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Design of Differential Signal Processing Circuitry for Single-Frequency Laser Interferometry Displacement Measurement

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Abstract: This thesis addresses the issues existing in traditional laser tracking displacement measurement technology in the field of ultraprecision metrology by designing a differential signal processing circuit for high-precision laser interferometric displacement measurement. A stable power supply module is designed to provide low-noise voltage to the entire circuit. An analog circuit system is constructed, including key circuits such as photoelectric sensors, I-V amplification, zero adjustment, fully differential amplification, and amplitude modulation filtering. To acquire and process signals, the PMAC Acc24E3 data acquisition card is selected, which realizes phase demodulation through reversible square wave counting, inverts displacement information, and a visual interface for the host computer is designed. Experimental verification shows that the designed system achieves micrometer-level measurement accuracy within a range of 0–10mm, with a maximum measurement error of less than 1.2μm, a maximum measurement speed of 6m/s, and a resolution better than 0.158μm.

Keywords: Displacement Measurement; Weak Signal Processing; Differential Signal; Data Acquisition

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1. Introduction

The development of laser interferometric displacement measurement systems is crucial for the advancement of tracking measurement technology and is a key component of high-precision large-scale laser trackers. As a micro-nano measurement technology, its market and technical demands are increasing. Improving the accuracy of this technology is an urgent need for current scientific and industrial development and is of great significance to the national economy and military fields. Some domestic universities, such as Tsinghua University, have proposed a high-precision laser interferometric displacement measurement method that combines PLL phase-locked loop technology to double the frequency of the laser interferometric measurement signal and the reference signal, and then calculate the displacement through a counter. The results show that the resolution of the measurement system can reach 3 nm and the measurement speed can reach 3 mm/s.

However, this method is only suitable for low-speed measurement scenarios. To overcome this limitation, Harbin Institute of Technology and ZYGO Company jointly proposed a direct frequency doubling measurement method, which can achieve a resolution of 0.62 nm and a measurement speed of 2.8 m/s [1–3]. On this basis, Harbin Institute of Technology further proposed a frequency doubling measurement method based on an external reference clock, which uses a high-frequency reference signal to count the pulses of the measurement signal and the reference signal, and then calculates the displacement change through phase demodulation [4-6]. The signal processing card UOI-3000A developed by Harbin Institute of Technology can achieve a resolution of 0.31 nm and a measurement speed of 1.5 m/s. Professor Zhang Shulian's team from Tsinghua University has studied the full-chain technology of "Ferrule-Glass Assembled Single-Frequency He-Ne Laser → Birefringent Dual-Frequency Laser → Dual-Frequency Laser Interferometer", eliminating the nonlinear measurement error that has always existed in the interferometer at the source [7]. The birefringent dual-frequency laser and interferometer have been mass-produced by Beijing LaiCe Technology Co., Ltd.

Thanh T V *et al.* proposed a displacement measurement interferometer based on a frequency-locked laser diode with a high modulation frequency [8]. By applying a high-frequency modulated LD, the frequency stability of the light source and the measurement speed of the frequency-modulated interferometer were improved. Utilizing the LD frequency locked at a high modulation frequency and the super-heterodyne transition, a stable displacement interferometer with high precision and high measurement speed was achieved, with a displacement result difference of less than 20 nm. Hao C *et al.* studied a microchip Nd:YAG dual-frequency laser interferometer with a frequency difference of 17.4 MHz and designed a down-conversion mixer circuit to reduce the beat frequency to approximately 5 MHz [9]. Experimental results showed that the displacement resolution of the microchip Nd:YAG dual-frequency laser interferometer was 10 nm and the measurement range was 500 mm. Siddiqui A A *et al.* utilized a deep neural network to achieve fringe detection and displacement sensing in self-mixing interferometry based on variable optical feedback [10]. The deep neural network was trained under variable optical feedback conditions, enabling interference fringe detection and corresponding displacement measurement. A method for automatically labeling SMI fringes under variable optical feedback conditions was proposed.

Based on the engineering background of laser interferometric tracking measurement, this paper addresses the problems of slow measurement speed, low resolution, and low accuracy in traditional technologies, especially the need to process multiple interferometric signals in real time in ultra-high-precision tracking measurement. It adopts the PMAC data acquisition card for real-time signal processing and designs a high-speed, high-resolution, and high-precision laser interferometric displacement measurement signal processing circuit to enhance the overall technical performance of the laser tracking displacement measurement system.

2. Principle of single-frequency laser interferometry

From the perspective of principle, laser interferometric displacement measurement can be divided into single-frequency laser interferometric displacement measurement and dual-frequency laser interferometric displacement measurement. Single-frequency laser interferometry is a DC measurement system. It acquires the displacement of a moving target by recording the number of cycles of the bright and dark changes in the single-frequency laser interference fringes. Its advantage is that there is no theoretical limit to the measurement speed, but the disadvantage is that as a DC measurement system, it has relatively high requirements for the environment during displacement measurement and is easily disturbed by the environment.

To overcome the shortcomings of single-frequency laser interferometry, the heterodyne interferometry measurement method was introduced. That is, a carrier of a certain frequency is introduced into the reference optical path of the single-frequency optical path, and the measured displacement signal can be transmitted through this carrier. Heterodyne laser interferometry is an AC system that can effectively avoid the problem of easy DC drift in interferometric measurement signals [11]. At the same time, heterodyne laser interferometry has the advantages of high signal-to-noise ratio, strong anti-interference ability, fast measurement speed, and easy realization of high measurement resolution. Generally, the larger the frequency difference between the dual frequencies, the higher the measurement speed of the heterodyne laser interferometry system [12].

The schematic diagram of the single-frequency laser interferometry is shown in **Figure 1**. The light emitted by the laser passes through the neutral beam splitter (Beam Splitter, BS) and is divided into two beams of light. One beam of light serves as the transmitted light and is transmitted horizontally towards the measurement mirror M, while the other beam of light serves as the reflected light and is reflected vertically towards the reference mirror R. The two beams of light reaching the measurement mirror and the reference mirror are reflected back. Then, the measurement mirror M is moved, and when the two reflected beams of light pass through the neutral beam splitter BS again, the two reflected beams of light will interfere at the neutral beam splitter. The interference light is detected by the photodetector. When the measurement mirror is moved, the interference fringes of the interference light will change in brightness and darkness, and the photodetector will detect a current signal with a periodically changing amplitude. By calculating the number of cycles of the amplitude change of the current signal, the displacement of the measurement mirror can be obtained.

This paper takes the Michelson interferometer as the basic optical path. To ensure real-time tracking of the target's displacement, the measurement mirror is often replaced by a target ball, and the emission light and the receiving light are coaxial [13, 14]. In addition, to improve the resolution of the single-frequency laser interferometry displacement measurement system, a wave plate is used in the optical path system to adjust the polarization direction of the light and obtain an optical subdivision signal.

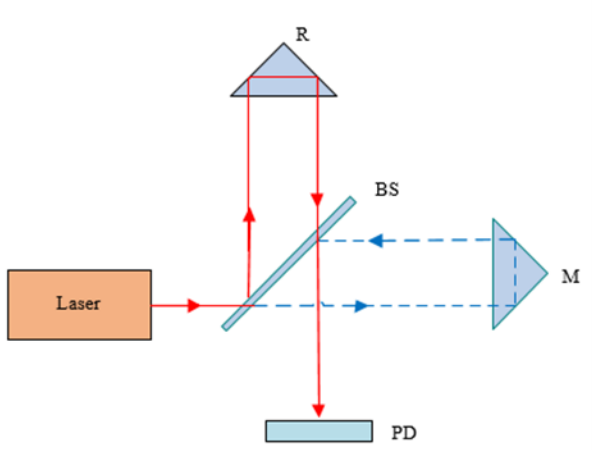

Figure 1. Schematic diagram of single-frequency laser interferometry principle.

3. Hardware circuit design

In the circuit design, a stable power supply module is first built to ensure that low noise voltage is provided, followed by photoelectric conversion, I-V amplification, zero adjustment, full differential amplification and amplitude modulation filtering. The overall structure of the circuit is shown in **Figure 2**, which is composed of a power module, a pre-amplification circuit, a signal amplification circuit, and an amplitude-modulation filter circuit. Take a pair of differential signals as an example, the signal is converted into a current signal through the photoelectric sensor, and then amplified by a first-level I-V amplifier circuit, into the full differential amplifier circuit, to achieve the zero function, the maximum range of zero adjustment is ± 1V, and then through the amplitude modulation filter circuit, and finally the signal output, the power module uses 12 V power supply.

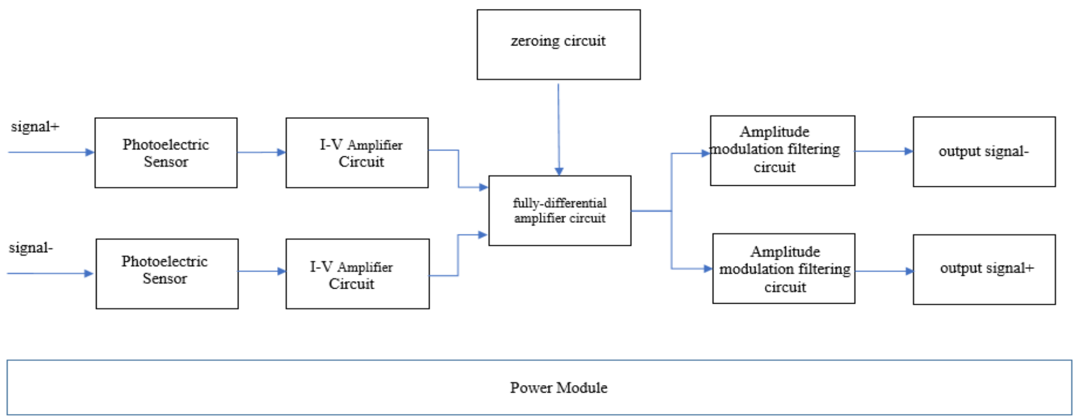

Figure 2. System structure diagram

The signal to be measured is four positive (residual) strings, phase difference 90° optical differential signal, optical power (30µW–60µW), the conversion efficiency of the photodetector is only 30%–40%, so the current signal obtained is only 10–20µA, the four-way signal amplitude (DC, AC) is approximately equal, and the input signal frequency DC 10MHz. The circuit includes photoelectric conversion module, differential amplification module and amplitude modulation tuning module, and finally outputs four positive (residual) string analog signals in real time, with a difference of 90° consistent with the input. The four signals are set with amplitude modulation tuning function, and the peak value of the four output voltage signals is 1 V (0 –1 V).

3.1. I-V transresistance amplifier circuit

The I-V amplifier circuit is used to convert the tiny current signal output by the photoelectric sensor S3072 into a voltage signal. Because the photoelectric signal is a current signal, the current input amplifier must be selected. The OPA847 is a wide-band, ultra-low noise operational amplifier with a piezoswing rate of up to 950 V/us to meet the needs of systems for fast amplification of high frequency signals. To reduce the influence of power supply noise, 0.1uF and 6.8uF tantalum capacitors are connected in parallel at ± 5V of the power supply for power supply filtering. The weak current signal is converted into a voltage signal through the input resistance and then amplified. In order to reduce the influence of the input resistance on the signal, the value of the input resistance must be as small as possible. By using the negative feedback of the amplifier to reduce the input impedance, the pre-amplifier circuit of the current input is realized. The design circuit is shown in **Figure 3**.

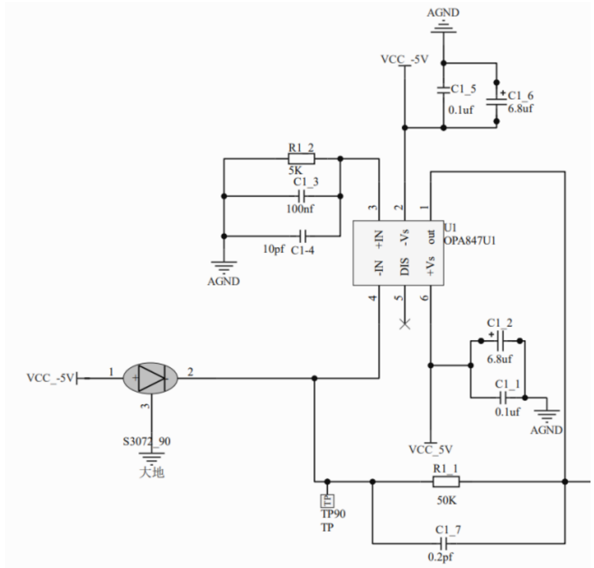

Figure 3. I-V amplifier circuit

In the circuit, the larger the feedback resistance R1_1, the more helpful to improve the signal-to-noise ratio, but too large feedback resistance will make the amplifier input conversion noise current value can not be ignored. Considering the frequency bandwidth and signal-to-noise ratio of the system, the feedback resistance value is selected as 50 kΩ. The transresistance gain of the OPA847 requires the feedback extreme value to be set to 74 MHz to obtain a nominal Butterworth frequency response design. This requires a total feedback capacitance of 0.2 pF. Therefore, the design does not require additional capacitors.

3.2. Fully differential amplifying circuit and zeroing circuit

After the I-V amplifier circuit converts the current signal into the voltage signal and amplifies it, the differential signal needs to pass through the second stage circuit to achieve further amplification and realize the circuit zero function. In this circuit, two differential signals are amplified twice by the fully differential signal, and a fully differential amplifying zeroing circuit as shown in **Figure 4** is designed by using the output common-mode control pin of the chip.

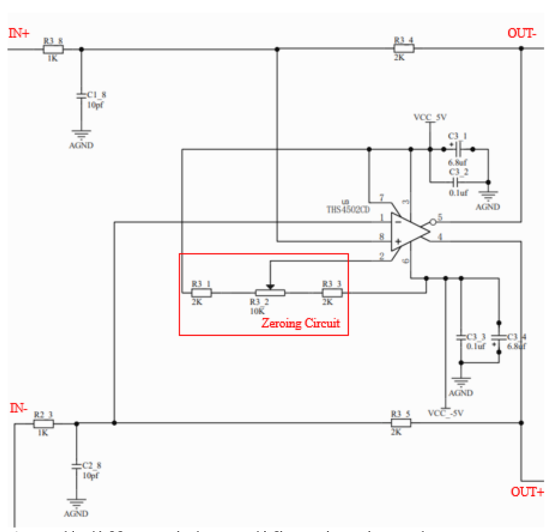

Figure 4. Full differential amplifier circuit and zero control circuit

The output waveform is adjusted by adjusting the resistance value of the sliding rheostat R3_2, and the function of zeroing the differential signal is realized. In order to reduce the noise caused by the power module, 0.1uF and 6.8uF capacitors are connected in parallel to the power supply part to filter the power supply noise. Using TI's full differential amplifier THS4502, this type of chip has the characteristics of ultra-low voltage noise, high-speed voltage feedback, etc., which is very suitable for application in low noise circuit.

3.3. Amplitude modulation filter circuit

To realize the amplitude-modulation function of the circuit and improve the quality of the output signal, the amplitude-modulation filter circuit is designed, and the circuit design is shown in **Figure 5**. The input signal IN is adjusted to the amplitude of the input signal by resistors R3_6 and R4_1. At the same time, the second-order active low-pass Butterworth filter is composed of resistors R4_ and R4_2 and capacitors C4_2 and C4_1. After filtering the signal, the signal is amplified by 2 times. More possibilities for back-end impedance matching.

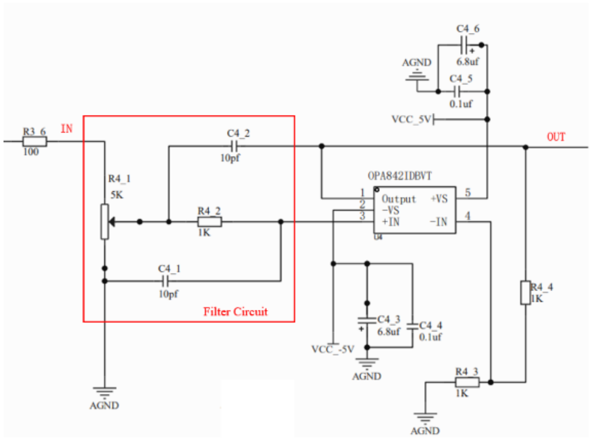

Figure 5. amplitude-modulation filter circuit

3.4. Power circuit

The power supply part mainly protects the safety of the circuit to avoid the burning of the circuit board due to problems such as power reverse connection and input voltage mismatch. First, the DC/DC power module UWE1212S-3WR3 is used to convert the 12 V voltage provided by the power supply to ±12 V. Then through the LDO power module ADP7182, +12 V is converted into low noise +5 V, and through the LDO power module ADP7182, -12 V is converted into low noise -5 V for the use of analog circuit.

4. Digital signal processing

The design of digital signal processing software generally includes two modules: PMAC data processing module and upper computer visual interface design. The digital signal transmission process is shown in **Figure 6**. PMAC Acc24E3 digital acquisition card is used to collect TTL signal of laser interference displacement measurement system, and the corresponding digital quantity of displacement information is obtained directly. The PMAC Acc24E3 digital acquisition card provides a digital quantity of distance information, which is then converted into a digital quantity of the corresponding physical unit in the Power PMAC system. The data processing module is used to collect, compare and output the signal output of the pre-processing circuit. The principle of the PMAC data acquisition card is mainly to convert the analog signal into the digital signal that can be processed by the computer.

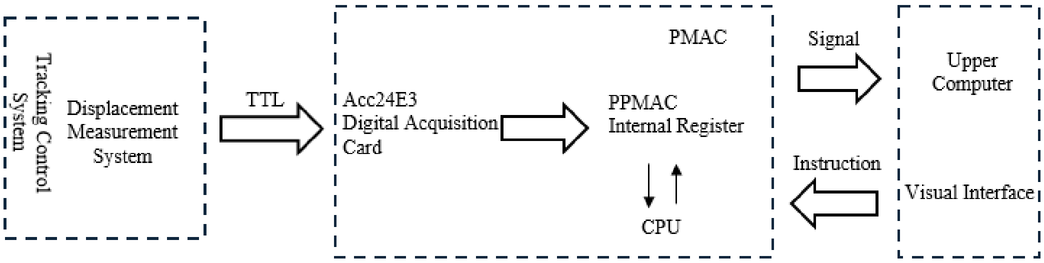

Figure 6. Digital signal transmission process

In this paper, the displacement signal is collected and processed by the displacement measurement system of the tracking control system, and the analog signal carrying displacement information is obtained. The output analog signal is TTL signal with peak-to-peak value of 1 Vpp. Then the TTL signal is sent to the analog-to-digital converter (ADC) in the PMAC data acquisition card, and the ADC converts the TTL signal into a digital signal. The converted digital signal also needs to carry out reversible square wave counting and directional subdivision through the Acc24E3 digital acquisition card in the PMAC, and demodulate the digital signal carrying displacement information. Finally, the demodulated digital signal is stored and processed through PPMAC internal register, and then the processed data is transmitted to the upper computer through the USB interface of the data acquisition card, and the upper computer analyzes and displays the data.

5. Experimental results and analysis

An optical system experiment platform was built according to the design scheme in this paper, and the function and accuracy of the system were tested. During the test, the test platform worked normally and could collect optical signals containing position information and solve the position information through the signal processing circuit. In order to verify the measurement accuracy of the laser tracking displacement measurement system, the displacement accuracy experiment was carried out, and the displacement measurement data of the laser interferometer displacement measurement system designed in this paper was compared with the XL-80 laser interferometer of Renishau Company of Britain. The length measurement resolution of XL-80 is 1 nm, which has high measurement accuracy and measurement stability. Therefore, this paper chooses XL-80 laser interferometer of Renishaw Company to carry out displacement experiment verification and comparison experiment.

The displacement measurement accuracy is compared between Renisau XL-80 and the common optical path of the laser interference displacement measurement test platform. The manual displacement table is given 10 displacements, and the experimental test is carried out in the range of 0–10mm with an interval of 1mm, and the uniform movement of the manual displacement table is guaranteed. By comparing the indicated value of the Renishao XL-80 laser interferometer with the test platform of the laser interferometer displacement measurement system designed in this paper, the readings were collected and recorded under the given displacement. The results are shown in **Table 1**.

Table 1. Comparative measurement results of single frequency laser interferometry

Times	XL80 Value (mm)	Test platform to collect readings (mm)	After the compensation data (mm)	Compare the error after compensation (mm)
1	0	0	0	0
2	0.9908	0.9804	0.9900	0.0008
3	1.9950	1.9781	1.9955	-0.0005
4	2.9961	2.9715	2.9967	-0.0006
5	3.9945	3.9871	3.9950	0.0005
6	5.0206	4.9755	5.0210	-0.0004
7	6.0239	5.9842	6.0227	0.0012
8	7.0452	6.9790	7.0459	-0.0007
9	8.0553	7.9773	8.0550	0.0003
10	9.0625	8.9743	9.0627	-0.0002
11	10.0712	9.9730	10.0712	0

After linear compensation, the comparison error between XL-80 laser interferometer and the laser interferometer displacement measurement test platform designed in this paper at a single step is less than 1.2μm, and the accuracy test diagram of the test system is shown in Figure 7.

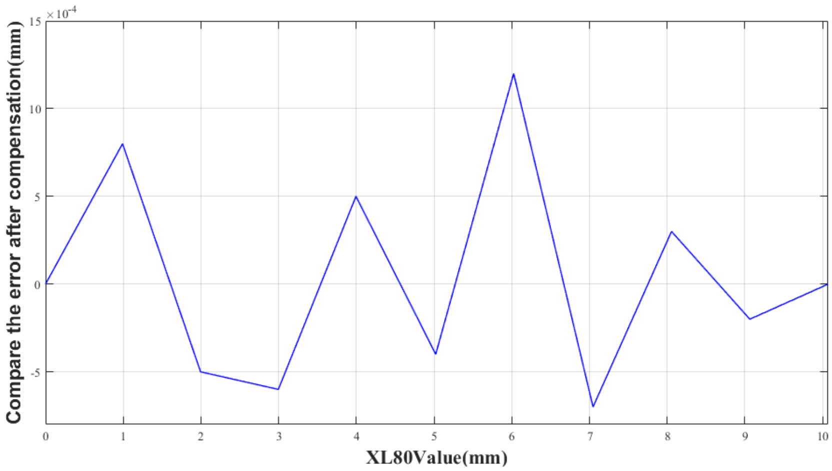

Figure 7. Accuracy test

Through Matlab data analysis of the experimental measurement data in **Table 1**, **Figure 8** shows the stability curve of the displacement measurement data obtained through data analysis of five displacement measurements of the same range. It can be seen from **Figure 7** that the maximum error of each measurement value is no more than 1.52 microns for multiple measurements of the same range. The measuring system has good measuring stability.

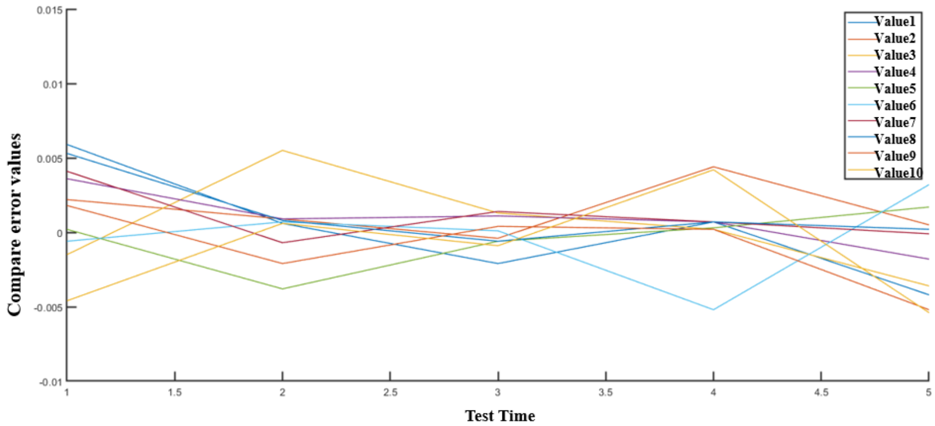

Figure 8. Stability curve

6. Conclusion

From this study, the displacement signal pre-processing circuit of the laser interference displacement measurement system is designed, including current and voltage conversion, I-V amplification, zeroing, full difference amplification and amplitude modulation filtering, etc., for laser interference signals. Additionally, with PMAC data acquisition card as the core, the digital signal processing module is designed, and the pre-processed analog signal is sent to PMAC for collection and analysis. The PPMAC Acc24E3 card is used to obtain the digital quantity of displacement information directly, and it is converted into the digital quantity of physical unit in the Power PMAC system, and displayed through the upper computer interface. The experimental verification was carried out, and the system performance was tested and optimized. The maximum error of single-frequency laser interference displacement measurement was no more than 1.2μm, the measurement speed was up to 6m/s, and the system resolution was 0.158μm.

Disclosure statement

The authors declare no conflict of interest.

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