Lens Design II

Lecture 7: Chromatical correction II
2016-11-30
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Winter term 2016
## Preliminary Schedule

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1. Partial dispersion
2. Apochromate
3. Spherochromatism
Relative partial dispersion

- Relative partial dispersion: Change of dispersion slope with $\lambda$
  Different curvature of dispersion curve

- Definition of local slope for selected wavelengths relative to secondary colors

$$P_{\lambda_1\lambda_2} = \frac{n(\lambda_1) - n(\lambda_2)}{n_C' - n_F'}$$

- Special $\lambda$-selections for characteristic ranges of the visible spectrum

$\lambda = 656 / 1014$ nm far IR
$\lambda = 656 / 852$ nm near IR
$\lambda = 486 / 546$ nm blue edge of VIS
$\lambda = 435 / 486$ nm near UV
$\lambda = 365 / 435$ nm far UV
The relative partial dispersion changes approximately linear with the dispersion for glasses

\[ P_{\lambda_1, \lambda_2} = a_{\lambda_1, \lambda_2} \cdot \nu_d + b_{\lambda_1, \lambda_2} \]

Nearly all glasses are located on the normal line in a \( P-\nu \)-diagram

The slope of the normal line depends on the selection of wavelengths

Glasses apart from the normal line shows anomalous partial dispersion \( \Delta P \)

\[ P_{\lambda_1, \lambda_2} = a_{\lambda_1, \lambda_2} \cdot \nu_d + b_{\lambda_1, \lambda_2} + \Delta P_{\lambda_1, \lambda_2} \]

these material are important for chromatical correction of higher order
Anomalous Partial Dispersion

- Arrows in the glass map: indication of the deviation from the normal line
- Vertical component: at the red horizontal: at the blue end of the spectrum

\[ P_{\lambda_1 \lambda_2} = a_{\lambda_1 \lambda_2} \cdot v_d + b_{\lambda_1 \lambda_2} + \Delta P_{\lambda_1 \lambda_2} \]
Anomalous Partial Dispersion

- Normal glasses:
  Partial dispersion changes linear with Abbe number

- Definition of P depends on selected wavelengths

- Normal line defined by F2 and K7

- Deviation from linear behavior: anomalous partial dispersion $\Delta P$
  \[ P_{\lambda_1 \lambda_2} = a_{\lambda_1 \lambda_2} \cdot \nu_d + b_{\lambda_1 \lambda_2} + \Delta P_{\lambda_1 \lambda_2} \]

- The value of $\Delta P$ depends on the wavelength selection

- Typical $\Delta P$ considered at the red and the blue end of the visible spectrum

- Large deviation values $\Delta P$ are necessary for apochromatic chromatical correction

\[ P_{C,t} = 0.5450 + 0.004743 \cdot \nu_d \]
\[ P_{C,s} = 0.4029 + 0.002331 \cdot \nu_d \]
\[ P_{F,e} = 0.4884 + 0.000526 \cdot \nu_d \]
\[ P_{g,F} = 0.6438 + 0.001682 \cdot \nu_d \]
\[ P_{i,g} = 1.7241 + 0.008382 \cdot \nu_d \]
- Preferred glass selection for apochromates

- N-SF1
- N-SF6
- N-SF57
- N-SF66
- P-SF68
- P-SF67

- N-FK51A
- N-PK52A
- N-PK51

- N-KZFS12
- N-KZFS4
- N-LAF33
- N-LASF41
- N-LAF37
- N-LAF21
- N-LAF35
- N-LAK10
- N-KZFS2
Residual Chromatical Aberrations

- Different states of chromatical correction
- Increasing number of zeros or coincident colors
- Reduced residual aberrations

Ref : F. Blechinger
- Effect of different materials
- Axial chromatical aberration changes with wavelength
- Different levels of correction:
  1. No correction: lens, one zero crossing point
  2. Achromatic correction:
     - coincidence of outer colors
     - remaining error for center wavelength
     - two zero crossing points
  3. Apochromatic correction:
     - coincidence of at least three colors
     - small residual aberrations
     - at least 3 zero crossing points
     - special choice of glass types with anomalous partial dispersion necessary
Apochromate

- Focal power condition

- Achromatic condition

- Secondary spectrum

- Curvatures of lenses

  \[ c = \frac{1}{r_1} - \frac{1}{r_2} \]

- Parameter E

  \[ F = F_1 + F_2 + F_3 \]

  \[ \frac{F_1}{\nu_1} + \frac{F_2}{\nu_2} + \frac{F_3}{\nu_3} = 0 \]

  \[ \frac{P_1 \cdot F_1}{\nu_1} + \frac{P_2 \cdot F_2}{\nu_2} + \frac{P_3 \cdot F_3}{\nu_3} = 0 \]

  \[ c_a = \frac{1}{f \cdot E \cdot (v_a - v_c)} \cdot \frac{P_b - P_c}{n_{a,\lambda_1} - n_{a,\lambda_3}} \]

  \[ c_b = \frac{1}{f \cdot E \cdot (v_a - v_c)} \cdot \frac{P_c - P_a}{n_{b,\lambda_1} - n_{b,\lambda_3}} \]

  \[ c_c = \frac{1}{f \cdot E \cdot (v_a - v_c)} \cdot \frac{P_a - P_b}{n_{c,\lambda_1} - n_{c,\lambda_3}} \]

  \[ E = \frac{1}{v_a - v_c} \cdot [v_a \cdot (P_b - P_c) + v_b \cdot (P_c - P_a) + v_c \cdot (P_a - P_b)] \]

- The 3 materials are not allowed to be on the normal line

- The triangle of the 3 points should be large: small \( c_j \) give relaxed design
- Choice of at least one special glass
- Correction of secondary spectrum: anomalous partial dispersion
- At least one glass should deviate significantly from the normal glass line
**Splitted Achromates**

- Split of cemented surface: reduced zonal residual aberration possible
- Larger distance of air gap: reduced spherochromatism
General Achromatization

- Contribution of a thin lens to the axial chromatical aberration

- Axial chromatical aberration of a system of thin lenses

- Condition of achromatization of a system of lenses

- Special case of lenses close together

- Condition of apochromatic (polychromatic) correction with the partial relative dispersion

\[
K_{lens}^{CHL} = \omega_j^2 \cdot \frac{F_j}{\nu_j} = \frac{\omega_j^2}{f'_j \cdot \nu_j}
\]

\[
\Delta s_{CHL}' = - \frac{s'^2}{\omega_N^2} \cdot \sum_j \omega_j^2 \cdot \frac{F_j}{\nu_j}
\]

\[
\sum_j \omega_j^2 \cdot \frac{F_j}{\nu_j} = 0
\]

\[
\sum_j \frac{F_j}{\nu_j} = 0
\]

\[
\sum_j \omega_j^2 \cdot \frac{P_j \cdot F_j}{\nu_j} = 0
\]
Two-Lens Apochromate

- Special glasses
- with anormal relative partial dispersion
- High refractive powers in the two components result in large spherical zonal aberration

Ref.: H. Zuegge
- Residual spherochromatism of an achromate
- Representation as function of aperture or wavelength
Spherochromatism

- Spherochromatism: variation of spherical aberration with wavelength, Alternative notation: Gaussian chromatical error
- Individual curve of spherical aberration with color
- Conventional achromate:
  - coinciding image location for red (C’) and blue (F’) on axis (paraxial)
  - differences and secondary spectrum for green (e)
  - but different intersection lengths for finite aperture rays
- Better balancing with half spherochromatism on axis
Spherochromatism

- Spherical aberration of a lens in 3rd order:

\[ A_s = \frac{1}{32n(n-1)f^3} \left[ \frac{n^3}{n-1} + \frac{n+2}{n-1} \left\{ X - \frac{2(n^2-1)}{n+2} M \right\}^2 - \frac{n^2(n-1)}{n+2} M^2 \right] \]

- Wavelength dependence of \( n \) induces spherochromatism

- Typical spectral variation of this aberration with wavelength

\[ \Delta z \]

a) single lens

\[ \Delta z \]

b) corrected