# Design a typical lock-in amplifier based on Arduino and MATLAB

Kun Lu*

School of Mechanical & Automotive Engineering, South China University of Technology, Guangzhou, China

* Corresponding Author Email: 202230114094@mail.scut.edu.cn

**Abstract.** The collection of low-frequency signals is very common in the use of sensors. However, 1/f noise and other low-frequency noise will drastically impact the quality of the low-frequency signal, which is why lock-in amplification is widely used to handle the original signal and improve the signal-to-noise ratio. So this research collected the original signal through Arduino and added 1/f noise to form the real data researchers usually got in reality, then MATLAB was used to perform the steps like modulating the mixed signal and demodulating it to get the final signal. Compared with the original data, the demodulated signal was similar, the causes of the differences between the two of them are likely because of the collecting part, the original signal is not a square wave in the true sense, and the changes from low to top resulted in the deviation. Generally speaking, lock-in amplification perfectly separates low-frequency signals from 1/f noise, which can help researchers better process signals and improve the sensors.

**Keywords:** Lock-in amplification, Modulation, Demodulation.

## 1. Introduction

In research and telecommunications, weak signals often get drowned in noise, presenting a challenge. Lock-in amplification, also known as synchronous or phase-sensitive detection, addresses this issue. It involves a lock-in amplifier comprising a low-pass filter and a multiplier. This setup multiplies the signal of interest by a reference signal and extracts the measured signal through the low-pass filter. This technology effectively isolates and amplifies periodic signals submerged in noise, reducing interference from noise signals, even in chaotic test environments or external conditions [1]. A phase-locked amplifier comprises an internal oscillator, a multiplier, and a lowpass filter. The oscillator generates a high-frequency wave, which, when combined with the original wave through the multiplier, produces a modulated signal with reduced 1/f noise. After demodulation, the signal passes through a lowpass filter to eliminate high-frequency components, revealing the original signal. This process enhances the signal-to-noise ratio, enabling accurate measurements even in scenarios with significantly higher noise amplitudes compared to signal amplitudes.

A phase-locked amplifier is primarily used to detect weak signals buried in noise. Weak signals can refer to either low signal amplitudes or signals overshadowed by noise. Extensive research has focused on understanding noise generation, signal properties, correlation, and noise characteristics to develop techniques for effectively separating useful signals from disturbances and detecting weak signals amidst noise [2]. Among all the methods, lock-in amplification has a high reliability and strong detection ability, so it is extensively used in detecting the sparkle of LEDs and other weak signals.

Generally, lock-in amplification falls into three categories: analog lock-in amplifier, digital lock-in amplifier, and virtual lock-in amplifier. The virtual lock-in amplifier is the latest; it runs software on CPUs and other computing devices to perform basic operations like phase-sensitive detection. In the author’s research, a typical lock-in amplifier is made. The author better understands what it can do by operating some necessary steps of the lock-in amplifier like modulation and demodulation.

## 2. Literature Review

After many years of development, lock-in amplifiers have become very mature and have many branches, including quantum double-locked amplifiers and two-dimensional locked amplifiers. The quantum double lock-in amplifier uses a quantum strategy to extract an alternating signal within a strong noise background. However, as the target signal usually has an unknown initial phase, obtaining complete information of its amplitude, frequency, and phase in a single lock-in measurement is difficult. To overcome this challenge, a general protocol is given for achieving a quantum double lock-in amplifier and illustrating its realization. In analogy to a classical double lock-in amplifier, the authors' protocol is accomplished via two quantum mixers under orthogonal pulse sequences. The two orthogonal pulse sequences act as two orthogonal reference signals in a classical double lock-in amplifier. The complete characteristics of the target signal can be obtained by combining the output signals. As an example, the authors illustrate how to realize our quantum double lock-in amplifier with a five-level double -Λ coherent population trapping system of 87Rb atoms. Our numerical calculations show that our scheme is robust against experimental imperfections such as finite pulse length and stochastic noise. Our study opens an avenue for extracting complete characteristics of an alternating signal within a strong noise background which is beneficial for developing practical quantum sensing technologies [3].

Simple lock-in amplifiers generally can only detect signals in a one-dimensional state, which is far from enough for future scientific research, so two-dimensional lock-in amplifiers came into being. Introducing a pioneering algorithm, a study unveils the utilization of a two-dimensional lock-in amplifier (2-D LIA) to discern intricate plane components amidst noisy images. This innovative approach operates directly within the image space, enabling precise isolation of target features while effectively suppressing noise interference. By harnessing the capabilities of 2-D LIA, the algorithm showcases remarkable proficiency in processing the complex waveforms inherent in image data, thereby enhancing the accuracy of component extraction. The efficacy of the algorithm is rigorously evaluated through a combination of numerical simulations and practical experiments, both of which consistently validate its effectiveness in various scenarios.

However, it is essential to acknowledge a potential limitation associated with the high cutoff frequency employed in the low-pass filter, which may inadvertently lead to a "lock-out" phenomenon under certain conditions. Despite this caveat, the overall performance and robustness of the algorithm remain impressive, promising significant advancements in the field of image processing.

In summary, this algorithm represents a substantial leap forward in the realm of complex image component extraction, offering a reliable and versatile solution validated through comprehensive simulations and real-world testing. Future research endeavors will focus on refining the algorithm's implementation to further enhance its real-time processing capabilities and address any identified limitations [4]. Mature and reliable lock-in amplifiers have become an important part of many instruments. The next step is to show the various application scenarios of phase-lock amplifiers.

An enhanced micromanipulation technology called Lock-in Amplifier Coupled Oscillating Magnetic Tweezers was developed for accurate measurements at the single-molecule level. Conventional magnetic tweezers work well for small-scale and nanoscale object manipulation, but increased sensitivity and accuracy are needed for studies involving single molecules. This method combines pulsating magnetic fields with a lock-in amplifier to meet this necessity. Electronic devices that are commonly employed to detect weak signals include lock-in amplifiers. It aligns with the frequency of the transmission, reducing interference and enhancing the signal-to-noise ratio. This method involves manipulating microscopic magnetic particles—which are frequently altered to connect with target molecules or cells—using oscillating magnetic fields. Under the magnetic field, these particles exhibit specific movements and mechanical responses. The lock-in amplifier then separates these response signals from background noise, enabling accurate measurements of tiny force variations and subtle object movements.

Potential applications include expanding the utility of magnetic tweezers to signal detection below background noise levels and facilitating research in areas such as biophysical mechanics and protein conformation dynamics. Furthermore, the apparatus can simultaneously detect and record single-molecule reactions in the presence of fluctuating magnetic fields, yielding incredibly accurate and sensitive data. This skill expands our knowledge of molecular-level occurrences and creates new avenues for scientific inquiry and advancement across a range of disciplines [5].

Phase-lock amplifiers can also be seen in the field of biomedicine. This article explores the widespread application of lock-in amplifiers in biomedical measurements, focusing on their basic principles, performance characteristics, and effective validation in experiments using an RC tissue model. Lock-in amplifiers excel in capturing impedance changes, particularly evident in experiments involving RC tissue models, owing to their outstanding sensitivity and precision.

The article begins by introducing the crucial role of lock-in amplifiers in biomedical measurements, emphasizing their superiority in capturing extremely weak signals and resisting interference. Lock-in amplifiers are extensively used in biomedical research, especially impedance spectroscopy techniques.

The methodology section provides a detailed examination of the triangular view of lock-in amplifiers, elucidating how they operate and amplify the phase relationship between the input signal and reference signal. The unique output behavior of lock-in amplifiers, linked to phase alignment, enables selective measurement of signals with the same frequency and phase as the reference signal.

Subsequently, the article delves into the results and analysis, testing the feasibility of using lock-in amplifiers to measure impedance in an RC tissue model. The experimental results underscore the excellent performance of lock-in amplifiers in detecting impedance changes within the RC tissue model, with minimal observed error. This confirms the potential application of lock-in amplifiers in the field of biomedical measurements.

In conclusion, the article synthesizes insights derived from experimental validation, affirming the capability of lock-in amplifiers to accurately detect subtle voltage changes in RC tissue models. This highlights their potential as reliable, sensitive instruments capable of filtering noise in biomedical measurements, contributing significantly to the biomedical field [6]. Terahertz technology has a wide range of applications in many fields, including imaging, communications, nondestructive testing, biomedical, and safety inspection. Lock-in amplifiers also play an important role in the terahertz field.

The article titled "Design of an Adaptive Lock-in Amplifier for the Terahertz System" introduces the design of an adaptive lock-in amplifier. This amplifier is tailored for terahertz systems, offering automatic adjustment of phase and amplification to enhance the system's dynamic range. Compared to traditional lock-in amplifiers, this design reduces the number of electronic components, thereby lowering development costs. Through an MCU control unit and feedback signals, it intelligently adjusts phase and amplification. Experimental results demonstrate a dynamic range of 70dB in terahertz systems, indicating practical utility. The article also references three related papers on topics such as continuous-wave THz radiation interference measurement, novel calibration devices, and plasma density measurement methods in multi-channel box-type THz time-domain spectroscopy. The conclusion suggests that while further optimization may be costly and unsuitable for commercialization, improving the dynamic range of terahertz systems can be achieved by reducing signal noise or adding a coded modulated signal [7].

Not only that, the phase-locked amplifier is also used in the C8051F060 microcontroller and optoelectronic spectroscopy A paper presents a lock-in amplifier design based on the C8051F060 microcontroller and its application in optoelectronic spectroscopy. The lock-in amplifier is an important tool for amplifying and measuring weak signals, and this paper introduces its working principle, design methods, and applications in measuring physical, chemical, and biological parameters. By utilizing the digital features of the C8051F060 microcontroller, the designers simplified the design process of the lock-in amplifier, while achieving advantages such as low cost, compact size, and low power consumption. The paper details the hardware and software implementation of the lock-in amplifier, including steps such as reference signal generation, sampling, processing, and display. Experimental verification demonstrates the performance of the designed digital lock-in amplifier in measuring sample temperature changes, highlighting its high sensitivity and accuracy. Furthermore, the paper discusses the potential application prospects of digital lock-in amplifiers in optoelectronics, such as photoacoustic imaging and optical coherence tomography. Finally, it points out that digital lock-in amplifiers have a wide range of applications and provide important support tools for various scientific [8].

## 3. Result and Discussion

To demonstrate the role of the lock-in amplifier, the author first uses Arduino to collect the original signal.


**Fig. 1** Arduino UNO (Photo/Picture credit: Original).

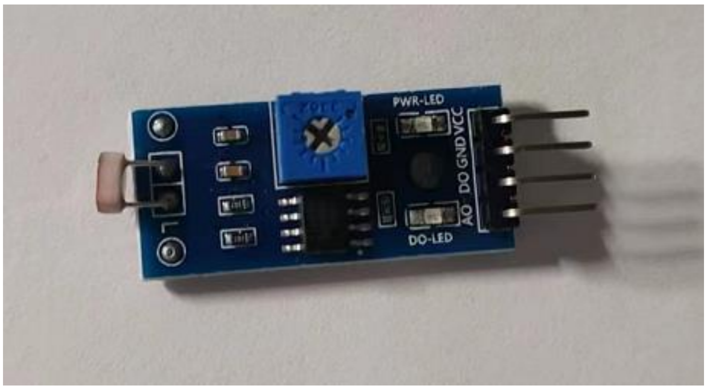


**Fig. 2** PPhotoresistor (Photo/Picture credit: Original).

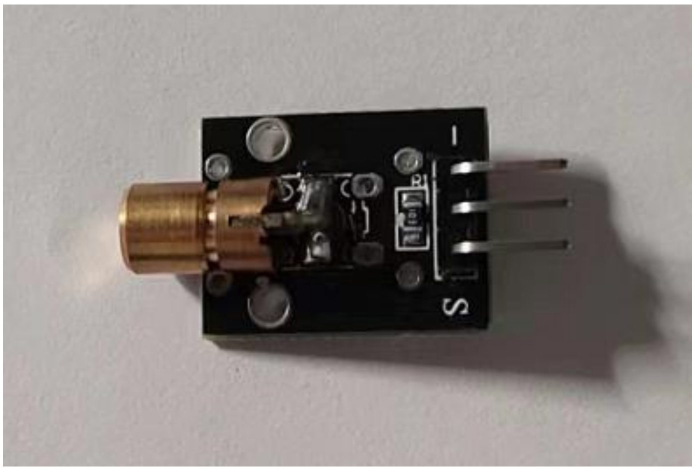


**Fig. 3** Laser transmitter (Photo/Picture credit: Original).

The device consists of five parts: Arduino UNO, as shown in Figure 1, a photoresistor, as shown in Figure 2, a laser transmitter, as shown in Figure 3, a breadboard, and a battery. Firstly, the Arduino UNO is given a series of codes to control the laser transmitter to emit a laser at a specific frequency, which is 1 Hz, so logically the image of the data should be in the form of a square wave. Then, the photoresistor receives the optical signal in a dark environment in order to avoid the influence of other light sources in the environment as much as possible and converts the signal into resistance values of a resistor. The values that contain 5000 points then are saved and demonstrated using MATLAB, as shown in Figure 4.

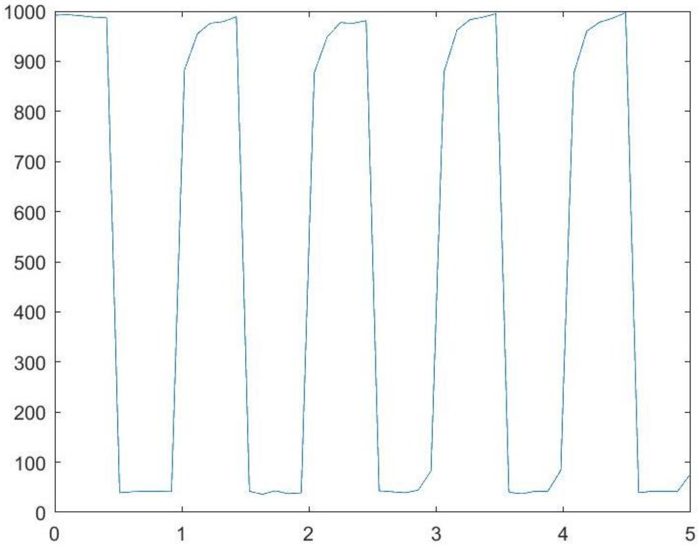


**Fig. 4** Original data presented in MATLAB (Photo/Picture credit: Original).

It is obvious that the image of the original data isn't a square wave. After analysis, the author believes that the reason for this error is due to the error of the photoresistor or the laser emitter. Due to accuracy problems, the photoresistor may not be able to accept low-frequency lasers well, or the laser transmitter may not be able to emit low-frequency lasers with square wave properties well.

After generating the original signal, a high-frequency wave needs to be made to carry the original signal. Because the original data waveform is similar to a square wave, the high-frequency wave better be a square wave, as shown in Figure 5 and Figure 6. The step that the low-frequency original wave multiplies with the high-frequency wave is called modulation, as shown in Figure 7. During this step, the key point is that the noise should not be included, otherwise, the original data can't be obtained in the last step.

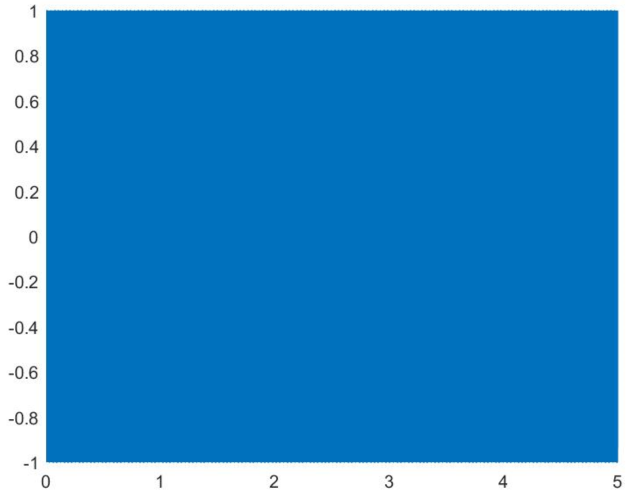


**Fig. 5** Carrier wave presented in MATLAB (unenlarged image) (Photo/Picture credit: Original).

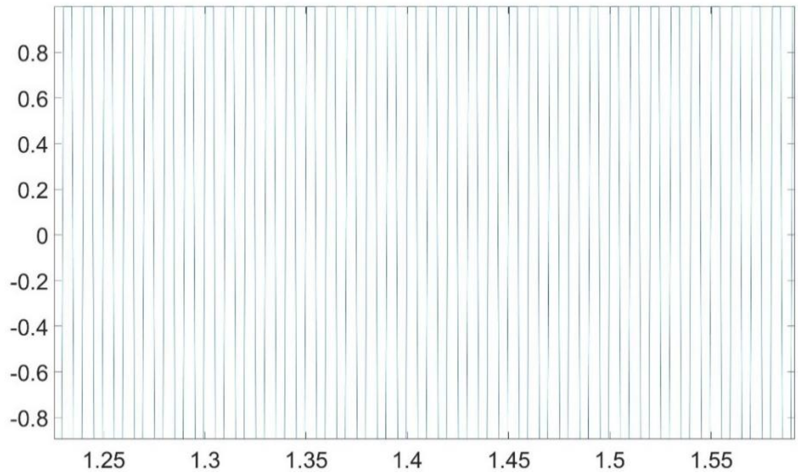


**Fig. 6** Carrier wave presented in MATLAB (the enlarged image) (Photo/Picture credit: Original).

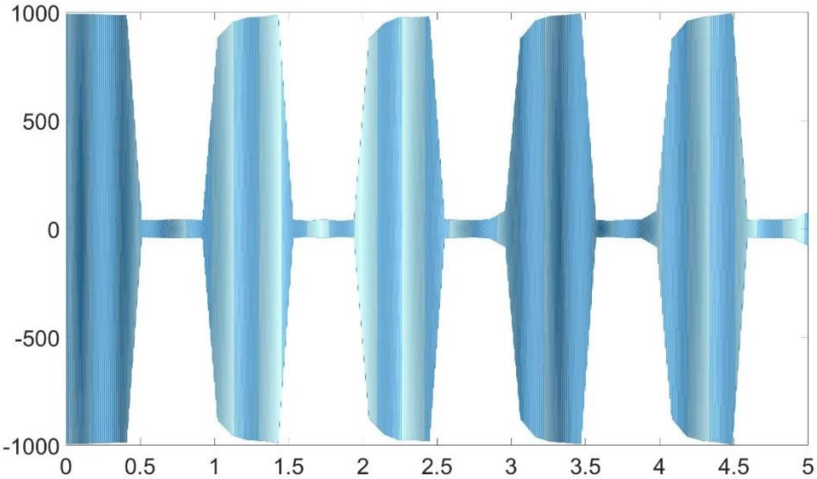


**Fig. 7** Presentation of the modulation (Photo/Picture credit: Original).

It is necessary to add noise to the modulated signal after it has been successfully modulated. Firstly, what is 1/f noise? Japanese scholar Hideki Takashi discusses this: the so-called 1/f noise is a general term for the oscillation of the power spectrum proportional to the reciprocal of the vibration number f. It is also called a flicker or pink noise [9]. It is very suitable for this experiment to simulate the reality that the low-frequency original signal is buried in the noise because of its significant effect at low frequencies, so it is generated in MATLAB, as shown in Figure 8 and mixed with the modulated signal. The mixed signal, as shown in Figure 9, is usually what the sensors receive in reality, not the original signal. In order to better be mixed with the modulated signal, the values of the 1/f noise also contain 5000 points. Below is the pictures of the noise and mixed signal:

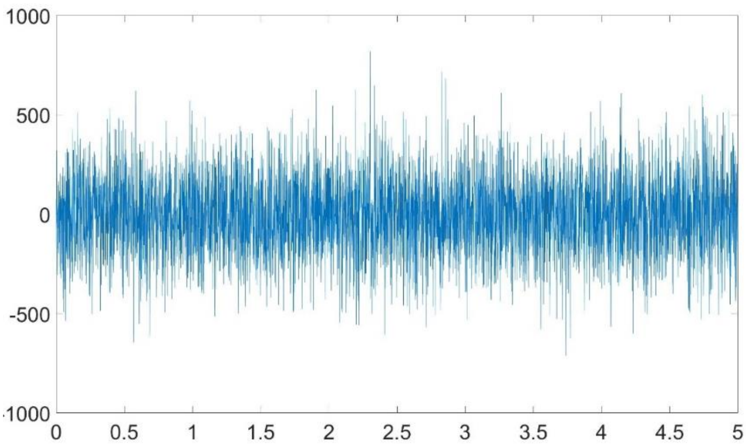


**Fig. 8** Image of noise presented in MATLAB (Photo/Picture credit: Original).

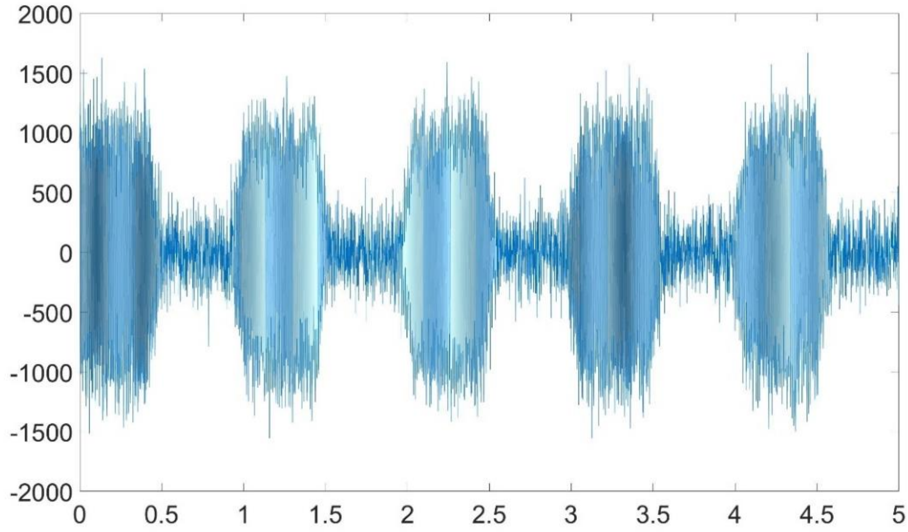


**Fig. 9** Image of the mixed signal presented in MATLAB (Photo/Picture credit: Original).

After mixing all the signals and noise, it is time to demodulate. The principle of demodulation is to multiply the mixed signal and the carrier wave so the noise can be moved. This is using the orthogonality of sinusoids. Orthogonality of sinusoids:

$$\int_0^T cos(2\pi m f_0 t) \cdot cos(2\pi n f_0 t)\, dt = \begin{cases} \frac{T}{2} (m = n) \\ 0 (m \neq n) \end{cases} \tag{1}$$

$$\int_0^T sin(2\pi m f_0 t) \cdot sin(2\pi n f_0 t)\, dt = \begin{cases} \frac{T}{2} (m = n) \\ 0 (m \neq n) \end{cases} \tag{2}$$

From the above, the mixed signal is composed of the original signal, the carrier wave, and noise. When the mixed signal multiplies the carrier wave, only the waves with the same frequencies as the carrier wave will be saved. Although there may be such a specific part in the noise, due to the disorder and chaos of the noise, in general, this specific part will have a small impact on the process of demodulation and can be ignored, so after demodulating, most of the noise will be removed, and there will be only the original signal and some part of high-frequencies parts left, as shown in Figure 10.

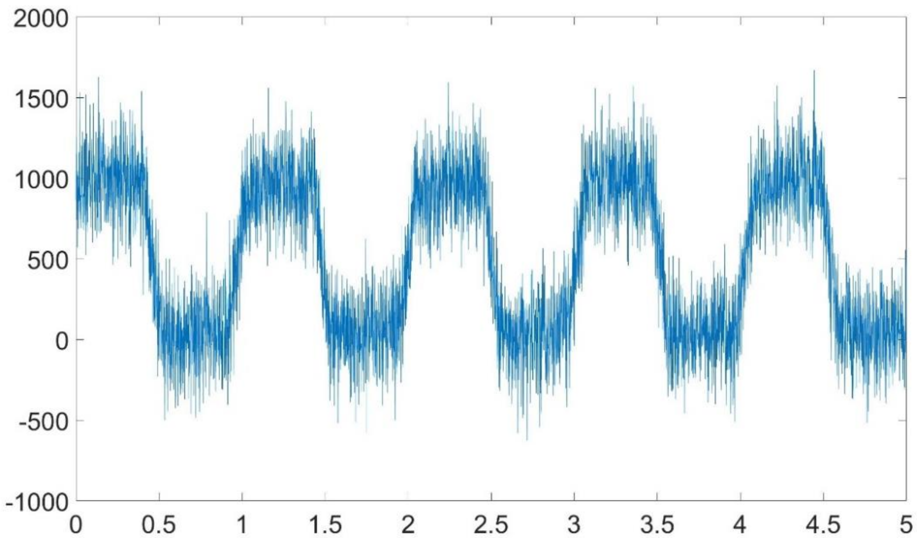


**Fig. 10** the demodulated signal presented in MATLAB (Photo/Picture credit: Original).

After demodulating the mixed signal, a lowpass filter is needed. The purpose of the filter is to remove interference components from the signal. A low-pass filter, for example, lets signals from zero to frequencies below the low-pass filter cutoff frequency pass through, but not signals from frequencies above the cutoff frequency [10]. After filtering, the original signal is able to be got in theory, as shown in Figure 11.

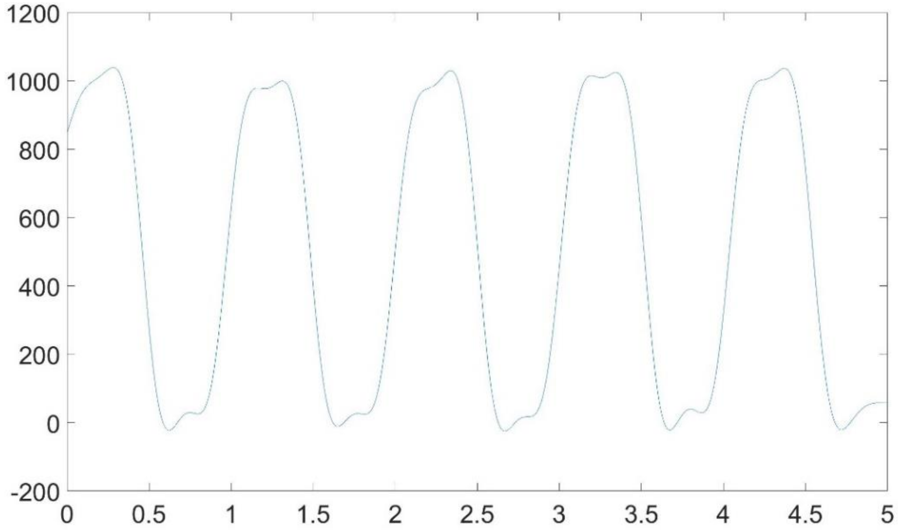


**Fig. 11** The final signal after the low-pass filter (Photo/Picture credit: Original).

Although there are some differences when the original signal and the signal after filtering are put together, they are still very similar. This just explains the role of the lock-in amplifier: by amplifying the low-frequency signal, so that it is extracted from the noise, and finally extracts the original signal.

After research, some benefits of the lock-in amplifier are obvious. The first is that the amplifier reduces the effect of 1/f noise on the signal. As shown in the Figure 11, it increases the signal frequency and reduces the effect of noise. Second, it enables detection at extremely narrow bandwidth and better q-factor than notch-filter design.

The most important question that needs to be considered in reflecting on the results is why is there still some error between the output signal and the original signal. After reflection, the author believes that the first reason is that our original image is composed of a large number of points, so the original signal is not a perfect periodic function, so the filtered image will have a certain error. The second reason is that in the case of nonlinear systems, there will be higher harmonics of the modulation frequency, while the square wave carrier is sensitive to noise at harmonics. The third reason mentioned in the previous article is the accuracy of the photoresistor and the laser transmitter.

More important after reflection is what can be improved. Firstly, a photoresistor that uses higher acquisition rates can replace the one that is used now. A more accurate photoresistor means that more accurate data can be collected. In the case of the same laser emitter, the more accurate collected data will present an image closer to the square waveform, and the result will be more accurate when demodulated. Secondly, other tools can be used to analyze the experimental data, such as oscilloscopes, FFT spectrum analyzers, etc., to make the experimental error smaller.

## 4. Conclusion

A crucial piece of equipment for signal processing, lock-in amplifiers are utilized extensively in engineering, medical, and scientific domains. Separating the target signal from the background noise primarily uses the synchronous detection or phase-sensitive detection technique to lock the phases of the input and reference signals. Phase-locked amplifiers are classified into digital, virtual, and analog. Each kind has unique properties, although they all operate on a similar underlying principle.

In the biomedical field, phase-locked amplifiers are used to process low-frequency signals from tiny organisms, such as electrocardiograms and electroencephalograms. In the communication system, it can improve the receiver's sensitivity to the signal and is used in the fields of radio and satellite communication. In terahertz technology, phase-locked amplifiers can be used for nondestructive testing and imaging, expanding the application range of material characterization and imaging techniques. In addition, phase-locked amplifiers in optical imaging and coherence tomography also play an important role in improving image quality and resolution.

When designing a phase-locked amplifier, several factors need to be taken into account, including power consumption, phase adjustment, and dynamic range. A reasonable design can guarantee a phase-locked amplifier with good signal processing capabilities and stable operation in various environments. Generally speaking, phase-locked amplifiers are excellent tools for signal processing because they can handle low-frequency signals. They also offer dependable technical assistance for a wide range of engineering and scientific applications.

It is anticipated that lock-in amplifier development in the future will concentrate on boosting automation, increasing feature integration, raising sensitivity, broadening frequency ranges, and improving noise suppression capabilities. To meet a wide range of application requirements, these developments provide more powerful instruments for engineering and scientific study.

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