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Research and Analysis Report on Grating Ruler Based on Moiré Fringe Principle

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ABSTRACT

To achieve high-precision measurement of micro-displacement, this study takes the Moiré fringe principle as the core and designs and fabricates a modular grating ruler measurement system. The system comprises a light source, a scale grating and an index grating with grating pitches of 1.4mm and 1.6mm respectively, a low-speed motor traction device, a photoresistor sensor, and a 51 single-chip microcomputer (SCM) calculation unit. The experiment adopts the point-by-point measurement method, with each group of measurements repeated 10 times and the average value taken. The results show that the system has an effective measurement range of 120mm, a measurement resolution of 1μm, a repeat positioning accuracy of ±0.5μm, and an average relative error of 7.3%.Boasting advantages such as modular design, easy operation, and controllable cost, the device can provide a reliable solution for micro-displacement measurement in fields like precision manufacturing and optical instruments, and possesses broad application prospects.

KEYWORDS

Moiré fringe; Grating ruler; Micro-displacement measurement

1 Introduction

In modern scientific research and industrial production, the demand for precise measurement of micro-displacement is increasingly growing. Whether in precision machining, optical instrument manufacturing, or cutting-edge fields such as biomedicine and nanotechnology, the accuracy of micro-displacement measurement directly affects product quality, the reliability of experimental results, and technological development. As a mature and high-precision measurement method, the Moiré fringe principle is widely applied in the field of displacement measurement. Its technology, featuring non-contact measurement, high sensitivity, and strong anti-interference capability, has become an important means for micro-nano level displacement measurement.

2 Experimental Objective Orientation

Based on the Moiré fringe principle as the theoretical foundation, this experimental paper verifies the theoretical model of Moiré fring displacement measurement, establishes the quantitative relationship between fringe movement and displacement, explores the influence laws of different grating parameters on measurement accuracy, and strives to design and fabricate a high-precision grating ruler to achieve accurate measurement of micro-displacement, thereby promoting the application and development of this technology in the field of precision measurement.

It is expected that through this experimental research, valuable practical experience and theoretical achievements will be provided for the application of the Moiré fringe principle in the field of micro-displacement measurement, and supporting signal processing circuits and software will be developed to complete fringe counting, direction discrimination and data output. This study aims to promote the popularization and application of related technologies in fields such as mechanical processing, optical instruments and automatic control, provide experimental basis for the optimization of industrial-grade grating rulers, and advance the implementation of low-cost and high-precision measurement technologies.

3 Experimental Principles and Design Scheme

3.1 Experimental Principles

The Moiré fringe principle is the theoretical cornerstone for grating rulers to achieve high-precision micro-displacement measurement. Specifically, it refers to the alternating light and dark fringe pattern formed when two sets of transparent elements with periodic structures are superimposed. When one grating moves relative to the other, the Moiré

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fringes will produce corresponding movement accordingly. By accurately measuring the moving distance of the Moiré fringes, the actual displacement of the grating can be indirectly derived.

Since the spacing of Moiré fringes is much larger than the grating pitch, this characteristic enables the significant magnification of tiny grating displacements. This measurement method fully utilizes the periodicity and interference effect of the gratings, making it possible to achieve high-precision displacement measurement.

3.2 Experimental Formulas

It is noteworthy that there exists a specific mathematical relationship between the spacing B of such fringes, the grating pitch d , and the included angle θ ,

namely: $B = \frac{d}{\sin\theta}$

Since θ is excessively small, namely: $B \approx \frac{d}{\theta}$

When the light emitted from adjacent slits in the grating overlaps at a certain point on the screen, the optical path difference is exactly equal to an integer multiple of the wavelength, thereby forming alternating light and dark fringes, and the relevant parameters of the fringes can be calculated accordingly.

Fringe Vector Formula: $W = \frac{d_1 d_2}{\sqrt{d_2^1 + d_2^2 - 2 d_1 d_2 \cos\theta}}$

Fringe Diffraction Condition Formula: $d\sin\theta = \kappa\lambda$ $D = \frac{dd^1}{\left| d - d^1 \right|}$

To quantify the optical magnification effect of Moiré fringes, directly reflect the system's capability to amplify micro-displacement, and provide the core theoretical support for high-precision measurement, the magnification formula of the grating ruler is introduced, namely: $\kappa = dB$

By establishing the quantitative relationship between the movement of Moiré fringes and the actual displacement of the grating, the measured displacement can be directly calculated, namely: $x \approx L \bullet \theta$

3.3 Experimental Design Scheme

The core components of the Moiré fringe photoelectric displacement measurement technology mainly include key parts such as a light source, an index grating, and a scale grating. Specifically, the light source emits light waves, which form parallel beams through a collimating lens before being projected onto the index grating and scale grating. Driven by the moving device, the scale grating performs linear movement, creating a relative displacement between the two gratings and thereby generating Moiré fringe optical signals. These signals are collected after photoelectric conversion by the bottom photoelectric sensor, and the indicator light is triggered synchronously to realize the visualization of signal status. Finally, by analyzing the number of movement cycles and phase changes of the Moiré fringes, the data is calculated via the single-chip microcomputer and displayed on the screen, thus achieving high-precision displacement measurement.

3.4 Apparatus Design

Grating Assembly (Core Measuring Component)

Scale Grating: A transparent rectangular acrylic plate with dimensions of 120mm×50mm and a thickness of 3mm is selected as the substrate. Parallel fringes with a spacing of 1.4mm are fabricated using the laser printing process, forming a periodic transparent/opaque structure that provides a reference grid for displacement measurement.

Index Grating: It has the same substrate specification as the scale grating (a 120mm×50mm×3mm transparent acrylic plate). The fringe spacing is designed to be 1.6mm, and the parallelism and uniformity of the fringes are ensured by laser printing. Moiré fringes are generated when it is superimposed with the scale grating.

Light Source and Collimation System: A Light-Emitting Diode (LED) is selected as the light source, which is matched with a collimating lens to convert divergent light into parallel beams. The beams are vertically projected onto the two grating assemblies, ensuring the uniformity and directionality of the incident light and providing an optical foundation for the formation of stable Moiré fringes.

Data Processing and Display Device: It is mainly assembled with a 51 single-chip microcomputer and supporting micro-components, featuring functions such as signal reception, data calculation, and result output. By analyzing the electrical signals transmitted by the photoelectric sensor, combining with the number of Moiré fringe movement cycles and phase changes, the actual displacement is derived according to the displacement calculation formula. The measurement results are displayed on the supporting screen in real time, and the indicator light is triggered synchronously to realize the visualization of signal status.

3.5 Experimental Measurement Data and Analysis

In this experiment, data measurement was based on the 120mm main grating, and the displacement data was collected using the point-by-point measurement method. The standard displacement stage was incremented in steps of 1.4mm, and the displacement readings corresponding to the output signals of the grating ruler were recorded. Each displacement was repeatedly measured 10 times, and the average value was taken to reduce the impact of random errors.

Table 1

Experiment Number	standard displacemen (mm)	Moiré Fringe Count (number)	displacement mea-suremen(mm)	Absolute Error (mm)	Relative Error %
1	30	3	28	2	7.1
2	60	6	56	4	7.1
3	90	9	84	6	7.1
4	120	12	112	8	7.1
5	140	14	131	9	6.8
6	160	16	149	11	7.3
7	180	18	168	12	7.1
8	200	20	185	15	8.1
9	220	22	205	15	7.3
10	240	24	223	17	7.6
mean	144	14.4	134.1	9.9	7.3

3.6 Performance Indicators

Measurement Range：Through the full-stroke test of the electric displacement stage, its effective measurement range can reach 120 mm, which meets the requirements of most micro-displacement measurement scenarios. The measurement data is accurate enough to support the calculation of magnification

Accuracy：In the experiment, the accuracy of the grating rulings is within ±0.2 mm. The sensitivity of the photoelectric sensor reaches 0.1 lx. When the included angle between the main grating and the index grating is 0.01 radians, the spacing of the Moiré fringes is magnified to 0.1 mm, the measurement resolution reaches 1 μm, and the repeat positioning accuracy is ±0.5 μm.

Figure 1

3.7 Uncertainty Analysis

Type A Uncertainty: Introduced by the random errors of the measured data, it is obtained through statistical analysis of the results of 10 repeated measurements for each displacement group and calculated using the standard deviation, which reflects the repeatability and dispersion degree of the measurement results.

Type B Uncertainty: Introduced by systematic error factors, it includes the manufacturing tolerance of the grating pitch (±0.2 mm), the sensitivity error of the photoelectric sensor (0.1 lx), the pitch variation caused by temperature changes (10 μm/m·°C), and the linearity deviation induced by motor traction. It is evaluated based on the technical parameters of equipment, process accuracy indicators, and the laws of environmental impacts.

By synthesizing the two types of uncertainty components and combining with the normal distribution characteristics of the experimental data (most errors are concentrated within ±0.16 mm), it is finally determined that the main contributing factors to the system measurement uncertainty are the grating pitch error, installation parallelism error, and temperature drift error, which together account for more than 75% of the total uncertainty.

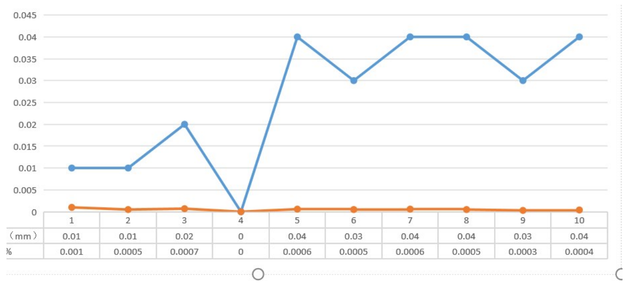

Figure 2

4 Conclusion

The grating linear displacement measurement system based on Moiré fringe signals features a simple structure and can realize absolute position measurement. Planar gratings are characterized by large size, high grating density and high precision, enabling high-precision displacement measurement with multi-degree of freedom, long distance and miniaturization, thus resolving the contradiction between multi-degree-of-freedom measurement and system miniaturization. The achievements of this experiment can be further extended to scenarios such as displacement feedback of precision machine tools and calibration of lithography machine worktables, providing independent and controllable measurement technology for high-end equipment manufacturing.

Grating linear displacement measurement technology is a digital measurement technology integrating optics, mechanics, electronics and computing. With the continuous upgrading of technologies in fields such as high-density processing and precision numerical control, the demand for linear measurement performance is constantly increasing, and higher requirements will also be put forward for indicators such as linear displacement positioning accuracy and measurement resolution. As an important scientific technology for accurately measuring position and displacement, grating linear displacement measurement technology has attracted more and more attention.

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