Tolerances analysis of planar diffraction grating interferometer for precise displacement measurement

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Abstract:

High accuracy XY platforms are widely used in modern industrial fields and measurement instruments, interferometers for its nano-resolution are usually employed to measure the platform's displacement. but the size of interferometers are large, expensive and sensitive to environments, what's more, the interferometers measurement systems are difficult to decrease the Abbe errors for its structure. So 2-D diffraction grating interferometer with insensitivity to alignment errors and air turbulence is proposed and it can detect planar displacement at the same time with compact system. In the paper, The effect of the interferometer geometry on the direction and period of the fringes is analyzed according to 2-D grating interferometer structure, the influence of the system geometry on the optical path difference is evaluated. the pitch and yaw of 2-D grating guide caused by planar guide is the main factors to decrease the measurement system's accuracy. The theoretical analysis of the three spatial axes guide error is carried out and the effected results are evaluated separately. According to the analysis, the measurement accuracy is sensitive to 2-D grating movement's pitch and yaw, the grating's location deflections are only systematic error and can be compensated by calibration experiments or software, some methods of system error correction and system mount are given. Based on the theoretical analysis, The experiments is carried out to verify the theoretically predicted error model.

1. Introduction

By using a grating as the measurement scale, the laser encoder is less prone to influences by environmental disturbances when compared with traditional laser interferometers. Miniature laser encoders using single diffraction grating as scale are ideally suited to precision measurement systems and position control systems. These linear measurement encoders have various forms, but they only can detect one dimension displacement, single encoder can't measure planar displacement. Precise XY positioning stages are important structures in modern industrial fields and measurement instruments, linear or angular displacement encoders with one direction are usually employed to measure the stage's displacement. and two encoders are used to measure X and Y axes displacement separately in one stage. In those structures, the mount errors of two encoders will be introduced into system and the system compaction will reduce. So 2-D diffraction grating interferometer is proposed based on one dimension grating interferometer and the interferometer can detects planar displacement at the same time with compact system.

However, traditional laser encoders possess optical configurations that are difficult to manufacture and usually have a tight head-to-scale tolerance that can restrict its applicability for many applications. So the key design of 2-D laser encoder should improve the alignment tolerance and make the system insensitive to disturbing shifts and tilts of the grating guide relative to the detector head. In linear encoders, many designs are proposed to solve the problems Several methods are used to solve these problems. Polarizing technique is widely employed to generate two interference zones with phase-shifted by $\pi/2$ and makes the system signal insensitive to the fringe tilts and its constant change. The cat eye type or cube corner type reflectors are used to compensate the tilts of the diffracted beam in some products. Those methods successfully used in 1-D encoder can also be adopted for designing 2-D grating interferometers.

In this paper the 2-D diffraction grating interferometer configuration and principle with high tolerance is presented, 2-D grating interferometers can achieve high resolution, small size, simple structure and can be used to detect the plane micro-displacement in microelectronics, ultra-precision fabrication and precise CMM etc. To reduce the system dimensions , laser diode is adopted as light source through inducing undesirable noise such as mode hopping, as well as additional errors. The error analysis of the head-to-scale mechanical runout will be given, and the theoretical relation between the detector head and inaccuracy of the grating guide and imperfect alignment is analyzed.

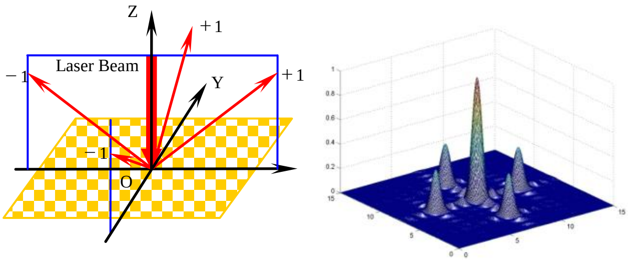
2. 2-D Grating Interferometer Principle

In 2-D diffraction grating interferometer system, cross diffraction gratings are taken as the fundamental scale elements to diffract measurement beams. The diffraction beam schematic diagram is shown in fig.1(a), laser beam perpendicularly projects on the surface of 2-D reflecting diffraction grating, sets of spatial symmetrical diffraction beams along grating's X and Y axes are diffracted, usually the first order diffraction beams are adopted as measurement beams. The grating's modulation formula can be expressed as:

$$t_{(x,y)} = \sum_m Arect(\frac{x-md_x}{a_x}) \times \sum_n Brect(\frac{y-md_y}{a_y}) \quad (1)$$

Where d_x and d_y are the grating constants, a_x and a_y are the groove widths, m and n is the groove's number in X and Y directions, A and B is the grating's size.

Fourier theory can be adopted to analyze the light intensity distribution, the four beams have same intensity simulated with 2-D grating of 1200l/mm in X and Y direction as shown in fig. 1. If 2-D grating moves in the plane of grating, the four diffraction beams will have different frequency, and can be used as measurement beam to measure the displacement.



a.Distribution of diffraction beam b.Energy distribution simulation

Fig.1. Diffracted beams of 2-D diffraction grating

The measurement principle of 2-D diffraction grating is similar to 1-D grating in single direction, the optical system forms interference fringes from the separate horizontal & vertical rulings of the grating. The fringes can be understood interference fringes between the ±1 order diffracted beams and the fringes signals are independent of the laser diode wavelength.

One direction optical layout is shown in fig.2, the schematic optomechanical configuration of the optical head employed a focusing len which can simplify mechanical assembly and manufacturing. In order to improve the tolerance of the optical head, a circular polarization interferometer and a wavefront conjugate optics with a focal len are adopted to design the optical configuration. Laser beam emitted from a diode laser transmit through the collimator, a circularly polarized light beam will be focused on the surface of the grating after the polarization beam splitter(PBS1)and λ/4 waveplate which can block the reflected beam to protect the laser diode. laser diode beam perpendicularly projects on the 2-D grating, the first order diffraction beams along X and Y axis are diffracted by reflecting grating separately and will be parallel after the focusing len, and the interference fringes can be detected behind beam splitter by photo detectors. When 2-D grating is moved in the grating plane, the light frequencies of first diffraction orders change according to the Doppler law. As a result two sine-wave periods per grating pitch displacement in X or Y direction is obtained according to the Doppler law separately. So the plane displacement of grating can be measured by counting fringe. This design proposition improve the system tolerance to some extent, Polarizing detection technique generating two interference zones with π/2 phase difference can be used to decrease the sensitivity to variations of interference pattern.

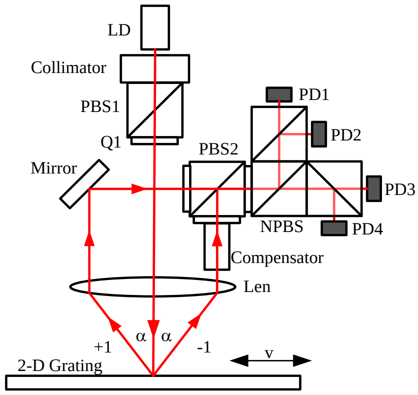


Fig.2. one direction optical measurement configuration

The frequency changes of first order diffraction beams diffracted by reflecting grating along X and Y axis can be deduced with Doppler law:

$$\Delta\omega_{+1} = \omega_0 + \frac{v}{d}; \qquad \Delta\omega_{-1} = \omega_0 - \frac{v}{d} \tag{2}$$

Where v is the grating Velocity, d is the grating period. the interference pattern's phase of the Symmetrical diffraction beam can be expressed as follows:

$$\Delta\phi = \int_0^t 2\pi(\Delta\omega_{+1} - \Delta\omega_{-1})\cdot d_t = \int_0^t 2\pi\cdot 2\frac{v}{d}\cdot d_t = 4\pi\frac{s}{d} \tag{3}$$

Here, s is the measured displacement. So the measured displacement is linear to the interference pattern's phase, and the light intensity detected by Photodetectors should be as follows:

$$\begin{aligned} I_{PD1} &\propto A^2(1+\sin\Delta\phi) = A^2(1+\sin 2\pi\cdot\frac{s}{d/2}) \\ I_{PD2} &\propto A^2(1+\cos\Delta\phi) = A^2(1+\cos 2\pi\cdot\frac{s}{d/2}) \end{aligned} \tag{4}$$

Photodetectors can detect sin or cos signal of the interference, when the grating move $d/2$, the Photodetectors signal will be change one period, by interpolation of the quadrature signal electronically, this system can be measure the micro- or nano-scale displacement by interpolation technique. For example, the measuring resolution of the laser encoder system can be improved to better than 10nm with a grating pitch of 1/1200mm.

3. Tolerances Analysis of Grating Interferometer

3.1 Optical Tolerance Analysis

In the system optical configuration, the circular polarized light beam is focused on the surface of the grating, and the grating has the same symmetrical diffraction property in any directions, it is can be proved that the proposed optical design can avoid the effect of differences in the polarization diffraction efficiencies.

Misalignment between the polarization beam splitter and wave-plate can usually affect measurement results and the displacement is no longer linear with respect to the signal phase change. As shown in fig.3, if the signal Lissajous pattern becomes elliptical because of the misalignment and optical component tolerances, the optical signal will encounter a different resolution when it is located to a different part of the ellipse. Signal errors will occur when the two PBSs in front of the corresponding photodetectors are misaligned at wrong relative polarization angles. By Jones calculus the misalignment angle δ can be related to the polarization misalignment error which shows up as an additional phase difference δ in the quadrature signals:

$$\begin{aligned} I_{PD1} &\propto A^2(1+\sin\Delta\phi) = A^2(1+\sin 2\pi\cdot\frac{s}{d/2}) \\ I_{PD3} &\propto A^2(1+\cos(\Delta\phi+\pi+\delta)) = A^2(1+\cos(2\pi\cdot\frac{s}{d/2}+\delta)) \end{aligned} \tag{5}$$

The polarization misalignment at the detector modules induce an sysmatic error with a period 2π. so it can improve the resolution of the system by the corresponding quadrature signal processing based on computer technique.

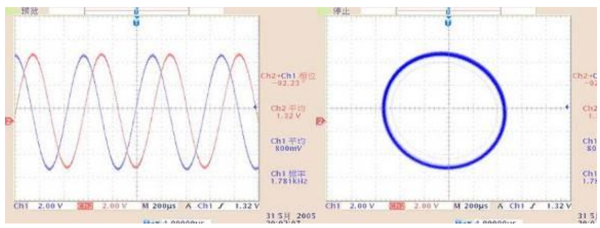


Fig.3 Interpolation error induced by the polarization misalignment

3.2 Head-to-Scale Mechanical Runout

What's more, the mechanical runout of the machine where the grating scale is mounted will directly influence the optical signals and may cause the opto-electronic signals to decay or even to disappear.

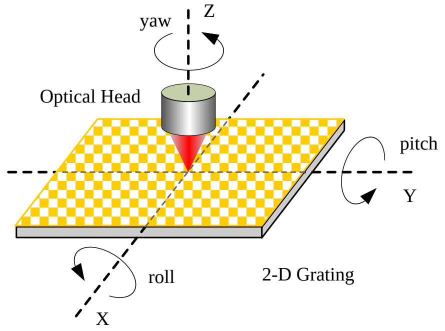


Fig.4 Schematics of the mechanical runouts affecting the performance of the encoders

As shown in Fig.4, there are two kind of mount error for the stage's straightness in the 2-D diffraction grating interferometer: 2-D grating mount error and XYZ displacement axes rotation error caused by grating plane guide. the grating mount error is the systematical error and can be compensated by calibration experiment, and the XY displacement axes rotation error is mainly random error caused by guide movement quality. 2-D diffraction grating mount tilts affecting measurement accuracy is much less than movement plane's pitch and yaw caused by plane guide.

3.2.1 Rotation of 2-D Grating in Displacement Plane and Grating mount

In the 2-D grating plane displacement interferometer, the grating movement plane's roll and pitch caused by X and Y guide's non-linearity will affect interference pattern. As is shown in fig.5 (a) and (b), when 2-D grating rotation angles are α and β in plane YZ and XZ in relation to the normal to the incident beam respectively, the angle variations of the interference are:

$$\Delta\varphi_x = 2\alpha \qquad \Delta\varphi_y = 2\beta \tag{6}$$

The space of interference fringes by superposition of two mutually coherent beams:

$$s = \frac{\lambda}{2\sin\varphi} \tag{7}$$

Where φ is angle of two mutually coherent beams; λ is laser wavelength. The space variation of interference fringes according to above formula:

$$\frac{\Delta s}{s} = \frac{1}{\tan\varphi}\cdot\Delta\varphi \approx \frac{\Delta\varphi}{\varphi} \tag{8}$$

So when 2-D grating is tilted by α and β, the space variations of interference fringes:

$$\frac{\Delta s_x}{s_x} \approx \frac{2s_x}{\lambda}\cdot 2\alpha \qquad \frac{\Delta s_y}{s_y} \approx \frac{2s_y}{\lambda}\cdot 2\beta \tag{9}$$

According to the formula, the system is sensitive to roll and pitch of 2-D grating movement guide. For example, the laser diode wavelength $\lambda = 650nm$, and X direction's interference fringe space $s_x = 0.2mm$, if the X guide tilts $\alpha = 2'$, the fringes space variations can reach 72%, and 76nm error will bring into the measurement results.

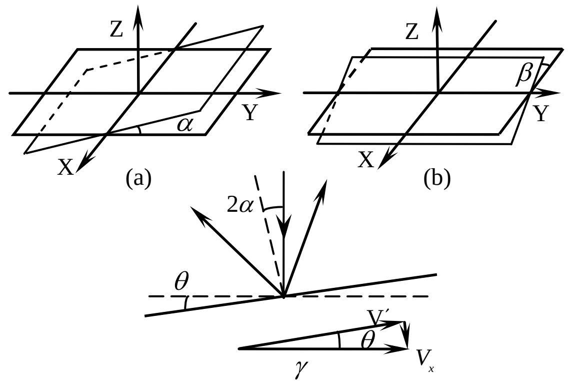


Fig.5 Errors analysis with 2-D grating guide and mount
(a) Rotation caused by X motion (b) Rotation caused by Y motion(c) 2-D grating mount tilt

When 2-D grating is mounted, the grating plane is not perfectly parallel to movement plane measured, we first analyze X direction, and the other Y direction can be the same method to analyze it. As shown in Fig.5(c), the angle θ_x between grating plane and displacement plane will bring the systematic errors, the measured value is just X guide displacement's component along grating plane according to Doppler law. So the relationship between measured value (L_x') and true displacement value (L_x) can be expressed:

$$L_x = \frac{L_x'}{\cos\theta_x} \tag{10}$$

If $\theta_x = 2', L_x = 25mm$, the measurement error can be evaluated by:

$$\Delta L_x = L_x(1-\cos\theta_x) \approx 4.2nm \tag{11}$$

So 2-D diffraction grating mount tilts affecting measurement accuracy is much less than movement plane's roll and pitch caused by plane guide, and the grating mount tilts is the systematic errors which can be measured by calibration and compensated through computer technique.

3.2.2 Rotation of Z axis and position of Grating mount along Z axis

As shown in Fig.6(a), the rotation angle γ around Z axis in grating plane caused by 2-D grating mount or grating movement plane will affect the interference pattern, the direction of fringes also changes the corresponding angle γ, The space of interference fringes on fixed position photodetectors are:

$$s_x' = \frac{s_x}{\cos\gamma} \qquad s_y' = \frac{s_y}{\cos\gamma} \tag{12}$$

And the variations of interference fringe space are:

$$\Delta s_x = s_x - s_x' = s_x\left(1-\frac{1}{\cos\gamma}\right) \qquad \Delta s_y = s_y - s_y' = s_y\left(1-\frac{1}{\cos\gamma}\right) \tag{13}$$

If γ is less than $5'$ which can be easily acquired in practice, the variations of interference fringe space will be less than 10^{-6} of the space of interference fringes, so fringe space variations caused by rotation around Z axis in 2-D grating plane can be omitted.

Rotation around Z axis in 2-D grating plane not only affects the interference fringe space, but also introduces the error between measured value and true value. As is shown in fig.6(c), if we don't consider 2-D Grating X and Y grooves' vertical error, when guides move L_x along the X-axis, the measured valued in X axis is L_x' and the corresponding Y axis displacement measured values is ΔL_{xy}, their relation can be express as below:

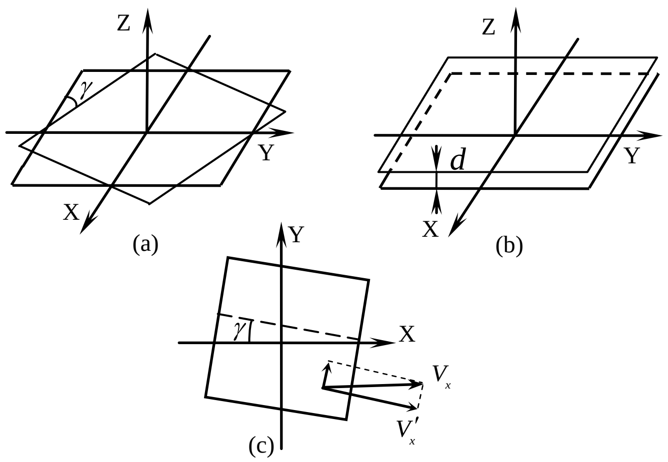


Fig. 6 Errors analysis related to Z direction
(a) Rotation around Z axis (b) mount position along Z axis (c) error caused by rotation around Z axis

$$L_x = \frac{L_x'}{\cos\gamma} \qquad \Delta L_{xy} = L_x \cdot \sin\gamma \tag{14}$$

Where, ΔS_{xy} is the Y axis displacement error caused by X axis movement. So the same to Y axis:

$$L_y = \frac{L_y'}{\cos\gamma} \qquad \Delta L_{yx} = L_y \cdot \sin\gamma \tag{15}$$

These errors can be used effectively to adjust grating direction and planar motion to parallel each other. When X axis guide moves only, 2-D grating position is adjusted until X direction detectors have continuous output signal yet Y direction detectors have no output signals, under the situation, X movement will be vertical to 2-D grating's Y grooves. In practice, planar movement X and Y axes guides isn't vertical to each other ideally, and the same to X and Y axes grooves of 2-D grating, so it is difficult to adjust X and Y axes of planar movement parallel to X and Y axes grooves of 2-D grating. One axis of movement can be adjust parallel to the same direction's grooves of grating by and large, the other axis of movement can't be parallel to the corresponding direction's grooves of grating very well, but the not good enough axis displacement can be modified though equation (14) or (15) by experiments, and also the equivalent grating coefficient can be adopted to compensated in real time by software:

$$\begin{bmatrix} d_x^1 \\ d_y^1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & (\cos\theta_y)^{-1} \end{bmatrix} \begin{bmatrix} d_x \\ d_y \end{bmatrix} \tag{16}$$

Here, θ_y is the angle between Y guide movement and Y direction grating while X movement guide is parallel to X direction grating, and the angle can be measurement according formula (14) and (15). In order to improve the 2-D diffraction grating interferometer's accuracy, two axes direction movement can't be carried out simultaneously especially under not so good X and Y movement guide linearity situation.

2-D grating positioning error along Z axis is shown in fig.6(b), the grating positioning error has the same effects on symmetrical diffraction beam, doesn't change the interference fringe pattern, so the system measurement accuracy isn't sensitive to the grating positioning error obviously.

4. Conclusions

Diffraction grating interferometer are ideally suited to modern control systems and precision measurement systems. In this paper the general 2-D diffraction grating interferometer configurations is introduced, In order to improve the system's adaptability, a circular polarization interferometer and a wavefront conjugate optics with a focal len are employed in the optical system design.The error sources of 2-D diffraction grating interferometer was analyzed. The grating movement plane's pitch and yaw caused by non-linearity of planar movement guides are the main error sources, and the mount defects like grating mount position and grating mount tilts does not effect the variation of interference fringe space. The mutual effects between X and Y direction movement can be compensated, but can't be completely eliminated in practice, so higher accuracy can be acquired if X and Y guide don't move in the same time.

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