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离轴非球面反射镜补偿检验的计算机辅助 装调技术研究*

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摘 要:利用零补偿器实施离轴非球面元件面形的干涉检测中, 为了实现反射镜的高准确度检测, 对其干涉结果中的误差信息进行了分析. 根据零补偿器的补偿原理, 提出一种新的调整误差分离方法, 建立了离轴非球面补偿检验的调整误差分离模型, 并利用该模型对一块离轴非球面反射镜进行了仿真实验. 调整前由调整误差引入的波像差为 $0.2332\lambda\text{RMS}(\lambda=632.8\text{ nm})$, 根据仿真结果调整后的波像差为 $0.0026\lambda\text{RMS}$, 表明该方法具有较高的准确度, 可有效提高检测效率.

关键词:非球面检测; 补偿器; 调整误差; 计算机辅助装调

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0 引言

离轴非球面反射镜被广泛应用于空间相机系统中, 以满足其对大视场、高分辨率的要求. 高分辨率光学系统对非球面面形准确度的要求越来越高, 而离轴非球面反射镜的加工准确度主要取决于反射镜的检测准确度^[1-4]. 在非球面检测中, 零补偿法的结构简单、补偿范围大、元件参数少等特点, 使之成为非球面检测的有效手段, 但是零补偿检测法的调整是非常困难和费时的, 在检测结果中不可避免地会包含反射镜相对于检测装置的调整误差^[5-8], 因此必须采取有效手段将调整误差从检测结果中分离, 才能正确地指导非球面的加工. 文献^[7-8]将离轴非球面反射镜检测工装视为具有 5 维自由度空间刚体设计的误差分离矩阵, 从波像差理论出发, 分析调整误差作用分量的分立表现形式.

基于补偿器的补偿原理, 本文提出了一种新的调整误差分离方法. 建立了离轴非球面补偿检验的调整误差分离模型, 并进行了仿真实验.

1 理论分析

图 1 是非球面补偿检测光路. 如果忽略反射镜由装夹和重力引起的镜面变形, 则干涉检验的波像差 $W(x, y)$ 中包含反射镜的面形误差 $W_m(x, y)$ 和反射镜相对于检测装置的调整误差引入的波像差 $W_a(x, y)$ ^[7].

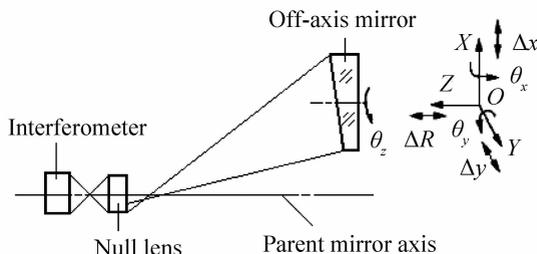


图 1 离轴非球面补偿检测装置

Fig. 1 Schematic of off-axis aspheric null testing system

$$W(x, y) = W_m(x, y) + W_a(x, y) \quad (1)$$

图 1 的离轴非球面镜有 6 个自由度, 分别是沿着 X, Y, Z 轴方向的平移 $\Delta x, \Delta y, \Delta R$ 和绕 X, Y, Z 轴方向的旋转 $\theta_x, \theta_y, \theta_z$. 由于离轴非球面反射镜补偿检测中需要控制的调整量越多, 调整越复杂, 实际通常采用精密刻线的方法来控制离轴镜面绕其自身几何中心的旋转 θ_z , 所以本文不考虑 θ_z 引入的波像差.

当被检非球面与检测系统存在调整误差时, 补偿器产生的补偿波前与被检非球面产生的非球面波前之间的偏离, 该偏离量就是由调整误差引入的波像差 $W_a(x, y)$, 建立调整误差和波像差 $W_a(x, y)$ 的函数关系.

1.1 轴对称非球面产生的非球面波前

对于轴对称二次非球面

$$z = \frac{cr^2}{1 + [1 - (K+1)c^2r^2]^{1/2}} \quad (2)$$

式中 r 是非球面反射镜的口径内任一点 (x_0, y_0) 到顶点的距离 ($r^2 = x_0^2 + y_0^2$), c 是非球面的顶点曲率 ($c = 1/R$), K 是二次曲线常数, 将式 (2) 展开成级数

形式为

$$z = \frac{r^2}{2R} + \frac{(K+1)r^4}{8R^3} + \dots \quad (3)$$

令 $K=0$, 得到

$$z = \frac{r^2}{2R} + \frac{r^4}{8R^3} + \dots \quad (4)$$

式(4)是以非球面顶点曲率半径为半径的球面,将式(4)和式(3)相减,就得到二次非球面相对于其顶点球面的偏离,即轴对称非球面产生的非球面波前

$$\Delta z = -\frac{Kr^4}{8R^3} - \dots \quad (5)$$

1.2 离轴非球面产生的非球面波前

根据图 2 的离轴非球面镜相对于母镜的关系,易得离轴反射镜上任意点坐标与母镜坐标的变换公式为

$$\begin{aligned} x_0 &= x \\ y_0 &= y + h \end{aligned} \quad (6)$$

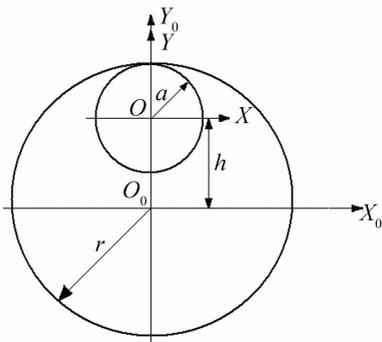


图 2 离轴非球面镜与母镜之间的几何关系
Fig. 2 Geometrical relationship of off-axis segment relative to parent mirror

式中 h 是离轴量,将式(6)代入式(5)中,得到离轴非球面产生的非球面波前

$$\Delta z = -\frac{K}{8R^3} [x^2 + (y+h)^2]^2 \quad (7)$$

将式(7)展开成 Zernike 多项式的形式^[9-10]

$$\Delta z = c_0^0 z_0^0 + c_1^1 z_1^1 + c_2^0 z_2^0 + c_2^2 z_2^2 + c_3^1 z_3^1 + c_4^0 z_4^0 \quad (8)$$

式中, $c_0^0 = -\frac{K(3h^4 + 6a^2h^2 + a^4)}{24R^3}$, $c_1^1 = -\frac{K(3ah^3 + 2a^3h)}{6R^3}$,

$c_2^0 = -\frac{K(4a^2h^2 + a^4)}{16R^3}$, $c_2^2 = \frac{Ka^2h^2}{4R^3}$, $c_3^1 = -\frac{Ka^3h}{6R^3}$, $c_4^0 =$

$-\frac{Ka^4}{48R^3}$, $z_0^0 = 1$, $z_1^1 = \rho \sin \theta$, $z_1^{-1} = \rho \cos \theta$, $z_2^0 = 2\rho^2 - 1$, $z_2^2 =$

$\rho^2 \cos 2\theta$, $z_2^{-2} = \rho^2 \sin 2\theta$, $z_3^1 = 3(\rho^2 - 2)\rho \sin \theta$, $z_3^{-1} =$

$3(\rho^2 - 2)\rho \cos \theta$, $z_4^0 = 6\rho^4 - 6\rho^2 + 1$. a 是离轴非球面镜的半口径, ρ 是归一化口径, $\rho^2 = x^2 + y^2$, $0 \leq \rho \leq 1$.

1.3 调整误差引入的波像差

首先讨论由平移误差 Δx 、 Δy 、 ΔR 引入的波像差,即引入 Δx 、 Δy 、 ΔR 后,被检反射镜产生的非球面波前与补偿器产生的补偿波前之间的偏离量

$$\Delta(\Delta z) = \frac{\partial(\Delta z)}{\partial x} \Delta x + \frac{\partial(\Delta z)}{\partial y} \Delta y + \frac{\partial(\Delta z)}{\partial R} \Delta R \quad (9)$$

由于是反射面,引入的波像差是波前偏离量的两倍,故调整误差 Δx 、 Δy 、 ΔR 引入的波像差

$$W_a = 2 \left(\frac{\partial(\Delta z)}{\partial x} \Delta x + \frac{\partial(\Delta z)}{\partial y} \Delta y + \frac{\partial(\Delta z)}{\partial R} \Delta R \right) \quad (10)$$

式(9)中

$$\begin{aligned} \frac{\partial(\Delta z)}{\partial x} &= \frac{1}{a} [c_4^0 (8z_3^{-1} + 4z_1^{-1} + c_3^1 (3z_2^{-2}) - \\ & c_2^2 (2z_1^{-1}) + c_2^0 (4z_1^{-1})] \end{aligned} \quad (11)$$

由于干涉测量得到的 Zernike 展开系数要扣除平移、倾斜和离焦因素,故式(11)改写成

$$\frac{\partial(\Delta z)}{\partial x} = \frac{1}{a} (8c_4^0 z_3^{-1} + 3c_3^1 z_2^{-2}) \quad (12)$$

同理

$$\frac{\partial(\Delta z)}{\partial y} = \frac{1}{a} (8c_4^0 z_3^1 + 3c_3^1 z_2^2) \quad (13)$$

$$\frac{\partial(\Delta z)}{\partial R} = -\frac{3}{R} (c_4^0 z_4^0 + c_3^1 z_3^1 + c_2^2 z_2^2)$$

将式(12)和(13)代入式(10),得

$$\begin{aligned} W_a &= 6 \left(\frac{\Delta y}{a} c_3^1 - \frac{\Delta R}{R} c_2^2 \right) z_2^2 + 6 \frac{\Delta x}{a} c_3^1 z_2^{-2} + \\ & 2 \left(8 \frac{\Delta y}{a} c_4^0 - \frac{3\Delta R}{R} c_3^1 \right) z_3^1 + \frac{16\Delta x}{a} c_4^0 z_3^{-1} - \frac{6\Delta R}{R} c_4^0 z_4^0 \end{aligned} \quad (14)$$

得到的波像差只是由平移误差引入的.从图 1 的被检镜和补偿器的相对位置可以看出 $\Delta y \approx R\theta_x$, 所以 Δy 和 θ_x 可以相互校正,同理 Δx 和 θ_y 也可以相互校正^[11].

2 模拟仿真

利用 ZEMAX 软件对一块圆口径椭球面离轴反射镜进行仿真.椭球面的顶点曲率半径 $R = 1\ 600\ \text{mm}$,二次曲面常数 $K = -0.966\ 324$,离轴量 $h = 166\ \text{mm}$,离轴反射镜的口径 $D = 192.5\ \text{mm}$.在 ZEMAX 软件中引入失调量 $\Delta x = 200\ \mu\text{m}$, $\Delta y = 100\ \mu\text{m}$, $\Delta R = -150\ \mu\text{m}$, $\theta_x = 0.005^\circ$, $\theta_y = -0.005^\circ$,将 ZEMAX 软件中得到的 Zernike 系数代入式(14)计算失调量.表 1 列出了仿真的结果.

表 1 仿真实验结果

Table 1 Experiment results

NO	Simulating value of misalignment		
	Δx	Δy	ΔR
1	11	-62	-100
2	6	-32	-50
3	3	-15	-2

图 3 是调整前后由调整误差引入的波像差图,图 3(a)是调整前的波像差为 $0.2332\lambda\text{RMS}$,经过调整后调整误差引入的波像差为 $0.0026\lambda\text{RMS}$.

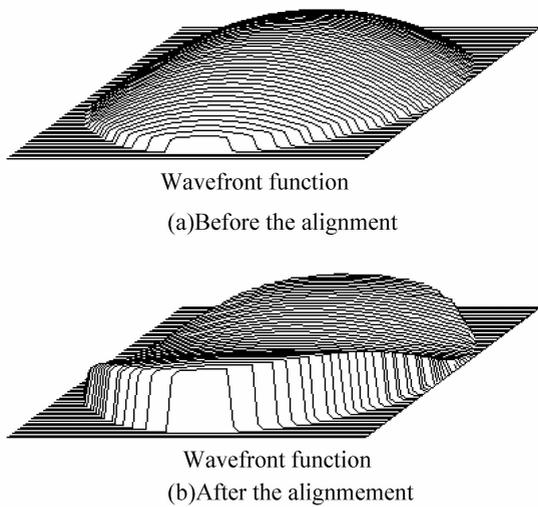


图3 调整前后由调整误差引入的波像差图

Fig. 3 Wavefront map before and after the alignment

3 结论

本文基于补偿器的补偿原理,通过分析该偏离量与调整误差的关系,建立误差分离的数学模型,该模型是计算机辅助装调的基础.仿真结果表明在离轴非球面反射镜补偿法检验中,采用本文的计算机辅助装调方法调整反射镜的位置,最终调整结果为 0.0026λ RMS.由仿真数据可知该计算机辅助装调算法收敛,调整准确度高.本文提出的调整误差分离原理不仅适用于二次非球面,也适用于高次非球面,具有较广的应用范围和较好的工程应用价值.

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Computer-aided Alignment of Off-axis Aspheric Mirrors in Null Testing

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Abstract: Based on the principle of null lens, a new method of error-separation was proposed in null testing. A mathematic model was developed to separate misalignment-induced aberration from the test result. The method was used in the simulations of an off-axis aspheric mirror. The wavefront aberration induced by misalignment is 0.0026λ RMS ($\lambda=632.8$ nm) after the alignment, compared with 0.2332λ RMS before the alignment, which reflects that this method has high accuracy and can improve the efficiency of the null test.

Key words: Asphere testing; Null corrector; Alignment error; Computer-aided alignment



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