

Real-time FPGA-LabVIEW homebuilt system for noise reduction in AFM imaging

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Abstract: Atomic force microscopy (AFM) probe vibration monitoring is essential for achieving accurate nanoscale imaging and reliable signal interpretation. This paper presents a low-noise vibration detection method based on a real-time FPGA-LabVIEW homebuilt system. The FPGA receives signals from a quadrant photodiode (QPD), performs analog-to-digital conversion and parallel processing, and integrates cascaded digital filters for noise reduction. A finite impulse response (FIR) low-pass filter extracts the static spot position, while an infinite impulse response (IIR) band-pass filter preserves the probe's resonance vibrations. Compared with conventional analog detection, the proposed system reduces background noise by approximately 50% (measured as 50.23%), enhances the signal-to-noise ratio (SNR) from 15 dB to 20 dB, and maintains FPGA signal-processing latency below 5 μ s. This work demonstrates that the proposed real-time FPGA-LabVIEW AFM noise optimization system significantly improves signal-to-noise ratio and real-time performance, providing a practical solution for high-precision, low-noise AFM imaging.

Key words: atomic force microscopy (AFM); FPGA-LabVIEW homebuilt system; real-time processing; noise reduction; digital filters

0 Introduction

Atomic force microscopy (AFM) is a nanoscale characterization technique widely used to acquire topographical, mechanical, and physicochemical properties of samples, playing a critical role in materials science and biology^[1-5]. Detection of tip-sample interaction forces is the key in AFM, which relies on highly sensitive probe deflection detection techniques. At present, the primary detection methods include piezoresistive^[6], piezoelectric, and its qPlus variant^[7-8], capacitive^[9], interferometric^[10], and optical beam deflection (OBD) techniques^[11-12]. Among these, the optical beam deflection method, also known as the optical lever or light deflection method, has gradually become the dominant technique for detecting probe vibration signals in AFM. This technique offers several advantages, including non-contact operation, high sensitivity, and a relatively simple structure, and it enables AFM imaging in ambient air, liquid environments^[13], and

ultra-high vacuum^[14].

In our previous work, a conventional optical beam deflection detection system based on analog circuitry and oscilloscope visualization was employed. However, this configuration suffered from high noise, limited anti-interference capability^[15], low data throughput, and restricted functionality, making it unsuitable for real-time monitoring of high-dynamic-range signals^[16-17]. Consequently, the imaging resolution and stability of AFM were constrained. To improve the detection performance of AFM systems, considerable efforts have been devoted to identifying and suppressing fundamental noise sources. Ma et al. conducted a combined theoretical and experimental study on thermal noise in contact-mode AFM, quantitatively evaluating cantilever fluctuations and their contribution to the deflection noise floor^[18]. Chen and Zou proposed a data-driven acoustic noise filtering method to suppress environmental disturbances and improve the signal-to-

noise ratio in AFM imaging^[19]. In addition, Chen et al. introduced a non-local means filtering approach for AFM image denoising^[20], while Zhang et al. proposed a Bayesian compressed sensing method to suppress impulse noise while preserving nanoscale structural details^[21]. These studies highlight the impact of thermal, acoustic, and electronic noise in AFM systems.

Besides noise suppression, improvements in signal acquisition and processing architectures have also been explored to enhance AFM measurement performance. For instance, digital signal processor (DSP) based systems enhanced signal processing through software algorithms but still encountered latency in high-frequency signal handling^[22]. Meanwhile, application-specific integrated circuit (ASIC) based solutions eliminated this bottleneck to achieve high speed^[23]. In contrast, field-programmable gate arrays (FPGAs) offer a promising alternative for AFM signal processing due to their parallel architecture and low-latency characteristics^[24-25]. Miyata and Fukuma proposed an advanced FPGA-implemented phase-locked loop (PLL) design, which achieved 165 kHz bandwidth and 3.2 μ s latency for high-speed FM-AFM imaging in liquid, significantly improving imaging speed^[26-27]. In these studies, the well-documented advantages of FPGAs in real-time signal processing are leveraged. Their implementation in AFM optical detection systems improves the system's bandwidth, data throughput, and overall stability.

Although commercial digital controllers and lock-in amplifiers are widely used for signal demodulation and feedback control in AFM systems^[24,26], they are typically designed for general-purpose operation and provide limited flexibility for directly modifying the optical beam deflection signal chain. For customized UHV-AFM platforms requiring application-specific filtering and microsecond-level real-time processing, a dedicated digital signal acquisition and processing architecture is therefore desirable. However, existing FPGA-based AFM systems mainly focus on feedback control or phase-locked loop (PLL) implementation, while integrated digital noise optimization within the optical beam deflection detection chain remains largely unexplored. In addition, several practical limitations persist, including suboptimal filter design, insufficient parameter optimization, inefficient coordination between FPGA processing and host-side data visualization, and limited integration with graphical programming environments such as LabVIEW^[25].

We present the real-time FPGA-LabVIEW homebuilt system for low-noise vibration detection in AFM optical

beam deflection, aiming to overcome the persistent challenges of noise interference and limited real-time performance in conventional AFM configurations. The FPGA integrates a cascaded FIR low-pass filter and an IIR band-pass filter, reducing noise power spectral density by 50.23% and improving the signal-to-noise ratio by 5 dB, while keeping the internal FPGA signal-processing latency below 5 μ s. Simultaneously, the LabVIEW host replaces conventional oscilloscopes and establishes a fully digital closed-loop workflow, supporting real-time monitoring with refresh rates above 1 kHz. By combining low noise, low latency, and high real-time performance with scalable software-hardware integration, this system not only significantly enhances AFM imaging quality and operational efficiency but also provides a high-performance, scalable, and modular framework conducive to the development of intelligent and reconfigurable precision instrumentation systems.

1 Instrument design

1.1 Design of a real-time FPGA-LabVIEW homebuilt system

The real-time FPGA-LabVIEW homebuilt system was developed to suppress mechanical and electronic noise in the optical beam deflection module of the AFM. The overall AFM measurement system is composed of an ultra-high vacuum (UHV) chamber, a Nanonis control system, a real-time FPGA-LabVIEW homebuilt module, an ion pump, and a vacuum gauge, as illustrated in Fig.1. This configuration enables precise vibration detection under low-noise and high-vacuum conditions. The AFM operates under high vacuum to minimize air damping and acoustic interference. The Nanonis control system performs scanning control and feedback control, while the FPGA-LabVIEW system handles real-time signal acquisition and digital noise optimization. Overall, the homebuilt AFM platform integrates low-noise design with high-speed, real-time operation, resulting in enhanced signal-to-noise ratio (SNR), stability, and response time compared with conventional systems.

In conventional AFM systems, the QPD outputs are processed directly by analog circuits before being transmitted to the AFM controller. In the proposed configuration, a digital processing chain is introduced into the optical beam deflection path. The QPD signals are first sampled by the ADC module. The digitized signals are then processed in real time within the FPGA. After digital filtering and logic operations, the signals are reconstructed by the DAC module and fed back to the Nanonis controller.

This modified signal path is illustrated in Fig. 1 and represents the main architectural improvement of the FPGA-LabVIEW homebuilt system.

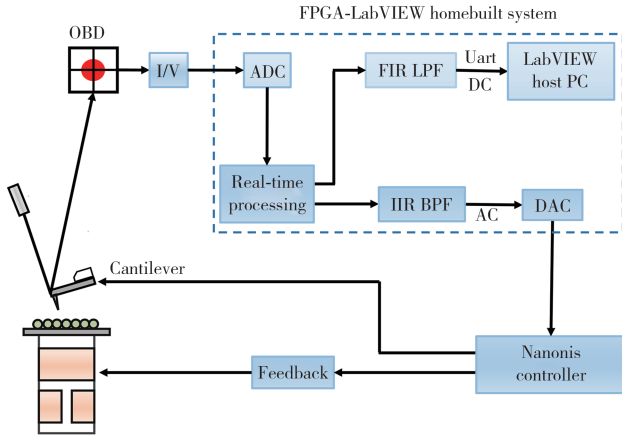


Fig. 1 Configuration of FPGA - LabVIEW co - optimized homebuilt system for noise reduction in AFM

The real-time FPGA-LabVIEW homebuilt system replaces the conventional analog detection circuit in the optical beam deflection (OBD) chain. As illustrated in Fig. 2, a laser reflected from the back of the cantilever strikes a quadrant photodiode (QPD) and generates four analog outputs, A , B , C , and D ^[28].

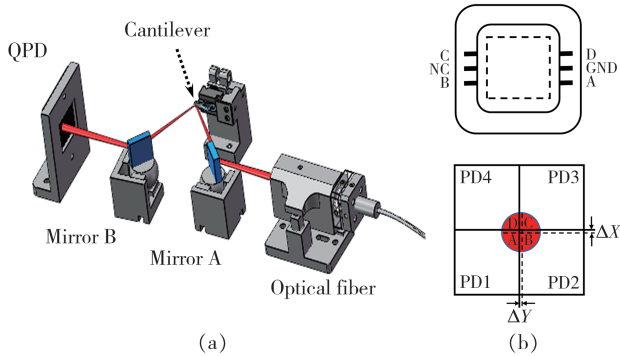


Fig. 2 Typical optical detection system in atomic force microscopy. (a) Schematic diagram of optical detection system, (b) Schematic diagram of four-quadrant photodetector

After current-to-voltage (I/V) conversion, the QPD signals are converted into low-impedance voltage outputs and fed into the high-input-impedance FPGA ADC interface, ensuring proper impedance matching and minimizing additional electronic noise during signal transmission. These signals are digitized directly by the FPGA's integrated 12-bit ADC. Inside the FPGA, the four channels are processed in parallel to calculate the differential deflection voltages along the X and Y axes. Offset correction and gain normalization are applied to compensate for detector imbalance and circuit variations. The processed data are then split into two paths: a finite impulse response (FIR) low-pass filter extracts the low-

frequency static beam-position component for monitoring, while an infinite impulse response (IIR) band-pass filter isolates the cantilever's resonance vibrations for feedback control. Consequently, this dual-path digital architecture can achieve simultaneous real-time monitoring and closed-loop imaging with low FPGA processing latency ($<5 \mu\text{s}$).

The LabVIEW host serves as the system's upper computer for monitoring, visualization, and data management. It receives the FIR-processed signals via the serial interface and displays them in real time with a refresh rate exceeding 1 kHz, allowing the operator to adjust scanning parameters, observe the laser spot position, and record vibration data simultaneously. Meanwhile, the IIR-filtered signals are converted back to analog via the FPGA's DAC and sent to the AFM controller (Nanonis) for amplitude- modulation or frequency-modulation imaging feedback. This real-time FPGA-LabVIEW architecture ensures high-fidelity vibration detection while maintaining minimal processing delay, effectively integrating monitoring and imaging control.

Compared with conventional analog detection, the digitally optimized system reduces background voltage and deflection noise density by approximately 50%, improves the signal-to-noise ratio from 15 dB to 20 dB, and maintains a processing latency below $5 \mu\text{s}$. These enhancements enable stable, low-noise probe vibration detection, resulting in significantly improved AFM imaging quality and overall system performance.

1.2 Design of an FPGA-based system for real-time AFM vibration monitoring

FPGA technology is employed as the core processing platform to meet the real-time processing requirements of the differential voltages V_x and V_y . FPGAs, widely used in digital signal processing, offer high-speed computation, parallel processing capabilities, and low power consumption^[24,26]. A Xilinx Zynq-7000 FPGA development board serves as the core processor for AFM probe vibration signal processing. The 12-bit ADC module acquires analog signals from the quadrant photodiode (QPD) at 125 MHz. The core processing logic integrates the logic operation module, a FIR low-pass filter, and an IIR band-pass filter. Processed signals are converted back to analog via the DAC module and transmitted to the LabVIEW host through the UART module for real-time visualization. This tightly integrated, parallel architecture forms the foundation for deterministic, low-latency system performance.

The signal processing workflow is illustrated in Fig.3.

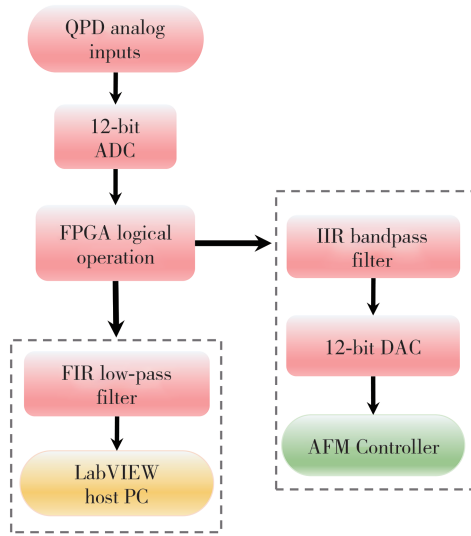


Fig. 3 Signal processing flowchart

Digitized QPD signals (A , B , C , D) are first processed by the logic operation module to calculate the real-time positional offsets V_x and V_y by

$$V_x = (A + B) - (C + D), \quad (1)$$

$$V_y = (A + C) - (B + D). \quad (2)$$

These signals are then split into two parallel pathways. The FIR path extracts the quasi-static beam position for spot calibration, which is transmitted to the LabVIEW host. The IIR path isolates Y -directional cantilever vibrations within the resonance bandwidth and outputs an analog signal to the AFM controller for closed-loop imaging. This dual-path modular architecture ensures high data throughput and maintains an FPGA internal processing latency below 5 μ s, supporting stable, real-time AFM imaging and control.

The system targets the core AFM probe vibration band (70 kHz—2 MHz) and employs a cascaded FIR low-pass and IIR band-pass filter architecture to suppress noise while preserving relevant signal components.

1.2.1 Design of FIR low-pass filter for quasi-static signal extraction

Positional signals in the X and Y directions (Δx , Δy), output from the logic unit, are primarily low-frequency DC components. To minimize the impact of circuit thermal noise on positioning accuracy, a low-pass FIR filter with strict linear-phase characteristics is employed. Its difference equation is expressed as

$$y(n) = \sum_{k=0}^{N-1} h(k) \cdot x(n-k), \quad (3)$$

where N is the number of taps of the FIR filter, i.e., the order of the filter; $h(k)$ is the k -th tap coefficient, i.e., the unit impulse response; $(n-k)$ is the input signal delayed by

k taps.

The transfer function of FIR digital filter can be represented as

$$H(z) = \sum_{k=0}^{N-1} h(k) z^{-k} = h(0) + h(1)z^{-1} + \dots + h(N-1)z^{N-1}. \quad (4)$$

The FIR filter, designed using a Hamming window to balance mainlobe width and sidelobe attenuation (-43 dB), has a cutoff frequency of 50 Hz at a sampling rate of 1 kHz. The FIR filter employs 239 taps, determined according to the required transition bandwidth and the attenuation characteristics of the Hamming window. As shown in Fig.4, it employs a direct-form structure consisting of multiple taps, delay units, multipliers, and adders. The filter coefficients were generated in MATLAB using the filter designer tool and implemented in the FPGA via an IP core. This linear-phase design ensures phase-distortion-free extraction of beam position information, effectively removing high-frequency noise and providing a high-precision foundation for real-time laser spot calibration in LabVIEW.

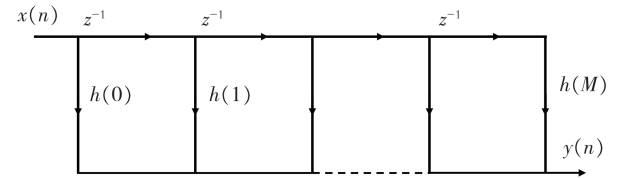


Fig. 4 Direct-form FIR filter structure designed using a Hamming window (cutoff=50 Hz, f_s =1 kHz). The filter uses multiple taps with delay units, multipliers, and adders to achieve linear-phase low-pass filtering for accurate positional signal extraction

Although linear-phase FIR filters are essential for preserving positional signal integrity, high-order FIR implementations are computationally intensive and can introduce significant latency at high sampling rates. To address this trade-off, the present design restricts the use of FIR filtering to low-frequency positional signals, whereas high-frequency vibration signals are processed using computationally efficient IIR filters.

1.2.2 Design of IIR Band-pass filter for resonant vibration detection

The AFM imaging signal is represented by the Y -directional AC voltage component, which reflects cantilever vibrations near its resonance frequency. Variations in surface topography modulate the cantilever's vibration, producing high-frequency fluctuations in the laser beam reflected onto the QPD. To extract this vibration signal, a band-pass filter is implemented following the logic operation unit, effectively removing low-frequency DC

components and high-frequency noise.

The band-pass filter employs an IIR design, which maintains acceptable phase characteristics within the passband, sufficient for AFM applications. Its simple structure, fast processing speed, and low memory usage prevent computational overload associated with high-order filters at elevated sampling rates, while maintaining high numerical accuracy and excellent frequency selectivity. The IIR filter was selected for its maximally flat passband response, effectively suppressing out-of-band noise without introducing additional distortion. Its difference equation can be expressed as

$$y(n) = \sum_{i=0}^M x(n-i) \cdot b(i) + \sum_{l=1}^N y(n-l) \cdot a(l), \quad (5)$$

where $b(i)$ represents the feedforward coefficient, $a(l)$ represents the feedback coefficient, M is the feedforward order, and N is the feedback order.

As indicated by its difference equation, the IIR filter includes a feedback network, which facilitates precise control and mitigates the effects of finite word-length limitations. In contrast, FIR filters generally require higher orders and lack feedback loops, and are typically implemented in direct-form structures. IIR filters can achieve comparable performance with substantially lower orders, enabling more efficient use of hardware resources. Consequently, cascade structures are preferred for IIR implementations. As shown in Fig. 5, the 8th-order Butterworth band-pass filter is realized as a cascade of four biquad sections $U_1 - U_4$ with quantized coefficients, ensuring numerical stability and efficient FPGA implementation.

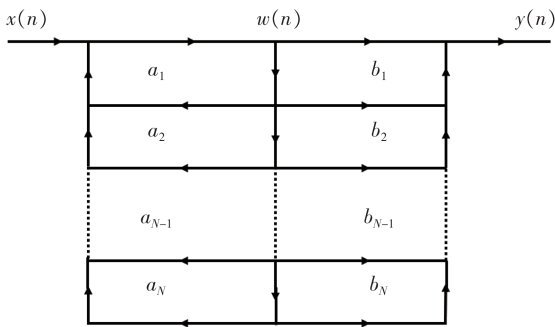


Fig. 5 Cascade-form structure of the 8th-order Butterworth IIR band-pass filter. Filter consists of four biquad sections $U_1 - U_4$ with quantized coefficients (Tables 1 – 2), providing numerical stability and efficient FPGA implementation for processing high-frequency vibration signals

The system function and signal-flow graph of this cascade-form IIR filter are

$$H(z) = A \prod_{k=1}^{N_c} \frac{1 + b_{1k}z^{-1} + b_{2k}z^{-2}}{1 + a_{1k}z^{-1} + a_{2k}z^{-2}}, \quad (6)$$

where $N_c = (N + 1)/2$ denotes the number of biquad sections $(N + 1)/2$.

The cantilever resonance frequency typically ranges from 150 kHz to 170 kHz. Therefore, we designed an IIR band-pass filter to preserve this high-frequency information while rejecting low-frequency noise. The implementation of this filter designed using MATLAB's filter designer and synthesized in Verilog for an FPGA enables real-time processing of probe vibration signals, which is critical for maintaining imaging fidelity. The filter parameters are as follows: a sampling rate of 125 MHz, a passband from 120 kHz to 180 kHz (with 0.1 dB ripple), and stopbands below 80 kHz and above 200 kHz (with 40 dB attenuation). This design results in an 8th-order, 4-section IIR band-pass filter. The 8th-order design was determined through theoretical estimation and MATLAB-based filter synthesis to satisfy the required stopband attenuation (>40 dB) and passband ripple (<0.1 dB) while maintaining efficient FPGA resource utilization. Table 1 lists the filter coefficients, including the gain coefficient G for each section. Proper configuration of G ensures consistent signal amplitude across stages and prevents arithmetic overflow.

Table 1 Coefficients of the 8th-order Butterworth band-pass filter

Section	U_1	U_2	U_3	U_4
b_0	0.965 1	0.993 8	0.957 9	0.948 5
b_1	−1.930 2	−1.987 6	−1.915 8	−1.897 0
b_2	0.965 1	0.993 8	0.957 9	0.948 5
a_0	1	1	1	1
a_1	−1.928 6	−1.986	−1.914 3	−1.895 6
a_2	0.931 6	0.989 1	0.917 2	0.898 6
G	0.965 1	0.993 8	0.957 9	0.948 5

The multi-stage IIR filter coefficients obtained from MATLAB are fractional. For efficient FPGA computation, they were quantized into 16-bit signed integers. Notably, the coefficient b_0 was quantized to a power-of-two value, enabling division via bit-shifting rather than resource-intensive arithmetic operations. The quantized coefficients are provided in Table 2. To evaluate the influence of coefficient quantization, the deviation between the floating-point coefficients and their quantized values was analyzed. The quantization results of all coefficients are summarized in Table 3. The results show that the absolute quantization error is on the order of $10^{-5} - 10^{-4}$, which corresponds to the resolution limit of the fixed-point representation. The influence of this deviation on the filter performance can be neglected.

Table 2 Quantization results of butterworth filter coefficients (16-bit signed integers)

Section	U_1	U_2	U_3	U_4
b_0	15 812	16 282	15 694	15 540
b_1	−31 624	−32 565	−31 388	−31 080
b_2	15 812	16 282	15 694	15 540
a_0	16 384	16 384	16 384	16 384
a_1	−31 598	−32 539	−31 364	−31 058
a_2	15 263	16 205	15 027	14 723

Table 3 Quantization errors between floating-point and 16-bit fixed-point IIR filter coefficients

Parameter	Coefficient value	Quantized value	Absolute error	Relative error/%
b_0	0.965 1	0.965 087	1.21×10^{-5}	0.001 25
b_1	−1.930 2	−1.930 176	2.42×10^{-5}	0.001 25
b_2	0.965 1	0.965 087	1.21×10^{-5}	0.001 25
a_1	−1.928 6	−1.928 589	1.11×10^{-5}	0.000 58
a_2	0.931 6	0.931 579 6	2.04×10^{-5}	0.002 19

These coefficients are subsequently incorporated into the difference equation to formulate the final filter transfer function. Based on these coefficients, zero and pole modules of the Butterworth filter were designed and connected after the logic operation module. Experimental results demonstrate that the filter effectively removes DC components and high-frequency noise, thereby significantly improving the detection accuracy of Y -direction high-frequency signals.

By integrating both FIR and IIR filters, the FPGA-based hardware logic implemented in this work substantially reduces background and voltage noise, enabling high-precision detection and imaging of probe vibration signals. Experimental validation confirms significant improvements in noise suppression and signal processing accuracy, fulfilling the requirements for high-resolution AFM imaging.

1.3 Experimental setup

To evaluate the overall performance of the signal processing system, the experimental setup was integrated into a vacuum test platform. The platform provided a controlled environment to ensure accurate measurement of high-frequency probe vibrations. The hardware configuration included: a non-conductive probe with a resonant frequency of $f_0=160$ kHz and a cantilever measuring $L=225$ μm in length and $W=38$ μm in width, which allowed sensitive detection of surface topography variations; a quadrant photodetector (Thorlabs PDQ80A) with a 10 MHz bandwidth, used to convert cantilever deflections into electrical signals; and an FPGA development board (Xilinx Zynq-7000) operating at a master clock frequency of 125 MHz,

responsible for real-time acquisition and digital signal processing of the QPD output.

The software environment comprised MATLAB 2018, Vivado 2017.4, and LabVIEW 2024, each serving a specific purpose in the experiment. MATLAB was employed for filter design and preliminary signal analysis, Vivado for FPGA synthesis and hardware implementation, and LabVIEW for experiment control, data acquisition, and visualization of the probe vibration signals.

The FPGA-LabVIEW homebuilt system integrates real-time signal acquisition, filtering, and visualization, ensuring synchronized hardware-software collaboration throughout the experiment. By combining this hardware and software configuration, the platform enabled precise measurement and processing of cantilever vibrations under vacuum conditions, effectively minimizing environmental noise. This setup ensured that the signal processing system could be thoroughly validated under conditions similar to those encountered during actual AFM imaging.

2 Results and discussion

In this study, the FIR and IIR filters were tested within the FPGA-LabVIEW co-optimized framework to validate the overall system's low-noise performance and real-time feedback capability. An FIR low-pass filter was employed for spot position signal detection, and its noise suppression performance was validated through simulation and experiment. Additionally, a band-pass IIR filter was evaluated using specific frequency AC signals to assess its ability to suppress out-of-band noise, including both low- and high-frequency components, while preserving the resonance characteristics. Fig.6 shows a comparison of the QPD spot position signals before and after filtering with the FIR filter. Fig.6 (a) presents the time-domain signals. It appears that frequency components above 50 Hz are effectively suppressed while the DC component is retained. Analysis of the signal statistics shows that the pre-filtered signal has a variance of 0.012, RMS of 0.11, and a peak amplitude of ± 0.15 , whereas filtering reduces the variance to 0.003, RMS to 0.054, peak amplitude to ± 0.08 , and increases the SNR from 15 dB to 20 dB, indicating a significant improvement in signal stability. Fig.6 (b) shows the frequency-domain signals. It can be found the signal before filter exhibits wideband high-frequency noise, while the post-filtered signal above 50 Hz is nearly eliminated, resulting in a substantially reduced bandwidth. These findings indicate that the FIR low-pass filter effectively suppresses high-frequency noise while preserving the DC component, significantly enhancing the accuracy of spot

position measurements and providing a reliable basis for subsequent AFM probe vibration signal processing.

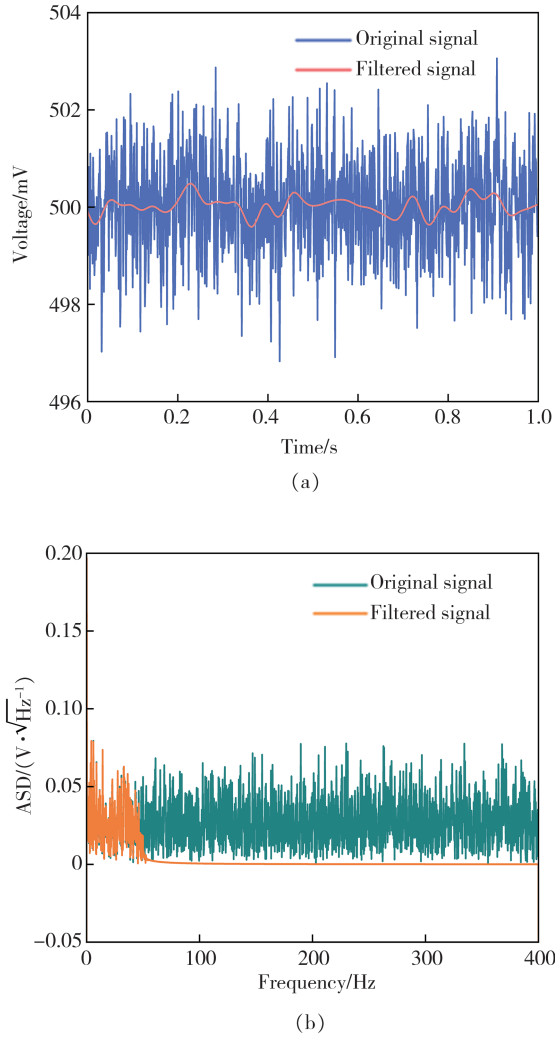


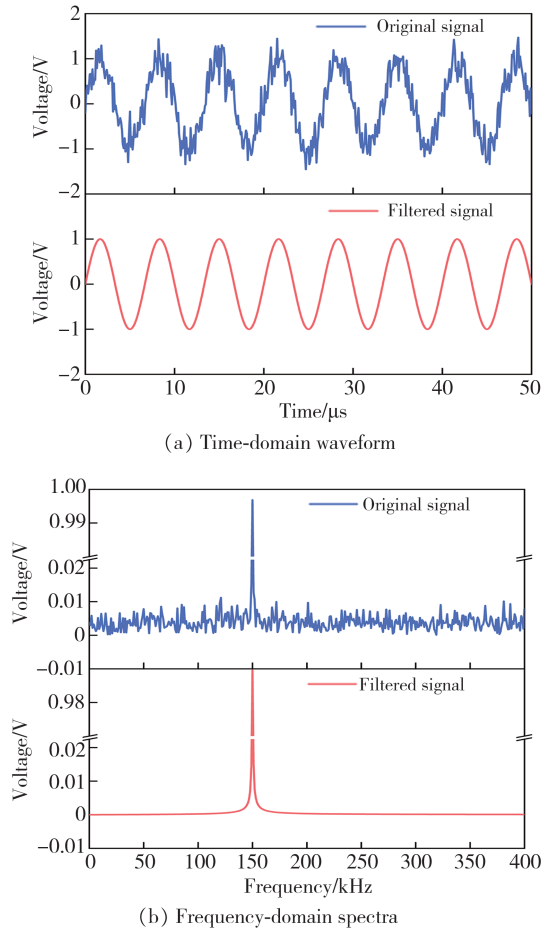
Fig. 6 Simulation results of FIR low-pass filter applied to positional spot signal. (a) Time-domain QPD signals before and after FIR low-pass filtering (cutoff frequency: 50 Hz, sampling rate: 1 kHz), (b) Amplitude spectral density (ASD) of QPD signals

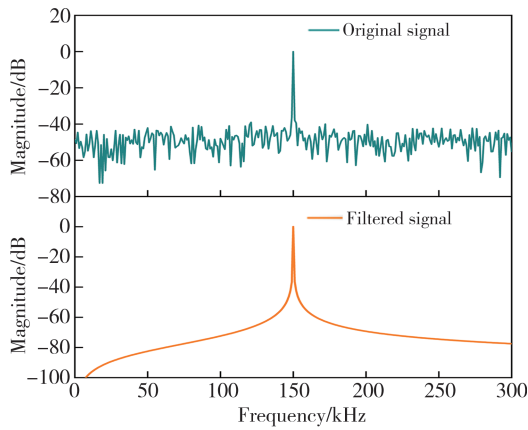
The band-pass IIR filter was evaluated using low-frequency AC signals and high-frequency AC separately to assess its ability to suppress out-of-band noise. Firstly, the performance of the band-pass IIR filter was further validated using a 150 kHz AC signal contaminated with white noise at a signal-to-noise ratio of 40 dB. In Fig. 7, we evaluate the performance of the band-pass IIR filter by applying a high-frequency signal combined with white noise.

It appears that the unfiltered time-domain signal in Fig. 7(a) exhibits substantial low-frequency fluctuations, with peak excursions reaching ± 1.5 V and noticeable zero-crossing jitter. After filtering, the signal maintains a smooth sinusoidal shape within ± 1 V, indicating effective suppression of low-frequency noise.

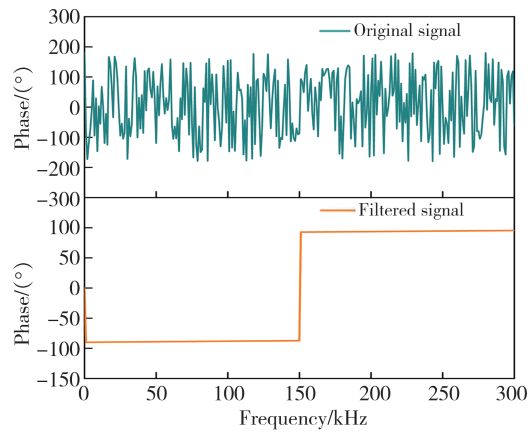
Analysis of the signal statistics shows that the RMS value of low-frequency noise decreases from 0.12 V to 0.03 V, and the SNR improves from 40 dB to 48 dB, demonstrating enhanced signal stability. The frequency-domain spectrum in Fig. 7(b) confirms that the high-frequency resonance at 150 kHz is preserved, with amplitude retention above 95%. Noise components below 50 kHz are attenuated by approximately 80%, and high-frequency components above 200 kHz are also effectively suppressed, narrowing the bandwidth to the target passband.

The magnitude response in Fig. 7(c) remains flat within the passband, with ripple below 0.5 dB, while the out-of-band attenuation exceeds 25 dB. The phase response in Fig. 7(d) is nearly linear, with a maximum deviation of $\pm 5^\circ$, indicating minimal phase distortion and stable group delay. In addition, the FIR low-pass filter used for quasi-static positional signal extraction is designed with linear-phase characteristics. Such a filter introduces only a constant group delay without phase distortion. Therefore, the cascaded FIR-IIR filtering architecture preserves the dynamic characteristics of the probe vibration signal and introduces negligible phase influence to the AFM feedback loop.





(c) Bode magnitude response



(d) Bode phase response

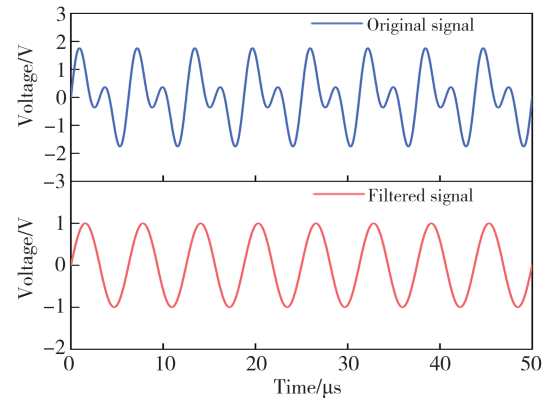
Fig. 7 Simulation results of band-pass IIR filter applied to a 150 kHz AC signal contaminated with white noise

These results demonstrate that the band-pass IIR filter effectively suppresses out-of-band noise, including both low- and high-frequency components, while preserving the cantilever's high-frequency resonance. The filtered signal maintains both amplitude fidelity and a nearly linear phase response, resulting in minimal distortion and stable group delay. Overall, the filter provides a robust and reliable foundation for high-precision AFM probe vibration measurements, ensuring accurate capture of the resonance signal.

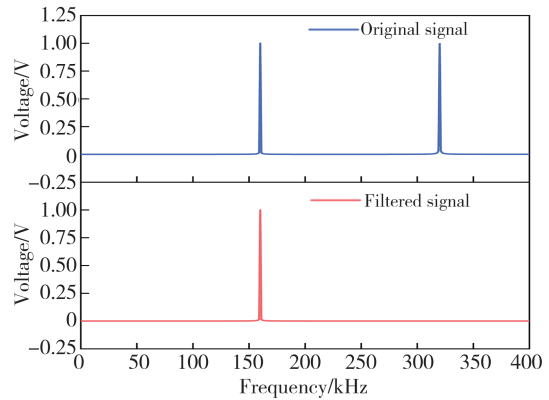
To further evaluate the filter performance, Fig. 8 illustrates the performance of the band-pass IIR filter when tested with a mixed-frequency signal containing 160 kHz and 320 kHz components.

It appears that the unfiltered time-domain signal in Fig. 8(a) exhibits pronounced amplitude modulation with peak excursions ranging from -1.76 V to 1.76 V and a standard deviation of 0.995. After filtering, the 160 kHz carrier is preserved with 100.01% of its original power, while the 320 kHz component is attenuated by 97.58%, and the modulation sidebands at 152.9 kHz and 165.5 kHz are maintained. Analysis of the signal

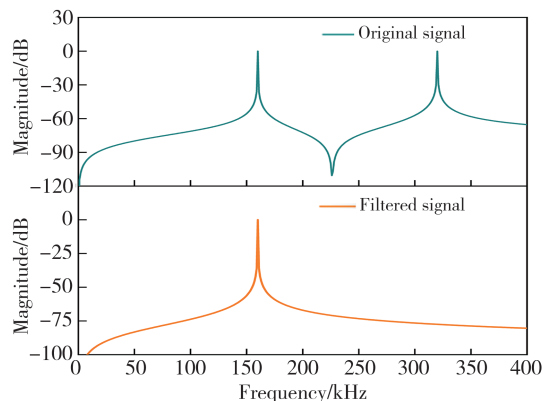
statistics confirms effective suppression of undesired components while retaining the desired signal amplitude. The frequency-domain spectrum in Fig. 8(b) further confirms that higher-order harmonics are effectively suppressed, narrowing the bandwidth to the target passband. The magnitude response in Fig. 8(c) shows a maximum gain of $+3$ dB at the carrier frequency, with sidebands attenuated by approximately 9 dB. The phase response in Fig. 8(d) is nearly linear, exhibiting minor high-frequency lag, which ensures minimal phase distortion and stable group delay.



(a) Time-domain waveform



(b) Frequency-domain spectra



(c) Bode magnitude response

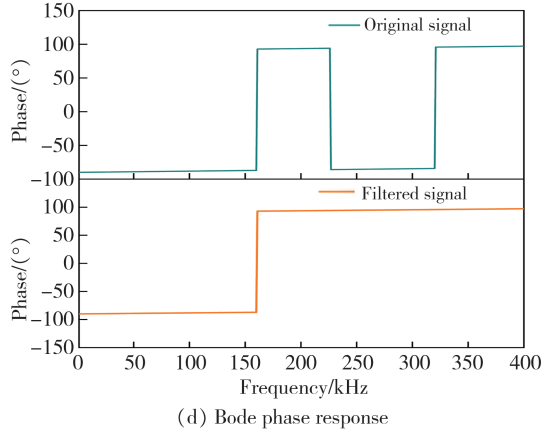


Fig. 8 Simulation results of band-pass IIR filter applied to a mixed-frequency AC signal containing 160 kHz and 320 kHz components

The results suggest that the band-pass IIR filter successfully attenuates low-frequency noise and undesired high-frequency components while preserving the 160 kHz carrier and its modulation sidebands. The filter maintains amplitude accuracy and phase stability across the passband, ensuring faithful reproduction of the resonant signal. This performance confirms the filter's effectiveness in enhancing the precision of AFM probe vibration detection under more complex excitation conditions.

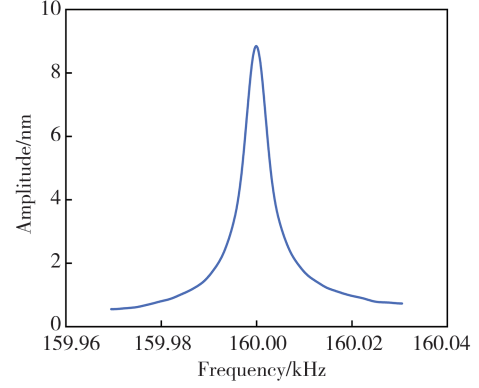
The filter was integrated into the real-time FPGA-LabVIEW homebuilt system and implemented in the UHV-AFM, while the power spectral density (PSD) of cantilever vibration was monitored using Nanonis. The resonance frequency of probe is 160 kHz and the quality factor is $Q=13\,796$.

To verify that the cascaded FIR-IIR filtering structure does not introduce additional phase delay in the AFM feedback loop, the resonance response of the probe is measured. Fig.9(a) shows the amplitude-frequency response near the resonance region, where a clear resonance peak is observed. Fig.9(b) presents the corresponding phase-frequency response. The phase exhibits a smooth and continuous transition across the resonance frequency. These results agree with the expected dynamic behavior of the cantilever and indicate that the FPGA-LabVIEW homebuilt system does not introduce noticeable phase distortion, ensuring stable AFM feedback operation.

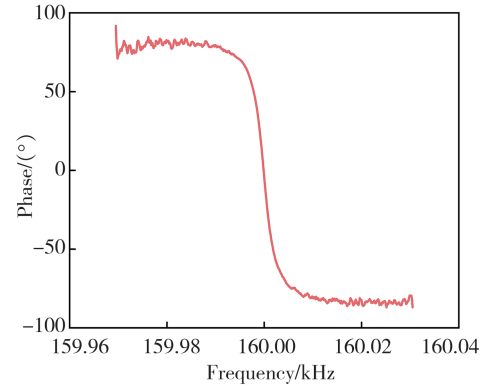
To clarify the origin of the noise components, the total deflection noise power spectral density can be expressed as the sum of thermal noise and electronic noise contributions. According to Brownian motion theory, the thermal noise PSD of the cantilever is given by

$$S_{th}(f) = \frac{4k_B T B}{k} \frac{f_0^2}{(f_0^2 - f^2)^2 + (ff_0/Q)^2}, \quad (7)$$

where k is the cantilever spring constant; k_B is the Boltzmann constant; T is the absolute temperature; f_0 is the resonance frequency, and Q is the quality factor. The measured deflection noise density is related to the voltage noise density through the system gain.



(a) Amplitude-frequency response near probe resonance



(b) Corresponding phase-frequency response showing a continuous phase transition across resonance frequency

Fig. 9 Resonance characterization of AFM probe using FPGA-LabVIEW homebuilt system

Fig. 10(a) shows the deflection noise density of the conventional system, reaching approximately $213.86 \text{ fm}/\sqrt{\text{Hz}}$ at the same frequency, indicating significant electronic noise interference from the conventional quadrant photodetector module. After replacing the traditional signal transmission module with the FPGA-LabVIEW digital acquisition system, the overall system noise is significantly suppressed. As shown in Fig.10(b), the deflection noise density decreases to approximately $106.42 \text{ fm}/\sqrt{\text{Hz}}$, with the entire spectrum shifting downward, corresponding to a total noise reduction of about 50.23%. According to Hooke's law $F = kz$, the force noise spectral density can be written as

$$S_F = k^2 S_z, \quad (8)$$

where k is the cantilever spring constant and S_z is the deflection noise spectral density^[28]. Assuming a typical cantilever spring constant of $k=2 \text{ N/m}$, the corresponding force sensitivity changes from $0.428 \text{ pN}/\sqrt{\text{Hz}}$

(conventional system) to $0.213 \text{ pN}/\sqrt{\text{Hz}}$ (FPGA-LabVIEW homebuilt system), confirming that the reduction in deflection noise enhances the minimum detectable force.

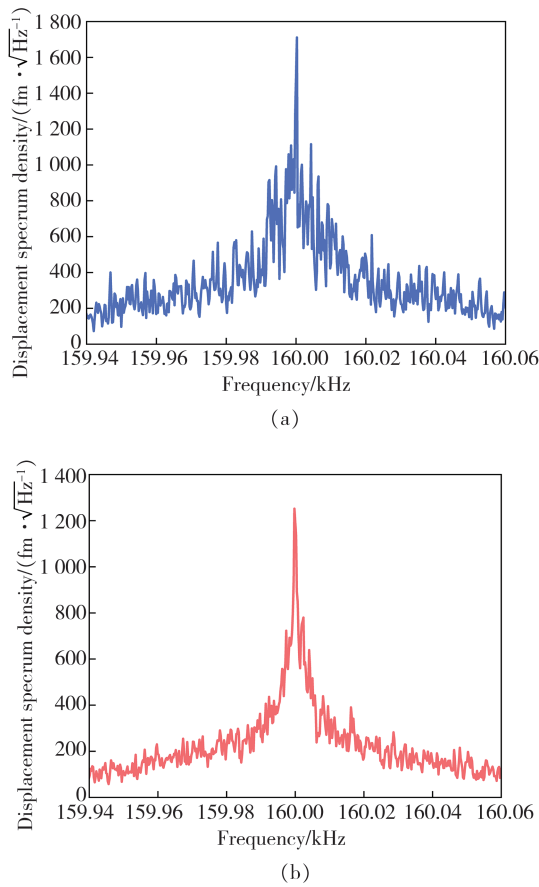


Fig. 10 Noise characterization of conventional AFM optical beam deflection system. (a) Corresponding deflection noise density in conventional system, approximately at 160 kHz, (b) Corresponding deflection noise density in real-time FPGA and LabVIEW homebuilt system, approximately at 160 kHz

The imaging performance was further verified using a standard silicon sample. Fig. 11 compares AFM topography images and corresponding surface height profiles obtained with the conventional analog module and the FPGA-LabVIEW system. The conventional image shows strong background noise that obscures fine surface details. The homebuilt system provides a cleaner contrast and clearly resolved nanoscale features. The height profiles along the dashed lines demonstrate the improvement. The conventional profile contains high-frequency fluctuations caused by measurement noise. The optimized profile is smoother and reveals the true topographic variation with reduced surface noise.

To quantify this improvement, height-profile data were extracted from the silicon scan. The conventional system produces a standard deviation of $9.13 \times 10^{-12} \text{ m}$, whereas the FPGA-LabVIEW system reduces it to $5.42 \times 10^{-12} \text{ m}$,

representing a 40.6% decrease in high-frequency noise. The processed profile preserves the genuine surface morphology and exhibits improved signal-to-noise ratio.

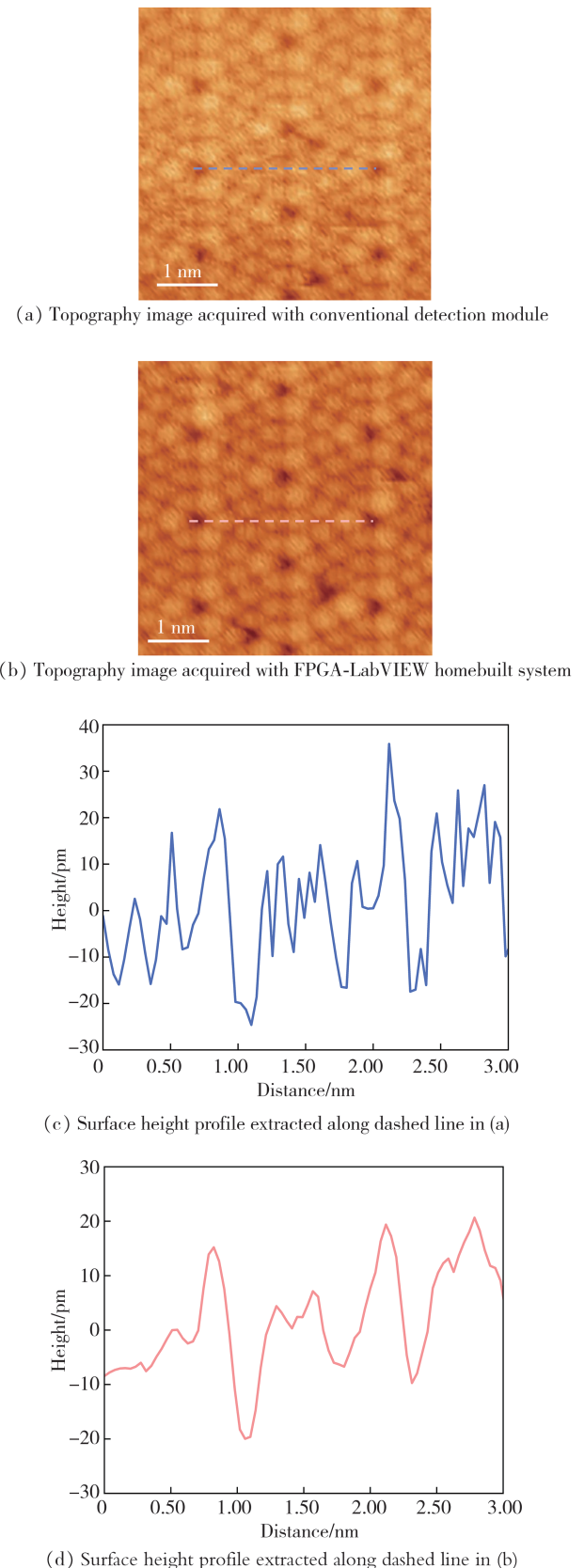


Fig. 11 AFM topography and corresponding surface profiles of Si sample measured before and after system optimization

The reduction obtained from the surface profile differs from the 50.23% noise suppression determined from the PSD analysis. PSD analysis reflects the intrinsic electronic noise at the cantilever resonance, whereas the profile standard deviation represents a combination of baseline noise and the actual nanoscale topography. The fact that the reduction in deviation is smaller indicates that the FPGA-LabVIEW system can effectively suppress baseline noise without affecting the actual surface signal. These results verify that the system reduces electronic noise, stabilizes surface profiles, and enhances the accuracy and reliability of AFM imaging.

3 Conclusions

In this study, a low-noise probe vibration detection system for an AFM platform was developed using a real-time FPGA-LabVIEW homebuilt system, effectively addressing electronic noise and limited real-time performance commonly observed in conventional detection modules. Experimental results demonstrated that the system reduced voltage noise density and deflection noise density by approximately 50%, indicating significant suppression of electronic noise. In addition, the FPGA's parallel computing architecture ensured that the internal signal-processing latency of the FPGA module remained below 5 μ s. These improvements fully satisfied the real-time requirements of AFM measurements.

Furthermore, the system enhanced imaging quality. The topography obtained with the FPGA-LabVIEW homebuilt system showed clearer surface features and a smoother surface profile, effectively suppressing background noise. Additionally, the LabVIEW host interface enabled synchronized multi-parameter display at refresh rates exceeding 1 kHz, supporting flexible parameter adjustment and long-term data acquisition.

In summary, these results indicated that the FPGA-LabVIEW homebuilt system significantly improved the accuracy, stability, and real-time capabilities of AFM probe vibration measurements. This framework provides a versatile reference for digital signal acquisition and processing in scanning probe microscopy and other precision measurement systems, facilitating future advancements in high-resolution nanoscale imaging and characterization.

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Declaration of conflicting interests

The authors have no conflict of interests related to this publication.

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FPGA-LabVIEW 原子力显微镜振动信号实时低噪声自制检测系统

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摘 要: 原子力显微镜(AFM)中探针振动信号的低噪声、实时测量是实现高分辨成像和稳定反馈控制的关键。针对传统光束偏转检测系统中模拟信号处理噪声大、实时性不足的问题, 本文提出了一种基于FPGA-LabVIEW的实时低噪声探针振动测量系统。该系统利用FPGA实现四象限光电探测器信号的高速并行采集与数字处理, 通过级联的FIR低通滤波器和IIR带通滤波器, 分别实现准静态光斑位置提取和探针共振振动信号的有效分离。在保证FPGA信号处理延时小于 $5\mu\text{s}$ 的前提下, 实现了对AFM探针振动信号的实时优化。实验结果表明, 与传统模拟检测系统相比, 该系统的电压噪声密度和挠度噪声密度降低约50%, 信噪比提升约5dB, AFM成像质量和测量稳定性显著改善。该研究为原子力显微镜及其他精密测量仪器的实时数字信号处理与低噪声系统设计提供了一种可行的工程实现方案。

关键词: 原子力显微镜; FPGA-LabVIEW系统; 实时信号处理; 低噪声测量; 数字滤波

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