Design and Correction of Optical Systems

Lecture 11: Correction principles II
2015-06-24
Herbert Gross

Summer term 2015
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<th>Date</th>
<th>Topic</th>
<th>Details</th>
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<tr>
<td>1</td>
<td>15.04.</td>
<td>Basics</td>
<td>Law of refraction, Fresnel formulas, optical system model, raytrace, calculation approaches</td>
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<tr>
<td>2</td>
<td>22.04.</td>
<td>Materials and Components</td>
<td>Dispersion, anormal dispersion, glass map, liquids and plastics, lenses, mirrors, aspheres, diffractive elements</td>
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<td>3</td>
<td>29.04.</td>
<td>Paraxial Optics</td>
<td>Paraxial approximation, basic notations, imaging equation, multi-component systems, matrix calculation, Lagrange invariant, phase space visualization</td>
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<td>4</td>
<td>06.05.</td>
<td>Optical Systems</td>
<td>Pupil, ray sets and sampling, aperture and vignetting, telecentricity, symmetry, photometry</td>
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<td>5</td>
<td>13.05.</td>
<td>Geometrical Aberrations</td>
<td>Longitudinal and transverse aberrations, spot diagram, polynomial expansion, primary aberrations, chromatical aberrations, Seidels surface contributions</td>
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<td>6</td>
<td>20.05.</td>
<td>Wave Aberrations</td>
<td>Fermat principle and Eikonal, wave aberrations, expansion and higher orders, Zernike polynomials, measurement of system quality</td>
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<td>7</td>
<td>27.05.</td>
<td>PSF and Transfer function</td>
<td>Diffraction, point spread function, PSF with aberrations, optical transfer function, Fourier imaging model</td>
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<td>8</td>
<td>03.06.</td>
<td>Further Performance Criteria</td>
<td>Rayleigh and Marechal criteria, Strehl definition, 2-point resolution, MTF-based criteria, further options</td>
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<td>9</td>
<td>10.06.</td>
<td>Optimization and Correction</td>
<td>Principles of optimization, initial setups, constraints, sensitivity, optimization of optical systems, global approaches</td>
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<tr>
<td>10</td>
<td>17.06.</td>
<td>Correction Principles I</td>
<td>Symmetry, lens bending, lens splitting, special options for spherical aberration, astigmatism, coma and distortion, aspheres</td>
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<td>11</td>
<td>24.06.</td>
<td>Correction Principles II</td>
<td>Field flattening and Petzval theorem, chromatical correction, achromate, apochromate, sensitivity analysis, diffractive elements</td>
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<tr>
<td>12</td>
<td>01.07.</td>
<td>Optical System Classification</td>
<td>Overview, photographic lenses, microscopic objectives, lithographic systems, eyepieces, scan systems, telescopes, endoscopes</td>
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<td>13</td>
<td>08.07.</td>
<td>Special System Examples</td>
<td>Zoom systems, confocal systems</td>
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<td>14</td>
<td>15.07.</td>
<td>Further Topics</td>
<td>New system developments, modern aberration theory,...</td>
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Contents

1. Field flattening and Petzval theorem
2. Field lenses
3. Chromatical correction
4. Achromate and apochromate
5. Diffractive elements
6. Miscellaneous
Petzval Theorem for Field Curvature

- Petzval theorem for field curvature:
  1. formulation for surfaces
  2. formulation for thin lenses (in air)

- Important:
  - no dependence on bending
  - no dependence on stop location

- Natural behavior: image curved towards system

- Problem: collecting systems with $f > 0$:
  If only positive lenses:
  $R_{ptz}$ always negative

- Typical scaling for single lens:
  $$\frac{R_{ptz}}{f} = -n = -1.6$$
Petzval Theorem for Field Curvature

- Goal: vanishing Petzval curvature
  \[ \frac{1}{R_{ptz}} = - \sum_j \frac{1}{n_j \cdot f_j} \]
  and positive total refractive power
  \[ \frac{1}{f} = \sum_j \frac{h_j}{h_1} \cdot \frac{1}{f} \]
  for multi-component systems

- Solution:
  General principle for correction of curvature of image field:
  1. Positive lenses with:
     - high refractive index
     - large marginal ray heights
     - gives large contribution to power and low weighting in Petzval sum
  2. Negative lenses with:
     - low refractive index
     - small marginal ray heights
     - gives small negative contribution to power and high weighting in Petzval sum
Flattening Meniscus Lenses

- Possible lenses / lens groups for correcting field curvature
- Interesting candidates: thick meniscus shaped lenses

\[ \frac{1}{R_{ptz}} = - \sum_{k} \frac{n_k' - n_k}{n_k \cdot n_k' \cdot r_k} = - \frac{1}{n \cdot f} + \left( \frac{n-1}{n} \right)^2 \cdot \frac{d}{r_1 r_2} \]

1. Hoeghs mensicus: identical radii
   - Petzval sum zero
   - remaining positive refractive power

\[ F' = \frac{(n-1)^2 d}{n \cdot r^2} \]

2. Concentric meniscus,
   - Petzval sum negative
   - weak negative focal length
   - refractive power for thickness d:

\[ r_2 = r_1 - d \]
\[ \frac{1}{R_{ptz}} = \frac{(n-1) \cdot d}{n r_1 \cdot (r_1 - d)} \]
\[ F' = - \frac{(n-1)d}{nr_1(r_1 - d)} \]

3. Thick meniscus without refractive power
   Relation between radii

\[ r_2 = r_1 - d \cdot \frac{n-1}{n} \]
\[ \frac{1}{R_{ptz}} = \frac{(n-1)^2 \cdot d}{n r_1 \cdot [nr_1 - d \cdot (n-1)]} > 0 \]
Correcting Petzval Curvature

- Triplet group with + - +

- Effect of distance and refractive indices

From: H. Zügge
Field Curvature

- Correction of Petzval field curvature in lithographic lens for flat wafer

- Positive lenses: Green $h_j$ large
- Negative lenses: Blue $h_j$ small

- Correction principle: certain number of bulges

$$\frac{1}{R} = -\sum_{j} \frac{F_j}{n_j}$$

$$F = \sum_{j} \frac{h_j}{h_1} \cdot F_j$$
- Possible setups for flattening the field
- Goal:
  - reduction of Petzval sum
  - keeping astigmatism corrected
Field Flatness

- Principle of multi-bulges to reduce Petzval sum

\[
\frac{1}{r_p} = -n' \cdot \sum_k \frac{1}{n_k \cdot f_k}
\]

- Seidel contributions show principle
Size Reduction by Aspheres

- Sensitivity of refractive lenses for aspheres
Effect of a field lens for flattening the image surface

1. Without field lens
   curved image surface

2. With field lens
   image plane
Field Lenses

- Field lens: in or near image planes
- Influences only the chief ray: pupil shifted
- Critical: conjugation to image plane, surface errors sharply seen
Field Lens im Endoscope

without field lenses

with 1 field lens

with 2 field lenses

Ref : H. Zügge
Various cases of chromatical aberration correction

a) axial and lateral color corrected

b) axial color corrected

c) lateral color corrected

d) no color corrected
Axial Colour: Achromate

- Compensation of axial colour by appropriate glass choice

- Chromatical variation of the spherical aberrations:
  spherochromatism (Gaussian aberration)

- Therefore perfect axial color correction (on axis) are often not feasible

Ref: H. Zügge
Achromate:
- Axial colour correction by cementing two different glasses
- Bending: correction of spherical aberration at the full aperture
- Aplanatic coma correction possible be clever choice of materials

Four possible solutions:
- Crown in front, two different bendings
- Flint in front, two different bendings

Typical:
- Correction for object in infinity
- Spherical correction at center wavelength with zone
- Diffraction limited for NA < 0.1
- Only very small field corrected
Achromate: Realization Versions

- **Advantage of cementing:**
  solid state setup is stable at sensitive middle surface with large curvature

- **Disadvantage:**
  loss of one degree of freedom

- **Different possible realization forms in practice**

  ![Diagram](image)
Achromate : Basic Formulas

- **Idea:**
  1. Two thin lenses close together with different materials
  2. Total power
     \[ F = F_1 + F_2 \]
  3. Achromatic correction condition
     \[ \frac{F_1}{v_1} + \frac{F_2}{v_2} = 0 \]

- **Individual power values**
  \[ F_1 = \frac{1}{1 - \frac{v_2}{v_1}} \cdot F \]
  \[ F_2 = \frac{1}{1 - \frac{v_1}{v_2}} \cdot F \]

- **Properties:**
  1. One positive and one negative lens necessary
  2. Two different sequences of plus (crown) / minus (flint)
  3. Large \( v \)-difference relaxes the bendings
  4. Achromatic correction independent from bending
  5. Bending corrects spherical aberration at the margin
  6. Aplanatic coma correction for special glass choices
  7. Further optimization of materials reduces the spherical zonal aberration
Achromate: Correction

- Cemented achromate:
  6 degrees of freedom:
  3 radii, 2 indices, ratio $\nu_1/\nu_2$

- Correction of spherical aberration:
  diverging cemented surface with
  positive spherical contribution
  for $n_{\text{neg}} > n_{\text{pos}}$

- Choice of glass: possible goals
  1. aplanatic coma correction
  2. minimization of spherochromatism
  3. minimization of secondary spectrum

- Bending has no impact on chromatical correction:
  is used to correct spherical aberration
  at the edge

- Three solution regions for bending
  1. no spherical correction
  2. two equivalent solutions
  3. one aplanatic solution, very stable
Achromatic solutions in the Glass Diagram

Abbe-Diagramm

Zeichenerklärung

Po/As-frei.......................... N-Typ......
Po/As-frei und alter Typ............
Alter Typ.............................
Zinkkrone........................... N-2K......
Kurzflintsondergläser............. KzFS......

SCHOTT glass made of ideas

crown positive lens

flint negative lens

Achromat
Achromate

- Achromate
- Longitudinal aberration
- Transverse aberration
- Spot diagram

\( \lambda = 486 \text{ nm} \)
\( \lambda = 587 \text{ nm} \)
\( \lambda = 656 \text{ nm} \)

\( \Delta y' \)

\( \Delta s' \) [mm]

\( r_p \)

\( \sin u' \)
Coma Correction: Achromate

- **Bending of an achromate**
  - optimal choice: small residual spherical aberration
  - remaining coma for finite field size
- **Splitting achromate**:
  - additional degree of freedom:
  - better total correction possible
  - high sensitivity of thin air space
- **Aplanatic glass choice**:
  - vanishing coma
- **Cases**:
  - a) simple achromate, sph corrected, with coma
  - b) simple achromate, coma corrected by bending, with sph
  - c) other glass choice: sph better, coma reversed
  - d) splitted achromate: all corrected
  - e) aplanatic glass choice: all corrected

### Table: Coma Correction

<table>
<thead>
<tr>
<th>Achromat bending</th>
<th>Image height:</th>
<th>y' = 0 mm</th>
<th>y' = 2 mm</th>
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<tbody>
<tr>
<td></td>
<td>Pupil section:</td>
<td>meridional</td>
<td>meridional</td>
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<tr>
<td></td>
<td>Transverse Aberration:</td>
<td>Δy' 0.05 mm</td>
<td>Δy' 0.05 mm</td>
</tr>
<tr>
<td>(a)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(e)</td>
<td></td>
<td></td>
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**Ref:** H. Zügge
Achromate

- Residual aberrations of an achromate
- Clearly seen:
  1. Distortion
  2. Chromatical magnification
  3. Astigmatism
- Residual spherochromatism of an achromate
- Representation as function of aperture or wavelength

![Diagram showing longitudinal aberration and defocus variation with different pupil heights.]
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
Anormal partial dispersion and normal line

Axial Colour: Apochromate
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
Axial Colour: Apochromate

- 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
Broken-contact achromate: different ray heights allow for correcting spherochromatism
Axial Color Correction with Schupman Lens

- Non-compact system
- Generalized achromatic condition with marginal ray heights $y_j$
  \[ \frac{y_1^2}{v_1} + \frac{y_2^2}{v_2} \cdot F_2 = 0 \]
- Use of a long distance and negative $F_2$ for correction
- Only possible for virtual imaging
Two-Lens Apochromate

- Special glasses and very strong bending allows for apochromatic correction
- Large remaining spherical zonal aberration
- Zero-crossing points not well distributed over wavelength spectrum
- Cemented surface with perfect refractive index match
- No impact on monochromatic aberrations
- Only influence on chromatical aberrations
- Especially 3-fold cemented components are advantages
- Can serve as a starting setup for chromatical correction with fulfilled monochromatic correction
- Special glass combinations with nearly perfect parameters

<table>
<thead>
<tr>
<th>Nr</th>
<th>Glas</th>
<th>$n_d$</th>
<th>$\Delta n_d$</th>
<th>$\nu_d$</th>
<th>$\Delta \nu_d$</th>
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<tr>
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<td>1.60718</td>
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<td>49.24</td>
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Principles of Glass Selection in Optimization

- Design Rules for glass selection

- Different design goals:
  1. Color correction: large dispersion difference desired
  2. Field flattening: large index difference desired

Ref: H. Zügge
Achromatic Hybrid Lens

- Lens with diffractive structured surface: hybrid lens
- Refractive lens: dispersion with Abbe number $\nu = 25...90$
- Diffractive lens: equivalent Abbe number
  \[ \nu_d = \frac{\lambda_d}{\lambda_F - \lambda_C} = -3.453 \]
- Combination of refractive and diffractive surfaces: achromatic correction for compensated dispersion
- Usually remains a residual high secondary spectrum
- Broadband color correction is possible but complicated
Diffractive Optics: Dispersion

- Dispersion by grating diffraction:
  Abbe number

  Relative partial dispersion

Consequence:
Large secondary spectrum

- \( v \)-P-diagram

\[
v_e = \frac{\lambda_e}{\lambda_{F'} - \lambda_C'} = -3.330
\]

\[
P_{g,F'} = \frac{\lambda_g - \lambda_{F'}}{\lambda_{F'} - \lambda_C'} = 0.2695
\]
Combination of DOE and aspherical carrier

diffractive surface, phase aspherical

diffractive surface, aspherical
d, a

diffractive surface, carrier aspherical

d, a

d, a

Diffractive Optics: Singlet Solutions
Data:
- $\lambda = 193$ nm
- $NA = 0.65$
- $\beta = 50$
- $s_{\text{free}} = 7.8$ mm

Properties:
- short total track
- extreme large free working distance
- few lenses
Parameter of Excentricity

- Relative position of stop inside system
- Quantitative measure:
  Parameter of excentricity
  \( \chi = \frac{h_{CR} - h_{MR}}{h_{CR} + h_{MR}} \)
- Special cases:
  - \( \chi = 1 \) image plane
  - \( \chi = -1 \) pupil plane
  - \( \chi = 0 \) same effective distance from image and pupil
Example:
excentricity for all surfaces

Change:
\( \chi = +1 \ldots -1 \ldots +1 \)
Influence of Stop Position on Performance

- Ray path of chief ray depends on stop position
Effect of Stop Position

- Example photographic lens
- Small axial shift of stop changes transverse aberrations
- In particular coma is strongly influenced

Ref: H. Zügge
Microscopic Objective Lens Initial System

- **a)** negative achromate
- **b)** reversed positive achromate
- **c)** symmetric to **c)** positive achromate
- **d)** non-infinite positive achromate
- **e)** AC-meniscus lenses