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Digital Lock-In Amplifier Technology for Harsh Environments: Challenges and Advances

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Abstract. Accurate detection of weak signals is crucial in the field of modern mechanical engineering, as these signals carry key information such as equipment status, early damage, and parameter changes, but they are easily overwhelmed by noise due to their extremely low amplitude, making them difficult to measure effectively by traditional methods. Lock-in amplifiers (LIA) use phase-sensitive detection technology to recover signals in noisy environments with a high signal-to-noise ratio by taking advantage of the frequency and phase properties of the signal and the reference signal. This paper reviews the research progress of digital lock-in amplifier (DLIA) in the field of mechanical engineering, and discusses the advantages and challenges of its detection technology under high temperature environments, low signal-to-noise ratio, and multi-frequency signal conditions. Based on literature review and case analysis, the efficacy of DLIA at elevated temperatures, the estimation ability of frequency amplitude under low signal-to-noise ratio, and the early fault diagnosis effect of rolling bearings are elaborated in detail. The results show that the DLIA can maintain good linearity at a high temperature of 200 °C, has a high detection accuracy for multi-frequency signals in a low signal-to-noise ratio environment of −1 dB, and can identify bearing fault signals several weeks in advance, which significantly improves the safety and economy of equipment operation. In the discussion section, the limitations of DLIA, it was proposed that future research should focus on algorithm optimization and system integration to improve performance and stability in complex environments.

Keywords: weak signal, lock-in amplifier, digital lock-in amplifier, phase sensitivity detection, fault diagnosis

1. Introduction

Detecting weak signals is of great importance in the field of modern mechanical engineering. Weak signals often include important information such as equipment operating status, early damage, or changes in critical parameters, but due to their extremely small amplitude, they are easily submerged in the background of high noise, resulting in the inability of traditional measurement methods to effectively obtain information about these signals.

For example, in the fields of mechanical vibration diagnosis, crack detection, electromagnetic disturbance monitoring, etc., how to effectively obtain weak signals has become the key to

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maintaining the safe operation of equipment, prolonging equipment life, and improving production efficiency. Therefore, the development of an efficient and stable weak signal detection technology is of great significance and has a wide application prospect for the development of the field of mechanical engineering [1]. LIA is an apparatus engineered to isolate faint signals from a noisy environment.

It is based on phase sensitivity detection (PSD) technology, which effectively improves the signal-to-noise ratio and detection accuracy of weak signals by using the specific relationship between frequency and phase between the signal and the reference signal.

Traditional analog lock-in amplifiers have the advantages of simple circuits and fast response speed, but they also have problems such as zero drift, temperature drift and high noise of analog components, which make them have obvious limitations in high-precision long-term measurement [2]. In order to overcome these limitations, researchers have focused more on digital lock-in amplifiers (DLIA) in recent years. Digital lock-in amplifiers achieve high-precision, low-noise signal detection through digital signal processing technologies such as the discrete Fourier transform and field-programmable gate array (FPGA) [3]. For example, Cheng. proposed a digital lock-in amplifier scheme for high-temperature environments (up to 200 °C), which successfully achieved reliable detection of nanovolt signals, demonstrating the advantages of digital technology in high-temperature scenarios.

In addition, Wang proposed a software digital lock-in algorithm based on automatic frequency estimation, which significantly improves the measurement accuracy under the conditions of low signal-to-noise ratio and multi-frequency signal, and expands the application scenarios of digital amplifiers. In practical engineering applications, such as early fault detection of rolling bearings, digital lock-in amplifiers also show great advantages, as they can identify fault signatures weeks in advance, greatly improving the safety and economy of the equipment [4]. Given the shortcomings in the current research, it is of great practical significance to further discuss and further improve the performance of digital lock-in amplifiers in complex environments, especially in high temperature, low ratio of signal to noise, along with multi-band real-time detection. At present, although there are many studies on the detection and extraction technology of weak signals in high-temperature environments, most of them are limited to performance evaluation under single-frequency or single-channel conditions, and there is a lack of in-depth research on comprehensive problems such as thermal stability control, computational efficiency optimization, and multi-frequency parallel processing.

In this paper, the latest research progress of digital lock-in amplifiers in the field of mechanical engineering in recent years is comprehensively and systematically reviewed, and the technical advantages and challenges of digital lock-in technology under high temperature conditions, low signal-to-noise ratio conditions, and multi-frequency signal real-time processing conditions are discussed in detail. It aims to provide a systematic reference for researchers and engineers in the field of mechanical engineering, clarify the future research direction, and promote the development of theories and technologies in this field.

2. Theoretical foundations

2.1. The significance of weak signals

A weak signal is a signal with a very low amplitude, but in the field of mechanical engineering, it carries important physical information. For example, vibration signals of mechanical equipment, sound emission signals of cracks after wear, and electromagnetic disturbance signals. Their key

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feature is that they have a very low signal-to-noise ratio and are easily overwhelmed by background sounds, making this information impossible to obtain with conventional measurement techniques

2.2. The basic concept of lock-in amplifiers

In order to solve the problem of extracting weak signals, lock-in amplifiers are widely used in this field. PLA is a measurement instrument that can directionally extract the frequency of a target signal from a cluttered background. PLA is a Phase phase-sensitive detection (PSD) technique that uses the specific relationship between the frequency and phase of the target to be detected and the reference signal to filter the background sound and improve the extraction accuracy of the weak target signal [5].

Modern lock-in amplifiers often use two-channel demodulation. The principle is to multiply the input signal with two quadrature reference signals and low-pass filtering, respectively, the result is two DC output signals X and Y. This technique allows for the simultaneous acquisition of the signal's amplitude and phase information.

The use of this dual-channel demodulation method can effectively extract the signal amplitude to a great extent, and at the same time provide more accurate phase information, which is more conducive to the comprehensive analysis of the dynamic characteristics of the mechanical system.

2.3. Structure and limitations of the analog LIA

The earliest LIA was realized by using analog circuits, which mainly included three parts, namely the input signal conditioning circuit, the phase sensitivity detection circuit, and the low-pass filter circuit. The signal to be measured is first fed into the preamplifier to boost the signal to a detectable level, and as the signal is delivered to an analog multiplier (consisting of an analog switch and mixer), To finish the phase-sensitive detection, the reference signal and the signal to be measured are combined. Finally, it is handed over to the low-pass filter, which completes the filtering of the high-frequency part of the signal and only retains the DC component output of the target frequency, so as to achieve accurate extraction.

Although the analog lock-in amplifier is easy to implement and has a fast response speed, it also has many limitations, such as zero drift and temperature drift of the analog circuit, which will produce a large offset due to the change of environmental conditions (especially temperature), which reduces the stability of long-term measurement. Due to the high noise of analog circuits, accurate measurements are often impossible due to errors, so the actual use of analog lock-in amplifiers is limited by the conditions and accuracy of use.

2.4. Key performance indicators and analysis

The performance index of the DLA mainly includes four points, namely signal-to-noise ratio (SNR), dynamic reserve (Dynamic Reserve), and spurious-free dynamic range (SFDR). The SNR determines the resolution of the lock-in amplifier for weak signals, which is most directly related to the accuracy and stability of the measurement. The higher this index, More importantly, for engineering applications, the more robust the anti-interference capability is, the more it can still identify weak signals steadily.

Phase noise mainly affects the accuracy of the phase of the signal measurement results, especially in high-precision occasions, and its magnitude will directly affect the stability and authenticity of the measurement results. The spurious-free dynamic range reflects the effective measurement range of

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the series system without interference and nonlinear distortion, which is of great significance for mechanical vibration monitoring and precision instrument calibration.

3. Case analysis

3.1. Case 1: Performance experimental verification of digital phase locked amplifier (DLIA) under high temperature conditions

To verify the extraction of weak signals from the DLIA at high thermal measurement, the researchers built a complete experimental platform and tested the linearity of the system at four different temperature conditions [6]. A straight line with an 800 kHz frequency and a variety of amplitudes makes up the input signal. 94.8 to 1896 nV, and the output voltage of the DLIA is measured by adjusting the output of the signal source, and the relationship between the input amplitude and the output voltage is analyzed.

At 800 kHz, the input signal is a sine wave with an amplitude range of 94.8 to 1896 nV, and the output voltage of the DLIA is measured by adjusting the output of the signal source, and analysis is done on the connection between both output and input amplitudes.

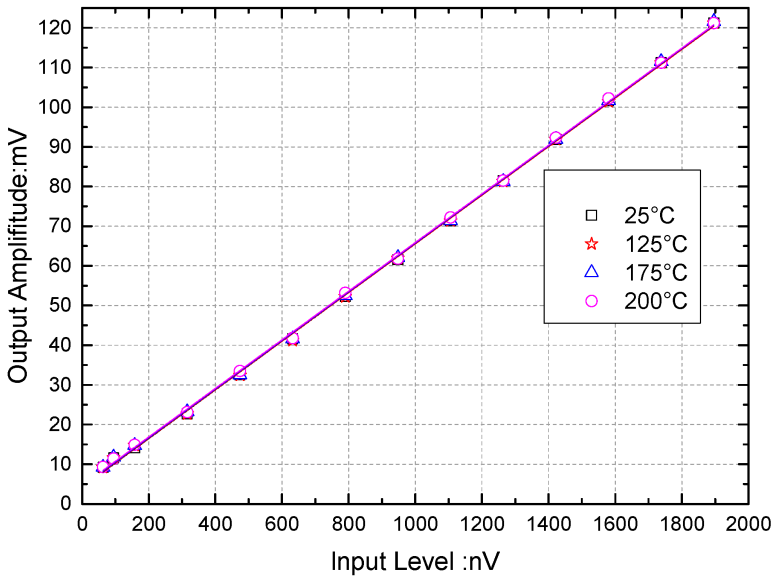

Figure 1: The output of DLA varies with the sine wave input of the variable amplifier(photo/picture credit: original)

Table 1: Relative nonlinearity error and comparable gain of DLA at varying the level of heat

parameter	temperature：T（°C）			
	25	125	175	200
ε	1.488%	1.488%	1.653%	1.736%
Equivalent gain (dB)	96.210	96.210	96.187	96.311

As can be seen from Figure 1, there is an obvious linear relationship between the output voltage of DLIA and the amplitude of the input signal at different temperatures, which indicates that the system has a strong signal amplification consistency.

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Combined with the quantitative analysis provided in Table 1, the nonlinearity error of DLIA is no more than 1.736%, and the equivalent gain is close to 96.2 dB at all four test temperatures. These data together verify that the DLIA can still maintain high-precision output under a thermal stress environment, and has excellent temperature drift resistance and signal fidelity.

3.2. Case 2: Experimental verification of software lock-in amplifier in multi-frequency signal detection with low signal-to-noise ratio

Based on the Discrete Fourier Transform (DFT), the researchers proposed an automatic frequency estimation algorithm, which can automatically generate a reference signal for the LIA under the condition of unknown signal frequency, and test the accuracy of the DLIA system for amplitude and frequency detection under multiple different signal-to-noise ratio (SNR) conditions. Weak signals at multiple frequencies are injected into the simulated signal source, and the output of the system is used to calculate the detection error and relative bias.

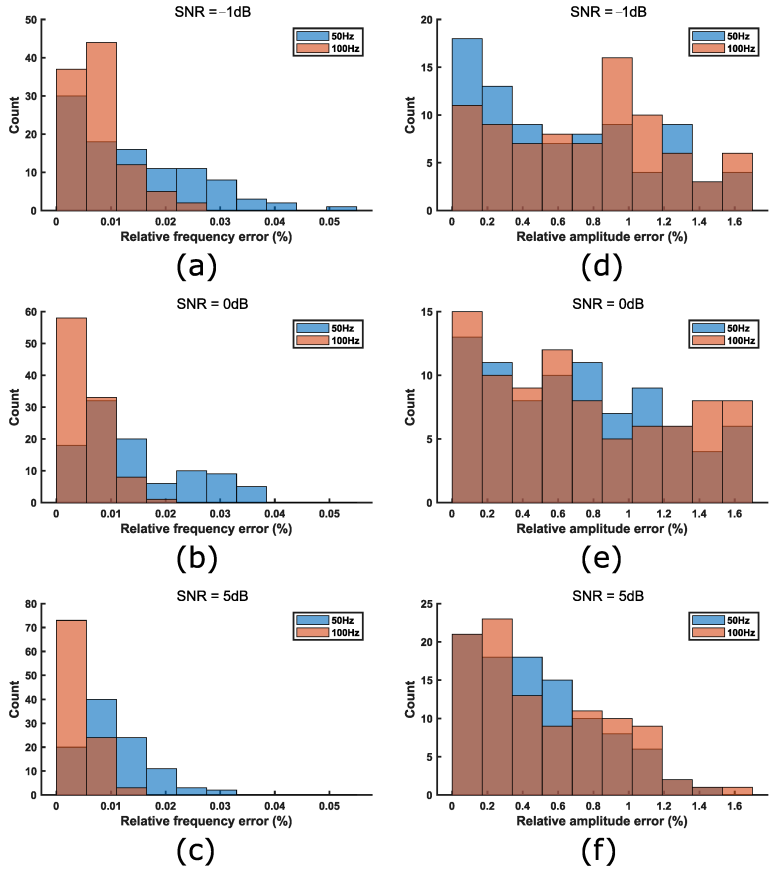

Figure 2: Distribution of the suggested DLIA method's frequency and amplitude estimation results (photo/picture credit: original)

As shown in Figure 2, even under the extremely low signal-to-noise ratio condition of SNR of −1 dB, the estimation error of the target frequency of the system is still less than 0.1%, and the amplitude detection error is controlled within 1.7%, which verifies the high robustness of the DLIA algorithm under low SNR.

The error of frequency estimation and amplitude demodulation decreases significantly with the increase of SNR, showing good noise adaptability. The system can also maintain a high recognition

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rate in the case of multi-frequency signals and extreme signal-to-noise ratios, showing its practicality in complex signal environments.

3.3. Case 3: Experimental verification of micro-vibration signal detection of early fault of rolling bearing

In order to verify the performance of the LIA in the early fault diagnosis of rolling bearings, the researchers designed a detection system consisting of a high-sensitivity accelerometer and a DLA to lock the characteristic frequency of the bearing inner ring fault with a target frequency of about 600 Hz [7].

In the experimental process, the bearing vibration signal was collected and processed by LIA and the traditional FFT method, and the signal-to-noise ratio, frequency clarity, and fault identification ability of the output results were compared. The findings of the experiment indicate that the LIA system can stably extract the 600 Hz eigenfrequency components under the strong noise background interference, while the traditional FFT analysis fails to resolve the obvious fault spectrum under the same signal conditions.

With LIA, the signal-to-noise ratio is improved by more than 20 dB, and fault signals can be accurately identified two weeks in advance, demonstrating the system's significant advantages in weak signal extraction and early diagnosis.

4. Discuss challenges and improvements

The system adaptability of weak signal extraction devices has also become the focus of research in recent years, and many studies have extended lock-in amplifier platforms to interdisciplinary fields, such as magnetic resonance and analytical chemistry [8]. Through the comparison of the three cases, it can be seen that the lock-in amplifier shows good weak signal extraction ability and system adaptability in different application scenarios.

Case 1 focuses on the telecommunication linearity amplification in an extremely high temperature environment, and the system's dependability in the face of great heat is demonstrated by the experimental results, that demonstrate that it can retain a high fit and stable gain even at 200°C.

The second case verifies the adaptability of the DLIA based on the DFT algorithm in the environment of unknown frequency and strong noise, and possesses excellent anti-interference and detecting accuracy. In contrast, case 3 is closer to the actual scenario of mechanical engineering, and the weak fault signal of the rolling bearing is measured, and the eigenfrequency is stably identified in advance in a complex background, which has strong engineering application value.

In all three cases, the digital lock-in amplifier accurately extracts weak signals and has excellent system stability, but the experimental results also show its limitations in different scenarios.

In case 1, although DLIA can maintain stable extraction capability at a high temperature of 200°C, the system used is limited by a fixed structure and analog hardware parameters, which makes it difficult to adapt to a wider range of signals. In the case of SNR multi-frequency signal recognition in case 2, although DLIA uses the DFT algorithm to achieve automatic frequency estimation, the actual performance is still limited by the ADC resolution and anti-aliasing filter performance in extreme noise environments [9].

Recent studies have also pointed out that even with the introduction of adaptive filtering or high-precision FFT schemes, DLIA systems still face ADC accuracy bottlenecks and mixing interference residues under the conditions of multi-frequency interference and ultra-low amplitude input [10].

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Figure 3 shows the limitations of the improved anti-interference performance due to high τ at the cost of slower measurement response.

Case 3 highlights the sensitivity of LIA in extracting micro-vibration signals in the event of mechanical failure, but it is still inevitably affected by 1/f noise in low frequency bands (e.g., 600Hz), especially when using low-end hardware platforms. As can be seen in Figure 4, in an OLI architecture using a 12-bit ADC with a simple antialiasing filter, the measurement sensitivity is limited, with a minimum effective measurable amplitude of about 0.81 μV.

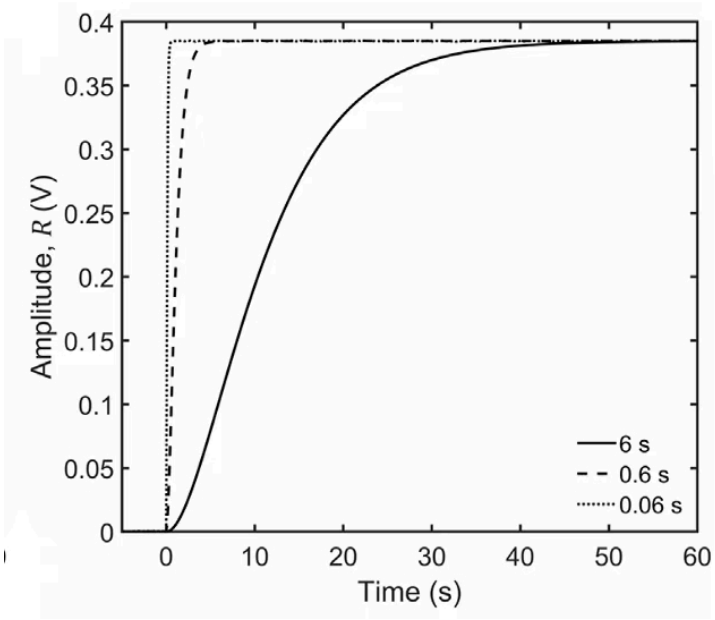

Figure 3: Response curves of lock-in amplifiers to sudden changes in signal amplitude at different time constants (photo/picture credit: original)

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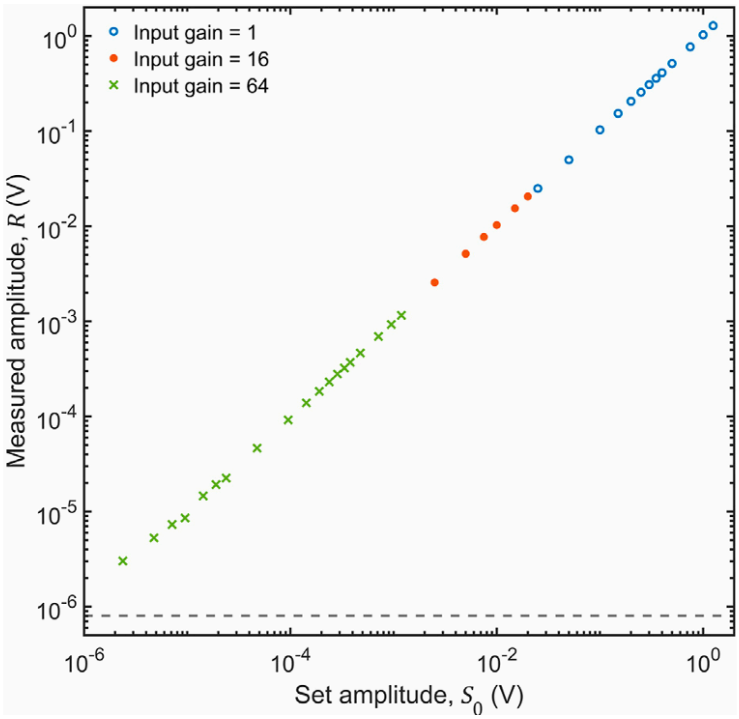

Figure 4: For a sinusoidal input signal of 1 kHz, the ratio of the measured intensity R to the input signal's amplitude (photo/picture credit: original)

5. Conclusion

In this paper, the principle, structure, and practical application of lock-in amplifiers in weak signal detection are discussed, focusing on the adaptability of digital lock-in amplifiers in extreme environments, such as high temperatures, low signal-to-noise ratios, and actual mechanical systems. Through the analysis of three case experiments, it is verified that the digital lock-in amplifier still maintains stable linear output ability at 200°C high temperature, high robustness to multi-frequency signals under the condition of extremely low signal-to-noise ratio of -1 dB, and the performance of early detection of special excellent frequencies of rolling bearing faults.

The experimental results show that the digital lock-in amplifier not only has strong anti-temperature drift, anti-noise, and automatic frequency tracking capabilities, but also can effectively improve the signal-to-noise ratio of the characteristic signal by more than 20 dB. Although there are still challenges, such as ADC resolution limitation and 1/f noise interference under specific conditions, its overall performance has been significantly better than that of traditional analog LIA, and it has a wide range of practical value in complex engineering environments. Although digital lock-in amplifiers perform well in high-temperature and weak signal detection, they still have some limitations.

For example, the influence of 1/f noise in the system at very low frequencies is not fully suppressed, and the ADC resolution and sampling rate are highly dependent. In addition, there is still room for optimization in terms of volume and power consumption of existing structures.

Future research can focus on integrated circuit optimization, low-noise algorithm design, and multi-channel parallel processing architecture to improve system adaptability and real-time performance.

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