the total signal will be composed of both of these. Taking the time average of the noisy signal with the reference frequency will give an amplitude proportional to the amount of the signal that is composed of the reference frequency.

III. PROCEDURE

A function generator was used to drive a pulsing LED as well as provide a reference signal to our lock-in amplifier at 500Hz. The photo-transistor circuit in Figure 1 was incorporated into the lock-in amplifier system and routed into the detector as the signal. The phase shifter plays an important part when reading detections on the lock-in amplifier as it allows us to adjust the amplitude of the resulting detection which varies like $\langle V_{\text{out}}\rangle = -(2E_s/\pi)\sin\phi$ where ϕ is the phase difference between the two signals.[2]

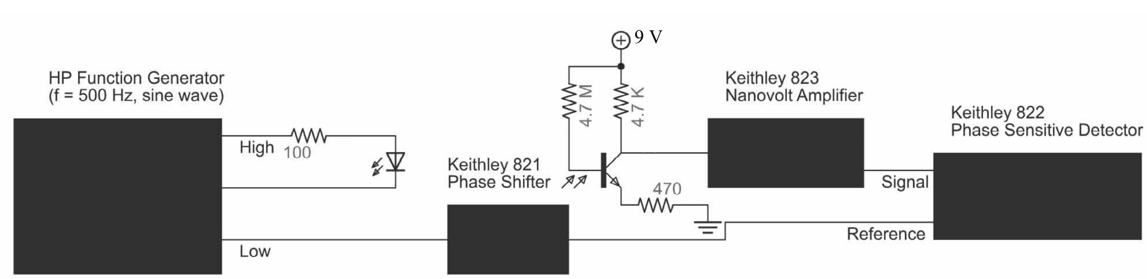

FIG. 1. Lock-In Amplifier and Photodetector Configuration

The output of the photodetector required routing through a nanovolt amplifier in order to increase the amplitude to a detectable level, and to meet the equipment signal requirement.

This amplification also amplified any noise present in the signal. The signal out of amplified photodetector contained large amounts of noise generated by to room lights at frequencies of 60Hz. Increasing the gain on the amplifier increased the aptitude of the noise in the signal which prevented any meaningful detections of our 500Hz LED signal past a few cm. Bringing the LED in close to the detector we were able to observe the 500Hz frequency, but larger distances required larger amplifications which increased the amount of noise visible on the oscilloscope. We were able to visibly see the 500Hz signal on the oscilloscope up to a maximum 40 cm away with the amplifiers filter in order to reduce unwanted signals of different frequencies. Turning the room light on and off affected the signal of the photodetector, even with filtering.

Connecting the photodetector into the lock-in amplifier and starting at a lower amplification level, all traces of noise from the lights were suppressed, even without filtering on the amplifier. Increasing the gain on the amplifier introduced a slight jitter to the output of the Phase-detector, but adjusting the time constant so that the lock-in sampled over a longer period would help suppress this effect. When the LED was pointed at the photodetector, the output of the lock-in would begin to read a voltage proportional to the distance away the LED was shown from. (See Figure 2.) Blocking the LED beam so that it was no longer hitting the photo-transistor would reduce this reading back down to our zero reading. Allowing the transistor to point at the overhead lights resulted in zero detection indicating our circuit was unaffected by these other signals. The only detection that could be produced is when the LED output interacted with the photo-transistor. We had a few strange sources of noise that came off of a set of unshielded wires we had to eliminate. This is discussed in the issues section.

Adjusting the time constant adjusts the amount of time that is sampled over. It is analogous to the period (T) in Equation 1. If this is set to high, the maximum amplitude that is detected can get trimmed so it is important to set this as low as possible for the given system without introducing disruptive amounts of noise. Increasing the time constant can improve stability of the detected signal which can exhibit slight fluctuations when the Lock-In is not sampled sufficiently.

A. Results

Once the lock-in was functional and configured correctly, the maximum amplitudes of LED detections were recored at different distances.

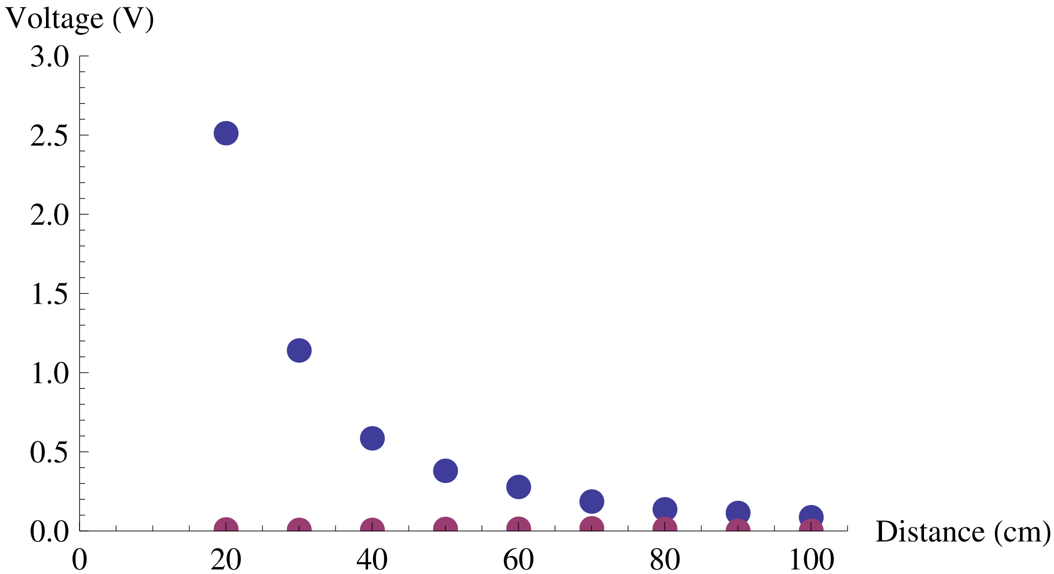

FIG. 2. Distance Vs. Voltage

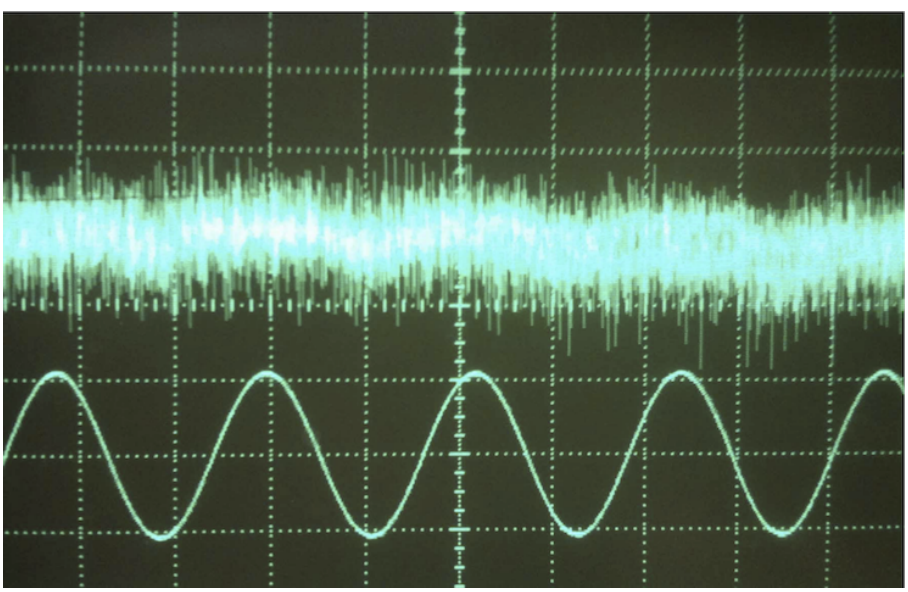

FIG. 3. Photo-Transistor and Reference Signal

Without filtering, at a distance, and with sufficient amplification, our signal coming into the detector contained a significant amount of noise to the point it was difficult to see when a 500Hz signal was present in the output of the photo diode. Figure 3 shows a picture of the 500Hz reference signal next to the noisy photo-transistor signal illustrating the level of noise present in our unprocessed signal. The Lock-In amplifier was still able to sufficiently detect the signal given the level of noise over a range of distances, although increasing the distance reduced the gain of the detection.

The zero reading had a slight fluctuation between 1mV and 15mV due to unknown reasons. Significant detections (87 mV) were made up to a meter away well above this noise threshold. Increasing the gain on our nanovolt amplifier would also increase the noise being sent into the lock-in amplifier. Enabling some form of filtering around the desired frequency would increase the stability of the reading when the gain was increased.

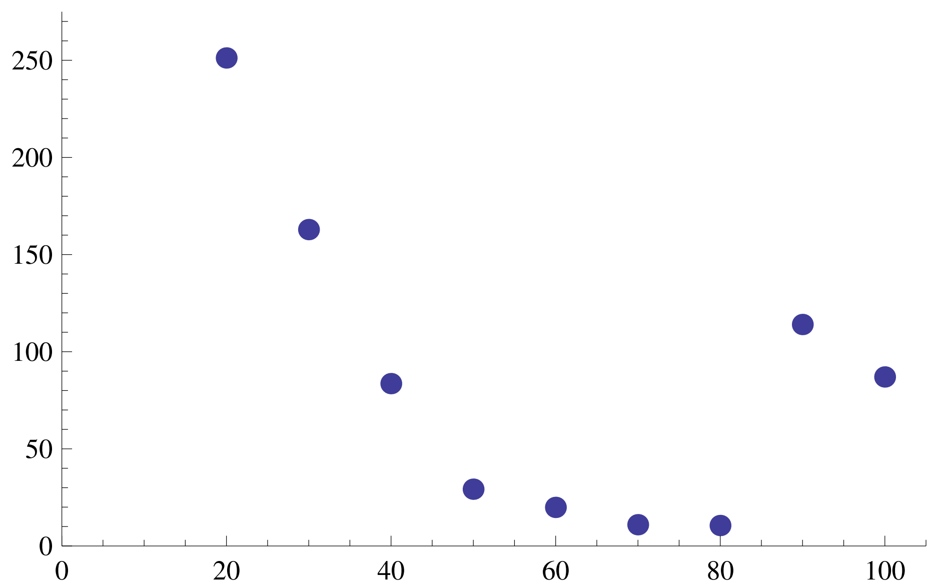

FIG. 4. Distance vs. $\frac{\text{Detection}}{\text{Zero Reading}}$

The noise in our configuration was small, and had a slight variation with time, although our recorded data was someone inconclusive in terms of its behavior. Further analysis may consider investigating noise in the system more in depth. Even though readings began to drop to the mV range around a meter away from the detector, convincing detections could still be made. Placing a hand between the LED and the photodetector would still result in very noticeable differences on the oscilloscope around that range.

B. Issues

A potentially unexpected issue can occur when unshielded wires are used near the photo-transistor. Unshielded wires can cause the unexpected detections in the lock-in, presumably due to the varying electric field around the wire generated by the function generator interacting with the photo-transistor. Using shielded BNC cables eliminated this issue and offered a simple way to reduce noise capable of throwing off lock-in readings.

The lock-in was very sensitive to any movement in the LED emission. The LED used in the procedure diffused quickly with distance and had visible variations in intensity of the pattern. When taking data, effort was made to maximize the reading by shining the brightest part of the LED emission onto the the photo-transistor. It is important to adjust the direction of the LED emission every time it is moved in order to maintain alignment with the photodetector.

IV. CONCLUSION

While lock-in amplifiers excel at detecting the presence of signals at a particular frequency, often you are amplifying the signal of sensitive equipment. Due to the amplification in place, any kind of undesired signal from unshielded cables cab be picked up by the sensitive detectors which might make it through the lock-in filter and produce a false positive. It is important to reduce any undesired signals that might match the frequency that your lock-in is looking for. Separating a signal out of unrelated noise however, works wonderfully.

Understanding the requirements and expected behavior of the different signals is critical for efficiently setting up a lock-in amplifier. Sufficient understanding with the mechanisms behind how a lock-in functions as well as hardware specific requirements should be adequately address before attempting to set one up in order to avoid headaches.

[1] Richard Haberman. *Applied Partial Differential Equations.* Pearson Prentice Hall, fourth edition edition, 2004.

[2] Paul Horowitz and Winfred Hill. *The Art of Electronics 2nd ed.* Cambridge University Press, second edition edition, 1989.