Optical Design with Zemax for PhD - Basics

Lecture 13: Tolerancing II

2020-02-19

Herbert Gross

Speaker: Dennis Ochse

Winter term 2019
<table>
<thead>
<tr>
<th>No</th>
<th>Date</th>
<th>Subject</th>
<th>Detailed content</th>
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<tbody>
<tr>
<td>1</td>
<td>23.10.</td>
<td>Introduction</td>
<td>Zemax interface, menus, file handling, system description, editors, preferences, updates, system reports, coordinate systems, aperture, field, wavelength, layouts, diameters, stop and pupil, solves</td>
</tr>
<tr>
<td>2</td>
<td>30.10.</td>
<td>Basic Zemax handling</td>
<td>Raytrace, ray fans, paraxial optics, surface types, quick focus, catalogs, vignetting, footprints, system insertion, scaling, component reversal</td>
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<tr>
<td>3</td>
<td>06.11.</td>
<td>Properties of optical systems</td>
<td>aspheres, gradient media, gratings and diffractive surfaces, special types of surfaces, telecenticity, ray aiming, afocal systems</td>
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<tr>
<td>4</td>
<td>13.11.</td>
<td>Aberrations I</td>
<td>representations, spot, Seidel, transverse aberration curves, Zernike wave aberrations</td>
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<td>5</td>
<td>20.11.</td>
<td>Aberrations II</td>
<td>Point spread function and transfer function</td>
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<td>6</td>
<td>27.11.</td>
<td>Optimization I</td>
<td>algorithms, merit function, variables, pick up’s</td>
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<tr>
<td>7</td>
<td>04.12.</td>
<td>Optimization II</td>
<td>methodology, correction process, special requirements, examples</td>
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<tr>
<td>8</td>
<td>11.12.</td>
<td>Advanced handling</td>
<td>slider, universal plot, I/O of data, material index fit, multi configuration, macro language</td>
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<td>9</td>
<td>08.01.</td>
<td>Imaging</td>
<td>Fourier imaging, geometrical images</td>
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<td>10</td>
<td>15.01.</td>
<td>Correction I</td>
<td>Symmetry, field flattening, color correction</td>
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<tr>
<td>11</td>
<td>22.01.</td>
<td>Correction II</td>
<td>Higher orders, aspheres, freeforms, miscellaneous</td>
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<tr>
<td>12</td>
<td>29.01.</td>
<td>Tolerancing I</td>
<td>Practical tolerancing, sensitivity</td>
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<tr>
<td>13</td>
<td>19.02.</td>
<td>Tolerancing II</td>
<td>Adjustment, thermal loading, ghosts</td>
</tr>
<tr>
<td>14</td>
<td>26.02.</td>
<td>Illumination I</td>
<td>Photometry, light sources, non-sequential raytrace, homogenization, simple examples</td>
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<tr>
<td>15</td>
<td>04.03.</td>
<td>Illumination II</td>
<td>Examples, special components</td>
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<tr>
<td>16</td>
<td>11.03.</td>
<td>Physical modeling I</td>
<td>Gaussian beams, Gauss-Schell beams, general propagation, POP</td>
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<tr>
<td>17</td>
<td>18.03.</td>
<td>Physical modeling II</td>
<td>Polarization, Jones matrix, Stokes, propagation, birefringence, components</td>
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<tr>
<td>18</td>
<td>25.03.</td>
<td>Physical modeling III</td>
<td>Coatings, Fresnel formulas, matrix algorithm, types of coatings</td>
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<tr>
<td>19</td>
<td>01.04.</td>
<td>Physical modeling IV</td>
<td>Scattering and straylight, PSD, calculation schemes, volume scattering, biomedical applications</td>
</tr>
<tr>
<td>20</td>
<td>08.04.</td>
<td>Additional topics</td>
<td>Adaptive optics, stock lens matching, index fit, Macro language, coupling Zemax-Matlab / Python</td>
</tr>
</tbody>
</table>
1. Adjustment
2. False light
3. Thermal properties
Compensators:
- changeable system parameter to partly compensate the influence of tolerances
- compensators are costly due to an adjustment step in the production
- usually the tolerances can be enlarged, which lowers the cost of components
- clever balance of cost and performance between tolerances and adjustment

Adjustment steps should be modelled to learn about their benefit, observation of criteria, moving width,...

Special case: image position compensates for tolerances of radii, indices, thickness

Centering lenses:
lateral shift of one lens to get a circular symmetric point spread function on axis

Adjustment of air distances between lenses to adjust for spherical aberration, afocal image position,...
- On-axis astigmatism due to cylindrical irregularity

- Vectorial addition of astigmatism in systems

Ref.: M. Peschka
Adjustment
Different types of compensators in a microscope

- Example Microscopic lens

- Adjusting:
  1. Axial shifting lens: focus
  2. Clocking: astigmatism
  3. Lateral shifting lens: coma

- Ideal: Strehl $D_S = 99.62\%$
  With tolerances: $D_S = 0.1\%$
  After adjusting: $D_S = 99.3\%$

Ref.: M. Peschka
- Successive steps of improvements

PSF (intensity normalized)

PSF (energy normalized)

With Tolerances

Step 1 \((Z_4, Z_9)\)

Step 2 \((Z_7, Z_8)\)

Step 3 \((Z_5, Z_6)\)

Step 4 ~ Step 2 \((Z_7, Z_8)\)

Ref.: M. Peschka
Adjustment of air gaps to optimize spherical aberration

- Reduced optimization setup

\[ c_j = c_{j_0} + \sum_{k=1,4} \Delta t_k \cdot \frac{\partial c_j}{\partial t_k}, \quad j = 2, 4, 6, 8 \]

- Compensates residual aberrations due to tolerances (radii, thicknesses, refractive indices)

<table>
<thead>
<tr>
<th></th>
<th>(d_2)</th>
<th>(d_4)</th>
<th>(d_6)</th>
<th>(d_8)</th>
<th>(c_{20})</th>
<th>(c_{40})</th>
<th>(c_{60})</th>
<th>(c_{80})</th>
<th>(W_{\text{rms}})</th>
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</thead>
<tbody>
<tr>
<td>nominal</td>
<td>0.77300</td>
<td>0.17000</td>
<td>3.2200</td>
<td>2.0500</td>
<td>0.00527</td>
<td>-0.0718</td>
<td>0.00232</td>
<td>0.01290</td>
<td>0.0324</td>
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<td>(d_2) varied</td>
<td>0.77320</td>
<td>0.17000</td>
<td>3.2200</td>
<td>2.0500</td>
<td>0.04144</td>
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<td>0.00277</td>
<td>0.12854</td>
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<tr>
<td>(d_4) varied</td>
<td>0.77300</td>
<td>0.17050</td>
<td>3.2200</td>
<td>2.0500</td>
<td>0.03003</td>
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<td>0.00264</td>
<td>0.1286</td>
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<tr>
<td>(d_6) varied</td>
<td>0.77300</td>
<td>0.17000</td>
<td>3.2250</td>
<td>2.0500</td>
<td>0.00728</td>
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<tr>
<td>(d_8) varied</td>
<td>0.77300</td>
<td>0.17000</td>
<td>3.2200</td>
<td>2.0550</td>
<td>0.005551</td>
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<tr>
<td>optimized</td>
<td>0.77297</td>
<td>0.16942</td>
<td>3.12670</td>
<td>3.2110</td>
<td>0.000414</td>
<td>0.00046</td>
<td>0.00030</td>
<td>0.01390</td>
<td>0.00468</td>
</tr>
</tbody>
</table>
- General proposals: arbitrary shapes of the correction
  1. Deformable adaptive mirrors
  2. SLM (spatial light modulator)

- Focusing or magnification:
  1. Liquid lenses
  2. Axial moving lenses, zooms

- Special low order correction options:
  Moving complex shaped masks:
  1. Alvarez plates, lateral shift
  2. Zernike plates axial movement
  3. Zernike plates, azimuthal rotation
Simple Zemax model calculation

1. centered

2. lateral shifted plates
False light
What is false light?

- Diffraction at aperture
diffraction-limited PSF, blurred image

- Ghosts
specular reflections from imperfectly
coated refractive surfaces

- Unwanted diffraction orders
imperfect diffracting surfaces generate
spurious images (e.g. Unintentional
gratings from diamond turning process)

Ref: K. Uhlendorf
False light
What is false light?

- Scatter from structures

- Scatter from optical surfaces contamination and sub-wavelength surface defects

- Thermal emission from optical and mechanical surfaces

Ref: K. Uhlendorf
False light
False light is

- Unwanted energy
- What keeps an optical system from performing as the designer intended

Typical stray light problems:
- Observing faint objects in the presence of sun, moon, planets orbiting telescopes or observatories
- High contrast imaging
  Digital cameras, DLP projection
- Thermal emission
  warm lenses, mirrors emitting into the FoV of the detector of infrared systems

Ref: K. Uhlendorf
- Scattering of light in diffuse media like fog

Ref: W. Osten
Ghost image in photographic lenses:
Reflex film / surface

Ref: K. Uhlendorf, D. Gängler
Different origins of false light in camera lenses:

1. ghost images
2. scattering from dust
3. diffraction from stop (star shaped blades)

Ref.: V. Blahnik
False light
Impact of coatings on ghost images

- Ghosts in coated / uncoated Distagon 2.8/21
- Increasing brightness of the source

Ref.: V. Blahnik
- Number of double bounce ghost images in a system with \( n \) surfaces:

\[
N_{\text{ghost}} = \frac{n(n+1)}{2}
\]

Ref.: V. Blahnik
- Decomposition of the system into different ray paths or nonsequential raytrace

- Properties:
  - extremely large computational effort
  - importance sampling guarantees quantitative results for large dynamic ranges
  - mechanical data necessary and important
    - often complicated geometry and not compatible with optical modelling
  - surface behavior (BSDF) necessary with large accuracy

- False light paths are determined and countermeasures can be performed
1. Mechanical system

2. Simplified mechanics only relevant parts of full CAD model

3. Critical straylight paths

Ref: R. Sand
Design and geometry of baffle diaphragms

- Comfortable:
  - Single reflection
  - Incident direction of secondary light source
  - No direct reflected light into signal direction

- Better:
  - Double reflection
  - Further optical system

- Uncomfortable:
  - No direct reflected light into signal direction
  - Double reflected light
Rise of temperature:
1. Scaling of components in size
2. Stress and strain (birefringence), especially at the glass-metal interface
3. Change of refractive indices with temperature (mostly dominant effect)

Reasons for changes in temperature:
- environmental changes
- absorption of light in components
  Problem: depends on actual power level

Homogeneous increase in temperature:
usually not critical, can be compensated by focussing for low NA systems

Temperature gradients inside the lenses:
- very critical, if transverse oriented
- changes of wavefront across the pupil

Boundary conditions in optical systems:
- heat conduction via mountings (dominant)
- air convection
- $T^4$ radiation
Physical modelling:
- heat conduction equation
- thermal loading by radiation absorption
- stress-strain by elasticity equations

Iterative calculation:
thermal effects influences beam profiles

Practice: boundary conditions only poorly known

\[
\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} - \frac{Q}{K} = 0
\]

\[
Q(r, z) = \frac{dP(r, z)}{dV} = \alpha I(r, z)
\]

Thermal properties
Thermal simulation

geometrical analysis

absorption of radiation

thermal analysis

thermal boundary conditions

mechanical boundary conditions

mechanical analysis

effects on optical system:
1. n-profil
2. Deformations
3. Birefringence
- FE calculation of temperature degradation of a microscopic lens
- Especially hot spot in the object space due to oil-parameters and high energy density
- Example:
  1. Distribution of temperature
  2. Cold and hot Psf

Ref: S. Förster
Zemax supports a linear homogeneous change of temperature in a system

- There are three changes performed:
  1. the linear expansion of the lengths by
  \[ L = L_0 \cdot (1 + \alpha \cdot \Delta T) \]
  2. the change of the index of refraction of glasses by
  \[ \Delta n = \frac{n^2 - 1}{2n} \cdot \left[ D_0 \Delta T + D_1 \Delta T^2 + D_2 \Delta T^3 + \frac{E_0 \Delta T + E_1 \Delta T^2}{\lambda^2 - \lambda_{tk}^2} \right] \]
  3. the change of the reference index of air

- Different temperatures are defined in a multi configuration by the operator TEMP
  A fast generation of several temperature setups can be obtained in the multi configuration with the tool 'make thermal setup'

- The temperature dependent parameters are:
  CRVT curvature (radii)
  THIC thickness (edge to edge)
  GLSS glasses
  SDIA diameter
  PRAM parameter, e.g. aspheric constants
The expansion coefficients $\alpha$ for glasses are obtained from the data archive. For mechanical materials this can be defined by the operator TCE (scaled in $10^{-6}$ mm/K).

- TCE can be optimized for athermalization.
- If some distances or parameters should not depend on temperature, they have to be skipped in the multiconfiguration.

In reality, very often the temperature is generated by absorption inside the bulk materials. In these cases, an index gradient must be defined, which is in first approximation parabolic:

$$T(r) = T_R + \Delta T \left(1 - \frac{r^2}{a^2}\right)$$

If the temperature difference $\Delta T$ is known the parameters are:

Linear approximation:

$$\frac{dn}{dT} = \frac{n^2 - 1}{2n} \cdot D_0$$

Index gradient:

$$n(r) = n_o + n_{r2} r^2$$

with

$$n_{r2} = \frac{n^2 - 1}{2na^2} \cdot D_0 \cdot \Delta T$$
• Thermal expansion coefficient nearly linear (stopping at $T_g$)

• Typical CTE of glasses: $\beta = 10^{-5} / K$

• Interfaces glass / metal are problematic (difference in CTE)

• Cemented lenses show problems for large curvatures and large difference in CTE