Phase subdivision of absolute coding grating in displacement measurement

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Abstract

A phase subdivision of absolute coding grating is proposed to improve the resolution and precision of displacement measurement. The used grating consists of multiple code channel grating of Gray code, and the basic code channel is high frequency Rochi grating. Fourier analysis method is adopted to extract the phase value of grating in decoding, and the wrapped phase distribution of basic code channel is obtained by Fourier transform, filtering, and inverse Fourier transform, then the unwrapped phase distribution could be recovered using the phase order information of Gray code. High resolution of phase subdivision can be achieved via linear fitting of phase distribution. Analysis of the basic principle and the subdivision of the phase to improve the resolution of displacement measurement have also been described in this paper. Experimental results show that the resolution and precision of absolute coding grating is enhanced greatly after phase subdivision and calibration.

Keywords: displacement measurement; absolute coding; grating; phase subdivision;

1. Introduction

With high resolution, high accuracy, high stability and other characteristics, precision displacement optical measurement has been deeply studied and widely used in recent years [1-2]. Usually, the moiré’ fringe generated by two gratings tilted at a small angle is subdivided by subsequent circuits in the traditional grating measuring system. However, as the subdivision number is increased, precision, reliability, and speed of measurement would be affected and the cost of measuring system would be greatly raised [3]. Relative to the measurement based on Moiré technique, the approach by using absolute coding grating is more dominant. There is no cumulative error in this method because that each point has a corresponding code value. And the larger coding range makes the large linear displacement possible. So, precision displacement optical measurement based on absolute coding grating could keep the measurement accuracy within the micron level in large measuring range.

In displacement measurement using absolute coding grating, a commercial CCD camera is usually employed to record the image of the coding grating, and the information between two neighboring coding bits could be

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subdivided the corresponding sampling pixels \( n \), but the \( n \) value is limited. The large \( n \) value will lead to the higher requirements on CCD’s resolution, the more complex of optical system and the much smaller measuring range. To this end, a phase subdivision of absolute coding grating has been proposed in this paper. The used absolute coding grating is multi-channel, in which, a basic channel is made by a high frequency Rochi grating and the others are encoded by natural code or Gray code. In data processing, Fourier analysis is used to calculate the relative phase information of the basic channel (Rochi grating). Natural codes or Gray codes of the rest channels are used to identify the phase order of each period of Rochi grating and recover the absolute phase information. And then, the high-resolution phase subdivision could be achieved by fitting the phase distribution using its linear nature.

2. Design of absolute coding grating

Natural binary code absolute coding gratings is taken as an example for describing the design and four of multi-channels are shown in Fig. 1. The absolute phase subdivision presented in this paper has two parts. The first one is a high frequency Rochi grating, which will be used to calculate the phase information using Fourier analysis, via Fourier Transform, spectrum filtering, inverse Fourier transform and phase unwrapping [4-6]. The other part is composed of several channels of natural codes. The number of the code channel is decided by the frequency of Rochi grating. Each period of Rochi grating has its corresponding and unique binary code, which collected one bit from each channel at the same position. These codes will be used to identify each period’s absolute phase order of the Rochi grating in phase unwrapping. In this grating, the system resolution is decided by the lower bits in the finest code channel. Considering the linear characteristic of the phase distribution, linear fitting of the phase distribution is helpful to subdivide the phase further and improve the measuring accuracy. In fact, many measurement methods have full use of the fringe phase information of a grating pattern for sub-pixel displacement measurement.

![Fig. 1 Diagram of natural coding absolute grating.](image)

After well designed, this absolute grating has been attached to the tested displacing target, and a 2D CCD camera is employed to record its image. Assumed the CCD camera is 800 × 600 pixels with 10 microns of each pixel pitch, and each period of Rochi grating is covering 100 microns in the image plate of the CCD camera. With the imaging ratio of 1:1, one fringe’s displacement in imaging plate of CCD is equal to 10mm/100 (or 100 microns) displacement of the absolute coding grating in the tested target. If the phase measuring accuracy of one single pixel reaches \( 2\pi/100 \), the displacement measurement resolution will reach 1 micron. Due to the phase value of Rochi grating under current situation is an average result of hundreds pixels’ data in one line of the detector array, the actual resolution of displacement measurement will be much higher than 1 micron.

Putting this coding grating into a 1:1 imaging system, the relationship between the number of code channels \( m \), the displacement measurement range \( L \) and the period of Rochi grating \( p \) can be expressed as:

\[
L = p \times 2^m \tag{1}
\]

For a \( K:1 \) zoom ratio imaging system, it can be expressed as:

\[
L = K \times p \times 2^m \tag{2}
\]
The imaging ratio K does not affect the relative accuracy of displacement measurement. It will affect the absolute precision of the displacement measurement. Different measuring system with suitable imaging ratio can be designed to meet the measuring precision requirement.

Meantime, the increasing of code channel number will enlarge the measurement range.

3. 2. Phase measuring and unwrapping

For the Rochi grating, a periodic rectangular signal, its sampling sequence at difference discrete time is shown in Figure 2. And its Fourier spectrum is shown in Figure 3.

![Fig. 2 Sampling result of the Rochi grating.](image1)

![Fig. 3 Fourier spectrum of the Rochi grating.](image2)

An appropriate filter window is selected to filter out the basement component of Fourier spectrum, and inverse Fourier transform is executed to calculate the phase information (shown in Fig. 4 (a)). Combined the phase order obtained from the other code channels, the wrapped phase will be unwrapped in a continuous absolute phase, shown in Fig. 4 (b).

Then, an average value of the unwrapped phase has been taken as the phase value of coding grating under current situation.

![Fig. 4 Phase unwrapping process. (a) Wrapped phase; (b) Unwrapped phase (the diagonal).](image3)

4. Experiment results

To prove this method, an actual absolute coding grating with one Rochi grating and nine code channels has been produced by precise lithography. The period of Rochi grating is \(54.72 \mu m\), so the length of this absolute coding grating is \(54.72 \mu m \times 29 = 28.016 \ mm\). The experiment setup is shown in Fig. 5. A CCD camera with 720×616 pixels is used to capture the image of coding grating which is tightly attached on a precision translator. One of the images of coding grating is shown in Fig. 6, which is a part of the absolute coding grating. When the translator is moving, a micrometer head with an accuracy of 1/100 micron is employed to track and display the displacement value.
One line signal of Rochi grating as shown in Fig.6 has been read-out and deal with Fourier analysis to calculate the phase distribution. At the same time, the corresponding phase orders of each grating period at different sampling times can be extracted from the different values of nine coding channels, which will be used to unwrap the phase correctly.

Three experiments have been done on this setup. The first one is to determine the phase resolution and test the stability of this experimental setup. Nine different positions on the whole measuring range have been taken as of investigation points and 50-frame images at each position have been captured. All the data have been processed according to the presented algorithm. The result is shown in Fig. 7. The standard deviation is 0.0113 radians, which approximates 1/500 of the equivalent wavelength (0.1μm) of this measuring system. This result demonstrates the setup is more stability.

The second experiment is completed when the precision translator is moving on 3-micron steps, the digital micrometer displayed the total journey is 132.02μm and the measured result is 131.68μm.

Figure 8 gives the relationship between the results of two methods, and Fig.9 illustrates the measured errors of the proposed method. Compared to the micrometer display results, the maximum error are -0.340μm and +0.469μm, and the standard deviation is 0.2057μm. This result identifies the measuring accuracy is sub-micron.
The third experiment is carried out when the precision translator is moving on 300-micron steps, the digital micrometer displayed the total journey is 7845.36μm and the measured result is 7845.356μm.

Figure 10 gives the relationship between the results of two methods under this condition, and Fig.11 shows the measured errors of the proposed method. Compared to the micrometer display results, the maximum error are -1.362μm and +0.239μm, and the standard deviation is 0.4349μm. This result illuminates that the measuring accuracy could also achieve micron level when the displacement is as large as centimeters.

5. Conclusion and discussion

To improve the precision of displacement measurement, in this paper, a phase subdivision of the absolute coding is proposed as well as its principle. The experimental results show that this method can improve the resolution and accuracy of displacement measurement based on absolute coding grating. This phase subdivision method has higher accuracy, because: (1) Primitive code channel is a high frequency Rochi grating. Noise and other errors which could affect the measuring accuracy have been significantly suppressed in spectrum filtering process when Fourier analysis method is used to calculate the phase information. (2) Information of hundreds of pixel in image plate have been used to locate and average the phase value, which will further eliminate the error caused by the grating period and the detector pixel pitch. The many line of grating image can be used for the displacement calculation, which
greatly eliminates the errors from some random factors, such as unstability of the light source, fluctuation of electrical signals and vibration of displacement platform.

The next step is to produce high-precision scale grating and the establishment of measurement systems to improve measurement accuracy and measurement stability.

In this method, to reduce the zoom ratio of the imaging system could improve the measurement accuracy in a smaller measuring range.

Acknowledgments

This project was supported by the National Natural Science Foundation of China (No. 60838002 and 60807006).

Reference