Self-guiding method for ruling diffraction gratings

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Abstract

The paper presents a new approach to rule a long diffraction grating, in which a short ruled portion of the ruling grating blank is used as a new dividing element of the engine to continue its ruling . The main ruling errors are analysed and some formulae for the calculation of these errors are derived. The actual resolution of a specimen is 90% of its theoretical value . The tentative results have verified the correctness of the principle links to this method .

Introduction

Diffraction gratings are now used not only for optical spectrometers, but also for high precision measurement instruments. In order to rule a long diffraction grating, a correspondingly long dividing element in an engine as a reference is usually regarded as indispensable, but as we know, the long dividing system is very difficult to make . The dividing system with a datum grating has some advantages, but the controlling length is limited to the length of the datum grating as well .

To solve this problem, we suggest the "self-guiding method" for ruling diffraction gratings. The "self-guiding method" is different from the traditional method, in which the dividing elements of the ruling engines are independent of the being ruled grating . It uses a ruled section of the ruling grating as a dividing datum element, so that any long grating can be expected to rule in this way .

Principle of the self-guiding method and analysis of the switching error

Imagine of the self-guiding method

At first, the engine ruled a portion of the grating on the beginning of a long blank under the control of the signals from an interferometer with a conventional reference . When the length of the ruled section is long enough to the second interferometer, it is utilized as the datum element for generating the "self-guiding signals" (Fig.1) . By means of electronic circuits we regulate the amplitude and phase of the self-guiding signals to approach that of the signal from the first interferometer as close as possible . Then, the control signal of the engine is switched over to the self-guiding signal for further ruling . Obviously, in this way, any long gratings can be ruled.

Formation of the self-guiding gratings and its switching errors

The grating error caused by the phase difference between the first signal and self-guiding signal at the moment of switching over is called "switching error" . We must find out the relationship between the "switching error" and the ruled grating error .

The error transferences of the datum grating of splitting beam grating interferometer have been detailed in another paper, * here we only use its some conclusions and formulae to analyse the switching error transferences .

In the interferometer, two diffraction beams of the grating (m_1 and m_2 beams in Fig.2) interfere and form a set of "half-wave phase difference plane" . In the self-guiding method, the half-wave planes of the last segment of the grating become the control signals for ruling the following section .

Fig. 2 is the schematic diagram about the switching error transference . It is drawn according to the process in which the self-guiding grating is being ruled . The coordinate plane XOZ expresses the self-guiding grating; the XOY plane expresses the half-wave planes . The d is the length which is covered by diffraction beam; b is the space between two beams. The simple exposition about segments of self-guiding grating is explained below .

The segment L_0 is the beginning segment which was ruled by conventional control signals, its grating pitch is a , there is no errors . The Δa is the switching error . It is formed in the first ruling line after two signals have just been switched . The Δ is switching error coefficient . The segments L_1, L_2, and L_3 correspond respectively with the half-wave planes from the L_0 , L_1 and L_2 . The formulation of these half-wave planes is :

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* " The error transferrences of the datum grating with splitting beam grating interferometer for measuring linear displacement " has not been published .

$$x_k = \frac{a}{2m}\left(k+\frac{1}{2}\right) \qquad (1)$$

The space between two neighbouring half-wave planes is :

$$\delta x = \frac{a}{2m} \qquad (2)$$

The corresponding new grating pitch is :

$$\bar{a} = 2m\cdot\delta x \qquad (3)$$

Where k is an integer, m is the diffraction order number . From above-mentioned analysis we know the pitches of L_1, L_2 and L_3 all are a . These three segments all are normal segments .

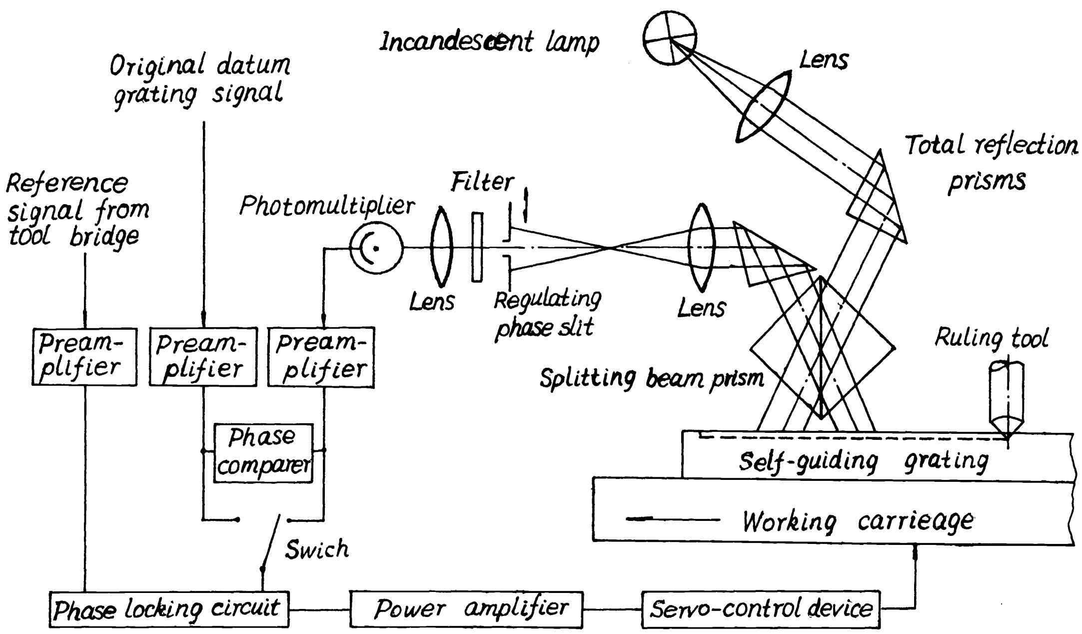


Fig. 1.Schematic diagram of self-guiding method for ruling diffraction grating .

The segment l_I is a transition segment which has been formed while two beams of the interferometer are crossing the switching error Δa . The x_0u and x_0v are named transition lines, they divide the half-wave planes, which are between y_1 and y_2, into A,B and C three different areas. The k-th half-wave plane equation is shown as follows :

$$X_k(X,Y) = \frac{a}{2m}\left(K+\frac{1}{2}\right) + \frac{1}{2}\int_0^{X_K - y\,tg\alpha} f_2(X)\,dX + \frac{1}{2}\int_0^{X_K + y\,tg\alpha} f_1(X)\,dX \qquad (4)$$

Where α is diffraction angle of the two beams; $f_1(x)$ is the grating pitch error coefficient of the section which is covered by diffraction beam m_1; $f_2(x)$ is the grating pitch error coefficient of the section which is covered by beam m_2. For the position of the k-th half-wave plane in various area is different, when along the y direction to compute the average position of the half-wave plane, the equation can approximately be shown (for l_{II}) :

$$\bar{X}_K = \frac{1}{y_2 - y_1}\left[\int_{y_1}^{y=-(X_K - X_0)\,ctg\alpha} X_{AK}(X,Y)\,dy + \int_{y=-(X_K-X_0)\,ctg\alpha}^{y_2} X_{BK}(X,Y)\,dy\right] \qquad (5)$$

According to different value of $\bar{x}_k$, we can divide this part into I,II and III segments . Finally, the new grating pitches of the above three segments are obtained respectively :

$$\bar{a}_{l_1 I} = a(1+\frac{a}{2d}\Delta)$$

$$\bar{a}_{l_1 II} = a$$

$$\bar{a}_{l_1 III} = a(1+\frac{a}{2d}\Delta)$$

The new pitch error coefficient is :

$$\bar{\Delta} = \frac{a}{2d}\Delta \quad (6)$$

The accumulated error from x_1 to x_2 is :

$$\int_{x_1}^{x_2} f(x)dx \quad (7)$$

The accumulated error in l_1 is :

$$\int_{X_0-\frac{b}{2}-d}^{X_0-\frac{b}{2}} \bar{\Delta}dx + \int_{X_0+\frac{b}{2}}^{X_0+\frac{b}{2}+d} \bar{\Delta}dx = \Delta a$$

Where x_0 is the position of the switching error . From the above-mentioned analysis, it is clear that the error value of Δa was spread into l_1I and l_1III , but the total accumulated error value is still Δa .

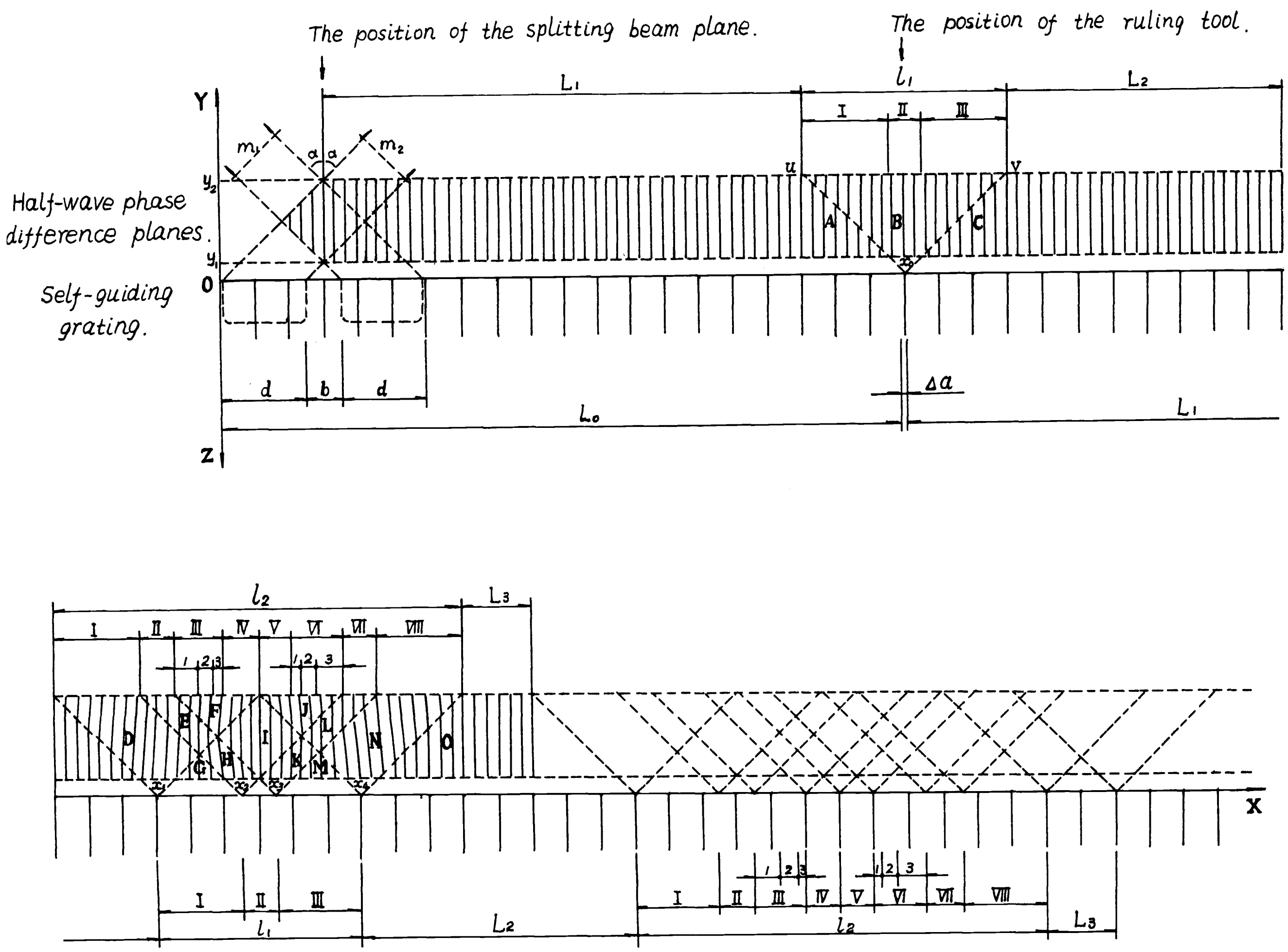


Fig. 2. " Half-wave phase difference plane " and error transfer of self-guiding method .

The segment l_2 is formed while the two beams are gradually crossing the l_1. From four boundary points between three portions of the l_1, there are eight transition lines, they divide the half-wave plane into C,D,...... , O, thirteen areas and I,II, ..., eight segments. Each area and segment can be analysed by means of the formulae (4) and (5) . Here we only give out the corresponding new grating pitches of each segment in

$$\bar{a}_{l_2 I} = a\left[1+\frac{\bar{\Delta}}{2d}(x-x_1+d+\frac{b}{2})\right] \quad , \quad \cdots\cdots \quad ,$$

$$\bar{a}_{l_2 VIII} = a\left[1-\frac{\bar{\Delta}}{2d}(x-x_1-3d-\frac{3}{2}b)\right] \quad .$$

Where x_1 is the beginning point of the l_1. The accumulating error of each segment can be evaluated according to formula (7) . Obviously, the total accumulating errors in the l_2 are still Δa.

Because of the length of L_3 is shorter than (2d+b), so that any normal segment will not arise . The transition lines will be closer and closer . The error function will be more complicated, but the amplitudes of errors will give more average values and they can be evaluated by the above formulae. Obviously, the maximum pitch error of a self-guiding grating is the Δa at the switching point; the next one is the $\frac{a}{2d}\Delta a$ in the l_1 segment; the later will be much smaller .

Since $2d \gg a$, so the $\frac{a}{2d}\Delta a$ and the later pitch errors can be usually neglected. If the phase difference between two signals while they are switched is s°, then

$$\Delta a = \frac{s}{360}\delta x = \frac{sa}{720m} \tag{8}$$

So long as $s<7.2m$, then $\Delta a < \frac{1}{100}a$, this precision can satisfy the requirement of good diffraction gratings. Practically, some phase comparision instruments can give $s < 1^\circ$.

Relations between self-guiding grating length and its accumulating errors

It is clear from the forming process of self-guiding gratings that the length of each normal segment becomes shorter and shorter with a quantity(2d+b) and the length of each error segment becomes longer and longer with a quantity (2d+b) .

(1) If $n(2d+b) \leqslant L_0$, n is an integer, then normal segments and error segments are formed n times alternately . The total length of the self-guiding grating is

$$L_{\Sigma 1} = (n+1)L_0 - n(2d+b) + n\Delta a \tag{9}$$

(2) If $(n+t)(2d+b) > L_0$, t is an integer, then no normal segment arises after L_n . If only consider the relation between the length of the grating and the accumulating errors, we can assume a combined segment $(2d+b)+l_{n-1}+L_n$ and repeat it t times , so the length is

$$L_{\Sigma 2} = t\left[L_0 - \frac{1}{2}(2d+b)\right] + t\,\Delta a \tag{10}$$

The total length of the first part n segments and the second part t segments is

$$L_{\Sigma} = (n+t+1)L_0 - (n+\frac{t}{2})(2d+b) + (n+t)\Delta a \tag{11}$$

According to formulae (8) and (11) , the accumulating errors can be written :

$$(n+t)\Delta a = (n+t)\frac{sa}{720m}$$

So long as $(n+t)s < 72m$ is satisfied, then the accumulating error is smaller than $\frac{1}{10}a$, it satisfies the requirement of good gratings .

If we know the sign of the accumulated error of the original datum grating signal before hand, we can control a suitable positive or negative switching error and make it to offset the original errors. In this way the self-guiding grating would have smaller accumulated error .

If we have a datum grating which would be used for guiding, the length of self-guiding grating can be evaluated from formula(9) . For example, L_0=120mm, (2d+b)=25 mm , n=4, then

$$L_{\Sigma 1} = 500 + 4\Delta a$$

We can get a 500 mm grating, in which the accumulated error is only $4\Delta a$. If the precision of phase comparing is $s=1°$ and $a=\frac{1}{600}$ mm , $m=2$, then

$$4\Delta a=\frac{a}{180m}\approx 0.005\mu .$$

When the datum grating which would be used for guidign is shorter, the length can be evaluated from formula (11) . For example , if $L_o=60$ mm , $n=2$, $t=8$, and the others are the same as the above, then

$$L_\Sigma = 510 + 10\Delta a$$

We can get a 510 mm new grating in which the accumulated error is $10\ \Delta a$.

$$10\ \Delta a=\frac{a}{72m}\approx 0.01\ \mu .$$

We can also get a good diffraction grating . When we assume the accumulated error less than $\frac{1}{10}a$, and the $L_o=120$ mm , $(2d+b)=25$ mm , if $s=10°$, then $L=1618$ mm $+\frac{1}{10}a$. If $s=1°$, then $L=15550$ mm $+\frac{1}{10}a$.

Experiment design of the self-guiding method

This experiment of the SG method has been carried out on a continuous move grating ruling engine. Fig. 1 is the scheme diagram and Fig. 3 is the photo of the experimental device. The self-guiding signal is generated from the self-guiding grating with pitch $a=\frac{1}{600}$ by using a splitting beam grating interferometer .The diffraction order number is $m=2$. The inetrfero-fringe is horizontal and has a width $e=10$ mm .

The splitting beam grating interferometer for self-guiding

The main requirement to the interferometer is its stability. If we want to keep the signal phase to 1°, the position of the splitting beam plane must be stabilized about 0.0012μ . This is a very high accuracy . We have to adopt a lot of steps to increase the stability of the interferometer both in design and technology

For getting the required interfero-fringes, the splitting beam prism must be able to move in vertical direction and to rotate both in vertical and horizental slightly (see Fig. 1) . The two reflective prisms must be able to move and rotate around certain scope. The imagery lens must be able to move in horizental and vertical direction . The collimator light source must be able not only to focus itself , but also to move and rotate as a whole. All of these adjustments and the high stability of the device are achieved by using appropriate adjustable mechanisms .

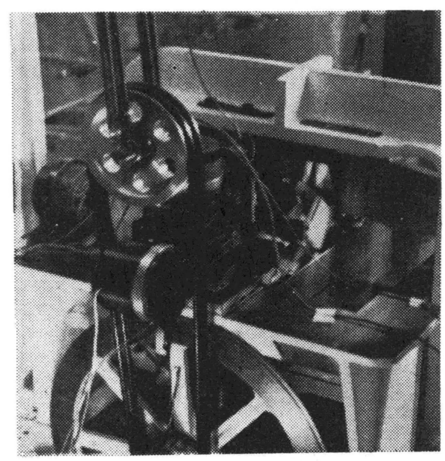


Fig.3 Experimental device .

The device for receiving the signals and regulating the phases of the signals

The receiving slit is cut in a small slide which can be driven in vertical direction on a small guide way . If we want to ensure the phase difference of the two signals 1°, the position regulating accuracy of the incident slit must be

$$\frac{1}{360}\ e \approx 30\ \mu$$

For the regulating of the receiving slit, we adopt following reduced speed driving systems: velocity adjustable small eledtrical machinery, belt reduced velocity machine, worm-gearing , screw-nut pair , small slide . This transmission system is smooth, steady and fine , it satisfies the requirements of the experiment .

Results of the experiment

Synopsis of the experiment

In the ruling period, do not allow to open the engine covers, so some adjustments must be carried out before ruling begins , some operation must be done out of the engine covers by means of electronical circuits . The main procedures of the experiment are as follows .

(1) Adjusting the interferometer

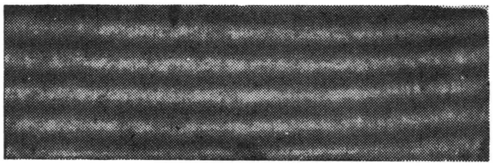
When the ruled section of the being ruled grating to a length equal or longer than (2d+b) , then, using this segment as a reference to adjust the interferometer, and make it generate the applicable signals .

(2) Comparing two signals phases and switching over the signals

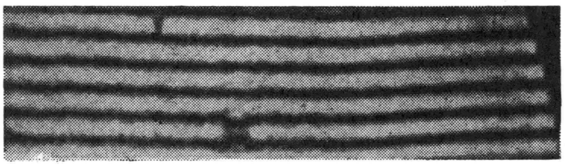
According to the figures shown in an oscillograph, regulate the position of the receiving slit to such a position that the two signals as the same in phase as possible . Choose any back stroke of the diamond to switch the control signal . All these operations have not any influence on the ruling engine . It continues its ruling to the given length .

Experimental results

Due to the limit of the engine travel, we can not be able to rule a long grating; the surface quality of the specimens remains to improve further, but the experiments have verified all of the principle links to the self-guiding method .



(1)



(2)

Fig. 4. Interference fringes.
(1) 1st order (2) 2nd order

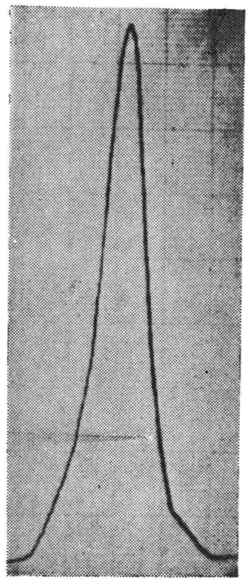


Fig. 5. Photo of the actual measured profile .

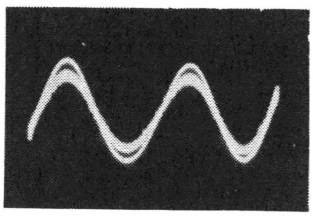


Fig. 6. Waveform photo for comparing phases .

The size of the first ruled self-guiding grating is 20x110 mm^2 ; the grating pitch is $\frac{1}{600}$ mm ; the groove shape is symmetric and blazing in the second order on both sides. The wavefront interferometric tests for it have been carried out , for first and second order interferograms (Fig.4 (1) and Fig. 4 (2)) , no any stagger and crook at the line where two signals are switched over and which is marked " ▼ " in the photo can be found . It is similar to the gratings which were not switched over . The actual resolution power has been measured for the grating segment which is on the both sides of the switching line , each side is 25 mm long . The actual resolution power of the segment in the second order is 5.4×10^4, this value is 90% of that of the theoretical value (half width method) . Fig.5 is the photo of the actual measured profile .

In this experiment, the comparing of the two signal phases was shown with a oscillograph . Fig. 6 is the waveform photo for the phases comparing . The phase difference is smaller than 10°, according to the formula (8), the switching error is

$$\Delta a = \frac{sa}{720m} = \frac{a}{144}$$

The grating belongs to a good diffraction grating, so its interfero-fringes are better and its resolution is higher . Later, the other two SG gratings were ruled . As the same as the first self-guiding grating, in their wavefront interfero-fringes, we can not observe any stagger in the first and second order, it seems the same as the grating which has not been switched . The experimental results and theoretical analysis show that if we have a ruling engine with enough long travel, the long and good diffraction gratings should be achieved by using this self-guiding method .

Discussions

(1) The ruled gratings in this experiment have symmetric grooves, they are ideal datum gratings for measuring the linear displacement. By means of this method, enough long gratings can be made . These gratings may be used in large diffraction grating ruling engines . and fine measurement devices .

(2) We can change the optical path to rule a blazing grating with unsymmetrical grooves

(3) If we use this method to rule a long diffraction grating, we need a long travel engine and further solution of ruling technology .

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References

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