光学学报

用长程面形仪对变线距光栅的线密度进行拼接测量

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摘要 随着同步辐射光源中光束线的分辨率不断提高，衍射光栅成为影响分辨率的关键因素，因此，在将光栅安装到光束线之前，需要进行准确的测试。用长程面形仪测量合肥光源光电子能谱线所需的变线距光栅的线密度，光栅衍射角变化范围超出长程面形仪的测量范围，因此采用拼接测量。用数据重叠测试及数据处理方法，消除了转台定位误差，有效抑制了随机误差，使光栅周期测量的重复性有较大提高。不同重叠率的测试结果显示，测量一致性优于 1.13×10^{-6}（RMS），满足了变线距光栅的测试需求。

关键词 测量；衍射测量；变线距光栅；拼接测量；长程面形仪

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1 引 言

同步辐射光源从20世纪40年代发展至今，光源的性能不断提高，为物理、化学、材料科学、生命科学等基础学科的研究提供了全新而高效的平台，并助力其取得了许多开创性成果[1-2]。在同步辐射光源和X射线自由电子激光装置中，无论是光束线还是实验站，光栅单色器和光谱仪都是核心设备。变线距光栅单色器所需的光学元件少、元件面型简单，容易实现高光谱分辨率和传输效率，成为软X射线单色器的主流光学元件[3-4]。新一代同步辐射光源中部分束线的能量分辨率 $\Delta E/E\leqslant10^{-5}$，要想实现这个目标，不但需要高精度的变线距光栅，还需要更高精度的线密度分布检测方法[5-6]。

检测光栅线密度的方法主要有干涉法[7]、扫描干涉测量法[8]、衍射法[9-10]和长程面形仪(LTP)法[11-12]等。这些方法各有优缺点，干涉法测量精度较高，多用于等线距光栅的线密度测量；衍射法可测量变线距光栅线密度，对仪器精度和环境稳定性有较高要求；LTP法从原理来看也属于衍射法的一种，借助于LTP设备条件，该方法检测精度高，能完整表征变线距光栅每个位置线密度及扣除光栅方程后的线密度残差。

使用LTP测量变线距光栅的线密度，当变线距光栅的1级自准直衍射角的变化范围大于仪器的角度测量范围时，无法单次测量整个变线距光栅，需采用类似于曲面反射镜的拼接测量法进行测试[13-14]。为了完成合肥光源光电子能谱光束线维修改造项目，合肥光源自主研制了一块变线距光栅。为对该变线距光栅的线密度进行精确测量，基于LTP的拼接测量方法，本文提出精确反演各段入射角的数据处理方法，给出LTP拼接测量法在变线距光栅线密度测量中的各种误差及精确分析。

2 测量原理和测量精度需求

2.1 测量原理

利用LTP法测量光栅线密度的基本原理与利用衍射法测量光栅线密度的基本原理相同，即在近Littrow角下测量光栅的1级衍射角[15-17]，如图1所示。

在近Littrow角条件下，光栅方程为

$$mN\lambda=\sin\alpha+\sin\beta,\tag{1}$$

式中：m为衍射级次；λ为测量中使用的激光波长；N为光栅线密度；α为入射角；β为衍射角。在检测过程中，假设入射角不变，衍射角β会随着变线距光栅线密度变化发生改变，即

$$m(N+\Delta N)\lambda=\sin\alpha+\sin(\beta+\Delta\beta),\tag{2}$$

式中：ΔN为光栅线密度变化量；$\Delta\beta$为衍射角的变化量

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（由LTP测量得到）。由式（2）可推导不同位置的线密度N'：

$$N'=N+\Delta N=\frac{\sin\alpha+\sin(\beta+\Delta\beta)}{m\lambda}。\tag{3}$$

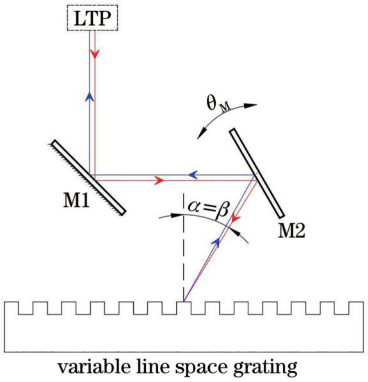

图1 光束在光栅近Littrow角入射时检测光栅线密度

Fig. 1 Detection of grating line density when the beam is incident at the grating Littrow angle

2.2 测量条件及测试目标

所用LTP的参数详见文献[16]，采用波长为402 nm的激光光源，对平面反射镜面形和2400 lp/mm光栅线密度一致性的测量重复性分别为30 nrad和$\Delta N/N_0=1.81\times10^{-7}$（RMS），其中$N_0$为光栅线密度，取值为2400 lp/mm。对光栅衍射角度的测量范围为±3 mrad，最大测量长度为1 m[16]。

变线距光栅的线密度在x轴方向（图2）上以多项式的形式表示[18]，即

$$N(x)=N_0+N_1x+N_2x^2+N_3x^3, x\in[-70,70]。\tag{4}$$

式（4）中的每一项系数都和特定的波前像差有关[11]。待测变线距光栅用在合肥光源光电子能谱光束线，其各系数的设计值分别为$N_0=1400$ lp/mm，$N_1=1.1543$ lp/mm^2，$N_2=4.2028\times10^{-4}$ lp/mm^3，N_3未作要求。根据式（1）计算出光栅1级衍射角变化量为33.856 mrad，超过LTP法的衍射角测量范围，因此必须拼接测量。

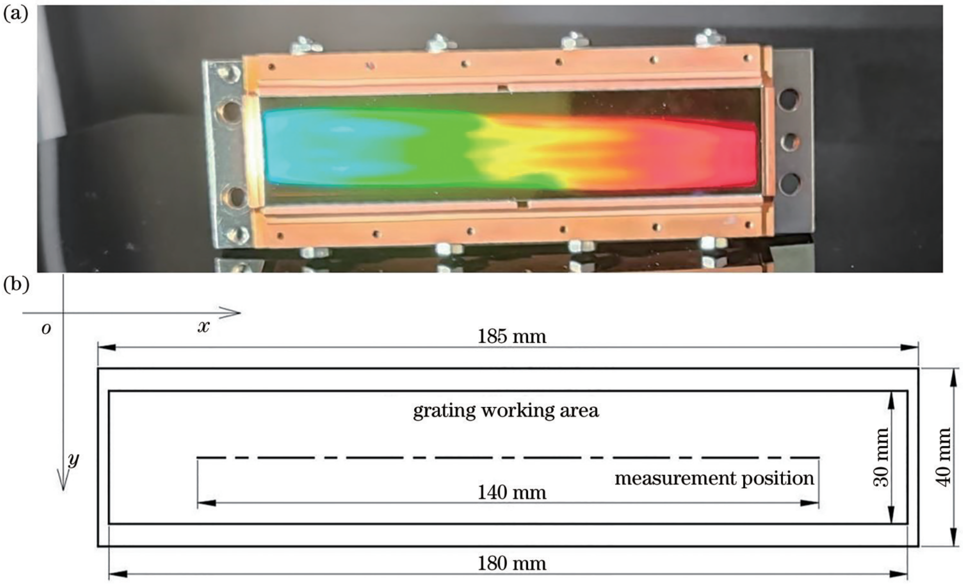

图2 实验所用的光栅图。（a）变线距光栅实物图；（b）光栅尺寸和测量位置示意图

Fig. 2 Experimental grating diagram. (a) Physical diagram of variable pitch grating; (b) diagram of grating size and measurement position

LTP系统所用激光束直径为1 mm，测量过程中激光光斑沿x轴方向扫描。变线距光栅的线密度检测目的是根据线密度测量值拟合出式（4）中的各项系数，并给出光栅在扣除拟合方程后的线密度偏差。

3 变线距光栅线密度拼接测量

3.1 拼接测量基本过程

线密度测量中，将待测光栅分成13段进行拼接测量，每段测量长度设为20 mm，步进长度为0.5 mm，每段有41个采样点，相邻两段重叠的测量点数量为21个，采样点数量的重叠率为51.2%，以消除转角误差及随机误差。为保证每段的1级衍射角的变化都在LTP的测量范围内和便于后续数据处理，在每一段测量前调整偏转镜M2的角度，使衍射光在该段的中心位置处沿近似自准直角返回探测器。为有效抑制LTP法在测量过程中的漂移误差，每段均采用往返一次测量数据均值处理[19]。不同测量段的入射角不同，在同一段内不同位置的入射角相同。

3.2 数据处理

为消除拼接测量中偏转镜M2的转动角度定位误差，变线距光栅的数据处理主要分为如下三步（图3）：

第一步，首先测量变线距光栅第7段中心位置即

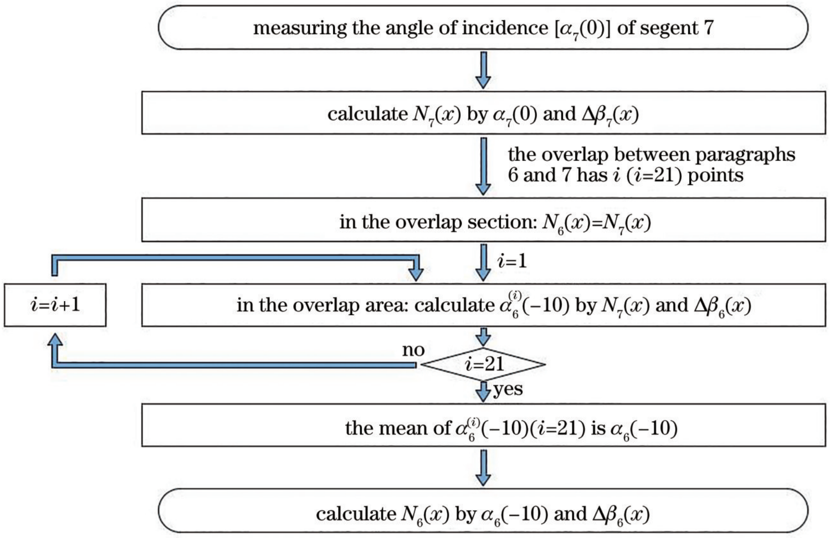

图 3 线密度计算流程图

Fig. 3 Flow chart for calculating line density

光栅中心位置$x=0$处的入射角度$\alpha_7(0)=16.344°$，并计算其对应的线密度$N_7(0)=1399.995$ lp/mm。在对第7段不同位置的线密度测量中，入射角均为$\alpha_7(0)$，根据不同位置衍射角的变化$\Delta\beta_7(x)$和式(3)，可以计算出这一段的线密度分布$N_7(x)$，$x\in[-10\ \mathrm{mm}, 10\ \mathrm{mm}]$。

第二步，以第7段的数据为基础，利用第6段和第7段的重叠部分，计算出第6段的入射角$\alpha_6(-10)$，再根据式(3)和第6段衍射角的变化量$\Delta\beta_6(x)$，计算出第6段的线密度分布$N_6(x)$，$x\in[-20\ \mathrm{mm}, 0]$。具体方法是：第6、7段的重叠部分长10 mm（$x\in[-10\ \mathrm{mm}, 10\ \mathrm{mm}]$），共有21个采样点，两段重叠部分的线密度相同，将第一步中计算出的这21个采样点的线密度$N_7(x)$和第6段衍射角的变化量$\Delta\beta_6(x)$作为已知量，分别代入式(6)，可计算出这21个采样点各自对应的第6段中心位置的入射角$\alpha_6^{(i)}(-10)$，然后取均值得到$\alpha_6(-10)$。将$\alpha_6(-10)$代入式(3)可得到第6段线密度$N_6(x)$。

$$N_6(x)=N_7(x),\ x\in[-10,0], \tag{5}$$

$$m\lambda N_6(x)=\sin\left[\alpha_6^{(i)}(-10)\right]+\sin\left[\beta_6^{(i)}(-10)+\Delta\beta_6(x)\right], \tag{6}$$

$$\alpha_6(-10)=\frac{1}{21}\left[\alpha_6^{(i)}(-10)\right], \tag{7}$$

式中：$\alpha_6^{(i)}(-10)$、$\beta_6^{(i)}(-10)$分别表示以重叠部分第i个采样点为参考点计算出的第6段中心位置$x=-10$ mm处的1级入射角和衍射角，两个角度相等；$\Delta\beta_6(x)$表示第6段横坐标为x的位置与该段中心位置的光栅1级衍射角的差值。图4为相邻分段位置对应关系示意图。

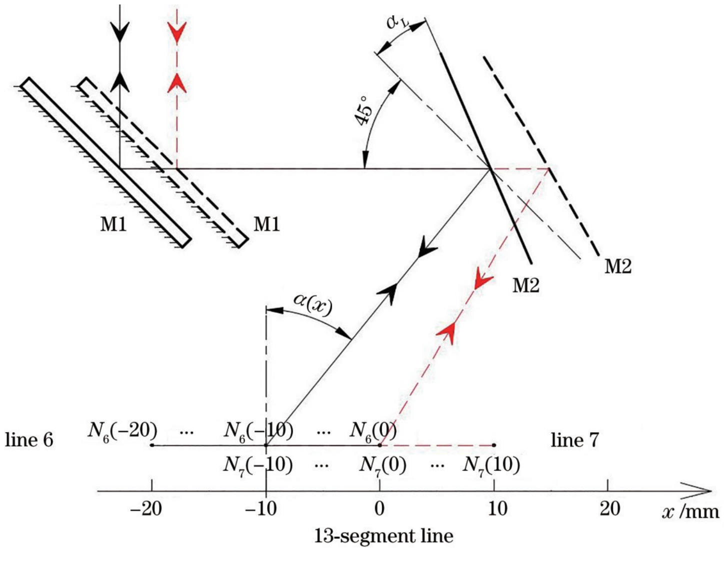

图 4 相邻分段位置对应关系示意图

Fig. 4 Diagram of correspondence between the positions of adjacent segments

第三步，重复第二步，以相同的方法，依次得到其余所有分段的线密度。将不同分段中重叠部分的线密度取均值，最终得到被测光栅的线密度值。用这种数据处理方法得到的13分段测量数据的重复性如图5(b)所示。

以往常用的数据处理方法是根据偏转镜的角度示数确定各段中心点的入射角$\alpha_L(x)$，各段内的相对衍射角变化值以LTP探测器给出的角度值为准。该处理方法中偏转镜M2的角度误差不可忽略，每段中心点的入射角$\alpha_L(x)$等于偏转镜M2相对于反射光原路返回的偏转角度$\alpha(L)$的2倍，$\Delta\beta_L(x)$为第L段1级衍射角变化量，把这些已知量代入式(3)可计算出每段的线密度。分13段测量的数据重复性如图5(a)所示，偏转镜的定位误差会造成相邻两段线密度出现跃变，导致测量重复性低。

由图5(a)、(b)的重复性对比可知，线密度拼接法的重复性达到了9.55×10^{-7}(RMS)，远高于拼接斜度处理方法的2.121×10^{-5}(RMS)。

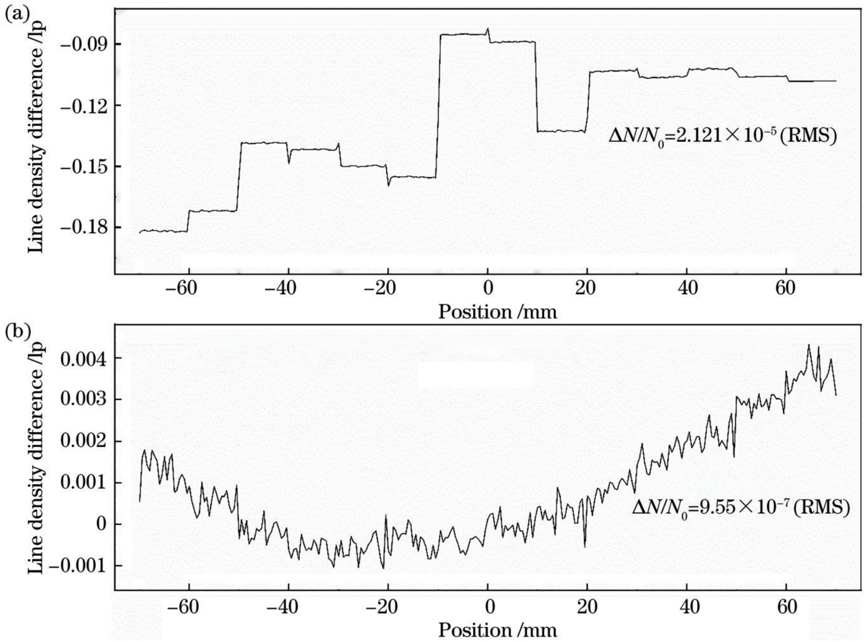

图5 两次分13段测量线密度的差值。(a)用线密度拼接法计算；(b)用斜度拼接法计算

Fig. 5 Difference between two measurements of line density in 13 segments. (a) Calculated by line density splicing method; (b) calculated by slope splicing method

3.3 对比实验

拼接测量中，重叠率是测试精度的关键影响因素之一，测量精度与重叠率成正比，测量效率与重叠率成反比。为平衡精度和效率的关系，验证相邻两段光栅的重叠率与测量精度的关系，增加3组相邻两段重叠率分别为2.4%、26.8%和75.6%的光栅进行实验，测量段的数量分别为7段、9段和25段，每个测量段长20 mm，总长度均为140 mm。各组的拟合方程如表1所示，各组线密度测量值减去自身拟合方程后的高次残差曲线如图6所示，扣除3次项后的线密度一致性为1.13×10^{-6}(RMS)。图6所示的误差包含了基底面形误差，但其对不同组测量结果的一致性无影响，因此测量结果未减去光栅基底面形误差。

由表1可知，4个实验组的线密度拟合方程中的系数N_1、N_2的一致性分别为$\Delta N_1/N_1\leqslant8.49\times10^{-5}$、$\Delta N_2/N_2\leqslant1.67\times10^{-3}$，光束线对光栅的$N_1$及$N_2$的精度要求一般分别在0.5%和5%左右，不同重叠率的测试精度均能满足测试需求。

当测量的总长度和每段的测量长度确定时，增加相邻两段的重叠率，可在测量中引入足够的冗余度[19]，

表1 各组线密度测量值对应拟合方程的系数

Table 1 Coefficients of fitting equation corresponding to each group of line density measurements

Grouping	N_0 /(lp·mm^{-1})	N_1 /(lp·mm^{-2})	N_2 /(lp·mm^{-3})	N_3 /(lp·mm^{-4})
7-segment line	1399.995	1.157408	4.164×10^{-4}	4.3×10^{-7}
9-segment line	1399.995	1.157366	4.162×10^{-4}	4.1×10^{-7}
13-segment line	1399.995	1.157464	4.164×10^{-4}	4.3×10^{-7}
25-segment line	1399.995	1.157422	4.169×10^{-4}	4.3×10^{-7}
Design value	1400	1.154300	4.203×10^{-4}	

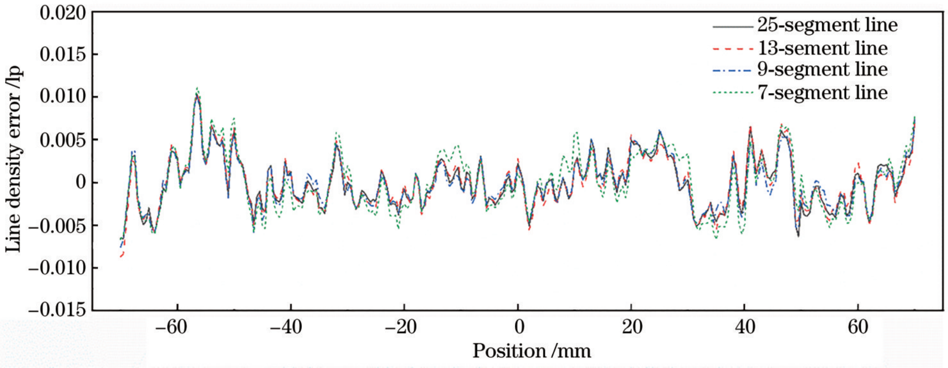

图 6　4 组实验中线密度测量值减去对应的线密度拟合方程后的差值曲线

Fig. 6　Difference curves of line density measurements minus the corresponding line density fits in four sets of experiments

从而降低仪器测量误差的影响，提高测量精度。根据这一理论，分 25 段测量的光栅线密度更准确，以其作为标准，计算另外 3 组测量结果的差值，分析重叠率对测量精度的影响。差值曲线如图 7 所示，3 组差值的一致性变化不大，但从 2.4% 和 51.2% 的数据曲线可以看出，随着重叠率的增加，拼接误差得到了明显抑制，如表 2 所示，其中 $a_{\mathrm{PV,max}}$ 为差值曲线各测量段峰谷（PV）值的最大值。可以看到，测量误差 PV 值的最大值从 2.4% 重叠率的 0.00658 lp/mm 降低到 51.2% 重叠率的 0.00382 lp/mm。

表 2　4 组线密度测量值之间的重复性和差值的平缓性

Table 2　Repeatability and smoothing of differences between 4 sets of line density measurements

Grouping	$\Delta N/N_0$ (RMS)	$a_{\mathrm{PV,max}}$ /(lp•mm^{-1})
25-segment line–7-segment line	1.13×10^{-6}	0.00658
25-segment line–9-segment line	1.12×10^{-6}	0.00542
25-segment line–13-segment line	1.02×10^{-6}	0.00382

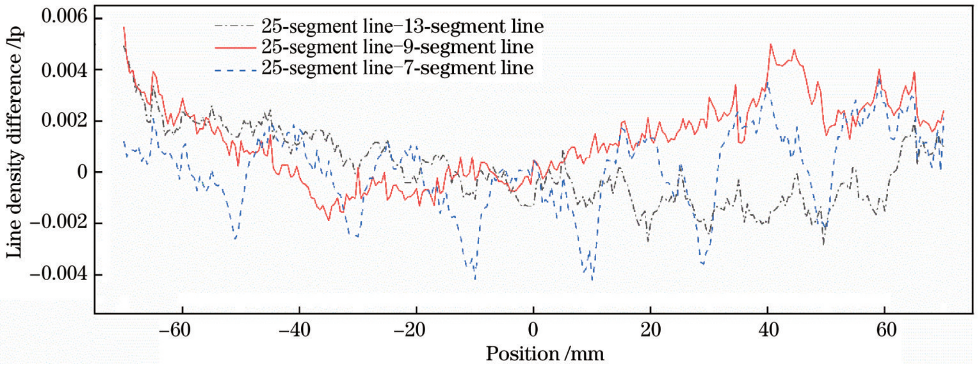

图 7　不同实验组之间的差值曲线

Fig. 7　Difference curves between different experimental groups

4　实验结果分析

将光栅真实线密度设为 $N_{\mathrm{R}}(x)$，利用拼接法测量变线距光栅过程中的误差主要包括随机误差 $R(x)$、系统误差 $S(x)$、漂移误差 $D(x)$、光栅基底误差 $J(x)$ 和拼接引入的误差 $L(x)$ 等[20-21]，将利用 LTP 法测量的线密度设为 $N(x)$，可表示为

$$N(x)=N_{\mathrm{R}}(x)+R(x)+S(x)+D(x)+J(x)+L(x)。\tag{8}$$

拼接引入的误差是由于 LTP 的量程有限，超出量程时反射光束偏离探测器，因此需要倾斜光栅或在光路中增加偏转镜，使反射光束回到探测器内部。在转动偏转镜改变光束入射角的同时也改变光束在光栅表面的照射位置，移动导轨修正位置偏移，修正后的定位精度达到 1 μm，对测量结果影响较小。利用拼接法计算线密度，用重叠区域所有采样点计算入射角的均值，不仅消除了偏转镜的定位误差，而且抑制随机误差和漂移误差，减小单个采样点的测量误差在相邻段传递，提高测试结果的准确性。

减小步进长度或增大相邻两段光栅的重叠率，可抑制由拼接引入的误差，但都会延长测量时间，可根据被测元件的测量精度要求，选择合适的测量参数。相邻两段光栅的重叠率不小于 50%，测量过程不存在未

重叠区域，线密度曲线的连续性好、波动小，而且由拼接引入的线性误差被抑制在较低水平。

5 结论

利用LTP系统拼接测量法测试变线距光栅参数，采用分段重叠的数据处理方法，避免了偏转镜的角度误差，对重复性有很大的提高。采用不同重叠率测量同一块变线距光栅，测试结果的一致性均优于1.13×10^{-6}（RMS），随着重叠率的增加，测试数据的重复性偏差的PV值明显减小。因此，合理选取步进长度和相邻两段光栅的重叠率，可在抑制拼接误差、保证一定的测量效率的同时提高测量精度。但受限于转台的相对精度，中心线密度绝对值的偏差约为0.1 lp/mm，需要采用相对定标法进行提升。后续将利用相关的实验方法来分析中心线密度误差的测量值对变间距光栅参数的影响，并进行实验验证。

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Stitching Measurement of Line Density of Variable-Line-Spacing Gratings with Long Trace Profiler

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Abstract

Objective Since its development in the last century, the performance of synchrotron light sources has been-increasingly improved, providing a new and efficient platform for research in many fundamental disciplines such as physics, chemistry, materials science, and life sciences, and helping to achieve many cutting-edge results. In synchrotron light sources and X-ray free electron laser devices, grating monochromators and spectrometers are crucial for both beamlines and experimental stations. Monochromators variable-line-spacing (VLS) grating is simple and easily achieve high spectral resolution and transmission efficiency. Thus, VLS gratings have become the dominant

optical elements in soft X-ray monochromators. As the resolution of beamlines in synchrotron radiation sources continuously increases, diffraction grating has become a key optical element affecting the resolution. Therefore, VLS grating needs to be accurately tested before being installed in beamlines. To achieve high energy resolution for some beamlines in new generation of synchrotron light sources, not only high precision VLS grating is required, but also more accurate methods of measuring the corresponding line density distributions are necessary.

Methods The main methods for measuring grating line densities include interferometry, diffraction, and long trace profiler (LTP) methods. These methods have their advantages and disadvantages. To meet the need of measuring line density of VLS grating, LTP with stitched data is used. In order to complete the Hefei Light Source photoelectron spectral beam line maintenance project, the Hefei Light Source independently developed a VLS grating. In order to characterize the line density more precisely, this paper proposes an improved stitching measurement method using LTP. In particular, the incident angle of each segment is inverted to improve based on the proposed stitching measurement method of LTP. In fact, for previous stitching methods, the angle of incidence at the central of each segment was determined from the angle of the deflector and the relative diffraction angle within each segment, which was based on the angle value given by the LTP detector. However, the angular error of the deflector is not negligible. In this method, first, taking the midpoint of the VLS grating as a reference point, the line density and incidence angle of the reference point is determined. Moreover, with the data of the reference point, the line densities of other positions of this segment are measured. Second, it is to measure the line density distribution of the next segment.

For the positions of the grating overlapping with those of the grating in the first step, it is assumed that the line densities of the overlapping positions are equal to each other. In this way, the incidence angle for the overlapping positions can be calculated, which is the same as that of the un-overlapping positions of the second segment. Using the inverted incidence angle, the improved line density of the un-overlapping positions can be obtained. Repeating the above two steps, the linear density of the entire grating can be calculated with improved precision.

Results and Discussions The key point of the method is to calculate the mean value of the incident angle using all sampling points in the overlapping area. This not only eliminates positioning errors in the deflector, but also suppresses random and drift errors, reduces the transfer of measurement errors from a single sampling point to adjacent segments and improves the accuracy of the test results. The effect of positioning errors in the rotary table can be eliminated. During the measurement process, the position offset of the measurement spot is corrected in time and the environmental stability is improved to further reduce the error. In this paper, by using a data processing method that accurately inverts the incident angle of each segment, the repeatability of the measurement of the line density of the VLS grating can be compared between the two methods, with a repeatability of 9.55×10^{-7} (RMS), which is much better than that of the previous method [2.12×10^{-5} (RMS)]. This paper also conducted four groups of comparison experiments with overlapping rates of 2.4%, 26.8%, 51.2%, and 75.6%. The consistency of the coefficients N_1 and N_2 in the fitted equations of the line density for the four groups were $\Delta N_1/N_1\leqslant8.49\times10^{-5}$ and $\Delta N_2/N_2\leqslant1.67\times10^{-3}$, respectively, The beamline requires an accuracy of around 0.5% and 5% for N_1 and N_2 of the grating. The accuracy of the test at different overlapping rates meets the test requirements. This result demonstrates the high repeatability and consistency of this method for measuring the linear density of VLS grating.

Conclusions The LTP stitching measurement method is used to test VLS grating parameters using a segmented overlapping data processing method, which avoids angular errors in the deflector and provides a significant improvement in repeatability. The consistency of the test results is better than 1.13×10^{-6} (RMS) for the same VLS grating using different overlapping rates, and the PV value of the repeatability deviation of the test data decreases significantly with increasing overlapping rate. Therefore, a reasonable selection of step length and the overlapping ratio of two adjacent segments can improve measurement accuracy while suppressing splicing errors and ensuring a certain level of measurement efficiency. However, due to the relative accuracy of the turntable, the deviation of the absolute value of the central density is about 0.1 lp/mm, which needs to be improved by using the relative calibration method. This will be followed by an experimental approach to investigate the effect of central line density error measurements on variable-line-spacing grating parameters and experimental verification.

Key words measurement; diffraction measurement; variable-line-spacing gratings; stitching measurement; long trace profiler