Proceedings of CONF-FMCE 2025 Symposium: Semantic Communication for Media Compression and Transmission
DOI: 10.54254/2755-2721/2025.GL24771

Advanced Applications of Lock-in Amplifier Technology in Modern Signal Detection Systems

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Abstract. Weak signal detection is a fundamental need across fields such as biomedical imaging, environmental monitoring, and nanoscale sensing. Traditional signal extraction methods struggle with poor noise rejection when dealing with signals with low signal-to-noise ratio (SNR), thereby limiting accuracy and reliability. Lock-in amplifier (LIA) technology addresses this gap by utilizing phase-sensitive detection to extract signals of interest buried in noise. This paper explores the principles of LIA operation, mathematical modeling, and digital implementation. Through detailed case studies, including fluorescence microscopy, electrochemical biosensors, interferometric vibration detection, and quantum magnetometry using NV centers, the paper demonstrates LIA's superior sensitivity and noise immunity. Further discussion highlights current challenges such as analog limitations and low-pass filter delay, alongside innovations in digital FPGA-based systems and AI-enhanced adaptive signal processing. The paper concludes with the identification of emerging interdisciplinary applications and proposes directions for future technological expansion and integration. The results support LIA as an indispensable tool in next-generation sensing and diagnostic systems.

Keywords: Lock-in Amplifier, Weak Signal Detection, Phase-Sensitive Detection, Digital Implementation

1. Introduction

Weak signal detection plays a vital role in scientific research and engineering. This process is applied not only in biomedical and optical imaging but also in environmental monitoring and materials testing, thus requiring researchers to extract useful information from exceedingly weak signals. However, these signals are often obscured by strong background noise, thus presenting several challenges to traditional measurement methods in terms of achieving high precision and sensitivity. This limitation severely restricts the development of related technologies and the reliability of subsequent practical applications.

To address the abovementioned issues, researchers have developed lock-in amplifiers (LIAs), which have gained extensive attention and application due to their superior interference resistance and remarkable signal-to-noise ratio (SNR) enhancement. Through the phase-sensitive detection between the input signal and a reference signal, LIAs can accurately extract the target frequency component and significantly suppress other noise components, thus facilitating the effective

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identification and amplification of previously obscured signals. Due to its several advantages, LIA technology has been utilized in various high-precision experimental systems since its inception and application, thus establishing itself as a crucial tool for weak signal detection.

The effectiveness of LIA technology has been validated in multiple practical cases. For example, in fluorescence endoscopic imaging, researchers have combined modulated light sources with fast digital lock-in algorithms to improve image definition. Experimental data show that the SNR of fluorescence images increased from 33.47 dB to 35.70 dB, while the SNR of white light images rose from 36.56 dB to 39.54 dB, fully demonstrating the advantages of phase-sensitive signal extraction [1].

Additionally, Scofield proposed a frequency-domain LIA model, which promoted the standardized application of this technology in physical measurements [2]. Karki et al. achieved the high-precision detection of picoampere-level currents at nanomolar concentrations by applying LIAs to electrochemical biosensors [3]. Meanwhile, Collett and Wolf employed LIAs to detect subnanometer vibration signals that are difficult to identify using traditional methods [4].

The above studies have demonstrated that LIAs are not only powerful tools for signal extraction but also high-precision measurement platforms with broad application prospects, which can be applied to multiple scientific and engineering fields. This paper aims to systematically review the theoretical basis and latest progress of LIA technology, analyze its application effects in different fields, and explore its future development trend and integration prospects in intelligent sensing systems.

2. Theoretical basis and principle

LIAs are an effective high-sensitivity signal detection method used to extract weak signals from strong background noise. The basic principle behind LIAs is phase-sensitive detection, which modulates the target signal to a known reference frequency. This chapter explains the theoretical principles of LIAs from several perspectives, namely, mathematical modeling, signal mixing, frequency filtering, and modern digital implementation.

2.1. Principle of phase-sensitive detection

The core principle of LIAs is to multiply the input signal $V_{in}(t)$ by a reference signal $V_{ref}(t) = \sin(\omega t)$. The product signal contains a zero-frequency (DC) component and a double-frequency component:

$$V_{mix}(t) = V_{in}(t) \bullet \sin(\omega t) = \frac{1}{2} A\cos(\theta) + high - frequency\ components, \quad (1)$$

where θ represents the phase difference between the input and the reference signal. After filtering out the high-frequency components using a low-pass filter, it determines that the remaining DC output is $\frac{1}{2} A\cos(\theta)$, which is directly related to the amplitude and phase of the original signal. This phase-sensitive detection mechanism allows the system to selectively amplify signals that are coherent with the reference frequency while suppressing unrelated noise components. Thus, the system is particularly suitable for handling typical interference sources such as 1/f noise, thermal noise, and harmonics.

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2.2. Mathematical modeling and signal spectrum analysis

The input signal is usually modeled as follows:

$$V_{in}(t) = A\cos(\omega t + \theta) + n(t) \tag{2}$$

where n(t) signifies the noise component. After multiplying with the reference signal, trigonometric identity transformations can convert the signal into the desired DC component and high-frequency components. This process depends on the cutoff frequency and time constant of the low-pass filter, both of which dictate the trade-off between the system's bandwidth and response speed. The relationship between bandwidth Δf and integration time τ is given by

$$\Delta f = \frac{1}{4\tau} \tag{3}$$

This means that integration time must be increased to enhance noise resistance (narrow bandwidth), thus resulting in longer response times.

2.3. Noise suppression capability and frequency selectivity

One of the greatest advantages of LIAs is their strong frequency selectivity, which enables the accurate extraction of a signal with an intensity that is only 1/10,000 of the background noise when its frequency equals that of the reference signal. The detection bandwidth can also be configured by adjusting the parameters of the low-pass filter, thus selectively suppressing various broadband or narrowband interferences. Moreover, due to the modulation–demodulation structure, LIAs inherently possess strong capabilities to resist DC drift and low-frequency fluctuations, thus ensuring their exceptional performance in long-term stable measurements.

2.4. Digital Lock-In Amplifiers (D-LIAs)

Modern LIAs generally employ field programmable gate array (FPGA), digital signal processors (DSP), or microcontroller platforms, with such digital implementations offering high precision, great flexibility, and real-time adjustability.

Furthermore, modern D-LIAs are capable of simultaneously tracking multiple reference signals and performing vector detection by analyzing both amplitude and phase components. These systems support advanced features such as automatic phase calibration, phase-locked loop (PLL) control, adaptive filter parameter adjustment, real-time spectrum visualization, and built-in signal generation with multi-channel sampling capabilities [5]. These enhancements enable lock-in amplifiers to transcend their traditional role as laboratory instruments and become core components in embedded systems and portable devices.

3. Case studies: practical applications of LIA technology in multiple fields

This chapter introduces the validated applications of LIAs in fluorescence imaging, biosensors, optical metrology, and quantum measurements, further illustrating the effectiveness of LIAs in high-sensitivity, low-noise signal extraction. This chapter offers four representative examples to validate the application advantages and practicality of LIAs.

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3.1. SNR enhancement in fluorescence microscopy imaging

Fluorescence microscopy is one of the most widely used research technologies in life sciences, one that assumes a significant role in organelle structure research, protein localization, and disease diagnosis. However, this technology often requires extremely weak fluorescence, making it highly susceptible to contamination from background light, autofluorescence, and system noise. Wang et al. developed a D-LIA-based fluorescence signal detection system that modulates the excitation light source at a specific frequency and uses high-speed D-LIA algorithms for coherent demodulation of fluorescence emissions [1].

The experimental results indicate that the signal-to-noise ratio (SNR) of fluorescence images increased from 33.47 dB to 35.70 dB, while that of white light images rose from 36.56 dB to 39.54 dB. These improvements collectively demonstrate the efficacy of the lock-in amplifier system in enhancing image quality and suppressing noise [1].

These improvements not only enhance image contrast and resolution but also reduce background noise, thereby boosting the reproducibility and stability of cell structure images. In turn, these results confirm the feasibility of live cell microscopic imaging through LIAs.

3.2. Microcurrent detection in electrochemical biosensors

Electrochemical biosensors typically produce weak current responses as output signals. However, these are easily obscured by environmental thermal noise and electrode noise. Karki et al. adopted an LIA-based glucose detection platform to improve the system's current resolution through the demodulation of current responses to periodic potential modulation [3].

The main achievements include the successful detection of picoampere-level currents, the attainment of nanomolar-level glucose detection limits, and the consistent maintenance of excellent linearity even under complex laboratory noise conditions.

Furthermore, the system exhibits higher sensitivity than traditional amperometric methods and adapts well to real-time response processes, thus offering a technological pathway for portable, low-power, point-of-care diagnostic devices.

3.3. Subnanometer resolution in optical interferometric measurements

In the fields of nanotechnology and metrology, high-precision displacement and vibration detection are considered important detection indicators. Collet et al. coupled LIA technology with interferometers to stably detect minute displacements at the subnanometer level [4]. They obtained results by modulating the surface of a piezoelectric reference mirror and performing lock-in demodulation of the interference phase difference.

The experimental system demonstrated the ability to achieve a displacement resolution as fine as 0.3 nm, offering superior signal stability when compared to conventional FFT and other time-averaging methods. Furthermore, its robustness and precision make it well-suited for applications such as atomic force microscope calibration, microvibration monitoring, and optical encoder systems [4].

This study indicates that LIAs can effectively expand the sensitivity limits of interferometric measurement systems while serving as a crucial technical foundation for precise nanoscale measurements.

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3.4. Quantum magnetic field sensing based on Nitrogen Vacancy (NV) centers

NV centers, which are controllable quantum defects within diamonds, find extensive use in the fields of high-resolution magnetic field detection and quantum imaging. The LIA's demodulation capability for fluorescence response signals is significantly improved by modulating the excitation microwave or laser, thereby greatly elevating the SNR and magnetic field sensitivity.

The experimental results demonstrated that the system improved magnetic field sensitivity by approximately fivefold, enabled precise detection of alternating current (AC) magnetic fields in the range of tens of nanoteslas, and supported real-time imaging and analysis of material magnetic domains. These outcomes highlight the strength of lock-in amplifiers in advancing the performance of quantum magnetometry based on NV centers, particularly in terms of enhancing signal-to-noise ratio and spatial resolution [6].

This method showcases the potential applications of LIAs in nanoscale quantum measurements and provides a technical basis for high-throughput, noninvasive magnetic imaging.

4. Challenges and future development

Although LIA technology exhibits outstanding interference resistance and detection sensitivity in many areas, technical and engineering bottlenecks in practical applications remain. These require future developments to emphasize scalability, timeliness, intelligence, and interdisciplinary use of system networking.

4.1. Bottlenecks of traditional technology

Traditional analog LIAs rely on reference signals with fixed frequencies and known phases. Therefore, for nonperiodic signals or signals with frequency drift, the demodulation performance of LIAs significantly decreases and may nearly fail when demodulating transient signals or broad-spectrum responses [7]. Additionally, low-pass filters in analog LIAs can filter out high-order harmonic noise. However, at the same time, they cause a considerable response delay, which prevents the system from obtaining high response speed. According to the literature, the time delay also makes LIAs difficult to apply in control feedback systems [6]. Furthermore, analog circuits often experience output offset or saturation after extended operations due to several factors, including device mismatch, temperature drift, and radio frequency noise [8].

4.2. Rise and optimization of digital systems

To overcome the limitations of analog LIAs, researchers have proposed D-LIAs based on FPGA/DSP to gradually replace analog LIAs. In addition to providing substantial advantages in circuit device integration, FPGA/DSP-based D-LIAs allow users to perform real-time adjustments to the system reference frequency, phase adjustment parameters, and band-pass filter parameters during operation [9]. These functions enable the system to operate with relatively strong adaptability, making D-LIAs especially suitable for complex or variable-frequency signals.

For example, Hoffmann et al. reported a microcontroller-based D-LIA that works stably over a range of temperatures and can be used in wearable sensing systems [9]. The literature indicates that adaptive filtering algorithms in D-LIAs can automatically modify the bandwidth based on real-time variations of the input signal, thereby enhancing detection efficiency [10].

Additionally, software-defined LIA architecture supports remote management and online upgrades while also improving the implementability of systems in real-world testing and distributed

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measurement networks.

4.3. Integration of AI and intelligent modulation

A development trend that has emerged in recent years is the application of AI and machine learning to LIA systems for enhanced signal demodulation. For instance, Zhou et al. designed convolutional neural networks (CNN)-based adaptive LIAs, which can automatically detect signal frequency, amplitude, and optimal phase and demodulate signals without being affected by high-noise environments [6].

AI-enhanced lock-in amplifiers (LIAs) offer several distinct advantages over traditional systems. These include adaptive frequency tracking that enables dynamic identification of reference signal fluctuations, noise pattern recognition that facilitates the extraction of target features from broadband interference, and edge decision analysis suitable for integration into embedded intelligent sensing platforms. Such advanced capabilities have been effectively implemented in applications such as autonomous vehicle sensors, satellite communication systems, and deep-space telemetry. Together, these innovations improve the system's noise resilience, fault tolerance, and real-time decision-making performance [6, 11].

4.4. Interdisciplinary applications and future expansion

With the growing demand for sensing and measurement in fields such as IoT, biomedicine, and environmental science, LIA technology is gradually being integrated into various interdisciplinary platforms. Terahertz imaging: Terahertz systems incorporating LIAs enable the noncontact detection of internal material defects. Such systems have also been applied to quality control in integrated circuit packaging [12].

Microfluidic biosensors: Lock-in demodulation technology is utilized in label-free conductance detection, facilitating the real-time monitoring of single-cell electrical behaviors [13]. Atmospheric environmental monitoring: LIAs combined with photoacoustic or modulated absorption spectrometers can achieve the continuous monitoring of ppb-level pollutant gases (NO_2, SO_2, etc.) and have been deployed in mobile field stations [14]. The modularity, digitization, and interference resistance of LIA technology make it a crucial component in "sensing-processing-feedback" closed-loop control across various intelligent systems.

5. Conclusion

Low signal detection is critical to many disciplines, including biomedical imaging, environmental sensing, and nanoscale sensing. Conventional signal extraction processes lack satisfactory noise rejection for detecting signals with low signal-to-noise ratio (SNR), leading to inaccurate and unreliable detection results. Lock-in amplifier (LIA) technology successfully compensates for this by employing phase-sensitive detection for identifying the signals of interest embedded under noise. The present paper, it considers the theory of operations of the LIA, the mathematical modelling, and the digital realization of it. As case studies on a number of applications, including a fluorescent microscope, an electrochemical biosensor, an interferometer to measure vibration, quantum magnetometry based on NV centers, and so forth, it clarifies the advantages of sensitivity and insensitivity against noise of the LIA. This section continues with a discussion about existing limitations, including analog and the delay imposed by low-pass filters, the latest advancements in digital FPGA implementation, as well as the integration of AI machine learning used in designing

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adaptive signal processing to dynamically derive the optimum phase parameters. Finally, it concludes by discussing the emerging interdisciplinary applications of the LIA and possible directions for future development in technologies that can be integrated and extended to add future functionalities. Overall, this reinforces the case that LIA serves as a critical function that can form the backbone of next-generation sensing and diagnostics systems.

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