

# 光学学报

## 光学自由曲面测量与误差评估技术研究进展

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**摘要** 光学自由曲面是现代精密光学领域的重大变革, 因其优异的光学、力学性能而有望进一步推进光学系统实现微型化、轻量化、集成化。随着光学自由曲面的面形复杂度不断提升, 光学自由曲面的检测技术已成为制约其制造水平的关键因素。回顾了近年来光学自由曲面测量与误差评估的关键技术, 包括点线式扫描、全口径光学测量方法以及面形误差评估方法, 结合各种技术的优缺点, 展望了该领域未来发展的新趋势, 并介绍了一种结合多传感器实现共体自由曲面的测量及误差评估的新方法。

**关键词** 光学设计; 光学自由曲面; 精密测量; 面形测量; 误差评估; 误差参数

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### 1 引言

超精密光学自由曲面是现代精密光学领域的重大变革, 以其优异的光学、力学性能而被广泛应用于成像和非成像领域, 包括采光和照明(如路灯控形、车灯)、显示器(如头戴式、智能眼镜)、遥感(如天文仪器、俯瞰卫星)、军事国防(如情报侦查、红外仪器)、绿色能源(如光伏、激光光束传输同步加速器), 以及医疗和生物传感(如人造关节、显微成像)等。

这类光学自由曲面通常缺少对称轴或不具有旋转对称性, 局部特征复杂且难以用数学公式直观描述。一般而言, 望远镜光学系统中的多自由度柱面<sup>[1]</sup>, 多项式曲面<sup>[2-3]</sup>, VR (Virtual Reality)、AR (Augmented Reality) 眼镜中用到的以菲涅耳透镜、共体面为代表的非连续面形<sup>[4-5]</sup>, 以及微透镜阵列<sup>[6]</sup>、微金字塔阵列等微结构表面<sup>[7-9]</sup>都可以归类为自由曲面。

自 1972 年自由曲面镜片成功应用于宝丽来折叠式单镜头反光相机 SX-70<sup>[10]</sup> 以来, 光学自由曲面在先进光学系统中得到了快速应用, 如图 1 所示<sup>[11]</sup>。与传统的平面、球面等光学元件相比, 光学自由曲面的多自由度设计属性, 不仅可以大幅减小系统误差、消除各类像差、大幅提升系统性能, 而且对光学系统实现微型化、轻量化、集成化<sup>[12-13]</sup> 提供极高的可行性方案。例如: 在高光谱成像中, 自由曲面的应用不仅可以提高 3 倍的空间带宽, 而且至少可以将整体体积缩小为原来的  $1/5$ <sup>[14-16]</sup>。

这类光学面形的制造归功于近年来计算机领域、

高精密加工工艺以及材料学科等多学科交叉融合的迅速发展。光学自由曲面的高性能特性往往需要其面形具备亚微米面形精度及纳米甚至亚纳米表面粗糙度。尽管如快刀伺服、慢刀伺服等超精密单点金刚石车、铣、抛、磨以及能场辅助如激光、超声、磁流变等新技术<sup>[17]</sup> 的快速发展进一步提升了制造水平, 但自由曲面需求向高动态尺度、极端面形复杂度及超光滑面形精度不断提高, 以及光学元器件向可见光波段甚至更短波长波段的应用发展, 使得现有加工技术、检测方法都面临极大的挑战。尤其是在光学自由曲面检测领域, 亚微米级面形及纳米级表面质量的精度要求, 对检测过程中复杂光学面形测量、面形加工误差评估等带来诸多难题, 目前光学曲面高精度检测已成为制约其发展及应用的主要因素。

随着光学自由曲面制造工艺的不断发展, 相应的商用测量设备也不断更新迭代, 图 2 中给出了部分典型的光学面形测量仪器<sup>[11]</sup>。本文针对光学曲面检测中的关键技术, 即面形测量技术和面形误差评估, 进行了研究和分析, 结合各个方法的优缺点, 展望了光学曲面检测未来的发展趋势。

### 2 光学自由曲面精密测量技术

Whitehouse<sup>[18]</sup> 将表面检测定义为被检测光学面形或元器件偏离其设计标准程度的测量, 主要包括表面轮廓误差测量及表面质量如粗糙度的测量。自由曲面的测量任务, 按照其面形特征, 大体可分为低频段表面面形误差、高频段表面特征粗糙度, 以及处于中间频段

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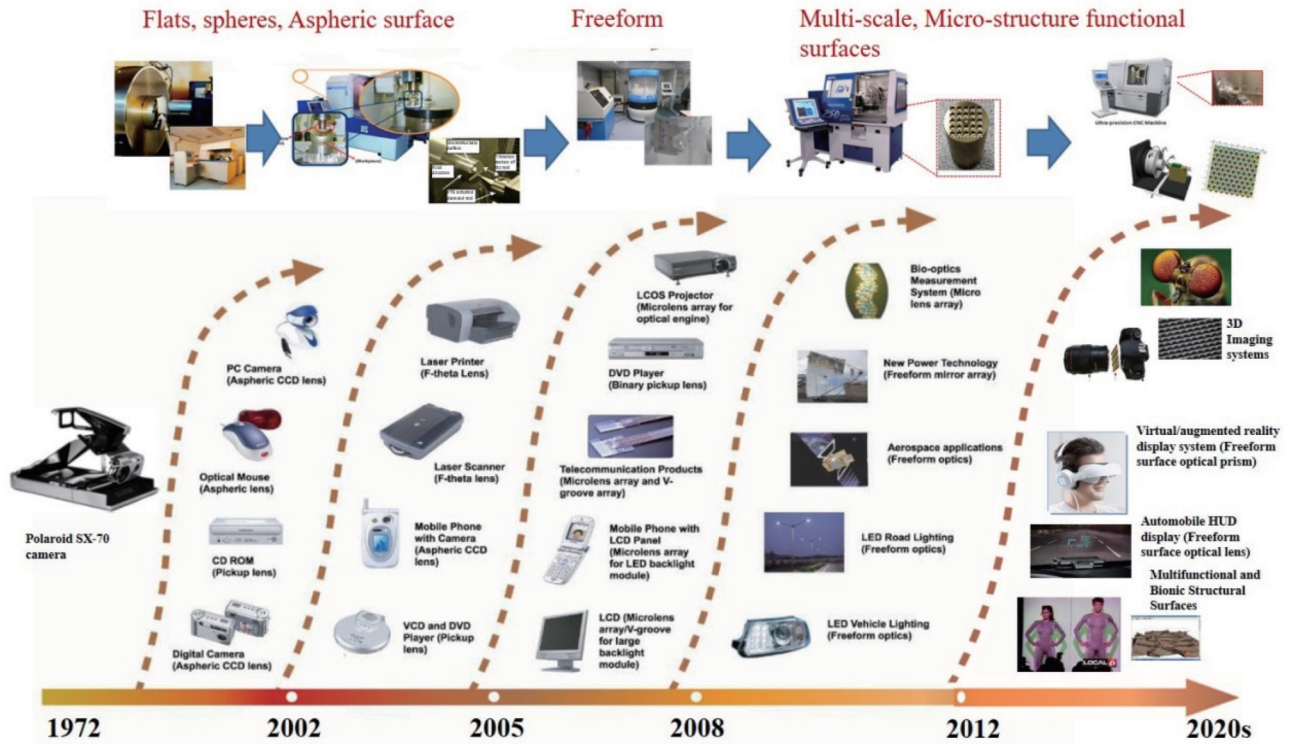


图 1 光学自由曲面的应用历程<sup>[11]</sup>

Fig. 1 Roadmap of wide application of optical freeform surface<sup>[11]</sup>

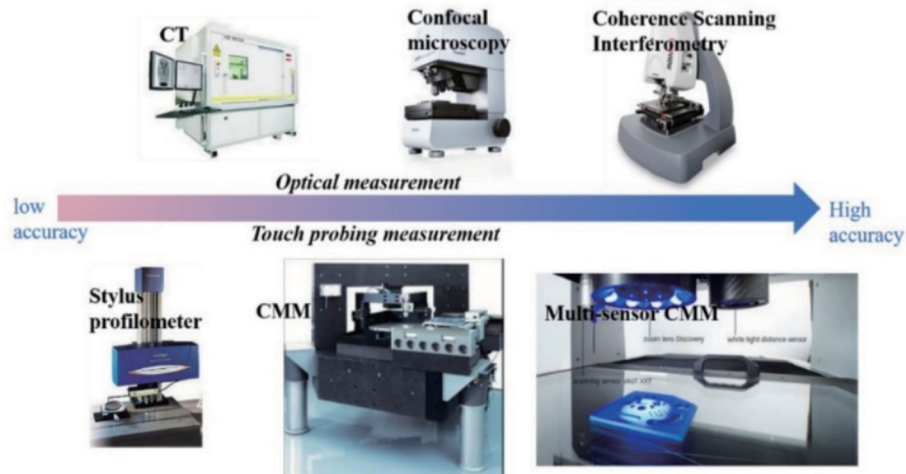


图 2 商用测量仪器<sup>[11]</sup>

Fig. 2 Commercial measurement devices<sup>[11]</sup>

的表面波纹度如加工刀具刀痕的测量<sup>[19-20]</sup>。Savio 等<sup>[21]</sup>调研了 2007 年之前应用于各领域的自由曲面测量方法,并按照测量时传感器是否与被测曲面接触分为接触式测量方法和光学非接触式测量方法两大类。

接触式测量方法通过探针对被测件进行点或线扫描,每个测量单元包含三个坐标的信息,最后通过将三维数据拟合,便可重构出物体的三维形貌。目前最为常见的接触式测量方法有高精度三坐标测量机(CMM)、2D 探针式表面轮廓仪、原子力显微镜(AFM)和隧道扫描显微镜(STM)。然而,接触式测

量方法极易划伤被测面,因此非接触式测量方法一直以来都是光学自由曲面测量的首要选择。非接触式测量方法主要包括点、线光学探针扫描的轮廓仪、干涉检测法、相位偏折术和 Shack-Hartmann 测量法。本文将根据测量方式的不同,将面形的测量方法分为扫描测量与全口径测量,并展开进行讨论。

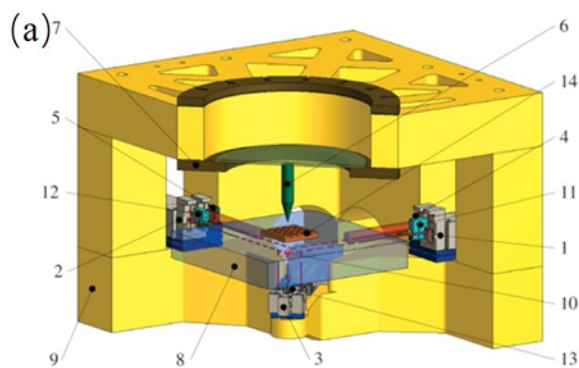
### 2.1 扫描测量

点、线扫描或小口径扫描方法基于采样策略,通过传感器获得自由曲面外形或结构的一个或两个维度的结构信息,结合机械运行维度信息重构出测量面形的

三维特征。这类扫描方法对机械运动部件的运动精度、动力学稳定性和传感器的要求极高。目前,最具代表性的精密扫描测量方法是CMM测量法。

CMM是应用最为广泛的三维测量设备<sup>[22-23]</sup>,通过高精度多轴运动系统带动如触发式探测器等传感系统对被测面矢高进行全区域点对点采样扫描。该过程中,如何保证多轴运动系统的精度和测头的高性能探测是CMM实现超高精密测量的重难点。引入激光位

移干涉技术降低或消除运动轴阿贝误差,开发多维、高灵敏响应特性的轻质3D微纳探针<sup>[24]</sup>,成为解决以上重难点的主要技术手段。德国IBS、SIOS公司、Werth Messtechnik等公司将这些技术集成于目前市面上纳米量级测量精度的CMM即Nanometric CMM中,其中最具代表性的有NMM-1<sup>[25]</sup>、Isara 400<sup>[26-27]</sup>、Werth VideoCheck系列<sup>[28]</sup>,图3呈现了两种超精密3D坐标测量机的内部构造及实物图。



1.interferometer x-axis, 2. interferometer y-axis, 3. interferometer z-axis, 4. angle sensor, 5. angle sensor, 6. probe system with vertical Abbe offset (fixed in space), 7. mounting points for the probe system, 8. mirror plate, 9. metrology frame, 10. Abbe point, 11. reference sensor x-axis, 12. reference sensor y-axis, 13. reference sensor z-axis, and 14. measurement object

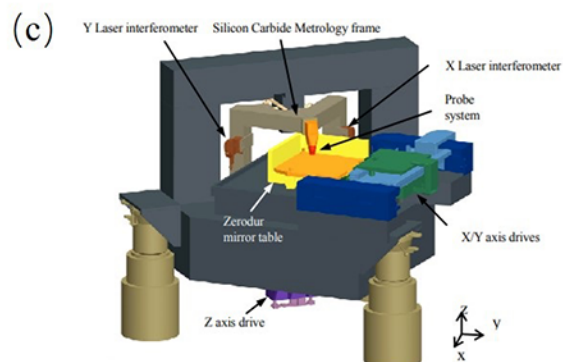
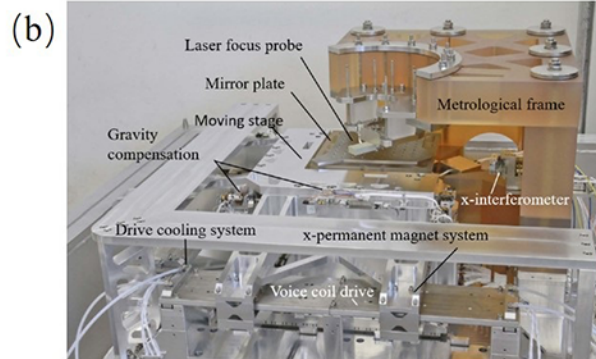


图3 纳米级CMM。(a) NMM-1使用阿贝准则示意图<sup>[25]</sup>; (b) NMM-1实物图<sup>[25]</sup>; (c) Isara 400使用阿贝准则示意图<sup>[27]</sup>; (d) Isara 400实物图<sup>[27]</sup>

Fig. 3 Nanoscale CMM. (a) NMM-1 following the Abbe principle<sup>[25]</sup>; (b) NMM-1 picture<sup>[25]</sup>; (c) Isara 400 following the Abbe principle<sup>[27]</sup>; (d) Isara 400 picture<sup>[27]</sup>

NMM-1系列的测量范围较小,可实现 $25\text{ mm} \times 25\text{ mm} \times 5\text{ mm}$ 的动态测量,测量分辨率低至 $0.1\text{ nm}$ 。相比较而言,Isara 400系列可实现大范围测量,在 $400\text{ mm} \times 400\text{ mm} \times 100\text{ mm}$ 测量空间内可达亚微米级测量分辨率。为进一步实现CMM的高动态高精度测量,Jäger等<sup>[29]</sup>进一步升级纳米定位及纳米测量机床至NPMM-200,利用卫星原子钟基准和光学频梳技术,实现 $200\text{ mm} \times 200\text{ mm} \times 25\text{ mm}$ 测量范围内 $20\text{ pm}$ 的测量分辨率。

除了不断提高的运动控制精度,CMM的高精度测量同样离不开高灵敏性探测器的不断发展。英国国家物理实验室NPL基于电容传感器开发了三角度倾斜式三维传感器<sup>[30]</sup>,随后被IBS公司商用于微型测头

传感器系统Triskelion<sup>[31]</sup>,这类探测头的三维测量偏转不确定度低于 $20\text{ nm}$ 。随后NPL增加了多个压电陶瓷驱动,开发了具有 $\mu\text{N}$ 尺度的极弱接触力以及高度各向同性的新型振动探针。与之相似的设计还包括Haitjema等<sup>[32]</sup>的研究基于单晶硅材料的压阻传感器,该器件是后来被Xpress公司商用的Gannen探针<sup>[31]</sup>,其可实现三维空间优于 $45\text{ nm}$ 的测量不确定度。另外,相关光学纤维探针、METAS等3D探头的原理及特性描述可见于文献<sup>[33-34]</sup>。

超精密三坐标测量法的通用性强,其测量精度高且测量范围大,能满足工业中多种口径自由曲面的测量要求,尤其是Zeiss公司XENOS CMM可实现 $1\text{ m}$ 量级测量范围且测量精度优于 $0.3\text{ }\mu\text{m}$ 的精密测量<sup>[35]</sup>。

然而,为了尽量减小接触式侧头对被测工件表面的损伤,CMM的测量速度普遍较慢,一般在 nm/s 到 mm/s 之间浮动。

相比于硬质机械探针,AFM 和 STM 利用极其微弱的作用力进行微结构表面的高精度测量。如图 4 (a)、(b)所示,AFM的原理是将探针安装在高灵敏性微弯曲悬臂的一端,当探针与被测面接触或保持特定距离时,微悬臂由于探针与表面材料原子之间的相互作用力而产生微形变,据此获得物体高度信息。STM 则基于量子隧穿效应,当探针与被测物体足够接近(通

常为几个纳米)时,探针与被测物体表面形成隧穿电流,该电流对距离的变化十分敏感,亚纳米级的距离变化量足以引起电流强度一个量级的变化,因此可通过监控电流的变化实现位移的测量。AFM与STM测量方法对工件的作用力几乎可以忽略不计,横向分辨率可达到 0.1 nm,测量垂直分辨率更是高达 0.01 nm,测量精度接近原子量级,其不足之处在于:两种方法的测量范围较小且需要较长时间完成工件扫描。另外,STM方法要求被测工件具备导电特性,仅适用于金属及部分半导体的测量。

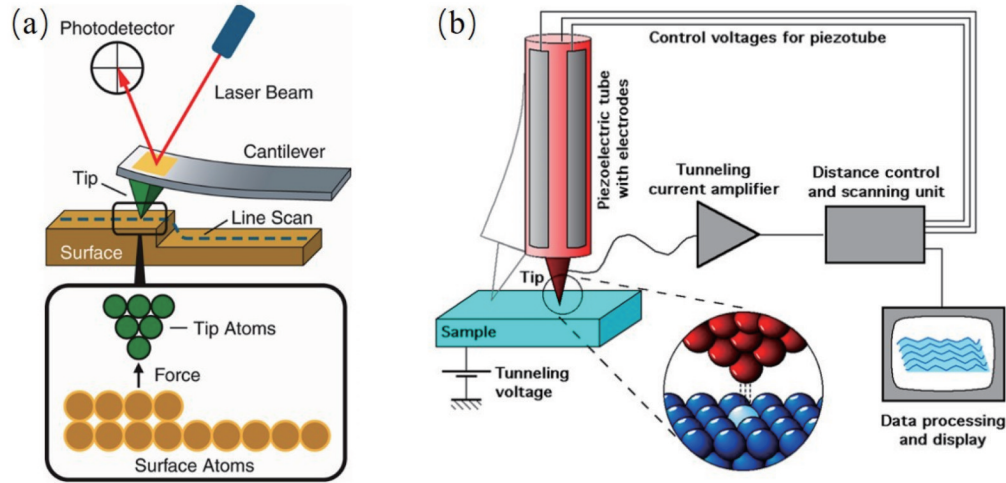


图 4 极弱力扫描方案。(a)AFM工作原理<sup>[36]</sup>; (b)STM工作原理<sup>[36]</sup>

Fig. 4 Scanning methods with negligible force. (a) Working principle of AFM<sup>[36]</sup>; (b) working principle of STM<sup>[36]</sup>

为了克服测量范围受限的不足,Manske等<sup>[26]</sup>提出了如图 5(a)、(b)所示基于激光聚焦原理的多种探针集成测量方案,将多探针设计为显微镜旋转结构并安装在 NMM-1 中。然而,考虑到转换探针过程中的温度、稳定性以及基准校准等问题,该多测头测量方法较难应用于商业领域。综合考虑测量微结构的稳定性和

准确度,日本松下公司将单个探针集成至 CMM 中,开发了利用原子力探针进行测量的超高精度三维轮廓仪 UA3P 系列<sup>[37]</sup>,其工作原理如图 5(c)所示,可实现陡度为 75°的工件测量,在 500 mm×500 mm×120 mm 工作空间内的测量精度优于 0.15 μm。

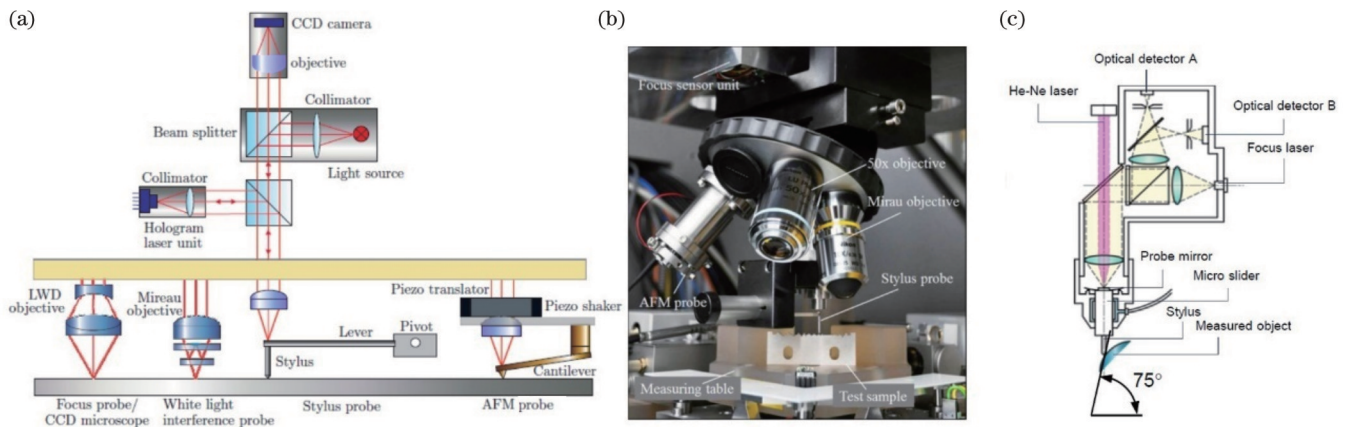


图 5 测量探针工作原理。(a)基于激光聚焦原理的多测头测量方案<sup>[26]</sup>; (b)基于多测头的显微镜头<sup>[26]</sup>; (c) UA3P-3000 的工作原理<sup>[37]</sup>

Fig. 5 Working principles of some measurement probes. (a) Multi-probe measurement scheme based on laser focus principle<sup>[26]</sup>; (b) microscope revolver with multiple probes<sup>[26]</sup>; (c) working principle of UA3P-3000<sup>[37]</sup>

相比于接触式探针,光学探针与被测表面无硬接触,也可集成至CMM中进行快速精确的测量。图6为光学轮廓扫描仪。目前,泰勒霍普森有限公司开发的LuphoScan多波长干涉测量轮廓仪<sup>[38]</sup>和Henselmans团队<sup>[39]</sup>开发的NANOMEFOS四自由度色散共聚焦测量轮廓仪是光学探针轮廓仪中应用较为成功的案

例。如图6(b)、(d)所示,这两种轮廓仪都是在原有CMM的基础上增加了独立运动的B、C轴,其中B轴安装了传感器系统,C轴可实现被测面的旋转。该方法的测量精度优于几十纳米,而且可实现较大坡度(90°)甚至不连续曲面的测量。

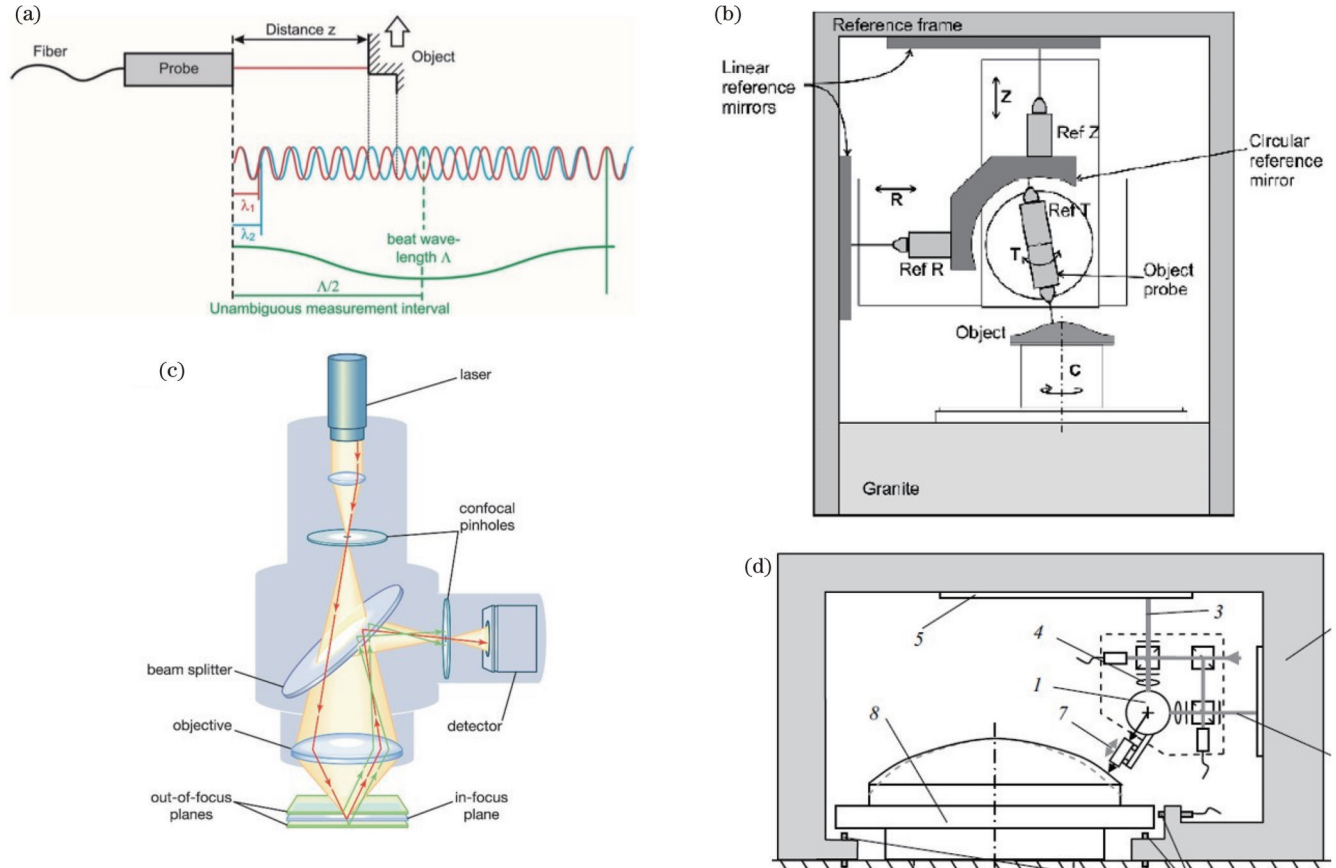


图6 光学轮廓扫描仪。(a)双波长干涉仪原理<sup>[37]</sup>; (b) LuphoScan 系统结构<sup>[38]</sup>; (c)色散共聚焦测量原理<sup>[39]</sup>; (d) NANOMEFOS 系统结构<sup>[39]</sup>

Fig. 6 Optical profile scanner. (a) Principle of multiwavelength interferometer<sup>[38]</sup>; (b) structure of LuphoScan<sup>[38]</sup>; (c) principle of chromatic confocal measurement<sup>[39]</sup>; (d) structure of NANOMEFOS<sup>[39]</sup>

相比于上述轮廓仪, Anderson等<sup>[40]</sup>提出了一种可用于测量大口径元器件的摆臂式轮廓扫描方法(SAP),该测量方法将光学探针安装在可旋转的摆臂末端,通过最佳拟合球体扫描轨迹,实现被测件的非球面偏离测量。摆臂式轮廓仪充分利用超精密旋转轴承,避免大冲程线性轴承,结构紧凑,测量精度高,通过改变臂长即可适应mm至m量级<sup>[41-42]</sup>口径光学元件的测量任务,但是毫米级的垂直测量动态范围不足以满足非球面偏离较大的复杂面形测量要求,另外面形拼接及误差校准也是该方法的难点。

## 2.2 全口径测量

光学自由曲面表面测量的要求极高,尤其对于材质较软的金属等面形,即使极小的接触也有可能对其表面造成损伤,而使用光学非接触方法不仅可以进行无损测量,而且有望实现全口径快速测量。目前主要

的光学全口径测量方法包括干涉测量、相位偏折术和 Shack-Hartmann 测量方法。

### 2.2.1 干涉测量

干涉测量方法一直是光学表面精密测量的首选方案,其在光线传播方向可实现亚纳米分辨率快速测量<sup>[43-44]</sup>,其测量原理简单,参考表面的波面和待测表面反射的波面相结合形成干涉条纹,条纹之间的距离正好代表光束之间的一个波长光程差。当参考面与被测面理想匹配时,可获得零条纹,即实现零位测量。当测量自由曲面时,需要额外的零位补偿光学元件来平衡由非球面偏离最佳拟合球面引起的像差,否则会产生过于密集的干涉条纹,从而超出干涉仪有限的斜率捕获范围,难以分辨条纹<sup>[45]</sup>。为实现自由曲面的干涉测量,研究人员提出了多种方案,其中应用较广且可实现干涉条纹获取的方法可分为3类,分别是:1)设计与被

测量面形一致的零位补偿元件、实现零位干涉的计算全息 (CGH) 法; 2) 缩小孔径以减少捕获的干涉条纹, 经多次测量后对结果进行拼接、缝合, 实现全面形测量的子孔径拼接测量法; 3) 设计合适的光学补偿元件, 补偿大部分像差, 使其产生可分辨的干涉条纹的部分零位补偿法。

CGH 于 1971 年由 MacGovern 等<sup>[46]</sup>应用于非球面的测量。CGH 的原理是通过给定的数学定义来计算

合成两个虚拟波前之间的干涉图案, 当全息图被相同的参考光照射时, 可以通过全息图的衍射而重建波前的振幅和相位, 从而实现任意面形的零位补偿测量。因此, CGH 器件成为实现自由曲面干涉测量的首选零光学器件<sup>[47]</sup>。在实际测量过程中, 需要将 CGH 图案制作成衬底上的衍射结构, 图 7 给出了 CGH 法测量自由曲面的示意图以及在衬底上制作的衍射结构光栅<sup>[48]</sup>。

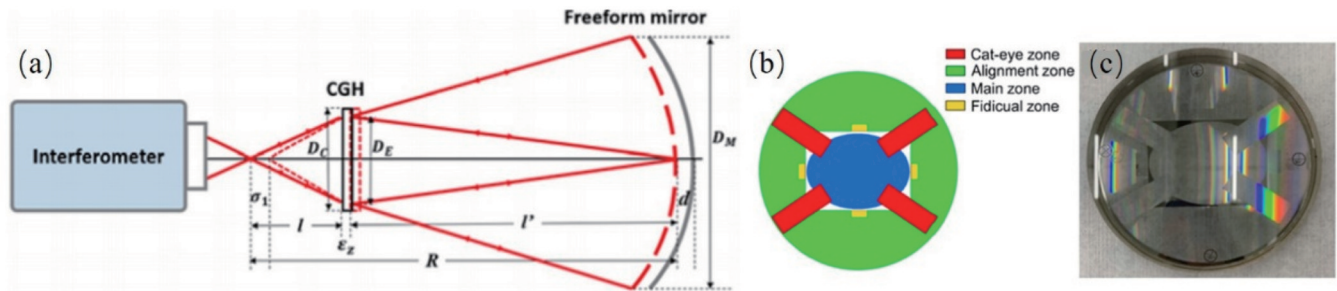


图 7 CGH 测量。(a) 自由曲面 CGH 零位干涉原理<sup>[48]</sup>; (b) Cat-eye CGH 设计图; (c) Cat-eye CGH 制作样品

Fig. 7 CGH measurement. (a) Schematic of zero interference of freeform surface CGH<sup>[48]</sup>; (b) design of Cat-eye CGH; (c) sample of Cat-eye CGH

CGH 法需要为被测自由曲面设计一一对应的条纹图样, 且相应器件的制作需要微纳结构加工工艺, 成本极为昂贵, 因而目前该方法的应用主要集中在大型项目如天文光学系统中大口径自由曲面测量。例如, Beier 等<sup>[49]</sup>对离轴四镜系统进行同步测量, 实现了面形峰谷值 (PV) 为  $0.5 \sim 1 \mu\text{m}$  的测量精度。中国科学院长春光学精密机械与物理研究所设计的相位型 CGH<sup>[50]</sup> 实现了口径为  $800 \text{ mm} \times 600 \text{ mm}$  自由曲面的均方根值 (RMS) 为  $12.7 \text{ nm}$  的面形精度测量。

CGH 图案需要更密集或制作在更大的基底上, 以应对自由曲面偏离, 目前的商用 CGH 能够补偿小于  $1 \text{ mm}$  的偏差<sup>[51]</sup>。另外, 衍射图案的最小线间距和 CGH 的可用尺寸受到制造工艺水平的限制, 且 CGH 制造精度难以表征, 从而限制了该方法的进一步应用<sup>[45, 52-53]</sup>。

为提高干涉测量动态范围以适用于偏离程度更高的自由曲面, 将全口径分成一系列更小的子孔径<sup>[54]</sup>, 通过孔径测量, 利用如环形子孔径<sup>[图 8(a)]</sup><sup>[55-56]</sup>、圆形子孔径等<sup>[57-58]</sup> 拼接算法间接获得全口径面形的子孔径拼接测量方法受到了广泛关注。其中 QED 开发的自动拼接干涉仪甚至可用于陡峭非球面和自由曲面的非球面拼接干涉测量<sup>[59]</sup>。该方法中, 子孔径之间的拼接误差直接影响着全口径的测量结果。另外, 子孔径的数量过多不仅耗费测量时间<sup>[60-61]</sup>, 而且大幅增加了拼接任务<sup>[62]</sup>, 目前该方法多应用于具有回转对称的光学面形测量中, 其他的应用鲜有报道<sup>[63]</sup>。

为提升扫描效率、克服上述子孔径扫描方法的局限性, 倾斜波干涉法 (TWI) 可同时测量多个子孔径。TWI 由 Osten 小组<sup>[64]</sup> 发明并商业化。TWI 的示意图

如图 8(b) 所示<sup>[65]</sup>, 该方法使用由微透镜阵列和针孔阵列生成的点光源阵列来照亮测试表面。离轴点源向测试波前引入必要的倾斜, 并补偿局部子孔径处的表面梯度。因此, 每个子孔径形成具有最小条纹密度的干涉图案。这类不满足零位测量的干涉测量方法, 不可避免地产生了回程误差, 测量时工件的空间位姿定位误差等造成的像差对后期自由曲面的高精度重构及面形误差评估带来挑战。

尽管设计合适的零位补偿元件可实现自由曲面的检测, 但是, 当被测件面形存在较大的加工误差时, 尤其是存在局部斜率较大的面形误差时, 捕获的干涉图太密集, 进而导致测量无效<sup>[66]</sup>。因此, 研制灵活自适应的光学元件已成为该领域探索的新方向。研究人员的眼光逐渐向自适应光学补偿元件转移<sup>[67-68]</sup>, 其中变形镜 (DM) 与空间光调制器 (SLM) 是最有代表性的自适应光学元件。

图 9 为自适应干涉测量。利用变形镜实现干涉测量的原理如图 9(a) 所示。2004 年, Pruss 等<sup>[69]</sup> 提出了将在 37 通道驱动下可实现  $40 \mu\text{m}$  量变形的薄膜镜作为非球面的动态零位补偿测量方法。2014 年, Fuerschbach 等<sup>[15]</sup> 提出利用 Zernike mirror 与传统零位透镜相结合的方法用于测量自由曲面, 校准非旋转对称引起的彗差及像散。该团队还利用 Offer 镜补偿球差, 通过变形镜来补偿高阶像差及彗差, 从而实现口径为  $80 \text{ mm}$  的 Zernike 面形的测量<sup>[70]</sup>。2016 年, Huang 等<sup>[71]</sup> 提出了类似的方法, 通过传统零位补偿法补偿自由曲面面形, 再通过偏折测量系统实时校准 DM 来补偿表面误差。该方法实现了 PV 值为  $101 \text{ nm}$ 、RMS 值

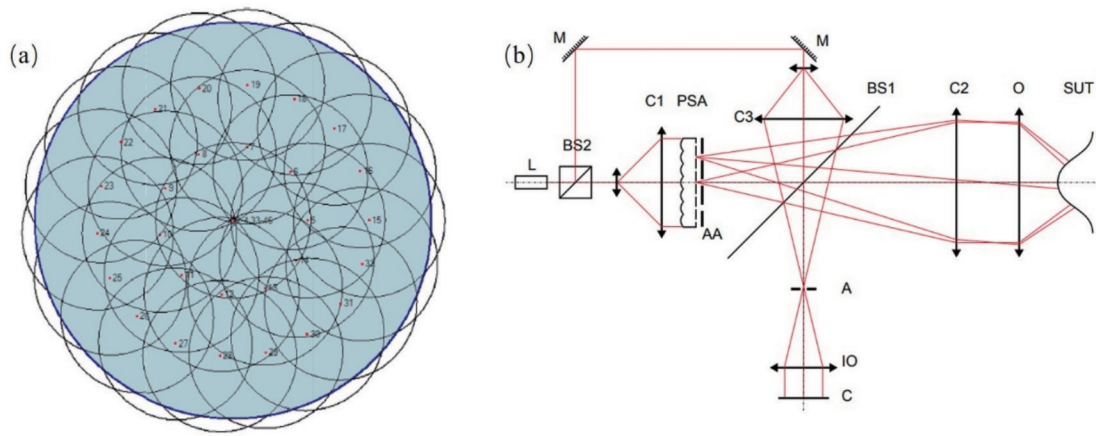


图 8 子孔径测量方法。(a) 环形子孔径拼接方法测量原理图<sup>[54]</sup>; (b) 倾斜波干涉法测量原理图<sup>[65]</sup>

Fig. 8 Subaperture measurement methods. (a) Schematic diagram of circular subaperture stitching interferometry<sup>[54]</sup>; (b) schematic diagram of TWI<sup>[65]</sup>

为 18 nm 的检测精度。该方法的一个难点在于 DM 的形变需要通过其他监控系统实时校准,这就需要其他

监控系统如偏折测量系统自身精度极高才能降低其对系统测量精度的额外影响。

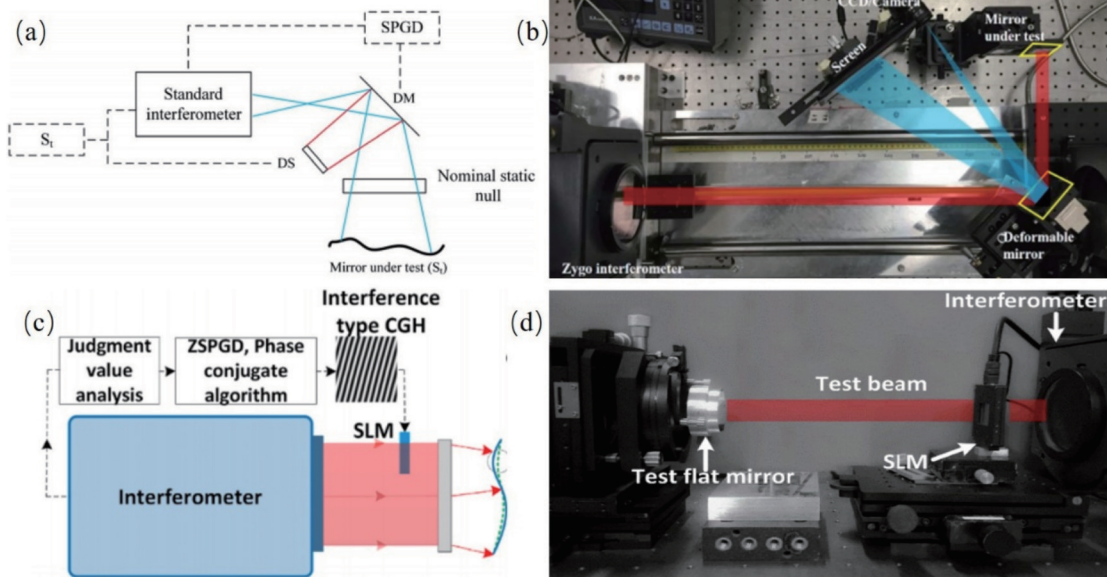


图 9 自适应干涉测量。(a) 变形镜自适应干涉测量示意图<sup>[71]</sup>; (b) 基于 DM 的干涉实验装置<sup>[71]</sup>; (c) 空间调制器自适应测量示意图<sup>[72]</sup>; (d) 基于 SLM 的干涉实验装置<sup>[72]</sup>

Fig. 9 Adaptive interferometry. (a) Schematic of DM adaptive interferometry<sup>[71]</sup>; (b) interference experimental device based on DM<sup>[71]</sup>; (c) schematic of SLM-based adaptive interferometry<sup>[72]</sup>; (d) SLM-based interference experimental device<sup>[72]</sup>

相比于 DM, SLM 像差补偿效果更好,且灵活性更高,通过精准控制光束并产生任意可重构的 CGH 干涉图样,所得到的检测精度更高。SLM 的工作原理与 DM 较为相似,通过快速迭代算法,实时控制 SLM 生成自适应被测面波前,直到获得稀疏至可用于测量的干涉条纹,如图 9(c) 所示。2005 年, Cao 等<sup>[73]</sup>提出了纯相位液晶 SLM 用于光学面形的检测。Xue 等<sup>[72, 74-75]</sup>开展了大量工作,对具有  $26\lambda$  非球面偏离量的二次 Zernike 曲面进行测量,测量精度与 Zygo 公司的 Verifire Asphere 测量误差仅相差  $0.039\lambda$ 。

### 2.2.2 相位偏折测量方法

相位偏折术 (PMD) 最早由 Knauer 等<sup>[76]</sup>于 2004 年提出,成功应用于自由曲面渐进式镜片的轮廓测量。如图 10 所示<sup>[77]</sup>,相位偏折术测量系统由呈现结构光的显示屏、样品台以及用于捕获被样品台反射的结构光的相机三部分组成。通过捕获的图案相位信息,在已知测量设备准确的位置信息的前提下,计算出二维平面内被测表面的梯度信息,然后重建出表面高度信息。为提升该方法测量的准确性及适用性,多显示屏<sup>[78-80]</sup>、多相机<sup>[81]</sup>以及多传感器<sup>[76]</sup>等 PMD 变种测量方法不断被开发出来。

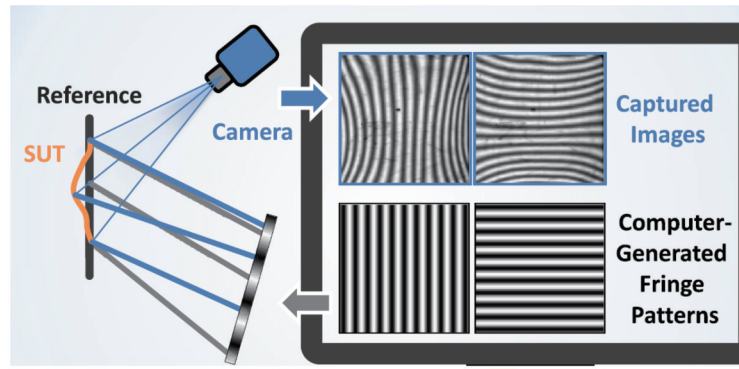


图 10 相位偏折术测量示意图<sup>[77]</sup>

Fig. 10 Schematic diagram of phase deflectometry measurement<sup>[77]</sup>

随着结构光条纹相位解析、相位展开、系统标定以及梯度三维重构技术的不断发展, Burge 团队<sup>[82-84]</sup>结合 PMD 提出了 SCOTS 系统, 实现了口径为 8.4 m 的平面镜、口径为 0.91 m 的非球面镜的纳米甚至亚纳米测量。Huang 等<sup>[85]</sup>改进 PMD, 通过增加双屏及分束器测量的方法, 对应用于中红外系统的非连续台阶面进行测量, 实现了微米级的测量精度。

偏折术测量方法基于光线反射原理, 因此被测面为凹面时较易实现三维全口径测量。当被测面为凸面时, 则只能测量部分面形, 需要通过旋转曲面或改变系统测量位置来实现全口径拼接测量<sup>[86]</sup>。Balzer 等<sup>[87-88]</sup>详细调研了 PMD 测量方法在系统校准、三维重构等方面的研究重难点。目前, 该方法主要应用在较为平滑的光学自由曲面测量中, 测量精度在微米至亚微米级。其中, 系统中各元件的位置标定是决定最终测量精度的关键因素, 也是目前该方法主要的研究方向。

### 2.2.3 Shack-Hartmann 测量法

Shack-Hartmann 测量法是在 Hartmann 波前测量法的基础上发展而来, 其原理如图 11(a) 所示<sup>[53]</sup>, 利用

已知参数的微透镜阵列聚焦被测面反射回来的波面, 结合 CCD 光斑信息, 计算波面斜率, 进而重构出自由曲面面形。

该方法通过系统中 CCD 成像光斑的位置偏移来实现面形测量, 而不同的微透镜阵列可适应自由曲面的尺寸与特征, 测量简便高效, 且测量范围可通过机械扫描来提高。另外, 随着 Shack-Hartmann 传感器在质心计算和波前重建方面的性能提升, 其测量精度和动态范围得到了进一步提高, 因此在波前像差<sup>[89]</sup>及自由曲面面形的测量中应用广泛。Pant 等<sup>[90]</sup>采用样条积分重构波前面形的方法, 实现了口径为 8 mm 的非球面的面形测量, 测量精度 PV 值优于 1.86λ。

然而, Shack-Hartmann 测量法受限于微透镜特性, 其横向分辨率往往不高, 且自由曲面局部变化较大引起光斑交叠时, 测量精度也随之下降。机械扫描方法可提升 Shack-Hartmann 测量的横向分辨率<sup>[91]</sup>, 扫描方法如图 11(b) 所示。Wei 等<sup>[92]</sup>利用可扫描的 Shack-Hartman 传感器探索了大口径三反离轴光学系统, 子扫描孔径为 20 mm 时, 测量精度 PV 值优于 0.7λ。

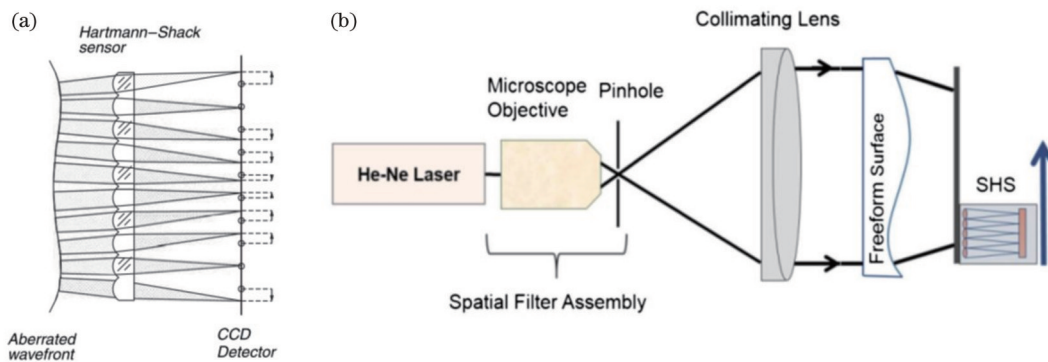


图 11 Shack-Hartmann 测量法。(a) Shack-Hartmann 测量原理<sup>[53]</sup>; (b) 基于扫描的 Shack-Hartmann 测量自由曲面<sup>[90]</sup>

Fig. 11 Shack-Hartmann measurement method. (a) Schematic of Shack-Hartmann measurement<sup>[53]</sup>; (b) freeform surface measurement by Shack-Hartmann measurement method based on scanning<sup>[90]</sup>

### 2.3 在线测量

面形测量是制造过程后处理的重要一环, 为了尽可能减少外部因素的干扰, 测量过程往往需要在可控

的实验室环境中进行。然而, 诸多先进制造过程如米级航天望远镜、飞机涡轮叶片等多工艺链制造过程中, 离线测量已然无法满足各工艺之间快速衔接、通过进



一步补偿加工提升精度的制造要求,测量条件从传统的非现场、事后稳定测量进入测量对象复杂化、测量条件极端化的制造现场。为了解决这类问题,在线测量技术近年来得到了快速发展。

Takaya 等<sup>[93-94]</sup>对这类在线测量的分类及定义作了详细的介绍,大体可分为过程中(in-process)测量和原位(on-machine)测量,为方便描述,本文将二者统称为在线测量。与前文提到的测量方法一致,在线测量技术按照传感器性能也可大体分为点对点或小口径扫描检测法(1D, 2D, 2.5D)以及全口径光学三维检测方法。

### 2.3.1 点对点或小口径扫描检测法(1D, 2D, 2.5D)

点对点或小口径扫描检测法基于采样策略,通过传感器获得自由曲面外形或结构的一个或两个维度的结构信息,结合机械运行维度信息重构出测量面形的三维特征。常用的技术方法是将离线测量系统的部分传感器或设备集成于加工机床的某个运动轴并使其随机床运动,实现实时或原位测量<sup>[23]</sup>。一维、二维接触式

或光学探针传感器以其轻便、易于集成、扫描速度快等优点,在在线测量系统中的应用较为广泛。Shimizu 等<sup>[95-97]</sup>将点激光位移传感器集成于超精密机床的 z 轴上,探索其测量可靠性,并实现了微结构表面如微透镜阵列的精密测量;房丰洲教授团队<sup>[98]</sup>利用 LVDT 设备,研究了接触式探头在线定位、测量自由曲面,实现了复杂曲面亚微米精度补偿。Tong 等<sup>[99-100]</sup>探索了如图 12 所示的色散共焦传感器的在线原位测量可行性,以此技术确保多工艺链中关键特征加工前基础结构的面形精度达到设计要求;Zhu 等<sup>[101]</sup>搭建了如图 13 所示的基于超精密飞切机床的扫描电镜显微镜,该测量微纳结构的在线检测系统与 Shibuya 等<sup>[102]</sup>利用压电陶瓷控制的 AFM 探测头检测 V 槽及微金字塔阵列的在线原位检测系统都实现了亚纳米级分辨率及亚微米测量精度;Li 等<sup>[103-104]</sup>不仅分析了干涉仪探针用于三轴超精密车床的可能性,并且研究了测量策略、测量环境及测量参数与在线测量系统性能的关系。

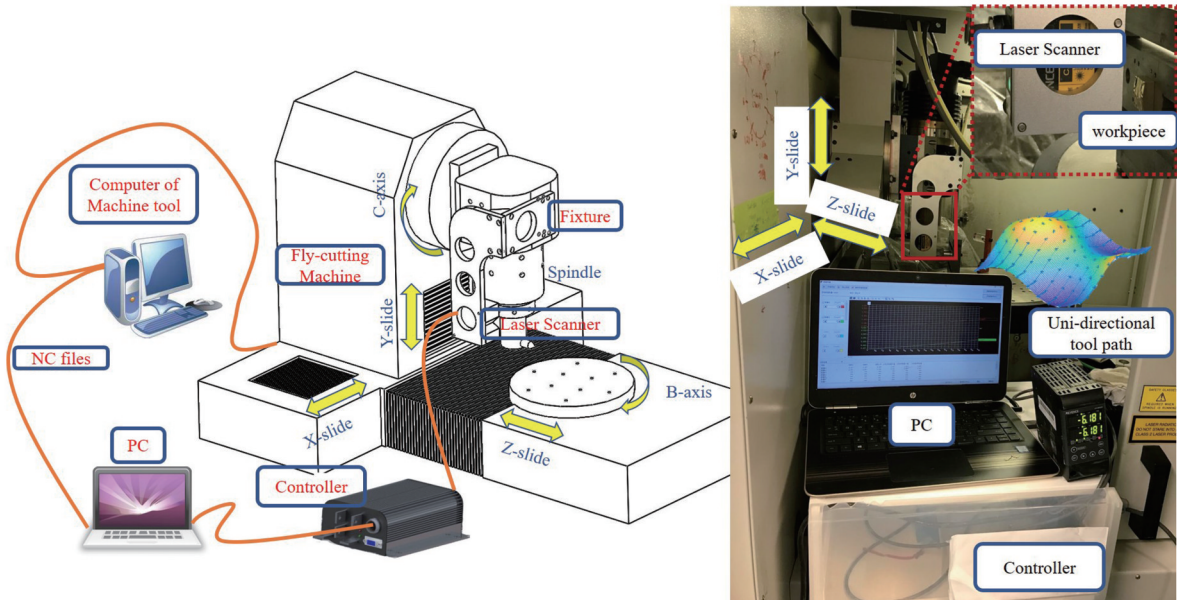


图 12 基于点激光的测量系统<sup>[97]</sup>  
Fig. 12 Measurement system based on point laser<sup>[97]</sup>

基于扫描在线原位测量技术,利用传感器的高精度特性及超精密机床纳米级分辨率,通过连续扫描获取工件高度方向(z 方向)的测量值,实现了其理论测量不确定度低至纳米级、测量精度为 0.1 μm 至 10 μm 的精密测量方法。然而,这类方法往往受限于其集成的机床本身的系统误差<sup>[94]</sup>。在线系统往往安装在机床运动轴上,每个运动轴有 6 个误差,这样测量设备受限于原有机床的误差,这些误差辨识与校准手续繁多,多需要专用的校准设备与方法,且测量设备安装后,对原有超精密设备可能造成干扰,这对在线设备的空间构型设置、重量要求都比较高。在不影响加工设备性能的基础上,校准测量系统整体误差困难,且测量精度、

测量有效范围及测量效率往往不可兼得。

### 2.3.2 光学三维检测法

光学三维检测法是一种利用光、机、电系统对自由曲面外形和结构进行扫描,通过分析光学信息实现物体的三维轮廓特征复现的方法。目前研究应用较多的是以菲索、泰曼格林干涉仪为代表的表面形貌干涉测量系统(图 14)及以结构光传感器为代表的三维表面视觉系统等。

杨树明教授团队<sup>[105]</sup>全面总结了不同测量原理的干涉系统及其应用场景,该技术具备的高动态测量范围和亚纳米级测量分辨率的优异性能引发了极高的研究热度。然而,对于复杂自由曲面的测量,其参考标准

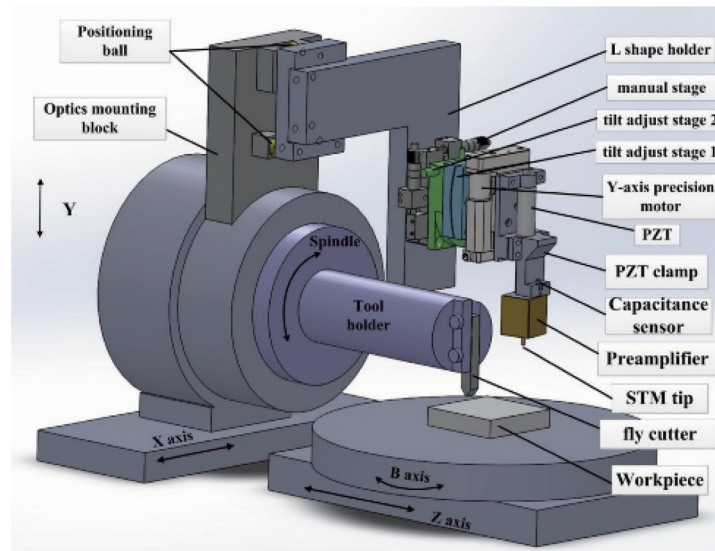


图 13 基于飞切机床的扫描电镜显微镜<sup>[101]</sup>

Fig. 13 Scanning electron microscope based on flying cutting machine<sup>[101]</sup>

面的制造、安装依旧是阻碍其应用的巨大难题。相比较而言,三维表面视觉方法更适用于自由曲面的测量。Mendikute 等<sup>[106]</sup>研究了基于铣床的结构光自校准系统,Zhang 等<sup>[107]</sup>开发了纵向分辨率为  $10\ \mu\text{m}$  的用于增材制造过程检测的光栅投影方法;蒋向前教授团队<sup>[80]</sup>提出了一种改进的可测量非连续镜面的全口径三维测量方法;Zhang 等<sup>[108-109]</sup>同样开发了基于如图 15 所示的相位偏折术的在线测量系统,实现了超精密光学曲面微米级定位及亚微米级测量精度。尽管该方法快捷、准确,但是其往往受限于系统较低的测量分辨率( $10\sim 20\ \mu\text{m}$ )。

基于全口径的测量方法,利用技术成熟的光学非接触三维测量系统,能够实现光学面形的无损快速准确测量。然而,测量系统中涉及到的系统标定以及大口径测量带来的较低测量分辨率问题依旧是目前该方法的缺陷。另外,该方法多适用于光滑、简单自由曲面面形,难以检测复杂多尺度曲面的局部特征。

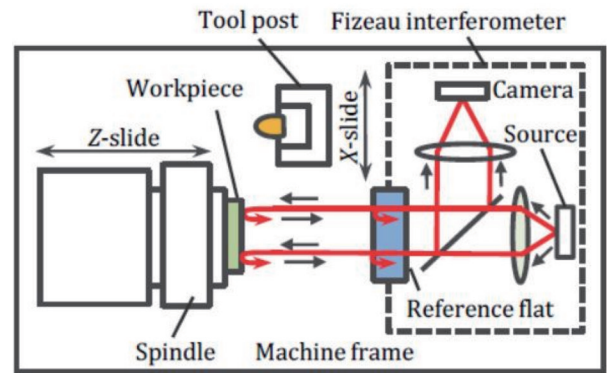


图 14 基于切削机床的索非干涉测量系统<sup>[94]</sup>

Fig. 14 Schematic of Fizeau interferometer based on diamond turning machine<sup>[94]</sup>

在线测量不仅可实现加工零件的在线定位、多次加工补偿,而且可通过过程监控实现机床诊断、质量控制等维护功能。然而,苛刻的加工环境使得测量结果

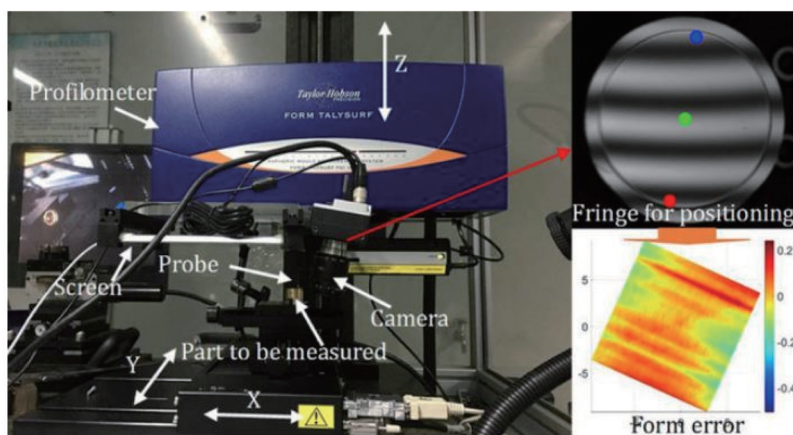


图 15 基于相位偏折术的面形测量<sup>[108]</sup>

Fig. 15 Surface measurement based on PMD<sup>[108]</sup>

易受到机床误差、热变形以及振动等外部因素的影响。另外,受限的工作空间、难以集成的软硬件系统对测量系统的稳定性及测量可靠性带来了极大的挑战。

### 3 自由曲面面形表征

自由曲面缺乏旋转对称轴,一般很难采用统一的数学方程式描述,通过各类测量方法得到自由曲面的面形点云数据与设计面之前的误差评定相较于传统面形难度较大。光学自由曲面的面形误差评估是指将测量数据与设计面经过一定的坐标变化达到最佳匹配,即完成坐标一致性配准,然后选择合适的表征参数,对它们之间的偏差进行面形误差评估。当设计面未知时,需要对测量离散点进行拟合重构(如多项式、样条曲线等),构造合适的参考基准面,以实现评估。面形配准作为光学自由曲面评估准确性及可靠性的前提,一直是研究者关注的重点。一般而言,还需要对测量数据进行预处理,尽量减少甚至消除测量数据中包含的测量仪器系统误差<sup>[110]</sup>。

#### 3.1 面形配准技术

Maiseli 等<sup>[111-112]</sup>总结概括了近年来三维点云配准方面的研究进展。对于光学自由曲面面形配准,其过程可归纳为基于最小二乘或最小区域法实现非线性优化的过程,寻找出最佳匹配的 6 自由度刚体传递参数  $T$ (旋转和平移)。该过程可表示为

$$\arg \min \left( \sum_{i=1}^N |P_{i, \text{measure}} - TP_{i, \text{reference}}|^2 \right), \quad (1)$$

$$\arg \min \left( \max |P_{i, \text{measure}} - TP_{i, \text{reference}}| - \min |P_{i, \text{measure}} - TP_{i, \text{reference}}| \right), \quad (2)$$

式中:  $P_{i, \text{measure}}$  为测量坐标系中的点;  $P_{i, \text{reference}}$  为参考坐标系中的点;  $T$  为旋转矩阵。

最为常用的面形配准方法是基于刚体匹配的最近迭代点(ICP)算法及以此为基础的改进算法。ICP 算法最早由 Besl 等<sup>[113-114]</sup>提出,并应用在曲线和自由曲面配准中。该方法通过式(1)进行参数优化,其计算复杂度低,且无需提取面形局部特征。然而,该方法对不同的初始优化位置点敏感,精度和效率也会因确定最近的点对难度提升而降低。Rusinkiewicz 等<sup>[115]</sup>通过从点云数据筛选、加权关联点对、离群值剔除<sup>[116-118]</sup>等方面解决 ICP 中的难题,例如通过随机采样、滤波<sup>[114, 119-120]</sup>等方式筛选部分能够准确描述基础曲面的点对。Mitra 等<sup>[121-122]</sup>提出了有助于识别潜在特征的区域选择方法,然后创建合适的对应关系<sup>[123-124]</sup>,在后续优化中通过分配更高的权重来提升性能。

刘又午<sup>[125]</sup>研究了基于共线性和封闭性约束来操纵由 ICP 标准建立的可能的点匹配。然而,如果未适当提供两个数据集的初始相对位置,则认为该方法容易收敛于局部最小值,甚至变得发散<sup>[126]</sup>。因此,通常进行粗略配准以为 ICP 迭代提供良好的初始值。在预匹配过程中,进行粗略的坐标变换,将测量表面与标称表面粗略对齐。如果测量表面的坐标与设计坐标有很大不同,则不能直接使用测量点来查找标称表面上的对应点。在粗略配准中,独立于坐标系的自由曲面的几何特征如局部形状特征<sup>[124]</sup>、曲率<sup>[127]</sup>和几何矩<sup>[128]</sup>,通常用作搜索对应点的曲面描述符。

Cheung 团队<sup>[129]</sup>在面形配准方面作了深入研究,提出了基于提取面形的 4 个边界角点及曲面重心点来完成预匹配的方法,随后又提出了曲面固有特征的评定方法<sup>[130-132]</sup>,通过提取曲面的高斯曲率、平均曲率等特征,实现了如图 16 所示的平滑自由曲面与微结构复合的多尺度面形配准,这有助于人们对于复杂尺度曲面不同尺度误差的准确认知,为可能存在的误差补偿加

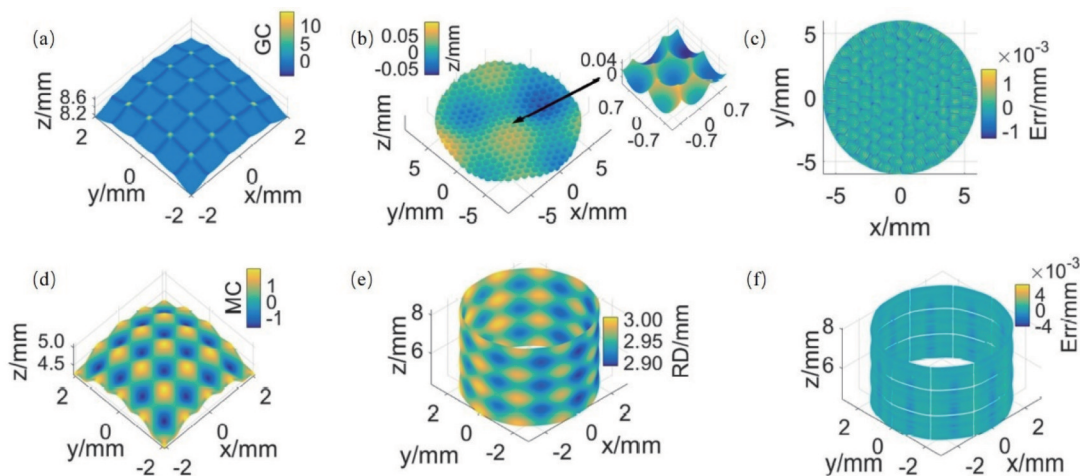


图 16 固有特征面形配准方法<sup>[132]</sup>。(a)微透镜阵列高斯曲率;(b) f-theta及微透镜复合结构(MLA)的测量值;(c)配准后微透镜面形误差;(d)正弦面阵列平均曲率;(e)柱面及正弦面复合结构测量值;(f)配准后正弦面阵列面形误差  
Fig. 16 Intrinsic feature surface registration method<sup>[132]</sup>. (a) Gaussian curvature of lens array; (b) measured results of MLA and f-theta; (c) surface error of microlens after registration; (d) mean curvature of sinusoidal surface array; (e) measured results of composite structure of cylinder and sinusoidal surfaces; (f) surface error of sinusoidal surface array after registration

工过程提供重要信息。

然而,平滑自由曲面往往缺乏固有特征,Kong等<sup>[133]</sup>提出了一种耦合参考数据方法,在加工自由曲面的同时加工诸如球面、平面等明显特征,在测量时利用这类明显特征可实现光学曲面的快速配准。考虑到参考数据依然受到加工误差及工件需再次切割分离等后处理因素,Wang等<sup>[134]</sup>提出了辅助基准的面形匹配方法,如图 17(a)所示,在工件为毛坯状态时,通过测量

获得毛坯自由曲面面形与基准的信息,将自由曲面的 CAD 数据最佳匹配至毛坯测量坐标系,然后记录 CAD 与基准之间的相对位置关系,从而形成带有基准信息的自由曲面(FA-CAD)。该方法不仅可实现测量阶段面形的快速配准,而且可提供误差补偿时自由曲面面形的在线定位<sup>[135]</sup>。图 7(b)为辅助基准配准与 ICP 的精度对比。

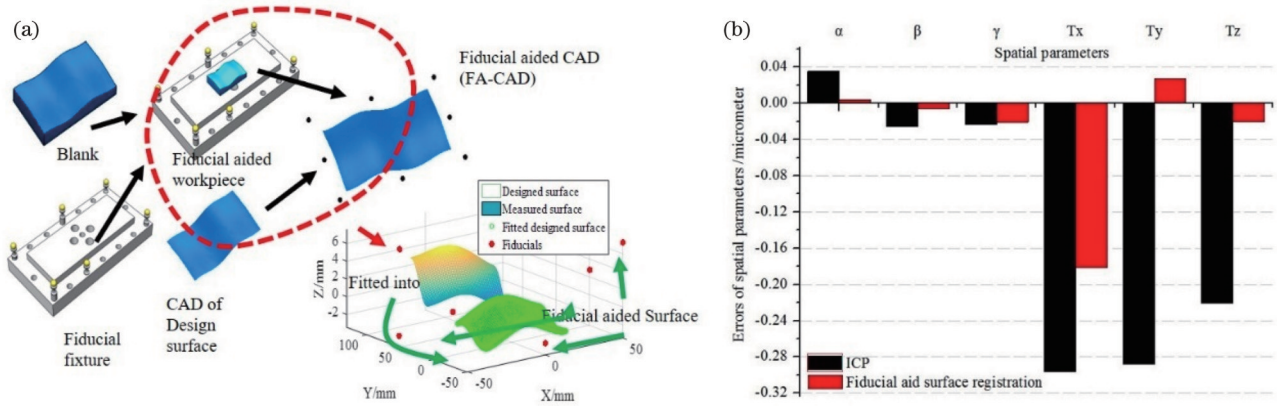


图 17 基于辅助基准的面形配准方法<sup>[134]</sup>。(a) FA-CAD 构造;(b)辅助基准配准与 ICP 的精度对比  
Fig. 17 Fiducial-aided surface registration method<sup>[134]</sup>. (a) Schematic of FA-CAD; (b) accuracy comparison of fiducial-aided registration and ICP

自由曲面因其缺乏明显的表面形貌特征,其配准、表征一直是自由曲面测量的热点和难点,目前仍缺乏统一有效的国际标准<sup>[136]</sup>。

### 3.2 多尺度数据融合

随着光学自由曲面的快速应用,其面形需求从亚微米尺度向米尺度不断延伸,跨尺度复杂结构的表征已经不能仅依靠面形配准技术来实现。这类面形大多需要多种传感器或测量技术才能获得相对完整的面形数据。然而,多仪器多传感器测量得到的数据往往存在不同坐标系、不同测量分辨率及不同测量不确定度的问题,如何保证多源数据表征的面形准确性及可靠性是复杂自由曲面检测面临的新的技术难题。多信息融合理论作为测量多尺度复杂曲面的核心,关键技术问题在于:如何在多项源数据中完成特征配准,构建高效、准确的融合算法,以达到提高多尺度面形测量可靠性、降低测量不确定度的目的<sup>[110]</sup>。而数据融合算法可分为常见的两类方法:1)残余误差法,通过同一算法模型重构单个传感器测量数据配准后的残余误差,得到的误差与理想面形直接融合;2)加权平均法,通过设置各个数据源的权重,利用线性拟合,融合数据配准后同一坐标下的所有数据值。

Colosimo 等<sup>[137-139]</sup>采用高斯建模(GP)的方法,将配准后的面形误差视为测量真值与服从正态分布的随机误差的线性组合。与此方法原理相似的还有 Pagani 等<sup>[140-141]</sup>利用 B-spline 对残余误差进行重构拟合的方

法。值得一提的是,这类通过线性方法拟合得到的  $n$  个数据点所表示的融合面形的测量不确定度都可以用  $K$  个多源数据的单个传感器测量值  $m_k$  及对应的测量不确定度  $\sigma_k$  来确定:

$$\mu_K^2(z) \approx \frac{n}{\sum_{k \in K} m_k / \sigma_k^2} \quad (3)$$

除此之外, Richard 教授团队<sup>[142-144]</sup>将测量值视为测量理论值与误差的线性函数,利用各个传感器数据的配准误差作为权重因子,直接对测量数据进行加权平均融合。

这类利用线性逼近的数据拟合方法不仅高效准确,而且大幅降低了各个传感器的测量不确定度。然而,由于多尺度自由曲面面形的复杂性,多源数据融合较集中于不同传感器检测重合区域,偏重数据缝合,对多源异构数据、复杂面形数据等处理乏力,导致线性拟合优化效率、精度出现大幅下降的问题。

### 3.3 面形误差评估参数

进行曲面配准后,测量面上任意点  $(x, y, z)$  与匹配基准面上的对应点  $(x', y', z')$  之间的距离  $d_i$  为

$$d_i = \pm \sqrt{(x_i - x'_i)^2 + (y_i - y'_i)^2 + (z_i - z'_i)^2} \quad (4)$$

假定沿着  $z$  的正向测量点位于基准面的上方为正,反之为负,则可通过定义或相应的参数评估面形误差。自 Reason 等<sup>[145]</sup>于 1944 年的研究之后,面形误差就主要被分为三类:第一类是与面形加工中加工机理对应的表面粗糙度;第二类是与加工过程密切相关的

动态性能如刀具振动、震颤以及热效应留下的刀痕等波纹度;第三类是机床自身系统误差以及夹具等表现引起的形状误差。Jiang 等<sup>[146-147]</sup>研究了光学曲面、多尺度复杂面形在不同应用场景下的面形误差数字化表征方法,并提出了相应的数据特征提取算法,包括稳健滤波<sup>[148]</sup>以及 Motif<sup>[149-150]</sup>等。

ISO 25178-2<sup>[151]</sup>中也制定了较为完整可靠的三维曲面表征方法,并分类描述了两种面形参数:利用面上所有点所定义的包括均方根、最小自相关长度等场参数和预定义的面形拓扑特征子集所定义的特征参数。在国际标准中提出的超过 25 个面形参数的表征中,最常用的被用来评价光学形状精度的参数有均方根(RMS)值和峰谷(PV)值。它们的定义也是诸多商用软件用来评估误差的主要参数<sup>[152]</sup>。RMS 和 PV 分别可表示为

$$m_{\text{RMS}} = \sqrt{\frac{1}{N} \sum_{i=1}^N (d_i - \bar{d})^2}, \quad (5)$$

$$V_{\text{PV}} = \max(d_i) - \min(d_i), \quad (6)$$

式中: $\bar{d}$ 为距离 $d$ 的平均值。

尽管场参数在各类拓扑光学面形上发挥了重要的表征作用,然而,Malshe 等<sup>[153]</sup>提出目前纹理参数表征不适应于具有超强光学性能的生物微结构<sup>[154-156]</sup>。随着各类仿生结构、光学调制超表面<sup>[157]</sup>的优越光学性能的不断开发,基于特征分析的方法可能会提供有力的表征方法。Jiang 等<sup>[158]</sup>在 CIRP 会议上总结表述了关于特征参数新的应用方法。面形分割技术是这类方法的支撑技术<sup>[150, 159]</sup>,通过稳健可靠的数学方法<sup>[160-161]</sup>,将表面划分为独特特征<sup>[162]</sup>,针对不同的特征,分别进行

普通的场参数表征或者根据需要利用语义标记<sup>[163-164]</sup>的方法表征。

自由曲面的面形误差评估直接关系到光学曲面的加工精度以及后续可能涉及的误差修正等,是确保其光学性能的前提。在平滑光学自由曲面领域,现有的国际标准数字化表征参数应用较为广泛,然而随着面形复杂度的不断提升,原有的参数已然无法满足表征方法。基于分割化处理的特征表征方法正在快速发展,以满足微纳尺度、仿生结构以及特殊结构等在光学领域的进一步发展。

## 4 共体光学自由曲面测量与评估新进展

虽然国内外学者已经针对自由曲面测量及面形评估技术进行了较为深入的研究,但是仍然缺乏有望进一步实现极限性能的共体自由曲面的检测手段<sup>[165]</sup>。共体自由曲面的制造通过对多个自由曲面基于统一基准进行设计、加工和测量,不仅方便放宽公差要求,同时显著降低了自由曲面光学系统的装配难度<sup>[166]</sup>。统一的设计和测量过程也可以对整个制造过程进行更加系统的评估<sup>[167-168]</sup>。

共体自由曲面工件的测量仍然局限于单一自由曲面表面的逐个测量<sup>[169]</sup>,图 18 为对多面共体自由曲面每个表面单独进行测量和校准后的面形偏差。但是共体自由曲面的多个表面测量结果仍然是传统配准方法经过自由曲面配准后得到的单个自由曲面的加工误差。而对于共体自由曲面各个表面间的位姿误差,目前仍然没有合适的方法进行评估。

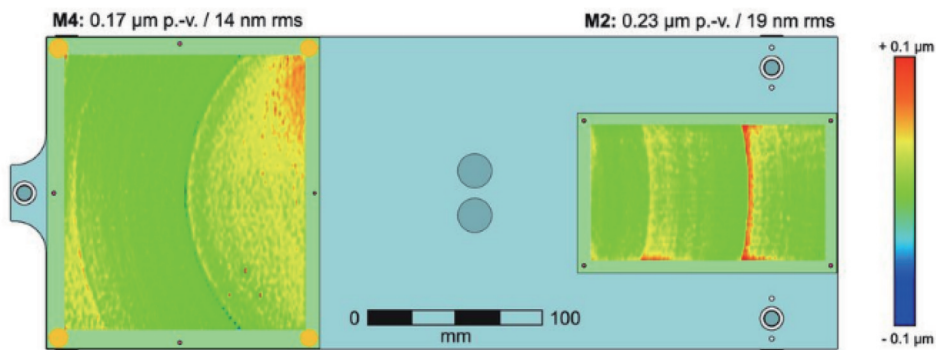


图 18 对多面共体自由曲面进行单独测量和校准后的面形偏差<sup>[169]</sup>

Fig. 18 Form deviation of integrated freeform surfaces after individual measurement and calibration<sup>[169]</sup>

此外,对于共体自由曲面工件一体加工结果的评估,目前的评估手段仅是测试光学系统最终成像的波像差<sup>[166, 170]</sup>。这种测量方式仅能提供最终的成像结果,难以对加工过程中的误差进行溯源。

对此,复旦大学孔令豹研究团队<sup>[171]</sup>研发了一种共体自由曲面测量系统(图 19),可以通过非接触式测量实现共体自由曲面形位误差的测量和评估。该系统采

用 Shack-Hartmann 传感器和色散共聚焦传感器组合的多传感器实现了自由曲面的非接触测量<sup>[172]</sup>,利用多自由度干涉仪对测量的位置结果误差进行校正,利用笛卡儿坐标系和设计制造过程对共体自由曲面表面位置和姿态参数进行定义,由基于信赖域的配准方法对共体自由曲面各个表面的形位误差进行了评估。

共体自由曲面测量系统通过干涉仪中角锥棱镜的

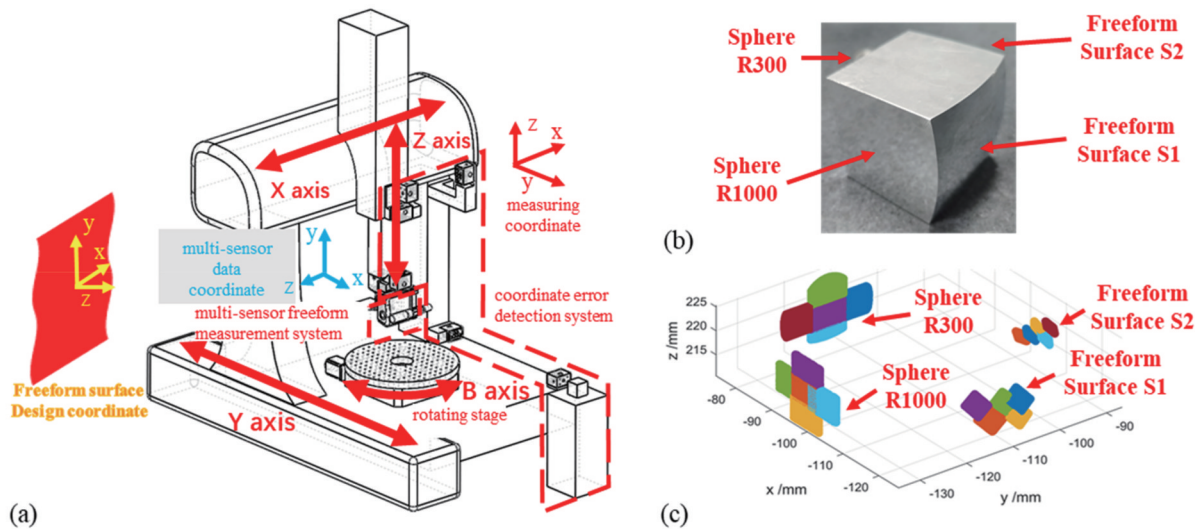


图 19 共体自由曲面的检测<sup>[171]</sup>。(a)形位误差测量系统；(b)样品；(c)测量结果

Fig. 19 Measurement of integrated freeform surface<sup>[171]</sup>. (a) Setup for shape and position measurement; (b) sample; (c) measurement result

检测,对坐标测量结果进行了校正;通过基于波前传播方程的光线追迹,在 $5\text{ mm}\times 5\text{ mm}$ 范围内实现 $10\text{ nm}$  (RMS)的测量精度;使用信赖域方法对自由曲面进行最小二乘配准,在 $25\text{ mm}\times 25\text{ mm}$ 自由曲面拼接中实现 $20\text{ nm}$  (RMS)的配准精度(配准后的轮廓误差),该方法对共体自由曲面的位置和姿态的测量不确定度分别达到了 $1.1\text{ }\mu\text{m}$ 和 $5.8\text{ }\mu\text{rad}$ 。

虽然共体自由曲面测量系统通过运动机构和多传感器实现了非接触式共体自由曲面的形位误差测量,但是:一方面,该系统目前还处于实验室研发阶段,集成化和适用性尚待进一步提高;另一方面,自由曲面的形位误差评估参数和评估方法还需要同设计和加工过程相结合,建立统一的评估标准。

## 5 结束语

随着智能制造的迫切需求,光学自由曲面的制造需求从材料性能、面形精度、结构尺寸等方面急剧提升。尽管诸多先进加工技术如多轴超精密、能量场辅助及特种加工等可实现自由曲面的加工,如何有效、快速、准确地检测其加工精度是否满足性能要求,已经成为光学曲面制造的瓶颈问题。

测量方面,点线式扫描测量方法依赖于高精度机械运动结构,测量精度高,适用范围广,可实现微纳结构、大尺度面形、高陡度局部特征的面形测量,然而其测量效率低,接触测量时有划伤光学表面的风险。相较而言,全口径测量方法以其测量速度快、非接触无损测量精度高的特点而被广泛关注。然而,这类方法的横向分辨率有待进一步提升,且测量动态范围受限,多用于球面、非球面以及简单的自由曲面的测量研究中。为提升制造效率,结合两类测量技术的优点,将在线测量技术与多种测量方法相结合实现复杂面形的多传感

原位测量已成为目前测量领域的发展趋势。

误差评估方面,ICP 以及其改进技术一直是面形配准的首要选择。尽管受到初始优化值的影响,但结合光学自由曲面的固有特征或构造的辅助基准的配准方法基本满足精度要求,然而其计算复杂度及效率仍然有待提高。针对多传感器数据,数据融合多依赖线性拟合,针对多源数据的异构特性、互补特性及关联特性的研究仍处于探索阶段,结合机器学习实现多源数据的深度融合可能成为该领域的一个重要方向。另外,随着研究人员对生物仿生结构、光调制超表面等多功能、微纳多尺度光学面形的不断探索,相应的测量和面形表征方法也成为光学自由曲面制造面临新的挑战。

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## Advances in Measurement and Error Evaluation Technique of Optical Freeform Surfaces

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### Abstract

**Significance** Freeform surfaces have been regarded as one of the major revolutions in the field of modern precision optics. They are expected to further promote miniaturization, lightweight and integration of optical systems due to their excellent optical and mechanical properties. The quality of machined freeform surfaces will significantly influence the performance of optical systems. Surface metrology including the measurement of surface texture and surface form errors is the important post-manufacturing part to determine which surface can be employed. In the past decades, various methods have been developed for measuring and characterizing freeform surfaces, mainly including probe-based scanning, full-aperture optical inspection, on-machine measurement technology, feature-based surface registration and multi-scale data fusion methods. Although many corresponding advances have been achieved, great challenges are posed to the quality of surface manufacturing with the complexity of freeform surfaces increasing. Moreover, the surface form error is required to be lower than  $0.1 \mu\text{m}$  and the surface roughness should be less than  $1 \text{ nm}$ . It is urgent to develop a new measurement technology for achieving a higher dynamic range and a higher accuracy. Hence, it is important and necessary to summarize the existing research to guide the future development of this field more rationally.

**Progress** Measurement and characterization of optical freeform surfaces are the key processes to check the quality of freeform surfaces. The widely used techniques related to these two processes are summarized. Firstly, the precision measurement methods for optical freeform surfaces are introduced, including probe-based scanning, full-aperture optical inspection and on-machine measurement. The probe-based scanning methods include nanoscale 3D coordinate measuring machine, non-contact profile scanner and swing arm profilometer. To further improve the dynamic and precision measurement performance of coordinate measuring machines, Manske's research group from Technische Universität Ilmenau, Germany, has conducted relatively pioneering studies by using an atomic clock-stabilized He-Ne laser via a high-stable-frequency comb. Secondly, full-aperture optical inspection methods are elaborated, including null test metrology of computer-generated holography (CGH), sub-aperture stitching test and adaptive interferometry. Subsequently, surface characterization processes such as surface registration, data fusion and error evaluation are reported. The iterative closest point (ICP) algorithm and its modified methods have been surveyed by Maiseli and Zhu. Liu and Wang from the Hong Kong Polytechnic University have engaged in plenty of studies on multi-sensor data fusion based on Gaussian processes (GP) after reliable surface registration. Jiang's team from the University of Sheffield summarized and expounded on the new application methods of characteristic parameters for complex freeform surfaces. Considering the latest application of freeform surfaces, a novel method is also presented for measuring and evaluating new freeform types called conjunctive multi-freeform surfaces. In the end, the problems and the ongoing research trends in this field are discussed, including measurement means and surface characterization techniques.

**Conclusions and Prospects** Rapid, accurate and reliable inspection technology is the core factor to judge whether the performance of an optical freeform surface meets the requirements of intelligent manufacturing. In the measurement process, the widely used point-line-based scanning measurement method can achieve high measurement accuracy and realize the measurement of micro-nano structure, large-scale surface, and local features with high steepness. However, the measurement efficiency is low and the optical surface may be scratched during contact measurement. In contrast, full-aperture measurement methods have the superiority of fast measurement and high accuracy without contacting the surface.

However, the lateral resolution of these methods needs to be further improved and the dynamic range of measurement is limited. Combining the advantages of the two types of measurement technologies is a promising way to improve manufacturing efficiency. As a result, on-machine measurement technology integrating multiple measurement methods to realize the multi-sensor *in-situ* measurement of complex surface shapes has become the development trend of the current measurement field.

On the other hand, in the error evaluation process, ICP and its modified technologies have always been the first choice for surface registration. Although it is influenced by the initial value, the registration method combined with the inherent characteristics of optical freeform surfaces or the auxiliary datum constructed basically meets the accuracy requirements. However, the computational complexity and efficiency still need to be improved. For multi-sensor data, data fusion mostly depends on linear fitting. The associated characteristics of the fusion process remain to be further explored. The deep fusion of multi-source data may become an important direction in this field by combining with the machine learning technique. In the future, with the rapid exploration of multifunctional, micro-nano and multi-scale optical surfaces, the corresponding measurement and surface characterization methods may encounter new challenges in the manufacturing of optical freeform surfaces.

**Key words** optical design; optical freeform surfaces; precision measurement; surface shape measurement; error evaluation; error parameters