



## 多芯光纤光栅形状传感性能与重构误差研究

周勇 胡文彬 程普 叶泓蕊 郭东来 杨明红

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## 多芯光纤光栅形状传感性能与重构误差研究

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**摘要:** 多芯光纤光栅形状传感技术利用空分复用以及应变监测的优势, 结合不同的栅点布设方案, 实现待测对象的连续曲率和形状传感。首先介绍了多芯光纤光栅曲率和挠率传感原理, 提出采用齐次矩阵变换的三维重构算法实现光纤的三维形状重构。为了探究不同光栅密度对实验精度的影响, 利用算法编程模拟了不同光栅间距下的三维形状重构精度, 依据模拟仿真的结果, 建立了不同光栅间距与三维重构误差之间的关系。三维形状传感实验使用光栅间距为 10 cm 和 5 cm 的七芯光纤光栅串。实验结果表明, 最大误差出现在尾点处, 分别为 2.56 cm 和 1.15 cm, 占全长的 3.2% 和 1.4%, 平均误差为 1.32 cm 和 0.62 cm, 占全长的 1.7% 和 0.8%。实验结果与仿真值比较接近, 说明可以依据仿真结果对不同光栅间距下的三维形状误差进行预测。结合具体的应用场景合理配置测点资源, 在较低的成本范围内实现高性能的检测。

**关键词:** 光纤形状传感; 多芯光纤; 布拉格光栅; 数值模拟; 光栅间距

**中图分类号:** TN253 **文献标志码:** A **DOI:** 10.3788/IRLA20220485

### 0 引言

光纤光栅 (Fiber Bragg Gratings, FBG) 传感技术广泛应用于各种 2D 和 3D 形状传感中<sup>[1-4]</sup>。相较于传统的电学形状传感器, 光纤光栅形状传感器具有体积小、质量轻、灵敏度高、抗电磁干扰等显著优点, 使其在建筑, 工业, 医疗等领域有着不可替代的优势<sup>[5-12]</sup>。基于光栅的多芯光纤形状传感技术经过多年的发展也愈加成熟。目前, 基于多芯光纤光栅的形状传感技术主要分为两类, 一类是以 LUNA 公司为代表的基于全同弱光栅的光频域反射 (Optical Frequency Domain Reflectometry, OFDR) 解调技术。2007 年, Duncan 等<sup>[13]</sup>人采用 OFDR 技术对长度为 110 cm 的多芯光纤光栅阵列进行了二维和三维形状重构实验, 实验误差分别为 1.9 mm 和 5.8 mm。基于 OFDR 解调技术空间应变传感分辨率较高, 但由于其解调方式决定了其采集速度相对较慢, 解调系统设备较复杂, 成本较高<sup>[14]</sup>。另一类是基于波长解调方式的多芯光栅或者集成光栅形状传感技术, 2019 年, Khan 等<sup>[15]</sup>人将四根长度为 11.8 cm 的多芯光纤集成到一个导管内, 进行形状重

构, 实验结果表明其最大平均误差和最大绝对误差分别为 0.44 mm 和 1.05 mm。2020 年, Omar Al-Ahmad 等<sup>[16]</sup>人提出了一种扭转补偿的方法, 将长度为 170 mm 的多芯光纤嵌入导管内对于静态几何形状进行测量, 结果表明其平均误差为 0.7 mm, 最大空间误差为 2.52 mm。基于波长解调方式的多芯光栅阵列传感系统具有体积小、信噪比高、采集速度快, 解调实时性高等<sup>[17]</sup>优点。鉴于实际应用领域中存在多种多样的形状传感需求, 采用波长解调方式的多芯光栅阵列多芯传感系统可根据实际需求进行光栅数量和间距的灵活配置, 可实现具有更灵活的传感距离、更多样的形状变化跨度的待测对象形状监测, 具有更广泛的应用前景。然而由于多芯光栅测点在空间上无法实现连续, 故无法获取测点之间空白无栅区域的形状, 存在测点盲区。在实际应用中, 为了提高形状传感的准确性, 需要研究待测对象的形状变形特点, 在兼顾关键点可测和待测区全范围可测的前提下, 设计合理的光栅分布配置方案。

文中基于七芯光纤光栅的应变传感特性, 采用了

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一种基于齐次变换矩阵<sup>[18-19]</sup>的三维形状重构方法,对两种不同光栅间距的七芯光纤光栅进行形状重构,通过光栅点波长相对变化值求解有栅测点所在区域的曲率和挠率,通过三次样条插值法求得 FBG 测点之间空白无栅区域的曲率和挠率,最后将所有点的曲率和挠率整合到同一坐标系下,实现待测对象的三维形状重构。为了探究光栅间距对形状重构精度的影响,利用算法编程模拟了基于该算法原理下不同光栅间距下的三维形状重构误差,通过搭建一套三维形状传感系统完成实验验证,探讨了实验中的误差和模拟误差的合理性,为今后多芯光栅形状传感技术应用中的光栅配置设计提供一定的参考依据。

### 1 三维形状重建理论和算法

多芯光栅阵列三维形状重构方法的前提在于有栅测点区域的曲率和挠率的精确监测,继而采用插值与坐标解算实现整体形状重构,解算过程共包括五个阶段,如图 1 所示。首先通过解调仪获取所有有栅测点未形变前与形变后的中心波长数据,根据每个 FBG 的波长漂移量进行曲率和挠率的计算,然后对这些 FBG 点之间的空白无栅区域的曲率和挠率利用三次样条插值法进行插值,再利用齐次矩阵法进行连续坐标解算,并整合至同一坐标系,最后绘制出光纤的整体三维形状。以下将重点对曲率和挠率计算以及齐次矩阵法进行阐述。

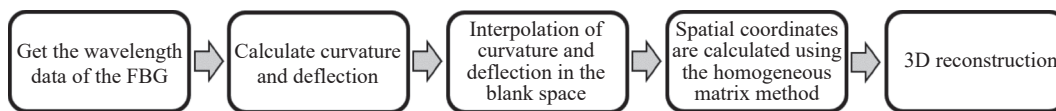


图 1 三维形状重建技术路线图

Fig.1 3D shape reconstruction technology flow chart

#### 1.1 曲率和挠率的计算

如图 2(a) 所示,当七芯光纤朝某一个方向弯曲时,边芯(顺时针编号 2~7)和中芯(编号 1)两纤芯的中心之间的距离为  $d$ ,一般称为芯间距。当光纤发生弯曲后,假设光纤弯曲的曲率半径为  $R$ ,  $N$  为垂直于弯曲方向的中性轴,则任意边芯的轴向应变  $\varepsilon$  可以表示为:

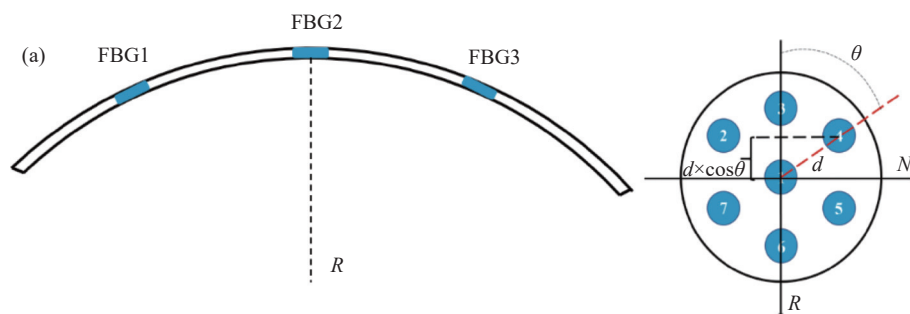
$$\varepsilon = \frac{d}{R} \cdot \cos\theta \quad (1)$$

式中:  $\theta$  为横截面上偏芯和弯曲方向之间的夹角。处于中性面的外侧的边芯为拉伸状态,处于中性面的内侧的边芯为压缩状态。由于中间芯位于中性面上,其中心波长可视为不受光纤弯曲的影响,可以进行轴向

应变和温度的补偿。光纤弯曲曲率与波长漂移之间的线性关系可以表示为:

$$\Delta\lambda_n - \Delta\lambda_1 = k \cdot d \cdot \rho \cdot \lambda_n \cdot \cos\theta_n, \quad n = 2, 3, \dots, 7 \quad (2)$$

式中:  $\Delta\lambda_n$  为偏芯波长漂移量;  $\Delta\lambda_1$  为中芯光栅中心波长漂移量;  $\rho=1/R$  为弯曲的曲率;  $k=(1-P_e)$  为标准石英光纤纵向应变敏感系数,通常为 0.784;  $\lambda_n$  为多芯光纤光栅中偏芯在自由平直无弯曲状态下的初始波长。实验过程中,当检测到波长漂移时,利用中芯和任意两个边芯的数据分别代入公式 (2) 联立起来,就可以推导出每个芯与弯曲方向的夹角以及弯曲的曲率。如图 2(b) 所示,以边芯 2 芯为例,可以求出相邻光栅的 2 芯与弯曲方向的夹角  $\theta$ , 再根据公式 (3) 就可以求出各相邻 FBG 点之间的挠率大小。



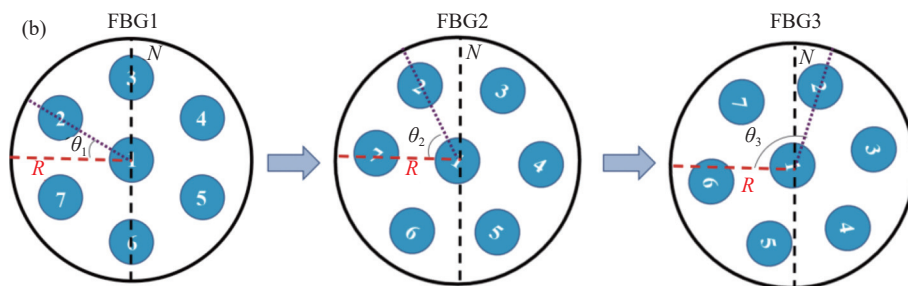


图 2 七芯光纤传感原理示意图。(a) 曲率; (b) 绕率

Fig.2 Schematic diagram of the seven-core optical fiber sensing principle. (a) Curvature; (b) Torsion

$$\tau_{12} = \theta_2 - \theta_1; \quad \tau_{23} = \theta_3 - \theta_2 \dots \quad (3)$$

根据公式 (1)、(2) 分析七芯光纤光栅的波长漂移量, 可以计算出 FBG 处的弯曲曲率与弯曲方向, 再根据公式 (3) 可以计算出绕率的大小。显然由于七芯光纤的六个边芯是对称分布的, 所有方向上都具有很好的弯曲分辨能力, 同时相较于只有两个边芯且互呈 90° 分布的多芯光纤, 七芯光纤多出来的边芯可以用作取平均值, 这样可以减小偶然误差对实验结果的影响, 提高测量精度。

$$M_{i+1}^i = \begin{bmatrix} \cos \alpha_i \cos \varphi_i & -\sin \alpha_i & \cos \alpha_i \sin \varphi_i & R_i(1 - \cos \varphi_i) \cos \alpha_i \\ \sin \alpha_i \cos \varphi_i & \cos \alpha_i & \sin \alpha_i \sin \varphi_i & R_i(1 - \cos \varphi_i) \sin \alpha_i \\ -\sin \varphi_i & 0 & \cos \varphi_i & R_i \sin \varphi_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

式中:  $\tilde{S}_{i+1}^i$  是以 FBG<sub>i</sub> 为坐标系来表示的 FBG<sub>i+1</sub> 的齐次坐标点;  $s_{i+1,k}^i$  中的  $k=\{x, y, z\}$  是  $\tilde{S}_{i+1}^i$  的位置分量;  $M_{i+1}^i$  是从坐标系  $i+1$  到坐标系  $i$  的齐次变换矩阵;  $\tilde{S}_{i+1}^i$  是 FBG<sub>i+1</sub> 在 FBG<sub>i+1</sub> 坐标系下的齐次坐标, 即  $[0 \ 0 \ 0 \ 1]^T$ ;  $\alpha_i$  为弯曲方向角的变化量;  $\varphi_i$  为光纤圆弧所对应的圆心角度数。齐次变换矩阵可以看成由四个矩阵组合而成, 每个矩阵发挥不同的作用, 其中  $R_{i+1}^i$  是一个 3×3 的旋转矩阵, 其作用为坐标系对齐,  $o_{i+1}^i$  是  $i+1$  坐标系的原点在  $i$  坐标系下的坐标,  $O_3^T$  是一个 1×3 的零向量。因此, 在形状重构期间将采用公式 (6) 这种坐标变换方法来计算以起始坐标系表示的所有 FBG 光栅点位置。齐次变换矩阵将每个独立坐标系中的点转换到同一坐标系下, 将这些点按照顺序连接起来即可实现三维空间曲线的重构, 如图 3 所示。

## 1.2 齐次矩阵法三维重构

根据 1.1 节中计算出的曲率与绕率, 利用齐次变换矩阵法 (公式 (4)~(6)) 将离散的点坐标解算出来。

$$\tilde{S}_{i+1}^0 = M_1^0 M_2^1 \dots M_i^{i-1} M_{(i+1)}^i \tilde{S}_{i+1}^{i+1} = M_{i+1}^0 \tilde{S}_{i+1}^{i+1} \quad (4)$$

$$\tilde{S}_{i+1}^i = \begin{bmatrix} s_{i+1,x}^i \\ s_{i+1,y}^i \\ s_{i+1,z}^i \\ 1 \end{bmatrix} = M_{i+1}^i \tilde{S}_{i+1}^{i+1} = \begin{bmatrix} R_{i+1}^i & o_{i+1}^i \\ O & 1 \end{bmatrix} \tilde{S}_{i+1}^{i+1} \quad (5)$$

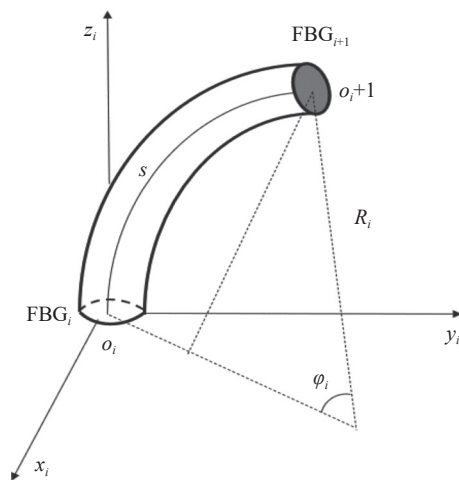


图 3 三维形状重构示意图

Fig.3 Schematic diagram of 3D shape reconstruction

## 2 模拟仿真

以半径为 10 cm、螺距为 9 cm、总长为 160 cm 的



圆柱螺旋线为对象,基于上述三维形状重构算法进行编程计算,探究七芯光纤光栅不同光栅间距对三维螺旋线形状重构精度的影响。选取光栅间距  $L$  为 12.5 cm、10 cm、8 cm、5 cm 和 1 cm,绘制出这些光栅间距下的三维重构曲线与真实曲线的图形,如图 4(a)所示。该模拟计算均假设有栅测点的曲率和挠率测量误差为 0。从图 4(b)中可以看,出当光栅间距  $L$  为 12.5 cm、10 cm、8 cm、5 cm 和 1 cm,空间位置误差随着光纤长度呈现一种逐渐上升趋势,光栅间距越大,误差也会越大,其重建最大误差均落在模拟长度的尾点,分别为 7.75 cm、4.35 cm、2.63 cm、0.94 cm 和 0.25 cm,占全长的 4.8%、2.7%、1.6%、0.6% 和 0.16%。其原理

是由于三维形状的每个坐标点都由前一个点经平移旋转变化而来,所以会由于算法的迭代引起发散误差。为了探究误差变化率与不同长度和间距的总体变化趋势,采用线性拟合方式对这几条误差曲线进行拟合,拟合的斜率分别为 0.048、0.027、0.016、0.006 和 0.001,改斜率即对应于不同光栅间距的三维形状的误差百分率。通过建立间距和线性拟合的斜率之间的变化关系,可探讨不同光栅间距与三维重建误差之间的对应关系。如图 4(c)所示,对这六个点进行指数拟合,拟合相关系数  $R^2$  达 0.999。因此,可以根据这一拟合曲线函数对任一光栅间距的三维形状重构的误差进行预测。

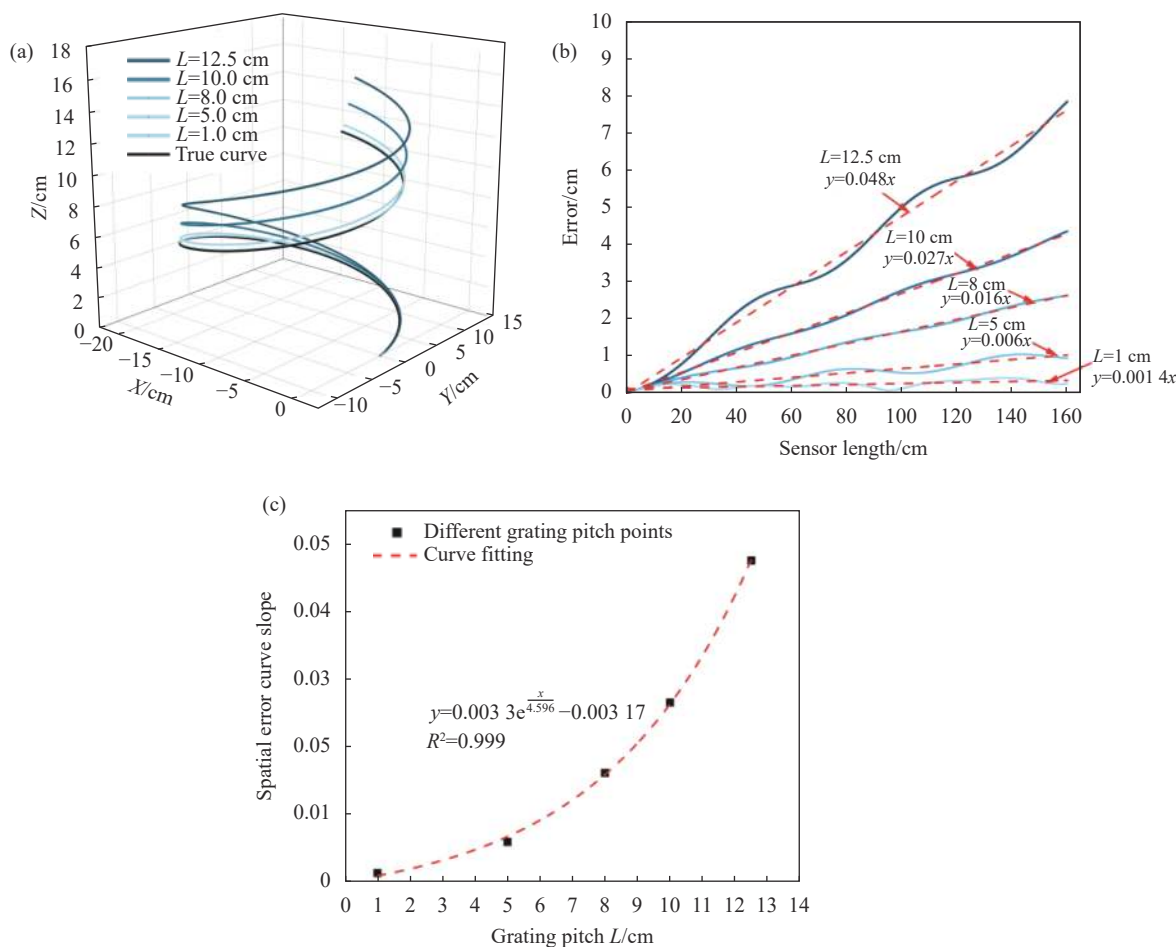


图 4 不同光栅间距的模拟结果。(a) 三维重构效果图; (b) 空间位置误差; (c) 光栅间距与误差曲线斜率之间的关系

Fig.4 Simulation results of different grating spacings. (a) Diagram of 3D reconstruction effect; (b) Spatial position error; (c) Relationship between grating spacing and error curve slope

### 3 七芯光纤三维形状传感装置

为了验证上述仿真结果的可靠性,设计了一套实

验装置。图 5(a)为实验系统图,该系统主要由七芯光纤光栅、七芯光纤扇入扇出装置、光纤光栅解调仪和

上位机构成。实验所选用的七芯光纤是长飞光纤光缆股份有限公司生产的, 由一个中芯和六个边芯组成, 芯间距为  $42\ \mu\text{m}$ , 如图 5(b) 所示。通过掩模版法, 在七芯光纤上写入不同中心波长的光栅。光纤光栅解调仪是由武汉高斯光电科技有限公司生产的, 其分

辨率为  $10\ \mu\text{m}$ 。光纤总长  $80\ \text{cm}$ , 选取了两种不同光栅间距的光栅串, 分别为  $10\ \text{cm}$  和  $5\ \text{cm}$ , 栅区的长度为  $1\ \text{cm}$ , 各个纤芯的光栅光谱以及光栅串的光谱如图 6(a)、(b) 所示。为了避免光纤的自然扭转效应引起的误差, 将光纤做成并带的形式, 即将多根光纤用

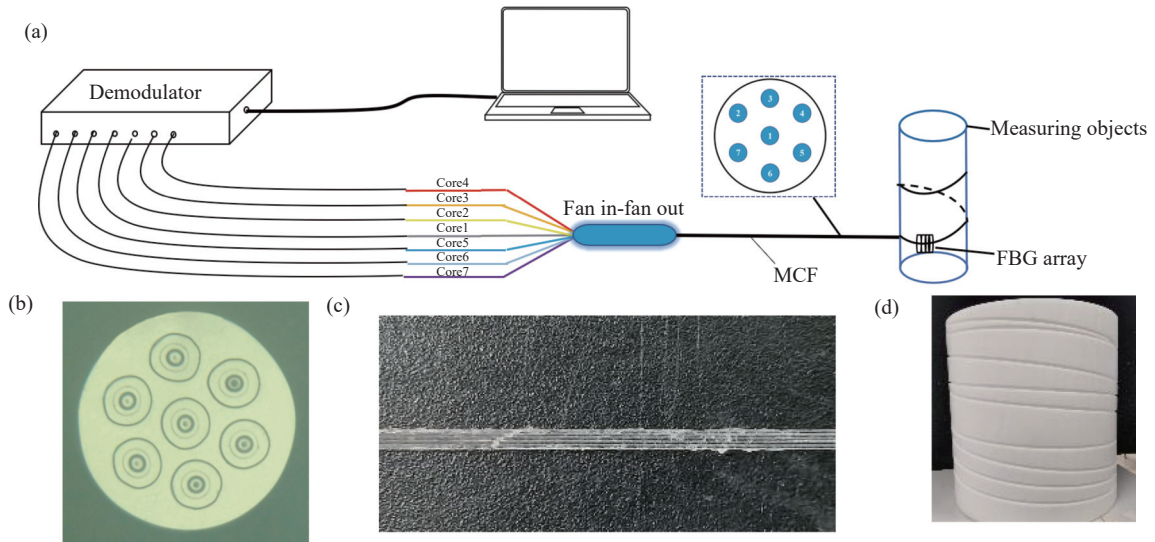


图 5 三维形状传感实验装置。(a) 系统简图; (b) 七芯光纤端面; (c) 光纤并带结构; (d) 三维螺旋曲率槽

Fig.5 Experimental setup for 3D shape sensing. (a) Schematic diagram of the system; (b) End face of seven-core fiber; (c) Optical fiber with ribbon structure; (d) 3D helical curvature groove

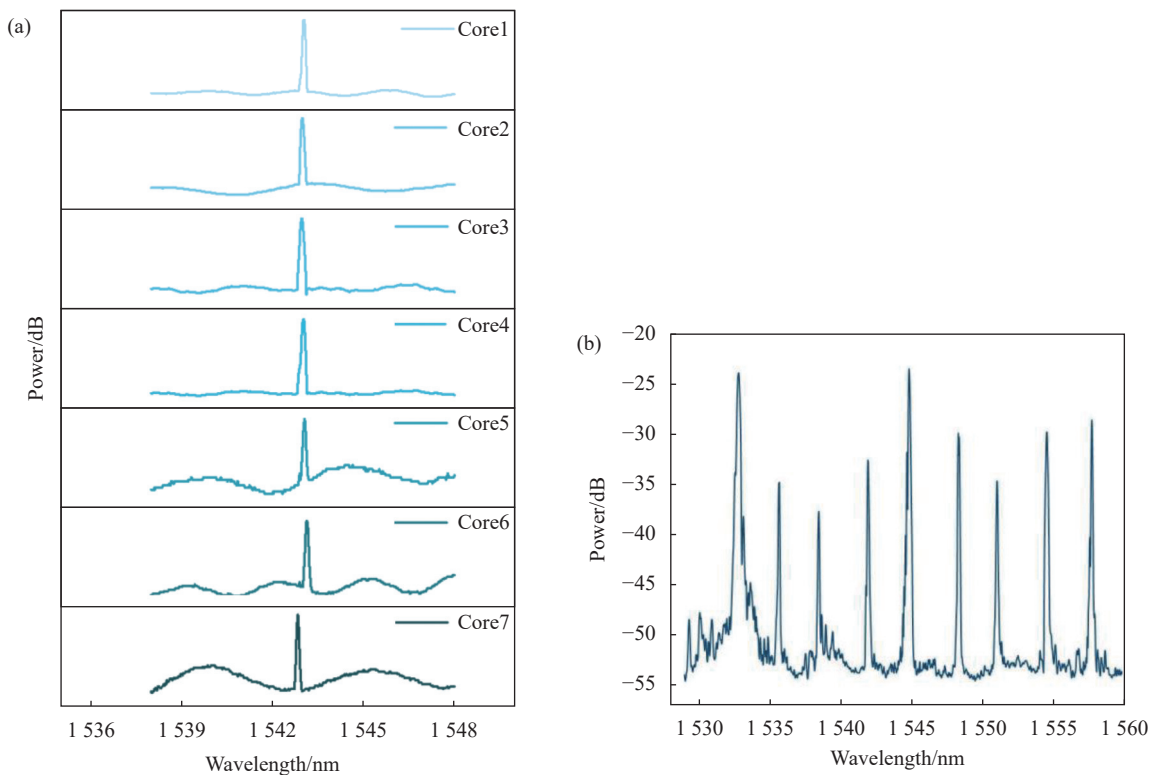


图 6 (a) 各个纤芯的光栅光谱; (b) 光栅串的光谱

Fig.6 (a) Grating spectrum of each fiber core; (b) Spectrum of grating string

并带胶粘在一起形成带状结构,如图 5(c)所示,这样就可以避免光纤在测量过程中发生扭转。然后将并带结构放入二维曲率槽内,再用公式(3)进行预先的扭转角标定。标定完后,需要将七芯光纤光栅笔直地放置实验平台上,在无任何应力应变的干扰下测量得到光栅的初始中心波长,初始波长是否准确将会影响后续算法的计算结果,所以必须十分准确地测量才能获得高精度的重构形状。随后将光纤放置在 3D 打印的圆柱三维螺旋线凹槽内,如图 5(d)所示。圆柱的半径为 100 mm,螺旋槽的螺距为 90 mm。

### 4 实验结果及误差分析

根据波长漂移量计算出各光栅点的曲率和挠率,实验先后进行了五次测量,取其平均值,利用三次样条插值法对空白处的曲率和挠率进行插值,再结合齐次变换矩阵重建算法得到了三维重建效果图,如图 7(a)所示。其中红色曲线为光栅间距为 10 cm 的实验重建三维螺旋线,蓝色曲线为光栅间距为 5 cm 的实验

重建三维螺旋线,黑色曲线为真实三维螺旋线。实验结果表明,重构出的三维形状与真实形状符合得较好。图 7(b)是对重建图形的误差分析,从图中可以看出,整体误差随着光纤长度的增加呈现出一种增长的趋势,最大误差出现在尾点处。表 1 为实验值与模拟值的数据对比,从表中可以看出,光栅间距 5 cm 时的最大误差为 1.15 cm,占全长的 1.4%,平均误差为 0.62 cm,占全长的 0.8%。光栅间距 10 cm 时的最大误差为 2.56 cm,占全长的 3.2%,平均误差为 1.32 cm,占全长的 1.7%。第 3 节得出模拟值的最大误差占全长的 2.7%和 0.6%,实验值与模拟值符合得较好,两组实验值与模拟值的相对误差分别为 0.5%和 0.8%。误差产生的主要原因有:(1)通过显微镜观察发现,实验所用的七芯光纤的六个边芯并非完全按正六边形排布的,而是有一定的误差,这对计算弯曲曲率会产生一定的影响,从而导致实验误差;(2)实验中采用的是分辨率为 10 pm 的解调仪解调 FBG 的峰值波长,当波长变化小于 10 pm 时无法检测到,存在系统误差。

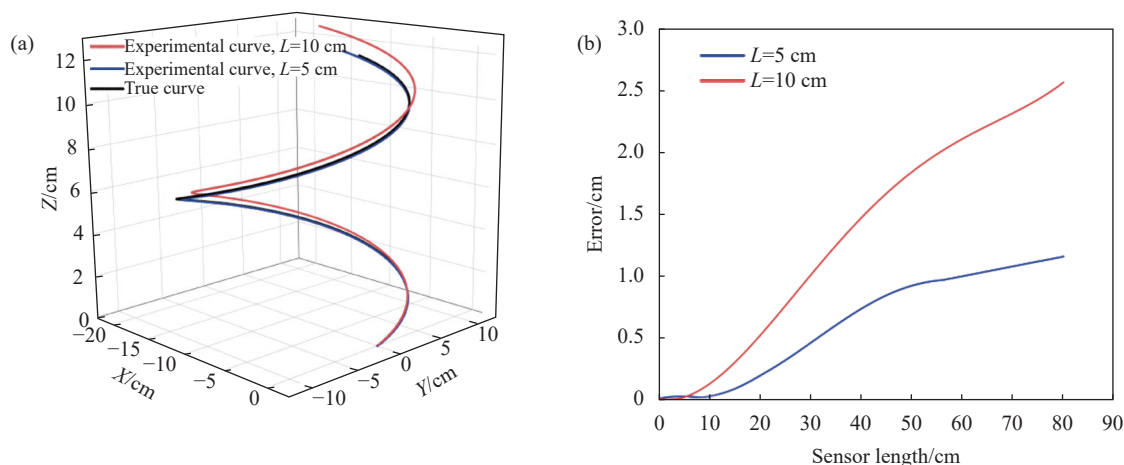


图 7 三维形状传感实验。(a) 重构曲线与真实曲线;(b) 误差

Fig.7 3D shape sensing experiment. (a) Reconstructed curve and true curve; (b) Error

表 1 实验值与模拟值对比

Tab.1 Comparison of experimental and simulated values

Grating pitch, L/cm	Maximum error/cm	Error percentage	Simulation error percentage
5	1.15	1.4%	0.6%
10	2.56	3.2%	2.7%

### 5 结论

文中探究了不同光栅间距对七芯光纤光栅三维

形状传感精度的影响关系,通过模拟计算五组不同光栅间距下的三维螺旋线形状的重构误差,建立了误差与光栅间距之间的关系,然后在选取两组光栅间距进

行实验,并将光纤做成并带的形式以防止光纤扭转带来的误差。结果表明,最大误差均出现在尾点处,分别为2.56 cm和1.15 cm,占全长的3.2%和1.4%,平均误差为1.32 cm和0.62 cm,占全长的1.7%和0.8%。无论是模拟仿真还是实验验证,误差值与待测对象相对长度的整体趋势符合线性增长的趋势。最大误差点均发生于尾点处。通过建立光栅间距和线性拟合的斜率之间的变化关系,可探讨不同光栅间距与三维重建误差之间的对应关系。根据该关系可以对相似的形状下的任一光栅间距、任意长度光纤的三维形状重构误差进行预测,这样就可以结合具体的应用场景选择合适的光栅间距以及解调方法,合理配置测点资源,在较低的成本范围内提高检测性能。此外,提高光纤光栅解调仪的分辨率将有利于获得更精确的波长数据,得出更精确的曲率值;该三维重构算法原理是三维形状的每个坐标点都由前一个点经平移旋转变化而来,所以会由于算法的迭代引起发散误差,可以通过增加等距校正点、可收敛发散误差有效抑制尾点处误差。该方法有望为不同距离待测对象的光栅布置方案与栅点间距参数提供一定的理论依据与设计参考。

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## Research on shape sensing performance and reconstruction error of multi-core fiber grating

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### Abstract:

**Objective** At present, shape sensing technology based on multi-core fiber grating is mainly divided into two categories, one is the optical frequency domain reflectometry (OFDR) demodulation technology based on the all-same weak grating. The other is multi-core grating or integrated grating shape sensing technology based on wavelength demodulation mode, and the multi-core grating array sensing system based on wavelength demodulation mode has the advantages of small size, high signal-to-noise ratio, fast acquisition speed and high real-time demodulation. In view of the diverse shape sensing needs in the actual application, the multi-core grating array multi-core sensing system using wavelength demodulation can be flexibly configured according to the actual needs of the number and spacing of the grating, which can realize the shape monitoring of the measured object with more flexible sensing distance and more diverse shape change span, which has a wider application prospect. However, because the multi-core grating measurement point cannot be continuously in space, the shape of the blank grating area between the measurement points cannot be obtained, and there is a blind zone of the measurement point. In practical applications, in order to improve the accuracy of shape sensing, it is necessary to study the shape deformation characteristics of the object to be measured, and design a reasonable grating distribution configuration scheme under the premise of taking into account the measurable key points and the full range of measurable areas to be measured.

**Methods** Based on the strain sensing characteristics of seven-core fiber gratings, this paper adopts a three-dimensional shape reconstruction method based on homogeneous transformation matrix to reconstruct the shape of two seven-core fiber gratings with different grating spacing, solve the curvature and torsion of the region where the grating measurement point is located by the relative change value of the wavelength of the grating point, and obtain the curvature and torsion of the blank grating region between the FBG measurement points by cubic spline interpolation, and finally integrate the curvature and torsion of all points into the same coordinate system. The three-dimensional shape reconstruction of the object to be measured is realized. In order to explore the influence of grating spacing on shape reconstruction accuracy, the three-dimensional shape reconstruction error under different grating spacing based on this algorithm principle is simulated by algorithm programming, and the experimental verification is completed by building a three-dimensional shape sensing system, and the rationality of the error and simulation error in the experiment is discussed.

**Results and Discussions** The simulation calculation selects the raster spacing  $L$  of 12.5 cm, 10 cm, 8 cm, 5 cm and 1 cm, and plots the 3D reconstruction curve and the real curve under these raster spacing. Both the simulation

assumes that the curvature and torsion measurement error of the gate measurement point is 0. The results show that when the grating spacing  $L$  is 12.5 cm, 10 cm, 8 cm, 5 cm and 1 cm, the spatial position error shows a gradual increasing trend with the length of the fiber, and the larger the grating spacing is, the larger the error is. The maximum reconstruction error falls at the end point of the analog length, which is 7.75 cm, 4.35 cm, 2.63 cm, 0.94 cm and 0.25 cm, accounting for 4.8%, 2.7%, 1.6%, 0.6% and 0.16% of the total length (Fig.4). In the experiment, a grating string with a grating spacing of 5 cm and 10 cm was selected to carry out a three-dimensional shape sensing experiment. The experimental results show that the reconstructed three-dimensional shape matches the real shape well (Fig.7). The maximum error at a raster spacing of 5 cm is 1.15 cm, accounting for 1.4% of the total length, and the average error is 0.62 cm, accounting for 0.8% of the total length. The maximum error at a raster spacing of 10 cm is 2.56 cm, accounting for 3.2% of the total length, and the average error is 1.32 cm, accounting for 1.7% of the total length (Tab.1).

**Conclusions** Whether it is simulation or experimental verification, the overall trend of error value and relative length of the object to be measured is in line with the trend of linear growth. The maximum error points all occur at the end point. By establishing the variation relationship between the raster spacing and the slope of the linear fit, the correspondence between different raster spacing and the 3D reconstruction error can be explored. According to this relationship, the three-dimensional shape reconstruction error of any grating spacing and any length of optical fiber under similar shapes can be predicted, so that the appropriate grating spacing and demodulation method can be selected in combination with specific application scenarios, reasonable allocation of measurement point resources, and improvement of detection performance in a lower cost range.

**Key words:** fiber shape sensing; multi-core fiber; Bragg grating; numerical simulation; grating pitch

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