基于多元散射校正的光谱共焦位移测量方法分析与研究

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摘　要：为提高光谱共焦位移测量系统精度，对样品表面散射特性的影响进行了研究。首先，介绍了光谱共焦位移测量系统的原理，基于标量散射理论，推导了表面散射特性影响下的光谱共焦轴向响应，建立了散射对位移测量影响的关系模型。然后，对散射引起的峰值波长曲线偏移导致的位移测量误差进行了理论研究和仿真分析；结果表明：在样品表面粗糙度较大时，会产生较大的散射效应，导致测量精度明显下降；同时，在进行光谱共焦位移测量时受各波长入射特性的影响。为校正散射的影响，提出采用多元散射校正方法结合广义回归神经网络 (General Regression Neural Network, GRNN) 对光谱数据进行处理，建立了散射校正算法模型。最后，搭建实验平台，选取样品进行了位移测量实验；实验结果表明，系统的测量性能随粗糙度的增大而降低，对于粗糙度为 20 nm 的样品散射误差校正后测量结果的最大位移测量误差从 12.6 μm 降为 1.9 μm，平均位移测量误差从 8.1 μm 降为 0.86 μm，提高了位移测量精度，验证了理论分析的正确性以及提出的散射校正方法的有效性。文中研究结果对提高光谱共焦位移测量系统的精度具有一定的参考意义。

关键词：光谱共焦；　表面散射特性；　位移测量；　光谱数据处理；　多元散射校正

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0　引　言

在光学精密制造、航空航天、微电子、生物医疗[1−2]等领域，位移测量技术可用于检测表面形貌特征、薄膜厚度、生物医疗中活细胞的三维结构[3−4]等，因此有着广泛的应用。光谱共焦位移测量技术采用宽光谱光源，利用光学色散原理建立各波长与其各自轴向聚焦位置的编码对应关系，根据获得的样品表面反射光谱特性进行信息解码，得出精确的轴向位置或微小位移数据，进而实现精密测量；该方法具有纳米级的超高距离测量分辨率，并且对环境与被测材料具有普遍的适应性，在无损测量的精密制造领域具有显著的应用优势和发展前景[5]。为提高测量精度和测量范围，学者们做了很多有益的工作。MINONIN[6]等人设计了具有纵向色差的共焦轮廓仪，结合数据处理算法，使得测量范围从 500 nm 延伸到 900 nm，相对精度达 0.36%，极大的提高了系统测量精度。YU[7]等人提出了一种颜色校正方法并进行了实验验证，测量误差在 10 nm 以内。另外，在前端光谱共焦光学系统设计及后端光谱信号处理领域，国内外学者也提出了很多的设计方法，对误差校正算法也进行了较多的研究[8−9]。而不同的被测样品其表面粗糙度特性不同，光束入射至样品表面时会出现一定的散射特性。韩松澎[10]等人基于蒙特卡洛法对粗糙表面的散射特性进行了分析研究。高瞻[11]等人采用随机行走理论对物体表面的散射场进行了研究，并分析了不同粗糙面

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散射光强的变化和对位移测量的影响。而系统性分析样品表面散射特性对光谱共焦位移测量的影响，还未见有报导。

采用光谱共焦法进行精密位移测量时，样品表面的散射特性会导致一部分散射光束进入系统中，使接收到的有效反射的光谱响应信号存在无效的散射噪声，测量数据产生漂移，引起测量误差。文中基于标量散射理论[12−14]，在光谱共焦位移测量系统中，通过构建表面散射与光强的函数关系，研究散射引起的峰值波长曲线偏移，对散射引起的位移测量误差进行了分析和研究；为校正散射的影响，提出采用多元散射校正方法结合广义回归神经网络 (General Regression Neural Network, GRNN) 建立散射校正模型，对光谱数据进行处理。最后，通过实验验证了校正方法的有效性。

1　光谱共焦位移测量原理

光谱共焦技术通过光学色散和共焦的原理，建立聚焦距离和波长之间的对应关系[15]，通过分析反射光谱信号的波长信息，实现精准的微位移测量。其工作原理如图 1 所示，白光光源发出的宽光谱入射光，经过针孔后可视为点光源，经分光棱镜和色散物镜，各波长光谱在色散物镜的作用下产生轴向色散，形成对应的单色聚焦点，聚焦位置与波长之间具有精确的对应关系。

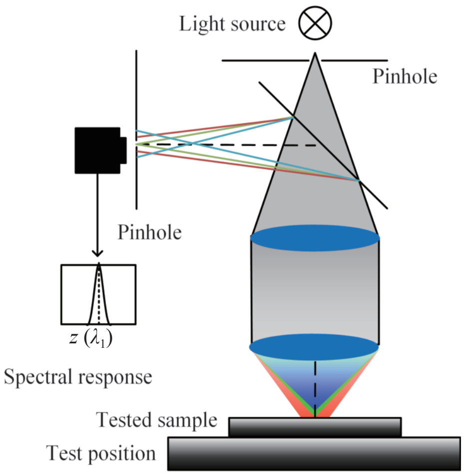

图 1　光谱共焦位移测量系统原理图

Fig.1 Schematic diagram of spectral confocal displacement measurement system

被测样品放置在测量范围内，色散光波照射在样品表面发生反射，并再次通过光谱共焦位移系统，在共焦小孔所在平面形成一个与测量光斑具有相同光谱分布的彩色光斑。由于共焦小孔的存在，导致彩色光斑中各光谱成分的光通量不能全部通过小孔，只有聚焦在被测样品表面的光线才能在反射后被检测器接收，其余光线由于不聚焦到达检测器端面的光束能量及其微弱可以忽略。设样品表面聚焦波长为 λ_0，则各波长对应的轴向响应光强分布为：

$$I(\lambda)=\left[\frac{\pi\alpha^2}{\lambda(z+k\lambda)}\operatorname{sinc}\left(\frac{\pi\alpha^2k(\lambda-\lambda_0)}{2\lambda(z+k\lambda)^2}\right)\right]^4 \tag{1}$$

当被测样品的位置发生改变时，光谱响应的峰值波长也会发生改变，利用聚焦位置与波长之间的对应关系即可获得表面位移 Δz：

$$\Delta z(\lambda)=z(\lambda)-z(\lambda_0)=k(\lambda-\lambda_0) \tag{2}$$

2　样品表面散射特性对测量的影响

采用光谱共焦技术测量表面位移时，由于被测样品不是绝对光滑表面，当光线照射在样品表面时会发生散射现象，使接收到的光谱响应特性发生改变。散射对测量影响的关系模型如图 2 所示，聚焦在样品表面的光束，在散射作用下，一部分光束将改变原来的反射特性散射至接收范围之外，不能到达探测器，使得该部分测量光束能量降低；其余光线在散射作用下，会有一部分进入系统接收，使接收到的有效反射的光谱响应存在无效的散射噪声，测量数据产生漂移，引起测量误差。标量散射理论[13] 通过对散射光相干叠加全积分，能够有效地表示表面粗糙度与散射光强分布之间的函数关系，该理论的一个假设前提是均方根粗糙度 δ 满足 $(\delta/\lambda)^2<<1$，在文中适用于样品表面粗糙度不大于 100 nm 的情况。因此，文中采用标量

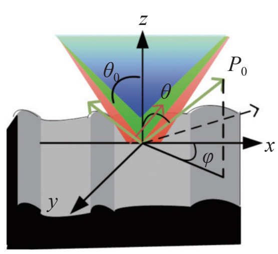

图 2　散射对光谱共焦位移测量影响的关系模型

Fig.2 Relationship model of scattering influence on spectral confocal displacement measurement

散射理论分析样品表面散射特性对光谱共焦位移测量的影响。

如图 2 所示，在样品表面聚焦的波长为 λ_0 的光束，其入射角为 θ_0，散射角为 (θ,φ)，则空间中任意观察点 P_0 的散射光强为：

$$I_{(p,q)}=|A|^2F^2\exp\left[-(2\pi g\delta)^2\right]\iint\limits_{\Sigma}\exp\left[-(2\pi g)^2R(x,y)\right]\cdot \exp\left[-j2\pi(px+qy)\right]\mathrm{d}x\mathrm{d}y \tag{3}$$

式中：δ 为样品表面均方根粗糙度；$R(x,y)$ 为样品表面形貌函数。

其中

$$\begin{cases} A=\dfrac{1}{j\lambda r}\exp(jkr) \\ F=\dfrac{1-\sin\theta_0\sin\theta\sin\varphi+\cos\theta_0\cos\theta}{\cos\theta_0+\cos\theta} \\ p=(\sin\theta\cos\varphi-\sin\theta_0)/\lambda \\ q=\sin\theta\sin\varphi/\lambda \\ g=(\cos\theta_0+\cos\theta)/\lambda \end{cases} \tag{4}$$

式中：r 为 P_0 到坐标原点的距离。

$$W(p,q)=\iint\limits_{\Sigma}R(x,y)\exp\left[-j2\pi(px+qy)\right]\mathrm{d}x\mathrm{d}y \tag{5}$$

式中：$W(p,q)$ 为样品表面轮廓的功率谱密度。

代入公式 (3)，可得：

$$I_{(p,q)}=|A|^2F^2\exp\left[-(2\pi g\delta)^2\right]\frac{\sin(p/2)}{p/2}\cdot\frac{\sin(q/2)}{q/2}+|A|^2F^2g^2W(p,q) \tag{6}$$

由公式 (6) 可知，经粗糙表面返回系统的光束由两部分组成，一部分来自表面反射，另一部分来自散射；公式 (6) 中的第一项反射部分仅在反射方向上不为 0，此时 θ=θ_0、φ=0、p=q=0，反射光强 I_R 为：

$$I_R=\frac{|A|^2\cos\theta_0}{4k^2}\exp\left[-\left(\frac{4\pi}{\lambda}\cos\theta_0\delta\right)^2\right] \tag{7}$$

其中，k=2π/λ，设 $I_{R_0}=|A|^2\cos\theta_0/(4k^2)$，经散射返回系统的光束强度 I_S 为接收角 $\Delta\theta$ 范围内的积分：

$$I_S=\int_0^{\Delta\theta}2\pi^4I_{R_0}\left(\frac{\sqrt{2}\delta}{m\lambda}\right)^2\left(\frac{\delta}{\lambda}\right)^2(\cos\theta+1)^4\cdot \sin\theta\cos^3\theta_0\exp\left[-\left(\frac{\sqrt{2}\pi\delta\sin\theta}{m\lambda}\right)^2\right]\mathrm{d}\theta= 2^5\pi^4\frac{I_{R_0}}{m^2}(\delta/\lambda)^4\cos^3\theta_0(\Delta\theta)^2 \tag{8}$$

式中：m 为样品表面均方根斜率。为分析样品表面散射特性的影响，由公式 (1) 可得，波长为 λ_i 的光束在样品表面处于聚焦位置时接收光强为：

$$I'(\lambda_i)=\left[\frac{\pi\alpha^2}{\lambda_i(z+k\lambda_i)}\right]^4 \tag{9}$$

波长为 λ_0 的光束在样品表面处于聚焦位置时，波长为 λ_i 的光束强度为 $I(\lambda_i)$，则波长为 λ_i 的光束处于离焦状态下相比于其在样品表面聚焦时光强降低了：

$$I_Z(\lambda_i)=I'(\lambda_i)-I(\lambda_i) \tag{10}$$

实际条件下，光源的功率分布特性、被测样品对不同单设光的反射特性以及探测器对不同波长的灵敏度不同等，均会对接收到的光谱信号产生影响，则轴向响应光强分布公式 (1) 在各因素影响下为：

$$I(\lambda)=\left[\frac{\pi\alpha^2}{\lambda(z+k\lambda)}\mathrm{sinc}\left(\frac{\pi\alpha^2k(\lambda-\lambda_0)}{2\lambda(z+k\lambda)^2}\right)\right]^4\cdot S(\lambda)O(\lambda)D(\lambda) \tag{11}$$

式中：$S(\lambda)$、$O(\lambda)$、$D(\lambda)$ 分别为光源、被测样品、探测系统等的影响因子；根据公式 (11)，设样品表面散射特性影响下的光谱共焦轴向响应光强为：

$$I_O(\lambda_i)=I(\lambda_i)\cdot(R_R+R_S)+I_Z(\lambda_i)\cdot R_S \tag{12}$$

其中，R_R、R_S 分别为反射和散射系数：

$$\begin{cases} R_R=\exp\left[-\left(\dfrac{4\pi}{\lambda_i}\cos\theta_0\delta\right)^2\right] \\ R_S=\dfrac{2^5\pi^4}{m^2}(\delta/\lambda_i)^4\cos^3\theta_0(\Delta\theta)^2 \end{cases} \tag{13}$$

同时，由公式 (8) 可知，散射光强受样品均方根粗糙度 δ 和入射角 θ_0 的影响，仿真结果如图 3 和图 4 所示。其中，图 3 为不同工作波长下散射光强随 δ 的变

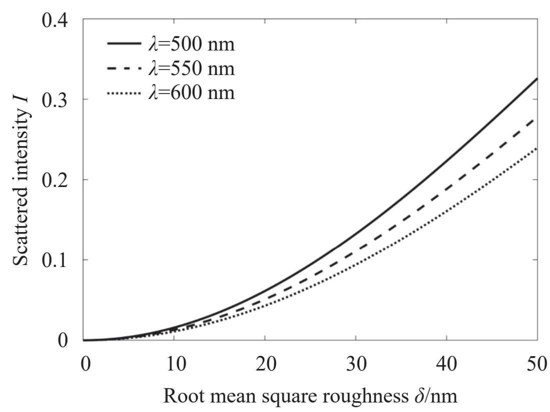

图 3 散射光强随 δ 的变化

Fig.3 Variation of scattered light intensity with δ

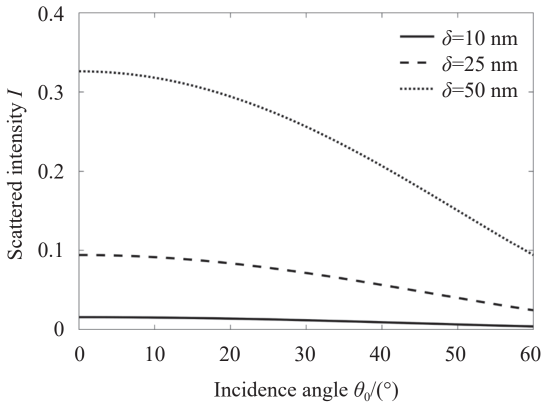

图 4　散射光强随入射角 θ_0 的变化

Fig.4　Variation of scattered light intensity with incident angle θ_0

化，纵坐标为归一化光强中散射光分量，可以看出当 δ 增大时，散射光强越大，此时，反射光强度相应降低。

由于物镜的色散，不同波长的光束入射至样品表明的入射角 θ_0 不同，散射光强随入射角 θ_0 的变化如图 4 所示。

由图 4 可知，随着入射角增大，散射光强度相应变小。因此，不同样品表面均方根粗糙度 δ 不同其散射强度不同，且在进行光谱共焦位移测量时受各波长入射特性的影响。

为具体分析散射特性对光谱共焦位移测量的影响，根据公式 (12)，文中选取均方根粗糙度 δ 分别为 0、5、10、20 nm，对聚焦波长为 550 nm 时系统接收到的光谱响应进行仿真，得到不同粗糙度下的光谱响应曲线图。由图 5 可知，峰值光强随被测样品表面粗糙度增大而减小，半峰全宽增大，系统的分辨率降低；同时，轴向响应峰值波长出现偏移，引起测量误差。

由上述分析可得，光谱共焦轴向光谱响应曲线的峰值波长与各波长聚焦位置一一对应，被测样品处于测量范围内某一轴向位置 z_i 时，波长为 λ_i 的光束聚焦在样品表面，表面绝对光滑的样品，其粗糙度 δ=0，此时轴向光谱响应中只含有反射信号，峰值波长为 λ_i，而实际样品的 δ 不为零，系统接收到的有效反射的光谱响应中存在和粗糙度相关的无效的散射噪声，峰值波长发生漂移，引起位置测量误差，且由公式 (8) 可知，散射特性和波长相关；因此，利用公式 (2) 和 (12)，仿真获得不同工作波长条件下粗糙度引起的位置测

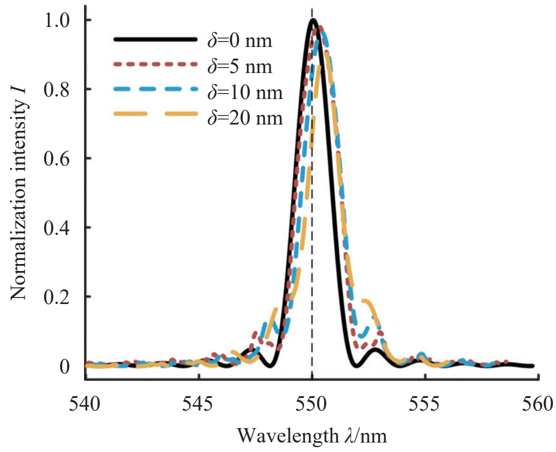

图 5　散射对接收信号光谱响应的影响

Fig.5　Influence of scattering on spectral response of received signal

量误差如图 6 所示。

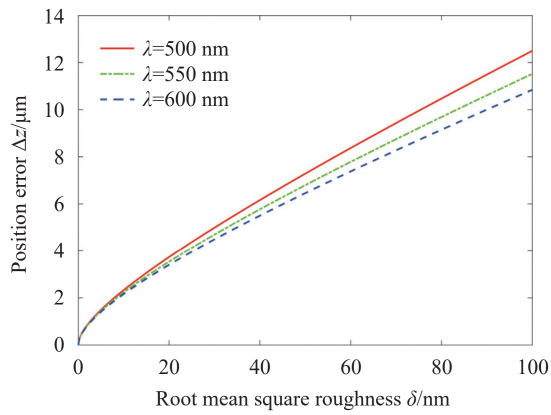

图 6　δ 引起的位置测量误差

Fig.6　Position measurement error caused by δ

由图 6 的仿真可知，使用波长为 500 nm 的光束测量表面均方根粗糙度 δ 为 100 nm 的样品时，会产生 12.4 μm 的位置测量误差，误差较大，因此需要进行散射误差校正，提高系统测量精度。

3　多元散射校正

多元散射校正是一种能有效去除散射影响的数据处理方法[16]，该方法可以降低散射噪声和数据偏移的影响，提高光谱数据的准确性。另外，GRNN 是一种基于概率密度函数的回归网络，训练过程简便，收敛迅速，且能提供高精度的非线性映射，用于拟合光谱共焦系统的光谱响应时能有效提高系统测量的分辨率和准确性[17]。

为校正样品表面散射特性对光谱共焦位移的影响，文中提出采用多元散射校正结合GRNN广义回归神经网络数据处理手段相结合的方式，对光谱数据进行处理，建立散射校正模型。该模型首先对系统接收到的离散光谱响应数据 (I, λ) 进行处理，计算并获得光谱数据的散射影响因子，利用散射因子对光谱响应数据进行校正，若直接提取校正后的离散光谱数据的峰值波长进行位移解算，容易因峰值波长定位不准确引起较大的测量误差。为提高峰值波长提取精度和准确性，利用GRNN对光谱数据进行处理。具体方法为：首先，建立光谱共焦轴向响应的离散化样本序列，作为多元散射校正方法的理论样本：

$$I(\lambda,z)=\begin{bmatrix} I_1(\lambda_1,z_1) \\ I_2(\lambda_2,z_2) \\ \vdots \\ I_n(\lambda_n,z_n) \end{bmatrix} \tag{14}$$

式中：I_1、I_2、$\cdots$、I_n 为各波长对应的光谱数据。其次，通过测量获得样品散射特性影响下的光谱数据，建立其与理论样本之间的线性回归函数，确定对应的数据偏移量：

$$I'(\lambda,z)=AI(\lambda,z)+B=\begin{bmatrix} a_1I_1(\lambda_1,z_1)+b_1 \\ a_2I_2(\lambda_2,z_2)+b_2 \\ \vdots \\ a_nI_n(\lambda_n,z_n)+b_n \end{bmatrix} \tag{15}$$

获得散射偏移因子 A、B，分别为回归系数(相对偏移系数)和平移量，根据散射偏移因子对光谱数据进行校正：

$$I_{msc}(\lambda,z)=\frac{I'(\lambda,z)-B}{A} \tag{16}$$

将校正后的光谱数据作为样本输入GRNN模型，其中输入变量为波长 λ_i，输出变量为各

波长对应的归一化光强，利用Parzen窗口通过非参数的方式来估计联合概率密度函数，对预测输出进行核回归，得到各波长对应的归一化强度的最大概率输出值，实现光谱共焦轴向信号响应的曲线表征，提高反射光谱的信噪比，并通过提取GRNN模型表征的光谱曲线峰值波长，修订色散波长与焦点位置之间的对应关系。具体流程图如图7所示。

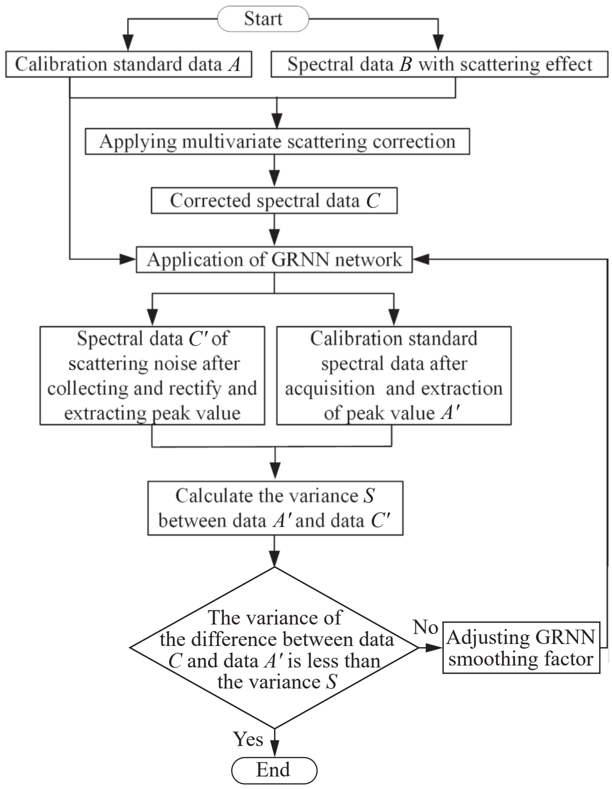

图7 散射校正模型流程图

Fig.7 Flow chart of scattering correction model

4 实验验证

根据实验室现有设备，搭建光谱共焦位移测量系统，如图8所示。

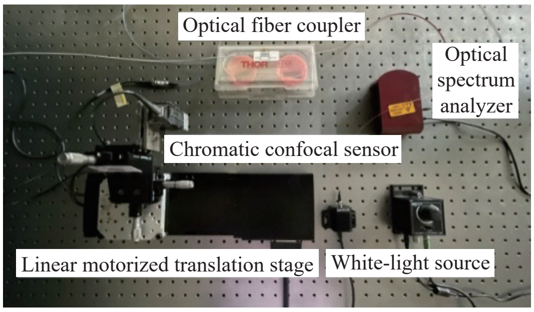

图8 光谱共焦位移测量实验系统图

Fig.8 Experimental system diagram of spectral confocal displacement measurement

实验采用欧姆龙ZW-S5030光纤同轴位移传感探头和Newport公司的M-ILS100 LM-S线性位移台，其中位移台的理论最小步进距离为10 nm，最大行程为100 mm。测量前，对色散光波波长与轴向距离进行精确标定及数据拟合，获得500~650 nm范围内色

散光波与轴向聚焦位置的标定函数关系 $z(\lambda)$[17−18]：

$$z(\lambda)=14.334\,2+0.000\,272\,22\lambda^2-0.131\,05\lambda+(-1.522\,3e-7)\lambda^3 \tag{17}$$

色散物镜像方孔径角 $\theta(\lambda)$ 与波长的关系为：

$$\theta(\lambda)=24.314\,1+(4.758\,1e-5)\lambda^2-0.040\,6\lambda+(-2.568\,4e-8)\lambda^3 \tag{18}$$

为验证文中提出的散射校正方法的有效性，对粗糙度为 20 nm 样块进行实验测量。首先选择一个合适的位置作为测量起点，设置精密线性位移台以 50 μm 的位移间隔进行移动，获得散射误差补偿前和补偿后的位移测量数据，并与理论值进行比较，测量结果如表 1 所示。

由表 1 中的测量结果可得，补偿前最大位移测量误差为 12.6 μm，平均位移测量误差为 8.1 μm，补偿后的最大位移测量误差为 1.9 μm，平均位移测量误差为 0.86 μm，测量误差减小，提高了位移测量精度。

表 1 实验测量结果

Tab.1 Experimental measurement results

Step displacement/μm	Theoretical center wavelength/nm	Direct measurement of central wavelength/nm	Measuring displacement/μm	Displacement deviation/μm	Corrected displacement error/μm
50	542.5	542.750 5	57.9	7.9	0.8
100	544.2	544.426 4	108.1	8.1	1.2
150	545.8	545.565 6	142.3	-7.7	-0.3
200	547.5	547.731 9	207.5	7.5	0.5
250	549.1	549.474 6	260.1	10.1	0.6
300	550.8	551.064 5	308.2	8.2	0.5
350	552.4	552.753 0	359.4	9.4	1.7
400	554.1	554.503 6	412.6	12.6	1.9
450	555.7	555.485 8	442.5	-7.5	-0.9
500	557.4	557.282 9	497.3	-2.7	0.1
550	559.0	559.144 9	554.2	4.2	0.6
600	560.6	560.360 2	591.4	-8.6	-1.2
650	562.3	562.489 7	656.7	6.7	1.5
700	563.9	564.198 5	709.2	9.2	1.3
750	565.5	565.826 6	759.3	9.3	0.9
800	567.2	567.523 7	811.6	11.6	1.4
850	568.8	569.085 6	859.8	9.8	0.8
900	570.4	570.195 8	894.1	-5.9	-0.3
950	572.0	572.239 1	957.3	7.3	0.4
1 000	573.6	573.398 5	993.2	-6.8	-0.6

为进一步验证文中提出的散射校正算法有效性，对粗糙度分别为 12、50、100 nm 的样块进行位移测量，采用 M-ILS100 LM-S 线性位移台，设置步进距离为 100 μm，移动并重复测量 10 次，校正前及校正后位移测量误差如图 9 所示。对误差结果进行分析，校正前及校正后不同粗糙度样块的最大位移测量误差和平均位移测量误差对比结果如表 2 所示。

由表 2 可知随着被测样品表面粗糙度增大，最大位移测量误差、平均位移测量误差均增大，其中，散射误差校正前，对粗糙度分别为 12、50、100 nm 的样块最大位移测量误差分别为 12.4、17.2、20.7 μm；平均位移测量误差分别为 7.15、10.88、15.02 μm；散射误差校正后各样块的最大位移测量误差分别 1.5、2.1、1.1 μm；平均位移测量误差分别为 0.79、0.92、0.75 μm，系统的测量精度得到了提高，验证了理论分析的正确性和散射校正方法的有效性。

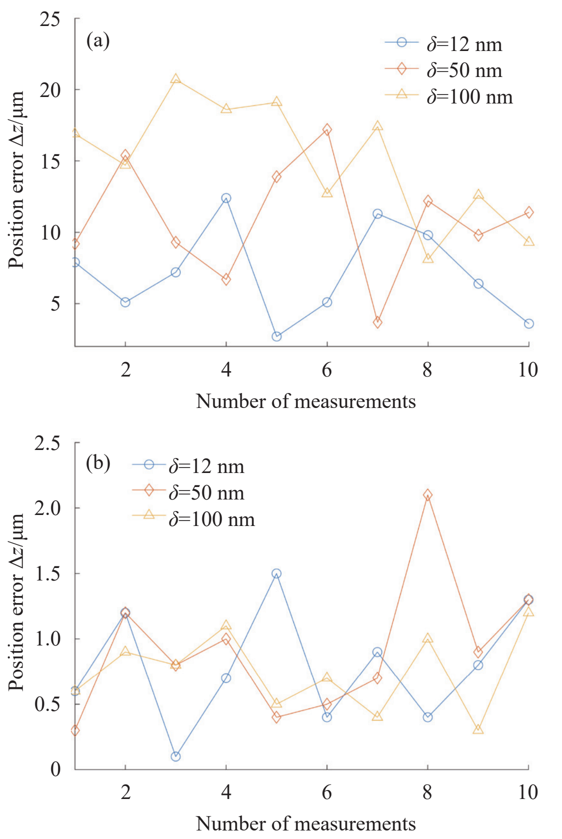

图 9 (a) 直接测量误差; (b) 补偿后误差

Fig.9 (a) Direct measurement error; (b) Error after compensation

表 2 对比实验测量结果

Tab.2 Comparing experimental measurement results

Measure sample roughness/nm	Direct measurement maximum error/μm	Direct measurement average error/μm	Maximum error after correction/μm	Corrected average error/μm
12	12.4	7.15	1.5	0.79
50	17.2	10.88	2.1	0.92
100	20.7	15.02	1.1	0.75

5 结 论

为提高光谱共焦位移测量系统的精度,文中研究并分析了粗糙样品表面散射特性的影响。首先,介绍了光谱共焦位移测量系统的工作原理,基于标量散射理论构建了样品表面散射特性与光谱响应之间的函数关系,分析了散射引起的峰值波长偏移及位移测量误差,样品表面的散射特性会使得反射光谱曲线发生偏移,影响位移测量精度,尤其在均方根粗糙度 δ 较大时,散射的影响较大,系统的分辨率明显降低。然后,为校正散射特性的影响,采用多元散射校正方法结合 GRNN 广义回归神经网络建立了散射误差校正模型,并进行了实验验证。实验结果表明,对 δ 为 20 nm 的粗糙度样块测量时,校正后的最大位移测量误差从 12.6 μm 降为 1.9 μm,平均位移测量误差从 8.1 μm 降为 0.86 μm;另外,对粗糙度分别为 12、50、100 nm 的样块测量数据进行对比分析,结果表明随着粗糙度增大引起表面散射增强,使得系统的性能降低,进行散射误差校正后,系统的测量精度得到提高。验证了文中提出方法的可行性。研究结果对进一步提高光谱共焦位移测量系统的性能具有指导意义,对系统的工程化应用具有一定的推进作用。

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Analysis and research of spectral confocal displacement measurement method based on multiple scattering correction

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Abstract: In order to improve the accuracy of spectral confocal displacement measurement system, the influence of surface scattering characteristics of samples was studied. Firstly, the principle of spectral confocal displacement measurement system is introduced. Based on scalar scattering theory, the axial response of spectral confocal under the influence of surface scattering characteristics is deduced, and the relationship model of scattering influence on displacement measurement is established. Then, the displacement measurement error caused by the peak wavelength curve shift caused by scattering is studied theoretically and simulated. The results show that when the surface roughness of the sample is large, it will produce a large scattering effect, which will lead to a significant decline in measurement accuracy. At the same time, the spectral confocal shift measurement is affected by the incident characteristics of each wavelength. In order to correct the influence of scattering, a multivariate scattering correction method combined with generalized regression neural network (GRNN) is proposed to process spectral data, and a scattering correction algorithm model is established. Finally, an experimental platform was built, and samples were selected for displacement measurement experiments. The experimental results show that the measurement performance of the system decreases with the increase of roughness. For the sample with roughness of 20 nm, the maximum displacement measurement error is reduced from 12.6 μm to 1.9 μm, and the average displacement measurement error is reduced from 8.1 μm to 0.86 μm, which improves the displacement measurement accuracy and verifies the correctness of theoretical analysis and the effectiveness of the proposed scattering correction method.This research result has certain reference significance for improving the accuracy of spectral confocal displacement measurement system.

Objective Displacement measurement technology can be used to detect surface morphology, film thickness,

three-dimensional structure of living cells in biomedicine, so it has a wide range of applications. Spectral confocal displacement measurement technology uses a broad spectrum light source, establishes the coding correspondence between each wavelength and its respective axial focusing position by using the principle of optical dispersion, decodes the information according to the obtained reflection spectral characteristics of the sample surface, and obtains accurate axial position or tiny displacement data, thus realizing precise measurement; This method has ultra-high distance measurement resolution of nanometer level, and has universal adaptability to environment and measured materials, and has obvious application advantages and development prospects in the field of precision manufacturing of nondestructive measurement. When the spectral confocal method is used for precise displacement measurement, the scattering characteristics of the sample surface will cause some scattered beams to enter the system, which will make the received effectively reflected spectral response signal have invalid scattering noise, and the measurement data will drift, causing measurement errors. Based on the scalar scattering theory, in the spectral confocal displacement measurement system, the shift of peak wavelength curve caused by scattering is studied by constructing the functional relationship between surface scattering and light intensity, and the displacement measurement error caused by scattering is analyzed and studied. In order to correct the influence of scattering, a multiple scattering correction method combined with General Regression Neural Network (GRNN) is proposed to establish a scattering correction model to process the spectral data. Finally, the effectiveness of the correction method is verified by experiments.

Methods The influence of surface scattering characteristics of samples on the measurement of spectral confocal shift is studied. When the surface of the sample is not smooth, it will lead to the scattering of reflected light on the surface (Fig.2). Analyze the relationship among root mean square roughness, incident angle and scattered light intensity (Fig.3, Fig.4). Compare the spectral data shifts under different root mean square roughness (Fig.5, Fig.6). The method of multivariate scattering correction combined with GRNN is used to process the spectral data and establish the scattering correction model. Experiments verify the effectiveness of the scattering compensation algorithm in spectral confocal.

Results and Discussions In the experiment, all kinds of measured samples can't be absolutely smooth. The accuracy of the spectral confocal displacement measurement system mainly depends on the reflection spectrum received by the system, and surface scattering is the main source that affects the reflection spectrum error. By analyzing the influence of surface scattering on the error of reflection spectrum, a scattering compensation algorithm is established to reduce the measurement error. The spectrum received by the system is mixed with scattered light. When the scattering situation is serious, the reflected light intensity will decrease Fig.3, Fig.4) and the peak wavelength will shift (Fig.5), which will lead to the decrease of measurement accuracy. The measurement error increases with the increase of root mean square roughness (Fig.6). The scattering correction algorithm established by multivariate scattering correction and GRNN generalized regression neural network can reduce the error caused by surface scattering and improve the accuracy of spectral confocal displacement measurement system.

Conclusions In order to improve the accuracy of spectral confocal displacement measurement system, the influence of surface scattering characteristics of rough samples is studied and analyzed. Firstly, the working principle of spectral confocal displacement measurement system is introduced. Based on scalar scattering theory, the functional relationship between surface scattering characteristics and spectral response of samples is constructed, and the peak wavelength drift and displacement measurement error caused by scattering are analyzed. The scattering characteristics of the sample surface will shift the reflection spectrum curve and affect the displacement measurement accuracy, especially when the root mean square roughness δ is large, the scattering

influence is great and the system resolution is obviously reduced. Then, in order to correct the influence of scattering characteristics, a scattering error correction model is established by using multivariate scattering correction method combined with GRNN generalized regression neural network, and it is verified by experiments. The experimental results show that the maximum displacement measurement error is reduced from 12.6 μm to 1.9 μm, and the average displacement measurement error is reduced from 8.1 μm to 0.86 μm when measuring the roughness sample with δ of 20 nm. In addition, the measured data of sample blocks with roughness of 12 nm, 50 nm and 100 nm are compared and analyzed. The results show that the surface scattering increases with the increase of roughness, which reduces the performance of the system. After the scattering error correction, the measurement accuracy of the system is improved. The research results have guiding significance for further improving the performance of the spectral confocal displacement measurement system and promoting the engineering application of the system.

Key words: spectral confocal; surface scattering characteristics; displacement measurement; spectral data processing; multiple scattering correction

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