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Practical method study on correcting yaw error of 500 mm grating blank carriage in real time

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We provided a method to correct the yaw error of a 500 mm grating blank carriage in real time, as the yaw error will bring down the quality of wavefront. We designed a structure with double piezoelectric devices to correct the yaw error. At the same time, to evaluate the correcting ability of our structure, we proposed a relative optical testing structure to verify the correcting accuracy by experiments. The experiment result showed that our method can accomplish the correction of yaw error in real time effectively, at the same time guaranteeing the grating quality.

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1. INTRODUCTION

Plane diffraction grating [1] with excellent optical functions, such as polychromatic light dispersion, polarization, and phase matching, are very popular for military, astronomy, defense, and civilian applications [2–4]. These gratings are mainly produced by mechanical ruling and ion-beam etching [5]. Until now, because of deep grooves with strict shapes, echelles and infrared-laser gratings are still produced by mechanical ruling [6].

In mechanical ruling, most grating ruling machines prefer to Rowland structure [7–9], where the grating blank is mounted on the working carriage moving in the indexing direction. At the same time the diamond tool moves along the fused-silica guide to produce the reciprocating motion. The direction between the grating blank moving and the diamond tool ruling is vertical. However a variety of errors will be produced, including periodicity error of the screw, straightness error of the way, and so on. In this case the errors result in nonlinear grooves and the grating wavefront become bad [9,10]. Therefore, yaw control is necessary to offset errors of the blank carriage.

Now the top two grating ruling areas are ruled by M.I.T-C and M.I.T-B, respectively (M.I.T-C 450 mm × 635 mm, M.I.T-B 260 mm × 430 mm). M.I.T-C ruling engine had achieved yaw correction, the specific ways where they used interferometer as a measuring and feedback component, flywheel as a execute component, making up a closed-loop system to offset yaw errors. The blank carriage was fitted on an outside carriage. When there is yaw error produced by the outside carriage, the servo motor is used to correct yaw error to 0.02″ [11,12].

In this paper we established a yaw error correcting system that is used to correct the yaw error of CIOMP-6, the second largest grating ruling engine in the world, whose ruling area is 400 × 500 mm. We use an interferometer as a measuring and feedback component, double piezoelectric devices as an execute component. When the working carriage has a yaw error, we adjust the length of the double piezoelectric devices [13] to offset errors of the inside carriage in order to achieve the yaw error correction.

This paper is organized as follows. In Section 2, we explore the basic theory of grating wavefront quality that is influenced by yaw error. In Section 3, we introduce the structure of the grating blank carriage and principle of the yaw correction system. In Section 4, we design the optical testing structure to get the yaw error in real time. In Section 5, we apply the above technique to the actual experiment and the relative result is introduced. The conclusion is given in Section 6.

2. THEORY

As can be seen from Fig. 1, if there is a yaw error on the inside carriage, there will be a yaw error between the ideal grating groove P and the actual groove P′. In this section, we established a modal between yaw error and the grating wavefront.

The grating diffraction equation is $d(\sin\theta\mathrm{i} + \sin\theta\mathrm{m}) = \mathrm{m}\lambda$, where d is the grating constant, θi is the incidence angle, θm is the refraction angle, and m is the order of diffraction. Assuming that the grating ruling width is W, the

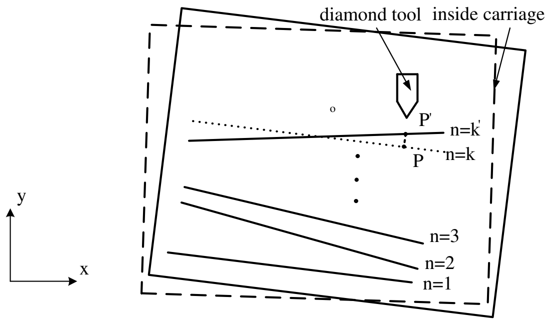

Fig. 1. Grating lines when there are yaw and position error of the blank carriage.

straightness of the grating guide is a(n), we can get the yaw error matrix A as

$$A = \begin{bmatrix} \alpha(1) & 0 & \cdots & 0 \\ 0 & \alpha(2) & \cdots & 0 \\ & & \vdots & \\ 0 & 0 & \vdots & \alpha(n) \end{bmatrix}. \quad (1)$$

In step-start mode, the yaw error can be calculated as

$$\begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1m} \\ y_{21} & y_{22} & \cdots & y_{2m} \\ & \vdots & & \\ y_{n1} & y_{n2} & \cdots & y_{nm} \end{bmatrix} = \tan(A) \times \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ & & \vdots & \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix}, \quad (2)$$

where the grating grooves are α(n) in different position x(m). The optical path difference is calculated as follows:

$$L = 2\sin\theta_i \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1m} \\ y_{21} & y_{22} & \cdots & y_{2m} \\ & & \vdots & \\ y_{n1} & y_{n2} & \cdots & y_{nm} \end{bmatrix}. \quad (3)$$

Under Littrow type, $\theta\text{i} = \theta\text{m} = \theta$. By combining Eqs. (1) and (2) with Eq. (3), the optical path difference can be calculated by

$$L = \tan(A)\frac{m\lambda}{d} \times \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ & & \vdots & \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix}. \quad (4)$$

The wavefront can be calculated as follows:

$$\Delta = \tan(A)\frac{m}{d} \times \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ & & \vdots & \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix}. \quad (5)$$

With increasing the length of the grating line and enlarging of the order of diffraction, the grating wavefront quality becomes worse because of the yaw error. For example, CIOMP-6 grating ruling engine is used to rule an echelle grating whose length is 500 mm, grating constant is 79 line/mm, diffractive order m is 36, and yaw error of the blank carriage is 0.2″. We can calculate the grating wavefront as 1.3788λ. At the same time for a high groove density grating whose grating constant is 6000 lines/mm, the diffractive order m is 1, we can calculate the grating wavefront as 2.9λ. To an echelle grating or a grating that has a large area or high groove density, when we carry out yaw error correcting, the grating wavefront will be improved greatly. In this case yaw error must be corrected.

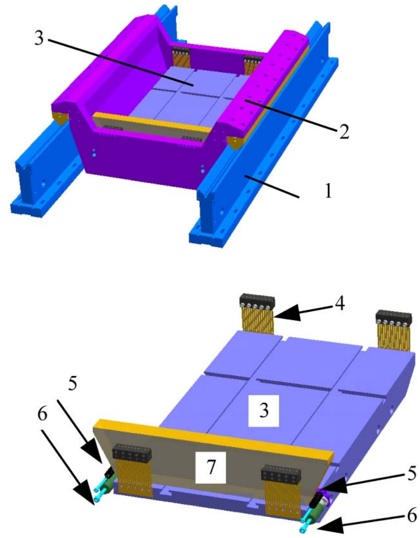

Fig. 2. Mechanical structure of the blank carriage. 2 and 3 are outside and inside carriages, which are connected by the leaf spring 4; 5 is extension spring for providing close force; 6 is piezoelectric device; and 7 is measure mirror.

3. EXPERIMENT

A. Structure of the Blank Carriage

It can be seen from Fig. 2, the mechanical structure of the blank carriage includes outside carriage 2, inside carriage 3, leaf springs 4, extension springs 5, and the double piezoelectric devices 6.

The outside carriage slides on the double V ways 1 whose length is 700 mm. In order to reduce friction, there are 64 balls between the double V ways. The grating blank is mounted on the inside carriage 3. The inside carriage 3 is hung in the outside carriage 2 by four parallel leaf springs 4. In this way the inside carriage moves without friction and the leaf springs also provide the freedom of yaw and position. The double piezoelectric devices 6 are installed between the inside and outside carriage in both sides. The length of this device is varied so as to cancel the continuous translation of the blank carriage and to make the inside carriage in the predetermined position. The extension springs 5 are installed between the inside and outside carriage to provide close force.

B. Principle of the Yaw Error Correction

The grating ruling engine includes a ruling system and an indexing system. The indexing system includes macropositioning and micropositioning. In the macropositioning, an indexing generator drives the blank carriage to run a groove by guide screw. The blank carriage moves from A to B. Because of the straightness error of the rails and machining error of the blank carriage, there is a yaw error in the outside carriage. At the same

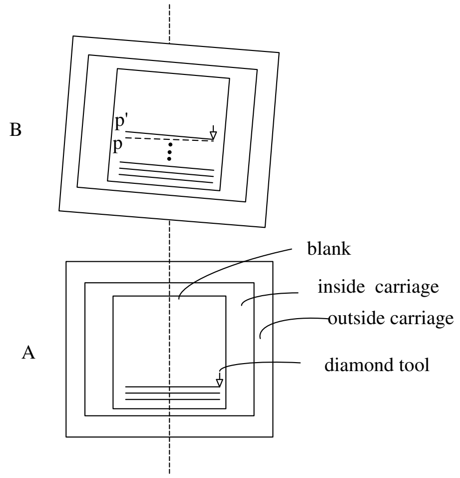

Fig. 3. Schematic of yaw errors that are produced by the indexing system of the grating ruling engine.

time the outside carriage drives the inside carriage to move a yaw error. Because the diamond tool's position remains invariant, in this case there will be a yaw error between the ideal grating groove P and the actual grating groove P′, which is shown in Fig. 3.

The yaw errors can be retrieved using the optical testing system. Then we adjust the length, l_1 and l_2, of the double piezoelectric devices [14] to the ideal position. In this case the grating lines can arrive at the preset spacing n = k in any time, shown in Fig. 4.

4. MEASURING SYSTEM

In order to measure the yaw error, we design a light testing structure.

Figure 5 shows the optical layout of the laser interferometer measuring yaw error in real time. A laser beam with $\lambda = 632.8$ nm is split into two parts by beam splitter A. Beam 1 incidents to interferometer A and beam 2 incidents to beam splitter B. Beam 4 incidents to the wavelength compensation interferometer in order to compensate errors which are produced by the change in refractive index air. Beam 5 incidents to interferometer B. The reference mirror position remains the same, while the position of the bar mirror (measuring mirror) has changed at the same time, producing Doppler frequency

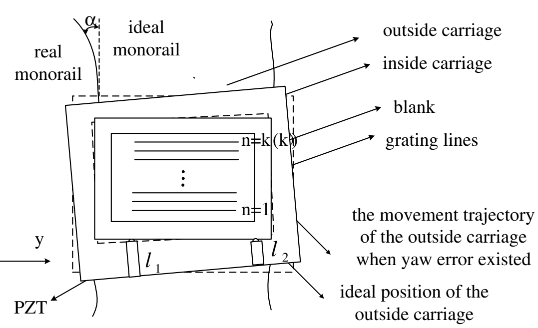

Fig. 4. Schematic of double piezoelectric devices achieved yaw error correction.

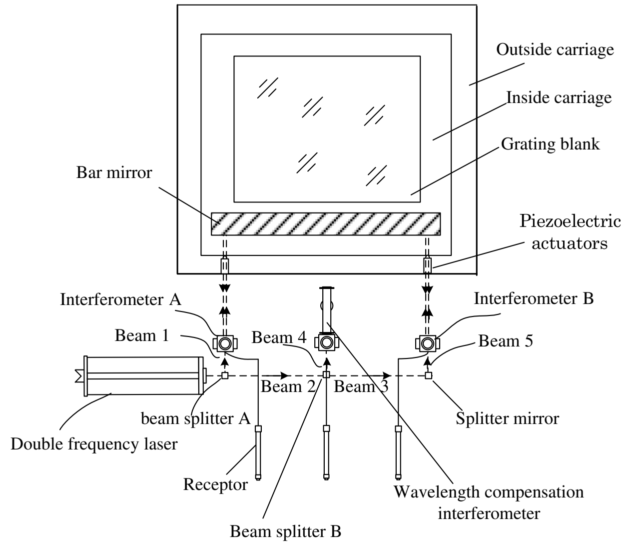

Fig. 5. Optical path of the yaw angle measurement.

shift Δf. The beat signal formatted is received by the receiver. The displacement error l of the bar mirror is as follows:

$$l = \frac{\lambda}{4}\int_0^t \Delta f \times \mathrm{d}t = N\frac{\lambda}{4}, \tag{6}$$

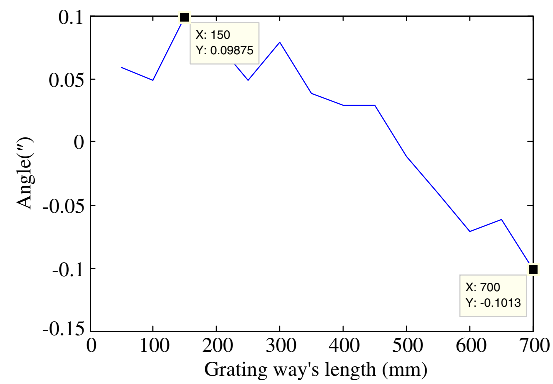

Fig. 6. Way errors of the grating engine.

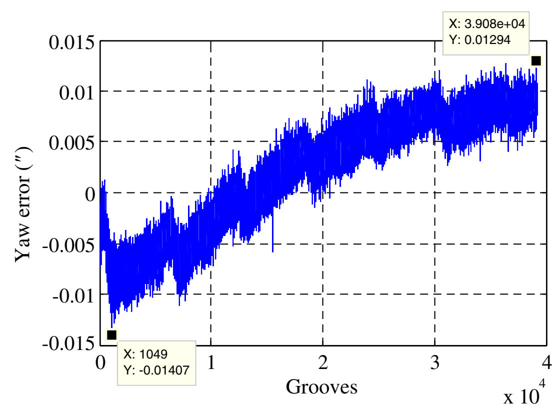

Fig. 7. Yaw error of the CIOMP-6 ruling engine after correcting.

Table 1. Design Parameter of the Grating

Ruling Size	Groove Spacing	Start Wavelength	End Wavelength	Center Wavelength	Blaze Angle
70 × 60 mm	294 line/mm	1.124 μm	1.403 μm	1.27 μm	10.1°

where λ is the laser wavelength, N is the value of the pulse count. We can compute the yaw error as follows:

$$\alpha = \tan^{-1}((l_1 - l_2)/L). \quad (7)$$

l_1 and l_2 are left and right displacement errors, respectively, L is the displacement between the measuring axes.

5. RULING EXPERIMENT

In order to prove availability of the yaw correction system, we used the CIOMP-6 grating ruling engine which can achieve 400 × 500 mm grating ruling area to carry out the comparison experiment. First, we used parallel light pipe to measure the yaw error of the CIOMP-6 grating ruling engine's way; second, we used the yaw correction system to rule a grating and get the yaw error after correcting.

Figure 6 shows the straightness of the way of the grating ruling engine which was processed by our laboratory of CIOMP in China. It could be seen that the way length was 700 mm (the length of way was longer than the length of the inside carriage) and the angle error was 0.2″. If we rule an echelle whose ruling width is 400 mm, the diffraction order is 36 and the grating constant is 79 groove/mm. The grating wavefront can be calculated by formula (5). The wavefront is 1.103λ after calculating.

With the yaw correction system we simulated a ruling process to a grating whose area was 400 × 500 mm. Figure 7 shows the yaw error, which was measured by the optical testing structure, abscissa representing the grating grooves and ordinate representing the yaw error value of the blank carriage during running 500 mm length (79 line/mm echelle grating). It could be seen that the yaw error was about 0.027″. Compared with Fig. 6, the yaw error had reduced 86.5%. In this case, if we rule the echelle whose ruling width is 400 mm, the diffraction order is 36 and the grating constant is 79 groove/mm, the grating wavefront will be 0.1489λ.

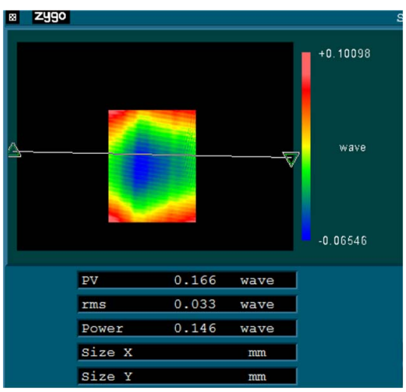

Fig. 8. Wavefront quality of the grating was measured by Zygo interferometer.

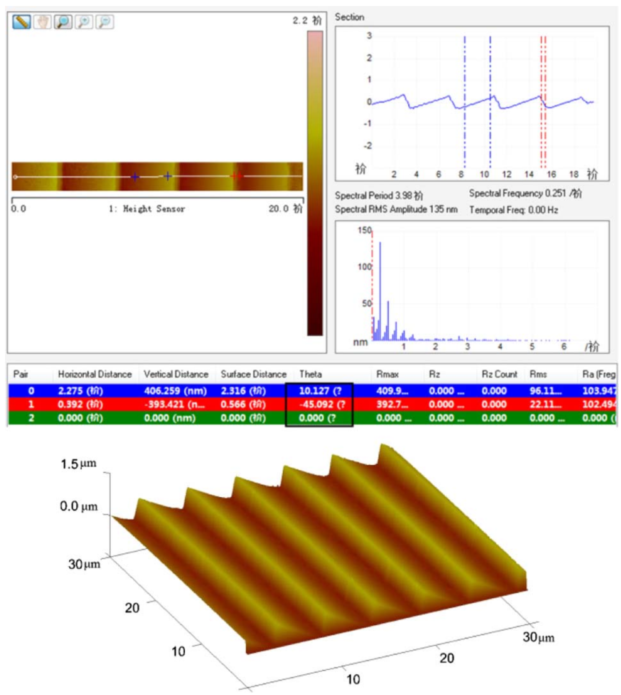

Fig. 9. Testing results of AFM for grating grooves.

We ruled a grating, whose parameter is shown in Table 1, by the yaw correction system. Then we measured the grating wavefront, grating groove quality, and diffraction efficiency in order to verify the system was effective.

Figure 8 shows the grating wavefront that was measured by the ZYGO interferometer. It could be seen that the wavefront value was 0.166λ.

Figure 9 shows the grating grooves, which were measured by an atomic force microscope (AFM). From the black frame we could get that the blaze angle was 10.127°, which was close to the ideal value in Table 1, proving the groove quality was very good.

We calculated the grating efficiency by electromagnetic field theory [14] and got the efficiency about 88%. At the same time we measured the actual efficiency of the grating, which was 87%. The measuring value and the theoretical value were nearly the same.

6. CONCLUSION

In this paper, we introduced a method correcting the yaw error by double piezoelectric devices in real time. We established a math model between yaw errors and grating wavefront. Based on the model we got that the yaw error affected the grating wavefront seriously. In the latter part we designed a measuring optical testing structure of the feeding system and carried out simultaneous ruling experiments. The experiment results showed that the yaw error reduced from 0.2″ to 0.027″ with the yaw correction system. Therefore we ruled a grating with the yaw correction system and got the PV (the grating wavefront value) was 0.166λ, the blaze angle was 10.127°, and the grating efficiency was 87%, which were close to the ideal values. In conclusion, the method can correct the yaw error in real time and the grating wavefront will be improved significantly.

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