光学系统设计技巧(续)

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ξ 4.11.3 实例

1. 例1. 设计35mm $10^{\times}$ 电影摄影物镜,其具体的技术要求为:

焦距:f'25 ~ 250,

相对孔径 D/f':1/3.2 ~ 1/22,

视场:35mm 电影摄影用胶片,尺寸16 ×22。

拍摄最近距离:2.5 米

设计步骤如下:

(1) 确定参数和选择型式

变焦距物镜的焦距、相对孔径和视场都是根据使用单位的要求提出来而确定下来的,本例的参数已确定。我们根据这些参数要求,选择合适的结构型式。根据焦距25 ~ 250mm $10^{\times}$ 的要求,倍数是中等的,相对孔径、视场都较大,而且摄影物镜对象质要求较高,因此我们选择机械补偿的结构型式,因为光学补偿达到 $10^{\times}$ 是困难的。根据国内外的设计情况,采用国内外普遍采用的型式四组元系统,正组补偿非物象交换原则。

(2) 分配焦距及间隔

取 $m_{2长} = -1.1^{\times}$, $f_2' = -1$, $f_3' = 1.3$, $d_{23长} = 0.5$,

长焦位置:

$$\because \frac{1}{l_2'} - \frac{1}{l_2} = \frac{1}{f_2'},\ \because m_{2长} = \frac{l_2'}{l_2},$$

$$\therefore \frac{1}{m_{2长}\cdot l_2} - \frac{1}{l_2} = \frac{1}{f_2'},\ \frac{1-m_{2长}}{m_{2长}l_2} = \frac{1}{f_2'},$$

$$l_2 = \frac{1-m_{2长}}{m_{2长}}f_2' = \frac{1-(-1.1)}{-1.1}(-1)$$

$= 1.909091$,

$$l_2' = m_2 l_2 = -2.1$$

$$l_3 = l_2' - d_{23长} = -2.1 - 0.5$$

$= -2.6$(见图4.110所示),

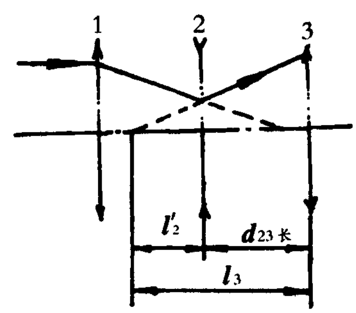

图 4.110

$$l_3' = \frac{l_3 f_3'}{f_3' + l_3} = \frac{(-2.6)\times 1.3}{1.3+(-2.6)} = 2.6$$

长焦的 $m_{2长}$ 取 $-1.1^{\times}$ 还是 $-1^{\times}$,还是 $-1.2^{\times}$,看取什么数有利于结构小,而象差容易校正,往大负数取接近物象交换原则,往小负数取远离物象交换原则。

短焦位置:

取 $m_{2短} = -0.26$,

$l_2 = \frac{1-m_2}{m_2}f_2' = \frac{1-(-0.26)}{-0.26} \times (-1)$

$= 4.84615,$

$l_2' = m_2 l_2 = -0.26 \times 4.84615 = -1.26,$

$q = l_{2短} - l_{2长} = 4.84615 - 1.909091$

$= 2.937059$(导程)

其图4.111所示的实线为短焦位置，虚线为长焦位置。

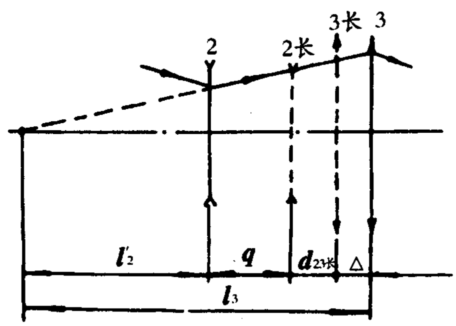

图4.111

$l_3 = l_2' - q - d_{23长} - \Delta$

$l_3 = -1.26 - 2.937059 - 0.5 - \Delta$

$= -4.697059 - \Delta$

$l_3' = l_{3长}' - \Delta = 2.6 - \Delta$

$\because \frac{1}{l_3'} - \frac{1}{l_3} = \frac{1}{f_3'}$

解上式得：

$\frac{1}{2.6-\Delta} + \frac{1}{4.697059+\Delta} = \frac{1}{1.3}$

$4.69706 \times 2.6 - 4.69706\Delta + 2.6\Delta - \Delta^2$

$= 1.3 \times 7.29706$

$\Delta^2 + 2.09706\Delta - 2.7262 = 0,$

$\Delta = \frac{-2.09706 \pm 3.91}{2}$，取绝对值小的根得到：

$\Delta = 0.9065$。

$\therefore l_3 = -4.69706 - 0.9065$

$= -5.60356$

$l_3' = 2.6 - \Delta = 1.6935,$

$\because m_{2长} = -1.1,\ m_{3长} = \frac{l_{3长}'}{l_{3长}} = \frac{2.6}{-2.6}$

$= -1$

$m_{2短} = -0.26,\ m_{3短} = \frac{l_{3短}'}{l_{3短}}$

$= \frac{1.6935}{-5.60356} = -0.3022186,$

$\Gamma = \frac{m_{2长} m_{3长}}{m_{2短} m_{3短}}$

$= \frac{(-1.1) \times (-1)}{(-0.26) \times (-0.3022186)}$

$= 13.999^{\times},$

得到的计算结果倍率太大，我们要求是$10^{\times}$，所以要重新取$m_{2短}$，直到总倍率Γ接近$10^{\times}$，而略大于$10^{\times}$。

重新计算短焦位置：

我们取$m_{2短} = -0.3$，进行计算，具体计算略，只列出计算结果：

$l_2 = \frac{1.3}{0.3} = 4.3333,$

$l_2' = -1.3$

$q = 4.3333 - 1.9091 = 2.4242,$

$l_3 = -5.0767,$

$l_3' = 1.7475,$

$m_{2长} = -1.1, m_{2短} = -0.3,$

$m_{3长} = -1, m_{3短} = \frac{1.7475}{-5.0767} = -0.344,$

得到$\Gamma = \frac{m_{2长} m_{3长}}{m_{2短} m_{3短}} = 10.65^{\times}$。

基本符合要求$10^{\times}$，略大于$10^{\times}$是合理的，因为理想系统变为实际系统往往由于间隔不够而使实际倍率降低，一般比实际要求倍率大$0.5^{\times}$左右是合适的。

求各组焦距：

取$d_{34短} = 0.4$（主要考虑3与4透镜组在短焦不相碰）

取 $d_{12短}=0$（主要考虑1与2透镜组在短焦位置不相碰），我们准备用复杂的前固定组，使主面往后移来实现 $d_{12短}=0$。

$$f_1' = l_{2短} + d_{12短} = 4.3333 + 0 = 4.3333,$$

$f_2' = -1$（前面取定的）

$f_3' = 1.3$（前面取定的）

我们取 $f_1' = 170$（或不取 f_1'，而由系统的总焦距〈长焦或短焦〉及取 m_4 值而求 f_1'，即按式 $F_{1234短} = f_1' m_{2短}\cdot m_{3短}\cdot m_4$，求出）。

$$f_2' = \frac{170}{4.3333}\times(-1) = -39.23,$$

$$f_3' = \frac{170}{4.3333}\times 1.3 = 51,$$

$$\because F_{1234短} = f_1' m_{2短}\cdot m_{3短}\cdot m_4 = F_{1234长}/\Gamma$$

$F_{1234长} = f_1' m_{2长}\cdot m_{3长}\cdot m_4 = 250$（∵ 我们要求长焦总焦距为250mm）

$$m_4 = \frac{250}{f_1' m_{2长}\cdot m_{3长}} = \frac{250}{170\times(-1.1)\times(-1)} = \frac{250}{187} = 1.3369$$

$$\because l_4 = l'_{3短} - d_{34短} = 1.7475 - 0.4 = 1.3475$$

$$l_4' = m_4 l_4 = 1.3475\times 1.3369 = 1.80147,$$

$$f_4' = \frac{l_4' l_4}{l_4 - l_4'} = \frac{1.80147\times 1.3475}{1.3475 - 1.80147} = -5.34723,$$

$$F_{1234短} = \frac{250}{10.65} = 23.474,$$

$$f'_{1234长} = 4.3333\times(-1.1)\times(-1)\times 1.3369 = 6.3725,$$

$$f'_{1234短} = \frac{6.3725}{10.65} = 0.5983568$$

$$M = \frac{250}{6.3725} = 39.23107 \quad \text{（缩放比）}$$

我们将上面的计算结果归纳如下：

$f_1' = 4.3333$	$f_1' = 170$
$f_2' = -1$ —缩放成实际值→	$f_2' = -39.23$
$f_3' = 1.3$	$f_3' = 51$,
$f_4' = -5.34723$	$f_4' = -209.777$
$\Delta = 0.8525$	$\Delta = 33.444$
$q = 2.4242$	$q = 95.104$
总长 $= q + \Delta + d_{34短} + l_4' + d_{23长} = 5.97817$	总长 $= 234.53$

短焦：

$d_{12} = 0$	$d_{12} = 0$
$d_{23} = q + \Delta + d_{23长} = 3.7767$	$d_{23} = 148.164$
$d_{34} = 0.4$	$d_{34} = 15.692$
$l_4' = 1.80147$	$l_4' = 70.6736$
	$F_{1234短} = 23.474$

长焦：

$d_{12} = q = 2.4242$	$d_{12} = 95.104$
$d_{23} = 0.5$	$d_{23} = 19.616$
$d_{34} = 0.4 + \Delta = 1.2525$	$d_{34} = 49.137$
$l_4' = 1.80147$	$l_4' = 70.6736$
	$F_{1234长} = 250$

(3) 求长、短焦的 h、h_p

短焦位置：

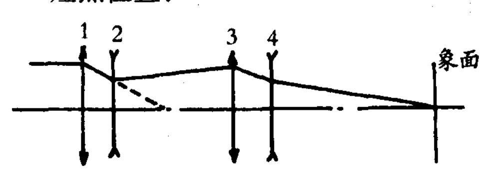

图 4.112

如图4.112所示是四组元的非物象交换原则的正组补偿系统。

求 h：

$\because h_1 = \frac{F_{1234短}}{2A} = \frac{23.474}{6.4}$

$h_1 = 3.6678$,

$u_1 = 0$

$\Delta u_1 = u_2 - u_1 = h_1\varphi_1 = 3.6678/170 = 0.02157529$,

$\therefore u_2 = h_1\varphi_1 + u_1 = 0.02157529$,

$\because h_2 = h_1 - d_{12}u_2 = 3.6678 - 0 \times 0.02157529 = 3.6678$,

$\Delta u_2 = u_3 - u_2 = h_2\varphi_2 = 3.6678 \div (-39.23) = -0.0934948$,

$\therefore u_3 = h_2\varphi_2 + u_2 = -0.0934948 + 0.02157529 = -0.0719195$

$\because h_3 = h_2 - d_{23}u_3 = 3.6678 - 148.164 \times (-0.0719195) = 14.3237$,

$\Delta u_3 = u_4 - u_3 = h_3\varphi_3 = 14.3237/51 = 0.280857$,

$\therefore u_4 = h_3\varphi_3 + u_3 = 0.2089375$,

$\because h_4 = h_3 - d_{34}u_4 = 14.3237 - 15.692 \times 0.2089375 = 11.0451$,

$\Delta u_4 = u_4' - u_4 = h_4\varphi_4 = 11.0451 \div (-209.777) = -0.0526516$,

$\because u_4' = h_4\varphi_4 + u_4 = -0.0526516 + 0.2089375 = 0.1562859$,

校对：$h_1/u_4' = 3.6678/0.1562859 = 23.468$（与 $F_{1234短} = 23.474$ 基本相符）

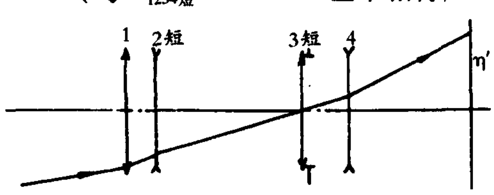

图 4.113

求 h_p：

已知：

$f_1' = 170$,

$f_2' = -39.23$,

$f_3' = 51$,

$f_4' = -209.777$, $d_{12} = 0$,

$d_{23} = 148.164$, $d_{34} = 15.692$,

$l_4' = 70.6736$, $F_{1234短} = 23.474$

我们先假定在补偿组 3 处在短焦位置处放置光栏，根据 η' 求出 h_{p4}。从图 4.114 中我们可以得出如下关系式：

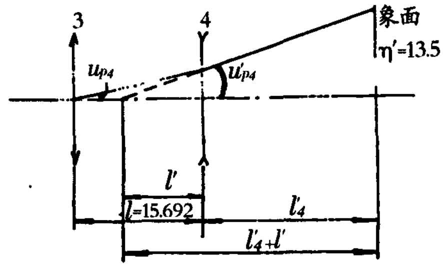

图 4.114

$$\because \frac{1}{l'} - \frac{1}{l} = \frac{1}{f'}$$

$$l' = \frac{lf'}{l+f'} = \frac{-15.692 \times (-209.777)}{-15.692 + (-209.777)}$$

$l' = -14.5998$

$$\because \frac{h_{p4}}{\eta'} = \frac{l'}{l' + l_4'}$$

$$h_{p4} = \frac{14.5998 \times 13.5}{14.5998 + 70.6736} = 2.311357,$$

$$\because u_{p4}' = \frac{\eta'}{l' + l_4'} = \frac{13.5}{85.2734} = 0.1583143,$$

$$\because u_{p4} = \frac{h_{p4}}{d_{34}} = \frac{2.311357}{15.692} = 0.14729525,$$

$\because h_{p3} = 0$

$\because \Delta u_{p3} = u_{p4} - u_{p3} = h_{p3}\varphi_3$,

$\therefore u_{p4} - u_{p3} = 0$,

$\therefore u_{p3} = u_{p4} = 0.14729525$,

$\because h_{p2} = u_{p3}d_{23} = 0.14729525 \times 148.164 = 21.82385$,

$\because \Delta u_{p2} = u_{p3} - u_{p2} = h_{p2}\varphi_2 = 21.82385/(-39.23) = -0.556305$,

$\therefore u_{p2} = 0.14729525 + 0.556305 = 0.7036$,

$\because h_{p1} = h_{p2} + u_{p2}d_{12} = h_{p2} = 21.82385$,

$\because \Delta u_{p1} = u_{p2} - u_{p1} = h_{p1}\varphi_1 = 21.82385/170 = 0.1283756$,

$\therefore u_{p1} = 0.7036 - 0.1283756 = 0.5752244$.

校对：$\eta' = u_{p1}F_{1234短} = 23.474 \times 0.5752244 = 13.5028$（与 $\eta' = 13.5$ 基本相符）

长焦位置：

同样方法求长焦位置的 h、h_p，这里我们不具体计算，只是在后面结果中列出计算结果。

(4) 中间插点

根据计算得到的长短焦位置的 h、h_p，看一下 h、h_p 是否太大，若外形尺寸可以，就继续计算中间几个点子，一般讲中间插上三个点子即可以，我们准备插上：

$$m_2 = \begin{cases} -0.79(\text{次长}) \\ -0.57(\text{中焦}) \\ -0.413(\text{次短}) \end{cases}$$

计算中焦位置：

焦距、间隔计算：

$m_2 = -0.57$

$$l_2 = \frac{1-m_2}{m_2}f'_2 = \frac{1-(-0.57)}{-0.57}(-1) = \frac{1.57}{0.57} = 2.754386,$$

$l'_2 = m_2 l_2 = (-0.57) \times 2.754386 = -1.57$,

$q = l_{2短} - l_2 = 4.3333 - 2.754386 = 1.578914$,

$\because l_3 = l'_2 - d_{23}$, $d_{23} = d_{23短} - q_1 - \Delta_1$,

$\therefore l_3 = l'_2 - d_{23短} + q_1 + \Delta_1 = -1.57 - 3.7767 + 1.578914 + \Delta_1 = -3.767786 + \Delta_1$

$l'_3 = l'_{3短} + \Delta_1 = 1.7475 + \Delta_1$

$\frac{1}{l'_3} - \frac{1}{l_3} = \frac{1}{f'_3} = \frac{1}{1.3}$，将上面两式代入此式得：

$$\frac{1}{1.7475+\Delta_1} - \frac{1}{3.7678+\Delta_1} = \frac{1}{1.3}$$

$\Delta_1^2 - 2.0203\Delta_1 + 0.5857 = 0$,

$$\Delta_1 = \frac{2.0203 \pm 1.319}{2}$$

$\Delta_1 = 0.35065$（另一根不合，因为 Δ_1 总是小于 Δ）

$\therefore l_3 = -3.767786 + 0.35065 = -3.417136$,

$l'_3 = 1.7475 + 0.35065 = 2.09815$,

$$m_3 = \frac{l'_3}{l_3} = \frac{2.09815}{-3.417136} = -0.614,$$

$d_{12} = f'_1 - l_2 = 4.3333 - 2.754386 = 1.5789$

$d_{23} = d_{23短} - q_1 - \Delta_1 = 3.7767 - 1.578914 - 0.35065 = 1.847136$,

$F_{1234中} = f'_1 m_{2中} \cdot m_{3中} \cdot m_4 = 4.3333(-0.57)(-0.614)(1.3369) = 2.0275$,

归纳如下：	实际值
$l_3 = -3.417136$,	$l_3 = 134.058$,
$l'_3 = 2.09815$,	$l'_3 = 82.313$,
$\Delta_1 = 0.35065$,	$\Delta_1 = 13.756$,
$d_{12} = 1.5789$,	$d_{12} = 61.942$,

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$d_{23} = 1.847136$，　$d_{23} = 72.465$，

$d_{34} = 0.75065$，　$d_{34} = 29.4488$，

$F_{1234中} = 2.0275$　$F_{1234中} = 79.541$.

h、h_p 的计算：

求 h：

$$h_1 = \frac{F_{1234中}}{2A} = \frac{79.541}{6.4} = 12.4283,$$

$u_1 = 0$，

$\triangle u_1 = u_2 - u_1 = h_1\varphi_1 = 12.4283/170 = 0.07310765$

$u_2 = 0.07310765$

$h_2 = h_1 - d_{12}u_2 = 12.4283 - 61.942 \times 0.07310765 = 7.900$，

$\triangle u_2 = u_3 - u_2 = h_2\varphi_2 = 7.9 \div (-39.23) = -0.2013765$，

$u_3 = -0.12826885$

$h_3 = h_2 - d_{23}u_3 = 7.9 - 72.465 \times (-0.12826885) = 17.195$

$\triangle u_3 = u_4 - u_3 = h_3\varphi_3 = 17.195/51 = 0.3371569$，

$u_4 = 0.3371569 - 0.12826885 = 0.20888805$，

$h_4 = h_3 - d_{34}u_4 = 17.195 - 29.4488 \times 0.20888805 = 11.0435$，

$\triangle u_4 = u_4' - u_4 = h_4\varphi_4 = 11.0435 \div (-209.777) = -0.052644$，

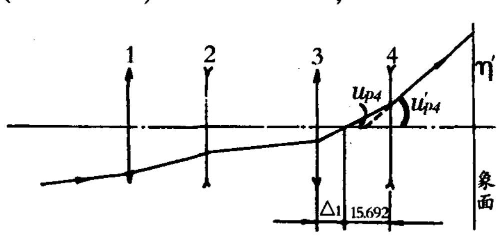

图 4.115

$u_4' = 0.20888805 - 0.052644 = 0.15624405$，

校对：$h_1/u_4' = \dfrac{12.4283}{0.15624405} = 79.544$（与 $F_{1234中}$ 相符）

求 h_p：

$\because u_{p4}' = 0.1583143$，

$u_{p4} = 0.14729525$

（在变倍过程中 u_{p4}、u_{p4}' 是不变的）。

$h_{p4} = 15.692 \times u_{p4} = 15.692 \times 0.14729525 = 2.31135$，

$h_{p3} = \triangle_1 \times u_{p4} = 13.756 \times 0.14729525 = 2.0262$，

$\triangle u_{p3} = u_{p4} - u_{p3} = h_{p3}\varphi_3 = 2.0262/51 = 0.0397294$，

$u_{p3} = 0.14729525 - 0.0397294 = 0.107565846$，

$h_{p2} = h_{p3} + u_{p3}d_{23} = 0.107565846 \times 72.465 + 2.0262 = 9.82096$，

$\triangle u_{p2} = u_{p3} - u_{p2} = h_{p2}\varphi_2 = 9.82096 \div (-39.23) = -0.2503431$，

$u_{p2} = 0.107565846 + 0.2503431 = 0.357808946$，

$h_{p1} = h_{p2} + u_{p2}d_{12} = 9.82096 + 0.357808946 \times 61.942 = 31.98436$，

$\triangle u_{p1} = u_{p2} - u_{p1} = h_{p1}\varphi_1 = 31.98436/170 = 0.1881433$，

校对：$\eta' = u_{p1}F_{1234中} = 0.169665646 \times 79.541 = 13.4954$（与 $\eta' = 13.5$ 相符）

同样的方法可计算次短焦、次长焦位置的间隔、h、h_p，这里不重复计算，只列出结果。

将计算的 h、h_p、u 归纳如下：

短焦：

$$\begin{cases} h_1 = 3.68 \\ h_2 = 3.68 \\ h_3 = 14.35 \\ h_4 = 11.04 \end{cases} \qquad \begin{cases} h_{p1} = 21.8 \\ h_{p2} = 21.8 \\ h_{p3} = 0 \\ h_{p4} = -2.31 \end{cases}$$

$$\begin{cases} u_1 = 0 \\ u_2 = 0.0216 \\ u_3 = -0.072 \\ u_4 = 0.2088 \end{cases} \qquad \begin{cases} \bar{u}_1 = 0 \\ \bar{u}_2 = -0.230682 \\ \bar{u}_3 = -0.25639 \\ \bar{u}_4 = -3.98169 \end{cases}$$

次短：

$$\begin{cases} h_1 = 6.719 \\ h_2 = 5.325 \\ h_3 = 15.577 \\ h_4 = 11.04 \end{cases} \qquad \begin{cases} h_{p1} = 32.502 \\ h_{p2} = 14.718 \\ h_{p3} = 0.909 \\ h_{p4} = -2.31 \end{cases}$$

$$\begin{cases} u_1 = 0 \\ u_2 = 0.0395 \\ u_3 = -0.096 \\ u_4 = 0.2088 \end{cases} \qquad \begin{cases} \bar{u}_1 = 0 \\ \bar{u}_2 = -0.29152 \\ \bar{u}_3 = -0.31493 \\ \bar{u}_4 = -3.98169 \end{cases}$$

中焦：

$$\begin{cases} h_1 = 12.4283 \\ h_2 = 7.9 \\ h_3 = 17.195 \\ h_4 = 11.043 \end{cases} \qquad \begin{cases} h_{p1} = 31.984 \\ h_{p2} = 9.8209 \\ h_{p3} = 2.0262 \\ h_{p4} = -2.31 \end{cases}$$

$$\begin{cases} u_1 = 0 \\ u_2 = 0.0731 \\ u_3 = -0.1282 \\ u_4 = 0.2088 \end{cases} \qquad \begin{cases} \bar{u}_1 = 0 \\ \bar{u}_2 = -0.36365 \\ \bar{u}_3 = -0.38099 \\ \bar{u}_4 = -3.98169 \end{cases}$$

次长：

$$\begin{cases} h_1 = 23.1 \\ h_2 = 12.1 \\ h_3 = 19.42 \\ h_4 = 11.04 \end{cases} \qquad \begin{cases} h_{p1} = 27.18 \\ h_{p2} = 6.86 \\ h_{p3} = 3.62 \\ h_{p4} = -2.31 \end{cases}$$

$$\begin{cases} u_1 = 0 \\ u_2 = 0.136 \\ u_3 = -0.172 \\ u_4 = 0.2088 \end{cases} \qquad \begin{cases} \bar{u}_1 = 0 \\ \bar{u}_2 = -0.44173 \\ \bar{u}_3 = -0.4525 \\ \bar{u}_4 = -3.98169 \end{cases}$$

长焦：

$$\begin{cases} h_1 = 39.1 \\ h_2 = 17.23 \\ h_3 = 21.325 \\ h_4 = 11.04 \end{cases} \qquad \begin{cases} h_{p1} = 25.093 \\ h_{p2} = 5.913 \\ h_{p3} = 4.913 \\ h_{p4} = -2.31 \end{cases}$$

$$\begin{cases} u_1 = 0 \\ u_2 = 0.23 \\ u_3 = -0.2084 \\ u_4 = 0.2088 \end{cases} \qquad \begin{cases} \bar{u}_1 = 0 \\ \bar{u}_2 = -0.52463 \\ \bar{u}_3 = -0.49939 \\ \bar{u}_4 = -3.98169 \end{cases}$$

$$\bar{u}_i = \frac{u_i}{h_i \varphi_i}$$

根据象差系数 $S_{\mathrm{I}} \sim S_{\mathrm{V}}$ 与 $\bar{P}$、$\bar{W}$ 的关系我们专门编一个程序，在电子计算机上进行计算，从而确定每一透镜组的 $\bar{P}$、$\bar{W}$。程序输入的数据为：

① $J = n'u'\eta' = 1 \times 0.156244 \times (-13.5) = -2.109294$，

② $\mu = 0.6$，

③ $B = 0.84$，

④ $c = 0.14$，

⑤ $M = 5$（要求 5 个位置即长、次长、中焦、次短、短焦等校正象差），

⑥ $K = 4$（透镜组数，即前固定组、变倍组、补偿组、后固定组），

⑦ φ（$1 \sim K$ 即 $1 \sim 4$，也就是前固定组、变倍组、补偿组、后固定组各组的光焦度）$= 0.005882$；-0.025445；0.019569；-0.004750，

⑧ h（共 20 个，即短焦 4 个、次短 4 个、中焦 4 个、次长 4 个、长焦 4 个），

⑨ h_p（共 20 个即与 ⑧ 相同），

⑩ 规化 $\bar{u}$（共 20 个即与 ⑧ 相同），

⑪ 校正象差的权（4 个 1，即有 $S_{\mathrm{I}} \sim S_{\mathrm{V}}$ 四种象差的权填 1）

⑫ S_i 目标值（S_{I} 5 个，S_{II} 5 个，S_{III} 5 个，

S_V5 个）共填 20 个零。

⑬ IP、IW 的权（4 个 IP 的权，4 个 IW 的权）共填 8 个零。

根据计算得出的各透镜组的 IP、IW，接下去进行 IP、IW 分配；选玻璃求半径等等，这里不详述，因为前面已经讲清楚了。

2. 例 2. 设计 35mm 电影摄影用的 $3^{\times}$ 变焦距物镜，其具体技术指标为：

焦距：25 ~ 75mm，

相对孔径 D/f'：1/2.8 ~ 1/22，

视场 2ω：57° ~ 19.3°（即底片尺寸 16 × 22）

最近距离：1.5 米。

（1）确定参数和选择型式

本例的参数已确定（指焦距、倍率、相对孔径、视场等），接下来是选择型式，选用三组元机械补偿，用 2、3 两组元运动来达到变焦目的，用前组 1 来调焦（是整组还是部分调焦根据具体情况而定），把光栏放于后组 3 上，在变焦过程中光栏作相应的小量变化，以保证孔径之不变，第 2 组元为变倍组作线性运动，第 3 组元为补偿组作非线性运动。关于倍率的选段问题，我们取正组补偿物象交换原则。

（2）分配焦距及间隔

取 $f_2' = -1$，$f_3' = 1.08$，

因为是 3 倍，且根据正组补偿物象交换原则，

$$\therefore\ m_{2短} = -\frac{1}{\sqrt{3}} = -0.5774,$$

$$m_{2长} = -\sqrt{3} = -1.732,$$

长焦位置：

$$l_2 = \frac{1-m_2}{m_2}f_2' = \frac{1+1.732}{-1.732}(-1)$$

$$= \frac{2.732}{1.732} = 1.57736721$$

$$l_2' = m_2 l_2 = -1.732 \times 1.57736721 = -2.732,$$

取 $d_{23长} = 0.738$，

$$l_3 = l_2' - d_{23长} = -2.732 - 0.738 = -3.470,$$

$$l_3' = \frac{l_3 f_3'}{l_3 + f_3'} = \frac{(-3.47)\times 1.08}{-3.47+1.08} = 1.56803347,$$

$$m_{3长} = \frac{l_3'}{l_3} = \frac{1.56803347}{-3.470} = -0.45188284,$$

$$m_{2长}\cdot m_{3长} = (-1.732)\times(-0.45188284) = 0.78266108$$

短焦位置：

$$m_{2短} = -0.5774,$$

$$l_2 = \frac{1-m_2}{m_2}f_2' = \frac{1+0.5774}{-0.5774}(-1) = 2.73190162,$$

$$l_2' = m_2 l_2 = (-0.5774)\times 2.73190162 = -1.5774,$$

$$q = l_{2短} - l_{2长} = 2.73190162 - 1.577367205 = 1.154534415,$$

$$l_3 = l_2' - q - \Delta - d_{23长} = -1.5774 - 1.154534415 - 0.738 - \Delta,$$

$$l_3 = -3.469937715 - \Delta,$$

$$l_3' = l_{3长} - \Delta = 1.56803347 - \Delta,$$

$$\frac{1}{l_3'} - \frac{1}{l_3} = \frac{1}{f_3'}$$

将 l_3 和 l_3' 代入上式得：

$$\Delta = \frac{-1.901900945 \pm 1.90186727}{2},$$

取较小值得：

$\triangle = -0.000016838$,

$l_3 = -3.469934415 + 0.000016838 = -3.46991758$,

$l_3' = 1.56803347 + 0.000016838 = 1.56805031$,

$$m_{3短} = \frac{l_3'}{l_3} = \frac{1.56805031}{-3.46991758} = -0.45189843,$$

$m_{2短} \cdot m_{3短} = (-0.5774) \times (-0.45189843) = 0.26092615$,

$$\Gamma = \frac{m_{2长} \cdot m_{3长}}{m_{2短} \cdot m_{3短}} = \frac{0.78266108}{0.26092615} = 2.99955 \doteq 3^{\times}$$（说明计算无误），

取 $d_{12短} = 0.3$，

$\therefore f_1' = l_{2短} + d_{12短} = 2.73190162 + 0.3 = 3.03190162$,

$f_{短}' = f_1' m_{2短} \cdot m_{3短} = 3.03190162 \times 0.26092615 = 0.791102417$,

$f_{长}' = f_1' m_{2长} \cdot m_{3长} = 3.03190162 \times 0.78266108 = 2.372951396$,

取 $F_{短}' = 25$（实例要求的短焦距值）

$$M = \frac{F_{短}'}{f_{短}'} = \frac{25}{0.791102417} = 31.6014708$$（缩放比）

计算总长：

$$L = (d_{12短} + d_{23长} + q + \triangle + l_{3短}')M = (0.3 + 0.738 + 1.154534415 - 0.000016838 + 1.56805031) \times 31.6014708 = 118.84$$

实际情况要考虑两主面的间距，估计还要略长一些。

将焦距归纳如下：

$f_1' = 3.03190162 \xrightarrow{\times M}$ 实际值：$f_1' = 95.81255051$

$f_2' = -1$ $\quad f_2' = -31.6014708$

$f_3' = 1.08$ $\quad f_3' = 34.12958846$

归纳长、短焦各数据：

长焦：

$l_3 = -3.47 \xrightarrow{\times M}$ 实际值：$l_3 = -109.65710368$

$l_3' = 1.56803347$	$l_3' = 49.55216392$
$\triangle = 0.000016838$	$\triangle = 0.00053211$
$d_{12} = 1.454534415$	$d_{12} = 45.96542684$
$d_{23} = 0.738$	$d_{23} = 23.32188545$
$f_{长}' = 2.372951396$	$f_{长}' = 74.98875425$
$q = 1.154534415$	$q = 36.48498560$

短焦：

$l_3 = -3.46991758 \xrightarrow{\times M}$ 实际值：$l_3 = -109.65449908$

$l_3' = 1.56805031$	$l_3' = 49.55269608$
$\triangle = 0$	$\triangle = 0$
$d_{12} = 0.3$	$d_{12} = 9.48044124$
$d_{23} = d_{23长} + q + \triangle = 1.889251758$	$d_{23} = 59.80633904$
$f_{短}' = 0.791102417$	$f_{短}' = 25$
$q = 0$	$q = 0$

中间插点：

我们准备中间插三个点，即为：

$$m_2 = \begin{cases} -1.3（次长焦） \\ -1（中焦） \\ -0.75（次短焦） \end{cases}$$

次长位置：

$m_2 = -1.3$

$$l_2 = \frac{1 - m_2}{m_2} f_2' = \frac{1 - (-1.3)}{-1.3}(-1) = 1.76923077,$$

$l_2' = m_2 l_2 = -1.3 \times 1.76923077 = -2.3$

$q_1 = l_{2短} - l_2 = 2.73190162 - 1.76923077 = 0.96267085$,

如图 4.116 所示可得 l_3：

$l_3 = l_2' - d_{23} = l_2' - (d_{23短} - q_1 - \triangle_1)$

$= -2.3 - (1.89251758 - 0.96267085 - \triangle_1)$

$l_3 = -3.22984673 + \triangle_1$

$l_3' = l_{3短}' + \triangle_1$,

又 $\because \frac{1}{l_3'} - \frac{1}{l_3} = \frac{1}{f_3'} = \frac{1}{1.08}$,将 l_3 和 l_3' 代入上式得:

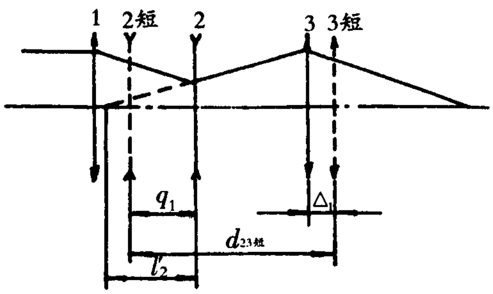

图 4.116

$\triangle_1 = \frac{1.66179642 \pm 1.51423}{2}$,取较小值得:

$\triangle_1 = 0.07378321$,

$l_3 = -3.15606352$,

$l_3' = 1.64183352$,

$m_3 = \frac{l_3'}{l_3} = -0.52021561$,

$m_2 m_3 = (-1.3) \times (-0.52021561) = 0.67628029$,

$d_{12} = f_1' - l_2 = 3.03190162 - 1.76923077 = 1.26267085$,

$d_{23} = d_{23短} - q_1 - \triangle_1 = 1.89251758 - 0.96267085 - 0.07378321$,

$d_{23} = 0.85606352$,

$f_{次长}' = f_1' m_2 m_3 = 3.03190162 \times 0.67628029 = 2.05041531$,

$F_{次长}' = f_{次长}' \times M = 64.79613955$,

将数据归纳如下:

$l_3 = -3.15606352 \xrightarrow{\times M}$ 实际值:$l_3 = -99.73624917$

$l_3' = 1.64183352$	$l_3' = 51.88435404$
$\triangle_1 = 0.07378321$	$\triangle_1 = 2.33165796$
$d_{12} = 1.26267085$	$d_{12} = 39.90225599$
$d_{23} = 0.85606352$	$d_{23} = 27.05286633$
$f_{次长}' = 2.05041531$	$F_{次长}' = 64.79613955$
$q_1 = 0.96267085$	$q_1 = 30.42181476$

用同样的方法求出中焦、次短两位置的数据,现将数据列于下:

中焦位置($m = -1$):

$l_3 = -3.05939543 \xrightarrow{\times M}$ 实际值:$l_3 = -96.68139535$

$l_3' = 1.66927084$	$l_3' = 52.75141371$
$\triangle_1 = 0.10122053$	$\triangle_1 = 3.19871762$
$d_{12} = 1.03190162$	$d_{12} = 32.60960891$
$d_{23} = 1.05939543$	$d_{23} = 33.47845375$
$f_{中焦}' = 1.65426963$	$f_{中焦}' = 52.27735341$
$q_1 = 0.73190162$	$q_1 = 23.12916767$

次短位置($m_2 = -0.75$):

$l_3 = -3.17533423 \xrightarrow{\times M}$ 实际值:$l_3 = -100.34523195$

$l_3' = 1.63666537$	$l_3' = 51.72103290$
$\triangle_1 = 0.06861506$	$\triangle_1 = 2.16833682$
$d_{12} = 0.69856829$	$d_{12} = 22.07578542$
$d_{23} = 1.42533423$	$d_{23} = 45.04265805$
$f_{次短}' = 1.17205182$	$f_{次短}' = 37.038561366$
$q_1 = 0.39856829$	$q_1 = 12.59534418$

(3) 计算 h 和 h_p

A、计算 h

长焦位置:

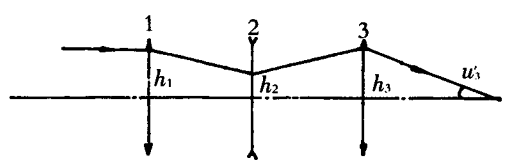

图 4.117

$$h_1=\frac{F'_{长}}{2A}=\frac{74.98875425}{2\times 2.8}=13.39084897,$$

$u_1=0$

$$\triangle u_1=u_2-u_1=h_1\varphi_1=\frac{13.39084897}{95.81255051}$$

$=0.13976091,$

$u_2=0.13976091,$

$h_2=h_1-d_{12}u_2=13.39084897-45.96542684\times 0.13976091,$

$h_2=6.96667909,$

$\triangle u_2=u_3-u_2=h_2\varphi_2$

$=6.96667909/(-31.6014708)$

$=-0.2204542,$

$u_3=-0.22045427+0.13976091$

$=-0.08069336,$

$h_3=h_2-d_{23}u_{23}=6.96667909+23.32188545\times 0.08069336,$

$h_3=8.84860039,$

$\triangle u_3=u'_3-u_3=h_3\varphi_3$

$=8.84860039/34.12958846$

$=0.25926478,$

$u'_3=0.25926478-0.08069336$

$=0.17857142,$

校对：$h_1/u'_3=74.9887578$（与 $F'_{长}=74.98875425$ 相符。）用同样的方法求出次长、中焦、次短、短焦的 h 值。

B、计算 h_p

长焦位置：

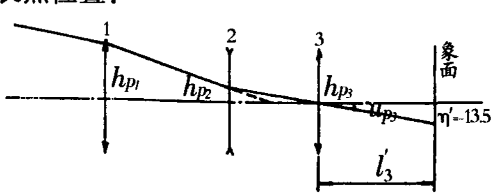

图 4.118

我们设光栏放置于第 3 透镜组上，所以 $h_{p3}=0$，

$$u'_{p3}=\frac{\eta'}{l'_3}=\frac{13.5}{49.55216392}$$

$=0.27244017,$

$u_{p3}=u'_{p3}=0.27244017,$

$h_{p2}=d_{23}u_{p3}=23.32188545\times 0.27244017=6.35381844,$

$\triangle u_{p2}=u_{p3}-u_{p2}=h_{p2}\varphi_2$

$=6.35381844/(-31.6014708)$

$=-0.20106085,$

$u_{p2}=0.27244017-(-0.20106085)$

$=0.47350102,$

$h_{p1}=h_{p2}+u_{p2}d_{12}=6.35381844+0.47350102\times 45.96542684,$

$h_{p1}=28.11849493,$

$\triangle u_{p1}=u_{p2}-u_{p1}=h_{p1}\varphi_1=28.11849493/95.81255051=0.29347403,$

$u_{p1}=0.47350102-0.29347403$

$=0.18002699,$

校对：$\eta'=u_{p1}F'_{长}=13.49999971$（与 $\eta'=13.5$ 相符。）

用同样的方法可以计算出次长、中焦、次短、短焦的 h_p 值。

（4）计算规化 $|u$

根据上面计算得到的各透镜组的 u 值，按如下公式进行规化：

$$|u_i=\frac{u_i}{h_i\varphi_i},$$

具体的数据在后面列出。

（5）计算 φ_i 值

$$\varphi_1=\frac{1}{95.81255051}=0.010437046,$$

$$\varphi_2=\frac{1}{-31.6014708}$$

$= -0.031644097$,

$\varphi_3 = \dfrac{1}{34.12958846} = 0.02930009$,

(6) 计算 J

$J = n'u'\eta' = 1 \times 0.17857143 \times (-13.5) = -2.41071431$,

到此,上机计算 $\mathbb{P}$、$\mathbb{W}$ 的数据已经准备完,现将上机计算的初始数据列于下(按上机程序要求的次序):

① $J = -2.41071431$

② $\mu = 0.6$

③ $B = 0.84$

④ $c = 0.14$

⑤ $M = 5$(五个焦距位置校正象差)

⑥ $K = 3$(三个透镜组参加校正象差)

⑦ φ: $\varphi_1 = 0.010437046$; $\varphi_2 = -0.031644097$; $\varphi_3 = 0.02930009$

⑧ h(长焦、次长、中焦、次短、短焦共五个焦距位置,15 个 h 值。列于下表。)

⑨ h_p(长焦、次长、中焦、次短、短焦共五个焦距位置,15 个 h 值。列于下表。)

⑩ $\mathbb{u}$(长焦、次长、中焦、次短、短焦共五个焦距位置,15 个 $\mathbb{u}$ 值。列于下表。)

	⑧ h	⑨ h_p	⑩ $\mathbb{u}$
长焦	$h_1 = 13.39084897$	$h_{p1} = 28.11849493$	$\mathbb{u}_1 = 0$
	$h_2 = 6.96667909$	$h_{p2} = 6.35381844$	$\mathbb{u}_2 = -0.63396781$
	$h_3 = 8.84860039$	$h_{p3} = 0$	$\mathbb{u}_3 = -0.31123918$
次长	$h_1 = 11.57073920$	$h_{p1} = 26.30925755$	$\mathbb{u}_1 = 0$
	$h_2 = 6.75196959$	$h_{p2} = 7.03899472$	$\mathbb{u}_2 = -0.56521741$
	$h_3 = 9.26506292$	$h_{p3} = 0$	$\mathbb{u}_3 = -0.34219843$
中焦	$h_1 = 9.33524168$	$h_{p1} = 25.75411911$	$\mathbb{u}_1 = 0$
	$h_2 = 6.15801085$	$h_{p2} = 8.56771583$	$\mathbb{u}_2 = -0.50000002$
	$h_3 = 9.41989494$	$h_{p3} = 0$	$\mathbb{u}_3 = -0.35301091$
次短	$h_1 = 6.61402881$	$h_{p1} = 25.73192083$	$\mathbb{u}_1 = 0$
	$h_2 = 5.09011703$	$h_{p2} = 11.75683957$	$\mathbb{u}_2 = -0.42856749$
	$h_3 = 9.23589913$	$h_{p3} = 0$	$\mathbb{u}_3 = -0.34012169$
短焦	$h_1 = 4.46428571$	$h_{p1} = 23.76434140$	$\mathbb{u}_1 = 0$
	$h_2 = 4.02255441$	$h_{p2} = 16.29347394$	$\mathbb{u}_2 = -0.36604543$
	$h_3 = 8.84869512$	$h_{p3} = 0$	$\mathbb{u}_3 = -0.31124657$

⑪ 校正象差的权,一般填写 4 个 1。

⑫ $S_{\mathrm{I}} \sim S_{\mathrm{V}}$ 的目标值,填写 20 个零(长焦至短焦共有五个焦距位置,每个焦距位置从 S_{I} 至 S_{V} 共有四种象差系数,所以共有 20 个目标值)。

⑬ $\mathbb{P}$、$\mathbb{W}$ 的权,填写 6 个零(三个 $\mathbb{P}$ 的权,三个 $\mathbb{W}$ 的权)。

经过上机计算,平衡后认为满意的一

组数据列于下：

$|P_1^\infty = 0.415346, |W_1^\infty = 0.105478,$

$|P_2^\infty = 0.316504, |W_2^\infty = 1.3550007,$

$|P_3^\infty = 0.126954, |W_3^\infty = 0.748264,$

焦距位置 / 象差系数	长焦	次长	中焦	次短	短焦
S_{I}	0.061377	0.052059	0.031479	0.006148	-0.007024
S_{II}	0.046903	0.042886	0.039678	0.035381	0.032244
S_{III}	0.121677	0.141491	0.176057	0.231194	0.286379
S_{V}	0.020404	-0.015098	-0.055529	-0.119069	-0.261443

总的要求是 $|P^\infty$、$|W^\infty$ 值较小，而且尽量使求得的半径较大。$S_{\mathrm{I}} \sim S_{\mathrm{V}}$ 的各值较小，另则使各象差系数随焦距变化而变动的范围较小。

(7) 分配 $|P$、$|W$

计算变倍组：

要求 $|P_2^\infty = 0.3165, |W_2^\infty = 1.355,$ 我们准备采用如图 4.119 所示的形式。我们取

$\varphi_1 = 0.6, \varphi_2 = 0.85,$

$\varphi_3 = -0.45, (\because \varphi_{变倍} = 1)$

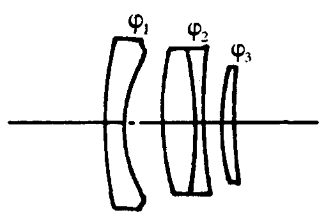

图 4.119

取第 1 块透镜材料为 LaK_6：$n = 1.69338$，$\nu = 53.4$，取第 3 块透镜材料为 ZF_6：$n = 1.75500, \nu = 27.5$，

(i) 求单透镜的 $|P_1^\infty$、$|W_1^\infty$、$|P_3^\infty$、$|W_3^\infty$

第一透镜：

取 $r_{1实} = 180.30, \because r_1 = \frac{1}{|c_1}$,

$$r_{1实} = \frac{f'_{变倍}}{|c_1\varphi_1}$$

$$c_1 = \frac{f'_{变倍}}{r_{1实}\varphi_1} = \frac{-31.6014708}{180.30 \times 0.6}$$

$= -0.292119$

$$|Q = |c_2 - 1 = |c_1 - \frac{n}{n-1} = -0.292119$$

$$-\frac{1.69338}{1.69338-1} = -2.734329,$$

$$|c_2 = |Q + 1 = -2.734329 + 1$$

$= -1.734329,$

$$r_{2实} = \frac{f'_{变倍}}{|c_2\varphi_1} = \frac{-31.6014708}{-1.734329 \times 0.6}$$

$= 30.369,$

$$|W_1^\infty = -\frac{n+1}{n}|Q - \frac{1}{n-1}$$

$$= -\frac{1.69338+1}{1.69338} \times (-2.734329)$$

$$-\frac{1}{1.69338-1} = 4.3490457 - 1.4422$$

$= 2.90685$

$$|P_{01} = \frac{n}{(n-1)^2}\left[1 - \frac{9}{4(n+2)}\right]$$

$$= \frac{1.69338}{(1.69338-1)^2}\left[1 - \frac{1}{4(1.69338+2)}\right]$$

$= 3.52218 \times 0.3908 = 1.37647$

$$|P_1^\infty = |P_0 + 0.85\left[|W_1^\infty - 0.15\right]^2$$

$= 1.37647 + 0.85[2.90685 - 0.15]^2$

$= 1.37647 + 6.460187 = 7.836657,$

规化 $\bar{u}$：

$$\bar{u}_2 = \frac{\varphi_1}{\varphi_2} = \frac{0.6}{0.85} = 0.70588$$

$$\bar{u}_3 = \frac{\varphi_1 + \varphi_2}{\varphi_3} = \frac{0.6 + 0.85}{-0.45}$$

$= -3.2222$,

第三透镜：

取 $r_{6实} = 22.8$,

$$r_{6实} = \frac{f'_{变倍}}{\bar{c}_6 \varphi_3},\ \bar{c}_6 = \frac{f'_{变倍}}{r_{6实}\varphi_3}$$

$$= \frac{-31.6014708}{22.8 \times (-0.45)} = 3.080065,$$

$$\bar{Q} = \bar{c}_7 - 1 = \bar{c}_6 - \frac{n}{n-1} = 3.080065$$

$$- \frac{1.755}{1.755 - 1} = 0.755565,$$

$$\bar{c}_7 = \bar{Q} + 1 = 0.755565 + 1$$

$= 1.755565$,

$$r_{7实} = \frac{f'_{变倍}}{\bar{c}_7 \varphi_3} = \frac{-31.6014708}{1.755565 \times (-0.45)}$$

$= 40$,

$$\bar{W}_3^{\infty} = -\frac{n+1}{n}\bar{Q} - \frac{1}{n-1}$$

$$= -\frac{1.755 + 1}{1.755} \times 0.755565 - \frac{1}{1.755 - 1}$$

$= -1.186085 - 1.3245 = -2.5106$,

$$\bar{W}_3 = \bar{W}_3^{\infty} - (2 + \frac{1}{n})\bar{u}_3 = -2.5106$$

$$-(2 - \frac{1}{1.755}) \times (-3.2222) = -2.5106 +$$

$8.2804 = 5.7698$,

$$\bar{P}_{03} = \frac{n}{(n-1)^2}[1 - \frac{9}{4(n+2)}]$$

$$= \frac{1.755}{(1.755 - 1)^2}(1 - \frac{9}{4 \times (1.755 + 2)})$$

$= 1.2339$,

$$\bar{P}_{\min} = \bar{P}_{03} - \frac{n}{n+2}(\bar{u}_3 + \bar{u}_3^2) = 1.2339$$

$$- \frac{1.755}{1.755 + 2}[-3.2222 + (-3.2222)^2]$$

$= 1.2339 - 3.3466 = -2.1127$,

$\bar{P}_3 = \bar{P}_{\min} + 0.84[\bar{W}_3 - 0.14(1 + 2\bar{u}_3)]^2 = -2.1127 + 0.84\{5.7698 - 0.14 \times [1 + 2 \times (-3.2222)]\}^2 = -2.1127 + 0.84[5.7698 + 0.14 \times 5.4444]^2$

$= -2.1127 + 21.064 = 18.95$,

(ⅱ) 求 $\bar{P}_{02}$

$$\because\ \bar{P}_{变}^{\infty} = \varphi_1^3 \bar{P}_1^{\infty} + \varphi_2^3 \bar{P}_2 + \varphi_3^3 \bar{P}_3$$

$$\therefore\ \bar{P}_2 = \frac{\bar{P}_{变}^{\infty} - \varphi_1^3 \bar{P}_1^{\infty} - \varphi_3^3 \bar{P}_3}{\varphi_2^3} =$$

$$\frac{0.3165 - 0.6^3 \times 7.837 - (0.45)^3 \times 18.95}{0.85^3}$$

$$= \frac{0.3165 - 1.6928 + 1.7268}{0.614125} = \frac{0.3505}{0.614125}$$

$= 0.57$

$$\bar{W}_{变}^{\infty} = \varphi_1^2 \bar{W}_1^{\infty} + \varphi_2^2 \bar{W}_2 + \varphi_3^2 \bar{W}_3$$

$$\bar{W}_2 = \frac{\bar{W}_{变}^{\infty} - \varphi_1^2 \bar{W}_1^{\infty} - \varphi_3^2 \bar{W}_3}{\varphi_2^2} =$$

$$\frac{1.355 - 0.6^2 \times 2.90685 - 0.45^2 \times 5.7698}{0.85^2}$$

$$= \frac{1.355 - 1.046 - 1.168}{0.7225} = -1.1889,$$

$\bar{W}_2^{\infty} = \bar{W}_2 - \bar{u}_2(2 + \mu) = -1.1889 - 0.70588(2 + 0.6) = -3.0242$,

$\bar{P}_2^{\infty} = \bar{P}_2 - \bar{u}_2(4\bar{W}_2^{\infty} - 1) - \bar{u}_2^2(3 + 2\mu) = 0.57 - 0.70588[4(-3.0242) - 1] - 0.70588^2 \times (3 + 2 \times 0.6) = 0.57 + 9.245 - 2.093 = 7.722$,

$\bar{P}_{02} = \bar{P}_2^{\infty} - 0.84(\bar{W}_2^{\infty} - 0.14)^2 = 7.722 - 0.84(-3.0242 - 0.14)^2 = 7.722 - 8.41 = -0.688$。

(ⅲ) 求色差系数 $\mathrm{I}c_2$

$$\mathrm{I}c_2 = -\left(\frac{\varphi_1}{\nu_1}+\frac{\varphi_3}{\nu_3}\right)\frac{1}{\varphi_2} = -\left(\frac{0.6}{53.4}+\frac{-0.45}{27.5}\right)\frac{1}{0.85} = (0.011235-0.01636)\times\frac{1}{0.85} = 0.00603,$$

故要求双胶为：$\begin{cases}\mathrm{I}P_{02} = -0.688 \\ \mathrm{I}c_2 = 0.00603\end{cases}$

根据 $\mathrm{I}P_{02}$、$\mathrm{I}c_2$ 进行选玻璃，接下来是求双胶透镜的曲率半径等，这里不一一计算了。关于其它两透镜组的 $\mathrm{I}P$、$\mathrm{I}W$ 分配及下面几步计算这里不作叙述了。

3. 例 3. 设计一个三组元光学补偿系统，要求 f'40 ~ 80，正组在前，正正连动（如图 4.120 所示）。

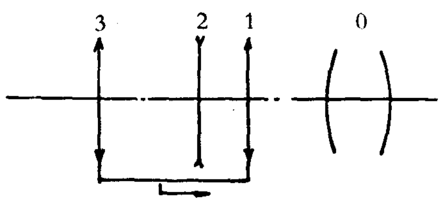

图 4.120

本例只分配焦距和间隔，达到要求的象面位移。

计算步骤如下：

1) 变倍比：

$$R = \frac{F_{max}}{F_{min}} = \frac{80}{40} = 2,$$

$$2)\ \tau = \frac{R-1}{R+1} = \frac{2-1}{2+1} = \frac{1}{3},$$

$$3)\ \theta = 0.0218\tau^4[(1-1.463\tau^2+0.722\tau^4)-0.171\tau(1-1.51\tau^2+0.67\tau^4)]$$

$$= 0.0218\times(\frac{1}{3})^4[(1-1.463\times(\frac{1}{3})^2+0.722(\frac{1}{3})^4-0.171\times\frac{1}{3}(1-1.51\times(\frac{1}{3})^2+0.67\times(\frac{1}{3})^4)] = 0.000212575.$$

$$4)\ y = \theta\frac{F_{max}^2}{zm} = 0.000212575\times\frac{80^2}{25} = 0.0544,$$

（这里取 $zm = 25$，即为最大导程，y 为最大象面位移）

$$5)\ l_1'(0) = \frac{1.703}{\tau}[(1-0.294\tau^2-0.171\tau^4)+0.44\tau(1-0.05\tau^2-0.01\tau^4)]$$

$$= \frac{1.703}{\frac{1}{3}}[(1-0.294\times(\frac{1}{3})^2-0.171\times(\frac{1}{3})^4)+0.44\times\frac{1}{3}(1-0.05\times(\frac{1}{3})^2-0.01\times(\frac{1}{3})^4)] = 5.676$$

6) $\epsilon = 0.1508\tau(1+0.17\tau^2+0.15\tau^4) = 0.1508\times\frac{1}{3}[1+0.17\times(\frac{1}{3})^2+0.15\times(\frac{1}{3})^4] = 0.0513$（补偿点偏移量），

7) 取 $z_1 = 0$

$z_2 = 0.5-\epsilon = 0.5-0.0513 = 0.4487,$

$z_3 = 1,$

8) $r_1 = z_1+z_2+z_3 = z_2+1 = 1.4487,$

$r_2 = z_1z_2+z_2z_3+z_1z_3 = z_2 = 0.4487,$

$r_3 = z_1z_2z_3 = 0$

9) $m = \frac{1}{4}(\frac{1}{\tau}+2\epsilon) = \frac{1}{4}(3+2\times0.0513) = \frac{3.1026}{4} = 0.77565,$

10) $\lambda = [l-0.5-|(m-\epsilon)|]$

$= 5.676 - 0.5 - |(0.77565 - 0.0513)|$
$= 5.176 - 0.72435 = 4.45165$,

11) $f_1 = (\lambda^2 - m^2)/2\lambda = (4.45165^2 - 0.77565^2)/(2 \times 4.45165) = \frac{19.215556}{8.9033}$
$= 2.15825099$,

12) $X' = l - f_1 = 5.676 - 2.15825099$
$= 3.51774901$,

13) $\beta_2 = X' - (\frac{1}{2} - \in) = 3.51774901 - (0.5 - 0.0513) = 3.06904901$,

14) $b_1 = \beta_2 - 1 = 3.06904901 - 1$
$= 2.06904901$,

15) $b_2 = \beta_2/(r-1) = \frac{3.06904901}{2-1}$
$= 3.06904901, (\because r = R)$,

16) $a_1 = b_2X'/f_1^2 = \frac{3.06904901 \times 3.51774901}{2.15825099^2}$
$= 2.31774032$,

17) $d_{23} = -a = -2.31774032$,

18) $d_{21} = d_{23} + b_1 = -2.31774032 + 2.06904901 = -0.24869131$,

19) $f_2 = -\sqrt{d_{23}d_{21} + b_2}$
$= -\sqrt{(-2.31774032) \times (-0.2486913) + 3.06904901} = -\sqrt{0.57640188 + 3.06904901}$
$= -1.9093064$,

20) $S_{21} = f_1 + d_{21} - |f_2| = 2.15825099 - 0.24869131 - 1.9093064$
$= 0.00025328$（即为第 2 组与第 1 组的主面间隔，认为太小。）

重新取 $l = 5.8$，从 10) 式开始计算：

10) $\lambda = [l - 0.5 - |m - \in|]$
$= [5.8 - 0.5 - |(0.77565 - 0.0513)|]$
$= 4.57565$,

11) $f_1 = (\lambda^2 - m^2)/2\lambda$
$= \frac{4.57565^2 - 0.77565^2}{2 \times 4.57565} = 2.22208221$,

12) $X' = l - f_1 = 5.8 - 2.22208221$
$= 3.57791729$,

13) $\beta_2 = X' - (\frac{1}{2} - \in) = 3.57791779 - (0.5 - 0.0513) = 3.12921779$,

14) $b_1 = \beta_2 - 1 = 2.12921779$,

15) $b_2 = \beta_2/(r-1) = \frac{3.12921779}{2-1}$
$= 3.12921779$,

16) $a_1 = b_2X'/f_1^2 = (3.12921779 \times 3.57791779)/2.22208221^2$
$= 2.26749273$,

17) $d_{23} = -a_1 = -2.26749273$,

18) $d_{21} = d_{23} + b_1 = -2.26749273 + 2.12921779 = -0.13827494$,

19) $f_2 = -\sqrt{d_{23}d_{21} + b_2}$
$= -\sqrt{(-2.26749273) \times (-0.13827494) + 3.12921779} = -\sqrt{3.44275521}$
$= -1.85546631$,

20) $S_{21} = f_1 + d_{21} - |f_2| = 2.22208221 + (-0.13827494) - 1.85546631$
$= 0.22834096$（此数可以。主要是考虑第 2 组元与第 1 组元实际不碰。）

21) 取 $S_{32} = 1.15$（S_{32} 为第 3 组元与第 2 组元在长焦时的主面间隔，要大于 1。）

22) $f_3 = |f_2| - d_{32} + S_{32} = 1.85546631 - (-2.26749273) + 1.15 = 5.27295904$,

23) $f_{max} = -\left(\frac{2\tau}{1 - |\tau|}\right)\frac{f_1f_2f_3}{\beta_2}$

$$= -\left(\frac{2/3}{1 - \frac{1}{3}}\right) \times \frac{2.22208221 \times (-1.85546631) \times 5.27295904}{3.12921779}$$

$$= \frac{21.74040316}{3.12921779} = 6.94755195,$$

24) $L'_{(0)} = l_{Zm} = 5.8 \times 25 = 145$（变倍组象距），

25) $W = \frac{f_{max} \cdot zm}{F_{max}}$

$$= \frac{6.94755195 \times 25}{80} = 2.17110999,$$

26) 取 $S_{10} = 25 \times 1.3 = 32.5$,

27) $L_0 = L'_{(0)} - S_{10} = 145 - 32.5 = 112.5$,

28) $L'_0 = \frac{L_0}{W} = \frac{112.5}{2.17110999} = 51.81681283$,

29) $F_0 = \frac{L_0}{W-1} = \frac{112.5}{1.171109999} = 96.06271055$,

小结：

$L'_0 = 51.81681283$,

$F_0 = 96.06271055$,

$S_{10} = 32.5$

$F_1 = 2.22208221 \times 25 = 55.55205525$

$S_{21} = 5.708524$,

$F_2 = -1.85546631 \times 25 = -46.38665775$

$S_{32} = 28.75$

$F_3 = 5.27295904 \times 25 = 131.823975$

总长 = 118.77534.

（未完待续）

消 息

可自动对焦的液体“露珠”镜头

透过一滴露珠，可以看清整个世界，人们在日常生活中往往忽视的细节被法国科学家捕捉到，开发出了不用机械部件就可以对焦的液体“露珠”镜头。

据法国媒体报道，2月13日在西班牙巴塞罗纳召开的3G世界年会上，法国 *Varioptic* 公司发明的可自动对焦的液体“露珠”镜头引起人们极大好奇。这种镜头的主要材料是油和水。露珠的伸缩弹性不同，所折射的景象就不同，这与机械镜头伸缩对焦是一个道理。利用这一特点，他们开发了世界首款用于手机的液体“露珠”镜头。

科学家介绍说，液体镜头是将水溶液和油密封在金属筒中，通过控制两种液体交界面的曲面半径调节焦距。当需要聚焦和变焦时，电子程序只需改变两极电压来修改两滴液体的外形，就可达到目的。与传统镜头相比，这种镜头体积很小、价格低、耗电量小、变焦速度只有0.02*s*、成像质量好。目前，全球许多手机生产厂商都已经准备广泛采用这种液体“露珠”镜头，推出可自动对焦拍照的手机。

一些专业媒体认为，法国科学家的这个奇想，有望改变光学领域的研究方向。液体“露珠”镜头由于省却了机械镜头大量的机械动作，可以大大延长使用寿命。此外，由于体积非常小，有望在未来取代相机、内窥镜、光网络设备、遥测设备、军用光学设备以及其他市场中的小型玻璃和塑料镜头。

摘自《科技日报》