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Reducing machine-ruling grating wavefront value by compensating grating substrate surface error in real time

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ABSTRACT

To improve the grating wavefront quality especially the grating size, which is more than 1 m, we provide a method based on conical diffraction theory and grating groove active control technology to correct the grating substrate surface error. We apply the grating groove active control technology to carry out an echelle grating ruling experiment whose line density is 79 lines/mm in 36th order. Compared with the grating substrate surface error, the grating wavefront value reduces from 0.105 λ to 0.056λ i.e., decreases by 47%. The experimental result proves that the grating substrate surface error compensation method can be used to improve the grating wavefront quality effectively.

1. Introduction

Plane diffraction gratings especially the echelle grating in meters, which is ruled on the surface of aluminum or other materials such as gold and used in the UV to infrared band, are very popular in military, astronomy, defense, and civilian applications because of their excellent optical functions [1,2]. The main production methods for the echelle grating are mechanical ruling and wet etching techniques [3]. Among them, the wet etching method, which is limited by the processing technology, is generally limited to the manufacture of small-scale echelle grating. Moreover, the etching object of the method is an anisotropic crystal material, for which it is difficult to arbitrarily change the groove shapes according to requirements. Thus, the effect of the manufactured grating is difficult to reach the ideal design value of grating diffraction efficiency. Therefore, the echelle grating is still produced by mechanical ruling currently.

As the quality of diffraction wavefront has a large impact on grating optical properties, foreign researchers paid much attention to it. For mechanically ruled grating, the diffracted wavefront error in fact comprises the substrate surface error and the ruling error [4,5]. Previous investigations have made considerable research on how the grating ruling error can be reduced. The American MIT-A grating ruling machine [6,7] corrected the link mode of the ruling tool system and the ball bearing structure; in this case, the torque can be absorbed by the ball bearing, reducing the grating ruling error, which is generated by the instantaneous torque. Harrison also made corrections to the grating ruling error of the United States MIT-C grating ruling machine, by increasing the thickness of the guide rail from 50 to 100 mm and reducing the grating curve line error, which is generated by the lateral force of the rail during the grating ruling process. Furthermore, the grating ruling machine has a double table carriage to correct the yaw error [8]. In our previous work, it was demonstrated that if we correct the yaw error by using the double piezoelectric ceramics (PZT) to control the inner carriage; the yaw error could be reduced from 0.2″ to 0.027″, i.e., reduced about 86.5% [9]. Furthermore, we have previously provided a method to monitor the grating ruling quality directly in real time, and thus, we can improve the grating ruling quality effectively [10]. Changes in the grating ruling environment will have an impact on the grating ruling error; therefore, the MIT-C grating ruling machine controlled the temperature in the ruling zone to be <0.005 °C and that in the vicinity of the laser to be <0.01 °C by air cooling [11]. The key components were made of Invar material to reduce the effects of thermal expansion. Japan's Hitachi-4 grating ruling machine was also placed under vibration isolation condition to maintain a temperature fluctuation within 0.01 °C [12]. CIOMP-2 grating ruling machine of China was placed in a double enclosure using four air springs to support the grating ruling machine body to achieve the vibration isolation effect, and the thermostat controlled the temperature fluctuation within

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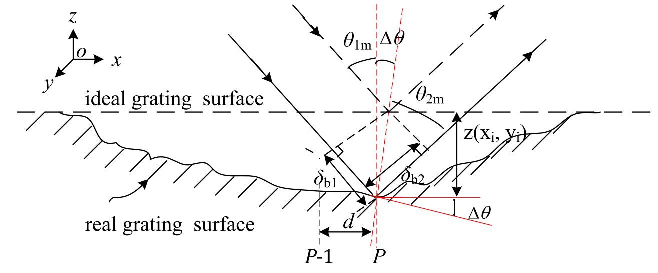

Fig. 1. Optical path difference caused by the grating substrate surface error.

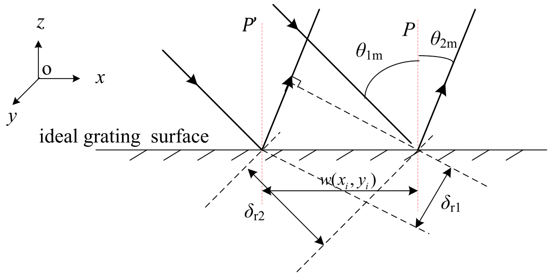

Fig. 2. Optical path difference caused by the ruling system error.

±0.05 °C [13,14]. Recently, the Changchun Institute of Optics and Fine Mechanics and Physics has researched a grating ruling machine CIOMP-6 with a maximum ruling size of 400 mm × 500 mm, whose thermostat controlled the temperature fluctuation within ± 0.007 °C.

The quality of the grating wavefront was also improved by reducing the grating substrate surface error. However, it is difficult to guarantee whether the grating substrate surface is good enough and the coating is completely uniform, especially for gratings at the meter level. The wavefront error generated by the substrate surface of grating will be added directly to the ruling grating as an initial error, which has a greater impact on the grating wavefront value. To solve these problems, this paper proposes a method for compensating the grating substrate surface error, and the paper is organized as follows. In Section 2, we establish a mathematical model for compensating the grating substrate surface error on the basis of the conical diffraction theory [15,16]. In Section 3, we introduce a method, namely the grating groove active control technology, to correct the grating substrate surface error in real time . In Section 4, we apply the above technique to the actual ruling experiment, and the relative result is provided. The conclusion is given in Section 5.

2. Mathematical model for compensating the grating surface error in real time

In Fig. 1, abscissa x represents the length of the grating and ordinate y represents the direction of the grating groove. $\Delta\theta$ is the error angle of the grating substrate surface of the Pth groove [17]. Considering a grating without groove errors but with substrate surface errors, and assuming that a monochromatic parallel light is incident on the planar reflection grating surface, the pattern of incidence is cone diffraction. $\theta_{1m}+\Delta\theta$ and θ_2 represent the incident angle and the diffraction angle, respectively. The angle between the incident ray and the principal section the grating is φ_1, and the angle between the diffraction ray and the main section of grating is φ_2. d is the grating constant. For the convenience of discussion, we assume that the light is incident along the principal section of grating, when $\varphi 1$ and $\varphi 2$ are equal to zero. The grating groove direction is along the y-axis, which is perpendicular to the plane of the figure. When a depth error exists in the form $z(x_i, y_i)$ at the actual position point P, the optical path difference of the incident light at this point δ_{b1} can be given as follows:

$$\delta_{b1} = \frac{z(x_i, y_i)\cos(\theta_{1m} \pm \Delta\theta)}{cos\Delta\theta} = z(x_i, y_i)(\cos\theta_{1m} \mp \Delta\theta \sin\theta_{1m}) \tag{1}$$

The optical path difference of the diffracted light at this point δ_{b2} can be given as follows:

$$\delta_{b2} = \frac{z(x_i, y_i)\cos\theta_{2m}}{cos\Delta\theta} = z(x_i, y_i)\cos\theta_{2m} \tag{2}$$

The optical path difference caused by the substrate surface error at point P is given as follows:

$$\delta_{blank} = \delta_{b1} + \delta_{b2} = z(x_i, y_i)(\cos\theta_{1m} + \cos\theta_{2m} \mp \Delta\theta \sin\theta_{1m}) \tag{3}$$

For different positions of the grating groove, the depth error $z(x_i, y_i)$ is different,

$$z(x_i, y_i) = \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \vdots & \vdots \\ x_i & y_i \end{bmatrix} \tag{4}$$

We intend to improve the grating wavefront quality by compensating the grating substrate surface error with the grating groove errors. When the grating substrate surface error does not exist, only the grating groove error is present; as shown in Fig. 2, P is the actual position of the grating groove and P' is the ideal position. If the Pth groove position error exists, the difference between the actual groove position and the ideal groove position is $w(x_i, y_i)$. The optical path difference at this time of the incident and diffracted light generated at point P is given as follows:

$$\delta_{ruling} = \delta_{r1} + \delta_{r2} = w(x_i, y_i)(\sin\theta_{1m} + \sin\theta_{2m}) \tag{5}$$

When φ_1 and φ_2 are not equal to zero, the optical path difference caused by the grating substrate surface error is the same as given in Eq. (3). Here, the optical path difference caused by the groove error is given as follows:

$$\delta_{ruling} = w(x_i, y_i)(\sin\theta_{1m}\cos\varphi_1 + \sin\theta_{2m}\cos\varphi_2) \tag{6}$$

Considering that m is the grating diffraction order and λ is the wavelength, the grating equation can be given as follows:

$$d(\sin\theta_{1m}\cos\varphi_1 + \sin\theta_{2m}\cos\varphi_2) = m\lambda \tag{7}$$

The optical path difference caused by the grating groove error can be calculated from Eqs. (6) and (7), as shown in Eq. (8):

$$\delta_{ruling} = w(x_i, y_i)\frac{m\lambda}{d} \tag{8}$$

Ideally, the grating wavefront error is equal to zero, which means that the sum of the grating substrate surface error and the ruling error is equal to zero.

$$\delta_{blank} + \delta_{ruling} = 0 \tag{9}$$

The grating substrate surface error can be compensated by controlling the ruling position of the diamond tool by the grating groove active control technology. Substituting Eqs. (3) and (8) into Eq. (9), we have the following:

$$w(x_i, y_i) = -z(x_i, y_i)(\cos\theta_{1m} + \cos\theta_{2m} \mp \Delta\theta \sin\theta_{1m})\frac{d}{m\lambda} \tag{10}$$

In general, when a ZYGO interferometer is used to test the grating diffracted wavefront, the monochromatic light incident angle is equal to the absolute value of the diffraction angle. Furthermore,

$$\sin\Delta\theta = \frac{z(x_i, y_i)}{d} \ll \theta_{1m} \tag{11}$$