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无光焦度校正器和单一反射镜组成的光学系统

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摘要： 从三级像差理论出发分析了由两透镜无光焦度校正器和单一反射镜组成的光学系统，讨论两透镜无光焦度校正器放置在单一反射镜前和后组成的光学系统的各种消像差条件。并给出求解两透镜无光焦度校正器参量的计算公式。

关键词： 几何光学；三级像差理论；无光焦度校正器；消像差条件

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1　三级像差理论

三级像差理论给出非球面单色像差的表示式为[1]

$$
\left.\begin{aligned}
S_1 &= \sum hP + \sum h^4 K,\\
S_2 &= \sum yP - \mathrm{J}\sum W + \sum h^3 yK,\\
S_3 &= \sum \frac{y^2}{h}P - 2\mathrm{J}\sum \frac{y}{h}W + \\
&\quad \mathrm{J}^2\sum \Phi + \sum h^2 y^2 K,\\
S_4 &= \sum (\Pi/h),\\
S_5 &= \sum \frac{y^3}{h^2}P - 3\mathrm{J}\sum \frac{y^2}{h^2}W + \\
&\quad \mathrm{J}^2\sum \frac{y}{h}(3\Phi + \Pi/h) - \\
&\quad \mathrm{J}^3\sum \frac{1}{h^2}\Delta\frac{1}{n^2} + \sum hy^3 K,\\
C_1 &= \sum \frac{h^2\Phi}{\nu},\\
C_2 &= \sum \frac{hy\Phi}{\nu}.
\end{aligned}\right\} \tag{1}
$$

其中

$$
P = \left[\frac{\Delta u}{\Delta(1/n)}\right]^2 \Delta\frac{u}{n},
$$

$$
W = \frac{\Delta u}{\Delta(1/n)}\Delta\frac{u}{n},\quad \Phi = \frac{1}{h}\Delta\frac{u}{n},
$$

$$
\Pi = \frac{\Delta nu}{nn'},\quad K = -\frac{e^2}{R_0^3}\Delta n,
$$

各表示式中 S_1 为球差系数，S_2 为彗差系数，S_3 为像散像差系数，S_4 为场曲（匹兹瓦和）像差系数，S_5 畸变像差系数，C_1 为轴上（纵向）色差系数，C_2 为倍率（横向）色差系数；J 为拉格朗日-亥姆霍兹不变量；h 为轴上光线在各面上的高度；通过光栏中心的光线 l_p 为主光线，y 为轴外主光线 l_p 在各面上的高度；n 和 n' 为光线经折射面折射或反射面反射前、后的折射率；u（物方孔径角）和 u'（像方孔径角）为光线经折射面折射或反射面反射前、后光线与光轴的交角；R 为面的曲率半径，R_0 为非球面顶点的曲率半径；e 为非球面的偏心率；ν 为阿贝数。

2　无光焦度校正器在单一反射镜前的各种消像差条件

无光焦度校正器如图 1 所示。

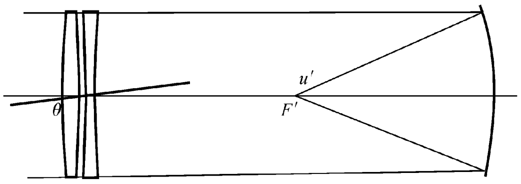

Fig. 1　Zero-power corrector is located in front of mirror

现在假定

1）物体位于无限远，即 $l_1 = \infty, u_1 = 0$；

2）光阑位于无光焦度校正器上，即 $x_1 = y_1 = 0$；

3）折射率 $n_1 = n'_2 = n_3 = n'_4 = n_5 = 1$，$n'_1 = n_2 = n'_3 = n_4 = n, n'_5 = -1$；

4）两透镜贴合，轴上光线在各面上的高度 $h_1 = h_2 = h_3 = h_4 = h_5 = h$。

当物体位于无限远时，令轴上高度 $h_1 = 1$，光学

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系统焦距 $f' = 1$，视场角 $\theta = -1$，无光焦度校正器与反射镜之间的距离为 $d_{45} = l_{p5}$，可得 $J = 1$，$u_1 = u'_4 = u_5 = 0$，$f'_5 = 1$，$R_{05} = -2f'_5 = -2$（反射镜顶点的曲率半径），$y'_5 = -1$，主光线在反射镜上的高度为 $y_5 = -\theta l_{p5} = l_{p5}$。按(1) 式求解反射镜的参量

$$\overrightarrow{P}_R = 1/4, \quad \overrightarrow{W}_R = 1/2, \quad \Pi_R = -1,$$

$$\Phi_R = 1, \quad K_R = -e^2/4.$$

由于无光焦度校正器是两块同样光学材料正负贴合薄透镜的组合，光焦度 $\varphi_1 + \varphi_2 = 0$，不存在色差 $C_1 = C_2 = 0$，所以本文不讨论色差问题。对于薄透镜而言[2,3]

$$\overrightarrow{P} = \overleftarrow{P}, \qquad \overrightarrow{W} = -\overleftarrow{W}.$$

上面的求解代入(1) 式，可得出光学系统的各种消像差的条件。

1) $S_1 = 0$

$$\left.\begin{aligned} S_1 &= \overrightarrow{P}_C + \frac{1}{4} - \frac{e^2}{4} = 0, \\ \overrightarrow{P}_C &= \frac{e^2 - 1}{4}. \end{aligned}\right\} \tag{2}$$

2) $S_2 = 0$

$$\left.\begin{aligned} S_2 &= \overrightarrow{W}_C + \frac{y_5}{4} - \frac{1}{2} - \frac{y_5 e^2}{4} = 0, \\ \overrightarrow{W}_C &= \frac{y_5(e^2 - 1)}{4} + \frac{1}{2}. \end{aligned}\right\} \tag{3}$$

3) $S_3 = 0$

$$\left.\begin{aligned} S_3 &= \frac{y_5^2}{4} - y_5 + 1 - \frac{y_5^2 e^2}{4} = 0, \\ e^2 &= 1 - \frac{4(y_5 - 1)}{y_5^2}. \end{aligned}\right\} \tag{4}$$

4) $S_4 \neq 0$

$$S_4 = \Pi_R = -1. \tag{5}$$

5) $S_5 = 0$

$$\left.\begin{aligned} S_5 &= \frac{y_5^3}{4} - \frac{3y_5^2}{2} + y_5(3 - 1) - \frac{y_5^2 e^2}{4} = 0, \\ e^2 &= 1 - \frac{6y_4 - 8}{y_5^2}. \end{aligned}\right\} \tag{6}$$

6) $S_1 = S_2 = 0$

$$\overrightarrow{P}_C = \frac{e^2 - 1}{4}, \quad \overrightarrow{W}_C = \frac{y_5(e^2 - 1)}{4} + \frac{1}{2}. \tag{7}$$

7) $S_1 = S_3 = 0$

$$\overrightarrow{P}_C = \frac{1 - y_5}{y_5^2}, \quad e^2 = \left(\frac{y_5 - 2}{y_5}\right)^2. \tag{8}$$

8) $S_1 = S_5 = 0$

$$\overrightarrow{P}_C = \frac{4 - 3y_5}{2y_5^2}, \quad e^2 = \frac{(y_5 - 2)(y_5 - 4)}{y_5^2}. \tag{9}$$

9) $S_1 = S_2 = S_3 = 0$

$$\left.\begin{aligned} \overrightarrow{P}_C &= (1 - y_5)/y_5^2, \\ \overrightarrow{W}_C &= (2 - y_5)/2y_5, \\ e^2 &= [(y_5 - 2)/y_5]^2. \end{aligned}\right\} \tag{10}$$

10) $S_1 = S_2 = S_5 = 0$

$$\left.\begin{aligned} \overrightarrow{P}_C &= (4 - 3y_5)/2y_5^2, \\ \overrightarrow{W}_C &= (2 - y_5)/y_5, \\ e^2 &= (y_5 - 2)(y_5 - 4)/y_5^2. \end{aligned}\right\} \tag{11}$$

11) $S_1 = S_3 = S_5 = 0$

$$P_C = -1/4, \quad y_5 = 2, \quad e^2 = 0, \tag{12}$$

12) $S_1 = S_2 = S_3 = S_5 =_0$

$$y_5 = 2, \quad e^2 = 0, \quad P_C = -1/4, \quad W_C = 0. \tag{13}$$

3　无光焦度校正器在单一反射镜后的各种消像差条件

如图 2 所示。

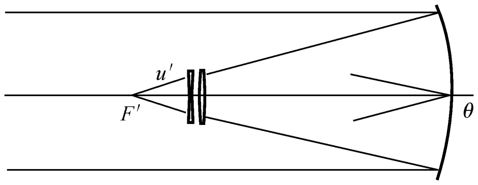

Fig. 2　Zero-power corrector is located in back of mirror

现在假定

1) 物体位于无限远，即 $l_1 = \infty$，$u_1 = 0$；

2) 光阑位于主镜上，即 $x_1 = y_1 = 0$；

3) 折射率 $n_1 = 1$，$n'_2 = n_3 = n'_4 = n_5 = n$，$n'_1 = n_2 = n'_3 = n_4 = n'_5 = -1$；

4) 物体位于无限远时，轴上光线在主反射镜上的高度为 h_1，无光焦度校正器的两透镜是贴合的，在无光焦度校正器上高度为 $h_2 = h_3 = h_4 = h_5$，遮栏比 $\alpha = h_2/h_1$。

当物体位于无限远时，令轴上光线的高度 $h_1 = 1$，光学系统焦距 $f' = 1$，视场角 $\theta = -1$，可得 $u_1 = 0$，$u_2 = u'_5 = -1$，$J = 1$，$f'_1 = 1$，$R_{01} = -2f'_1 = -2$，主光线 l_p 在无光焦度校正器上的高度 $y_2 = 1 - \alpha$。按公式(1.1) 求解反射镜的参量

$$\overleftarrow{P}_R = \overrightarrow{P}_R = \frac{1}{4}, \quad \overleftarrow{W}_R = \overrightarrow{W}_R = \frac{1}{2},$$

$$\Pi_R = -1, \quad \Phi_R = 1, \quad K_R = \frac{-e^2}{4}.$$

上面的求解代入(1) 式，可得出光学系统的各种消像差的条件。

1) $S_1 = 0$

$$\left.\begin{aligned} S_1 &= \frac{1}{4} - \frac{e^2}{4} + \alpha \vec{P}_{\mathrm{C}} = 0, \\ \vec{P}_{\mathrm{C}} &= \frac{e^2 - 1}{4\alpha}. \end{aligned}\right\} \tag{14}$$

2) $S_2 = 0$

$$\left.\begin{aligned} S_2 &= -\frac{1}{2} + (1-\alpha)\vec{P}_{\mathrm{C}} + \vec{W}_{\mathrm{C}} = 0, \\ \vec{P}_{\mathrm{C}} &= \frac{1 - 2\vec{W}_{\mathrm{C}}}{2(1-\alpha)}. \end{aligned}\right\} \tag{15}$$

3) $S_3 = 0$

$$\left.\begin{aligned} S_3 &= 1 + \frac{(1-\alpha)^2}{\alpha}\vec{P}_{\mathrm{C}} + 2\frac{(1-\alpha)}{\alpha}\vec{W}_{\mathrm{C}} = 0, \\ \vec{P}_{\mathrm{C}} &= -\frac{2(1-\alpha)\vec{W}_{\mathrm{C}} + \alpha}{(1-\alpha)^2}. \end{aligned}\right\} \tag{16}$$

4) $S_4 \neq 0$

$$S_4 = \Pi_{\mathrm{R}} = -1. \tag{17}$$

5) $S_5 = 0$

$$\left.\begin{aligned} S_5 &= \frac{(1-\alpha)^3}{\alpha^2}\vec{P}_{\mathrm{C}} + 3\frac{(1-\alpha)^2}{\alpha^2}\vec{W}_{\mathrm{C}} = 0, \\ \vec{P}_{\mathrm{C}} &= -\frac{3\vec{W}_{\mathrm{C}}}{1-\alpha}. \end{aligned}\right\} \tag{18}$$

6) $S_1 = S_2 = 0$

$$\left.\begin{aligned} \vec{P}_{\mathrm{C}} &= \frac{e^2 - 1}{4\alpha}, \\ \vec{W}_{\mathrm{C}} &= \frac{1}{2} - \frac{(1-\alpha)(e^2-1)}{4\alpha}. \end{aligned}\right\} \tag{19}$$

7) $S_1 = S_3 = 0$

$$\left.\begin{aligned} \vec{P}_{\mathrm{C}} &= \frac{e^2 - 1}{4\alpha}, \\ \vec{W}_{\mathrm{C}} &= -\frac{\alpha + (1-\alpha)^2\vec{P}_{\mathrm{C}}}{2(1-\alpha)}. \end{aligned}\right\} \tag{20}$$

8) $S_1 = S_5 = 0$

$$\left.\begin{aligned} \vec{P}_{\mathrm{C}} &= \frac{e^2 - 1}{4\alpha}, \\ \vec{W}_{\mathrm{C}} &= -\frac{(1-\alpha)(e^2-1)}{12\alpha}. \end{aligned}\right\} \tag{21}$$

9) $S_1 = S_2 = S_3 = 0$

$$\left.\begin{aligned} \vec{P}_{\mathrm{C}} &= \frac{1}{(1-\alpha)^2}, \\ e^2 &= 1 + \frac{4\alpha}{(1-\alpha)^2}, \\ \vec{W}_{\mathrm{C}} &= -\frac{1+\alpha}{2(1-\alpha)}. \end{aligned}\right\} \tag{22}$$

10) $S_1 = S_2 = S_5 = 0$

$$\left.\begin{aligned} \vec{P}_{\mathrm{C}} &= -\frac{3\alpha}{(1-\alpha)^2}, \\ e^2 &= 1 - \frac{12\alpha^2}{(1-\alpha)^2}, \\ \vec{W}_{\mathrm{C}} &= \frac{\alpha}{1-\alpha}. \end{aligned}\right\} \tag{23}$$

4　无光焦度校正器初始结构参量的求解方法

无光焦度校正器是由两个单透镜(一个正、一个负)组成的双贴合薄透镜,如图 3 所示[2]。

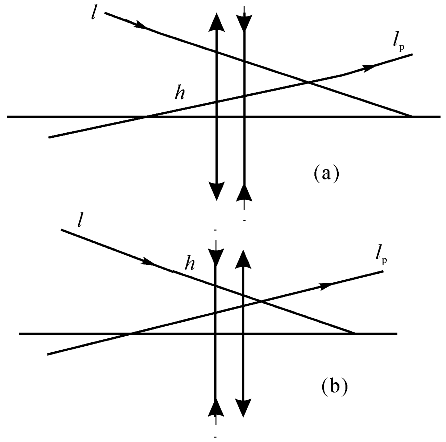

Fig. 3　Two lens zero focal power corrector. (a) First positive lens; (b) First negative lens

有两种不同的组合型式,一种为正透镜在前,图 3(a);另一种为负透镜在前,图 3(b)。选取同一种材料的光学玻璃,$n'_1 = n_2 = n'_3 = n_4 = n$;因为是无光焦度,$\varphi_1 = -\varphi_2 = \varphi$,$u_1 = u'_4$,一般情况的 P_{C}、W_{C} 与归一化条件的 P_{CN}、W_{CN} 的关系式为

$$P_{\mathrm{C}} = (h\varphi)^3 P_{\mathrm{CN}},\quad W_{\mathrm{C}} = (h\varphi)^2 W_{\mathrm{CN}},$$

归一化后的入射光孔径角为

$$\vec{\nu}_1 = \vec{u}_1 / h_1\varphi = 1/l_1\varphi.$$

如果 P_{C}、W_{C} 表示式中 u 用透镜的光焦度 φ 和曲率半径有关的参量 Q(简称透镜弯曲)来表示,就可以直接求解得到无光焦度校正器薄透镜的曲率半径,具体求解如下(详细求解见文献[2])

$$\left.\begin{aligned} &\vec{Q}_1 - \overleftarrow{Q}_2 = \vec{W}_{\mathrm{CN}}\left(\frac{n}{n+1}\right), \\ &\vec{Q}_1 + \overleftarrow{Q}_2 = \\ &\quad\left[\frac{\vec{P}_{\mathrm{CN}}}{\vec{W}_{\mathrm{CN}}} - \frac{3n}{(n+1)(n-1)} + 4\vec{\nu}_1\right]\left(\frac{n+1}{n+2}\right). \end{aligned}\right\} \tag{24}$$

按消像差条件求解无光焦度校正器双贴合薄透镜的 P_C、W_C，设定光焦度 φ，求解归一化条件的 P_{CN}、W_{CN}，再求解曲率半径有关的参量 Q 后，按下列计算顺序求解双贴合薄透镜各面的曲率半径

$$\left.\begin{aligned}
c_1 &= c_2 + \frac{1}{n-1} = \overrightarrow{Q}_1 + \frac{n}{n-1},\\
c_2 &= \overrightarrow{Q}_1 + 1,\\
c_3 &= -\overleftarrow{c} = -(\overleftarrow{Q}_2 + 1),\\
c_4 &= c_3 - \frac{1}{n-1},\\
r_1 &= \frac{1}{c_1\varphi_1} = \frac{1}{c_1\varphi},\\
r_2 &= \frac{1}{c_2\varphi_1} = \frac{1}{c_2\varphi},\\
r_3 &= \frac{1}{c_3\varphi_2} = -\frac{1}{c_3\varphi},\\
r_4 &= \frac{1}{c_4\varphi_2} = -\frac{1}{c_4\varphi}.
\end{aligned}\right\} \qquad (25)$$

结束语 本文分析了由两透镜无光焦度校正器和单一反射镜组成的光学系统，讨论了两透镜无光焦度校正器放置在单一反射镜前和后组成的光学系统的各种消像差条件；并给出求解两透镜无光焦度校正器参量的计算公式，通过这些公式可以求解光学系统的初始结构参量，由这些初始参量经过像差平衡就可以设计出满足使用要求的光学系统，这些公式为光学系统设计奠定了理论基础，经过具体的计算实例证实这些公式是正确的。

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Optical System with Two-Lens Zero Focal Power Corrector and Single Mirror

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Abstract： An optical system with two-lens zero focal power corrector and single reflector is discussed based on the third-order aberration theory. Non-aberration conditons of the system，in which two-lens zero focal power corrector are located in front and back of the reflector，is analyzed. At the same time，calculating fomula for solving the parameter of the two-lens zero focal power corrector is given.

Key words： geometrical optics；third-order aberration theory；zero focal power corrector；non-aberration conditions