Advanced Lens Design

Lecture 1: Introduction
2013-10-15
Herbert Gross
Overview

- Time: Tuesday, 8.15 – 9.45
- Location: PafPool, Helmholtzweg 4
- Web page on IAP homepage under 'learning/materials' provides slides, exercises, solutions, informations
- Seminar: Exercises and solutions of given problems
  - Time: Tuesday, 12.00 -13.30
  - Location: PafPool, Helmholtzweg 4
  - Mentors: Minyi Zhong and Moritz Eßlinger
  - starting date: 2013-10-22
- Shift of some dates could be possible
- Written examination, 90'
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<tr>
<td>5.</td>
<td>Geary</td>
<td>Lens Design with practical Examples</td>
<td>Willmann-Bell</td>
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<td>9.</td>
<td>Cox</td>
<td>A system of optical design</td>
<td>Focal Press 1967</td>
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<td>10.</td>
<td>Slyusarev</td>
<td>Aberration and Optical Design Theory</td>
<td>Hilger 1984</td>
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Contents

1. Introduction
2. Paraxial optics
3. Raytrace
4. Optical systems
5. Zemax
Modelling of Optical Systems

- Principal purpose of calculations:

  - System, data of the structure (radii, distances, indices, ...)
  - Function, data of properties, quality performance (spot diameter, MTF, Strehl ratio, ...)

- Imaging model with levels of refinement

  - Paraxial model (focal length, magnification, aperture, ...)
  - Analytical approximation and classification (aberrations, ...)
  - Geometrical optics (transverse aberrations, wave aberration, distortion, ...)
  - Wave optics (point spread function, OTF, ...)

Analysis
imaging aberration theorie

Synthesis
lens design

Ref: W. Richter
Formulas for surface and lens imaging

- Single surface imaging equation
  \[
  \frac{n'}{s'} - \frac{n}{s} = \frac{n' - n}{r} = \frac{1}{f'}
  \]

- Thin lens in air focal length
  \[
  \frac{1}{f'} = (n-1) \cdot \left(\frac{1}{r_1} - \frac{1}{r_2}\right)
  \]

- Thin lens in air with one plane surface, focal length
  \[
  f' = \frac{r}{n-1}
  \]

- Thin symmetrical bi-lens
  \[
  f' = \frac{r}{2 \cdot (n-1)}
  \]

- Thick lens in air focal length
  \[
  \frac{1}{f'} = (n-1) \cdot \left(\frac{1}{r_1} - \frac{1}{r_2}\right) + \frac{(n-1)^2 d}{n \cdot r_1 r_2}
  \]
Paraxiality is given for small angles relative to the optical axis for all rays.

- Large numerical aperture angle \( u \) violates the paraxiality, spherical aberration occurs.
- Large field angles \( w \) violates the paraxiality, coma, astigmatism, distortion, field curvature occurs.

**Paraxial Approximation**
Paraxial approximation:

- Small angles of rays at every surface
- Small incidence angles allows for a linearization of the law of refraction \( n \cdot i = n' \cdot i' \)
- All optical imaging conditions become linear (Gaussian optics), calculation with ABCD matrix calculus is possible
- No aberrations occur in optical systems
- There are no truncation effects due to transverse finite sized components
- Serves as a reference for ideal system conditions
- Is the fundament for many system properties (focal length, principal plane, magnification,...)
- The sag of optical surfaces (difference in z between vertex plane and real surface intersection point) can be neglected
- All waves are plane of spherical (parabolic)
- The phase factor of spherical waves is quadratic

\[ E(x) = E_0 \cdot e^{-\frac{i\pi x^2}{\lambda R}} \]
Linear Collineation

- General transform object \( \rightarrow \) image space
  \[ x' = F(x, y, z) , \ y' = F(x, y, z) , \ z' = F(x, y, z) \]

- General rational transformation
  \[ x' = \frac{F_1}{F_0} , \ y' = \frac{F_2}{F_0} , \ z' = \frac{F_3}{F_0} \]
  with linear expression
  \[ F_j = a_j x + b_j y + c_j z + d_j , \ j = 0, 1, 2, 3 \]

- Describes linear collinear transform \( x, y, z \rightarrow x', y', z' \)

- Inversion
  \[ x = \frac{F'_1}{F'_0} , \ y = \frac{F'_2}{F'_0} , \ z = \frac{F'_3}{F'_0} \]
  \[ F'_j = a'_j x' + b'_j y' + c'_j z' + d'_j , \ j = 0, 1, 2, 3 \]

- Analog in the image space

- Inserted in only 2 dimensions

- Focal lengths
  from conditions \( F_0 = 0 \) and \( F_0' = 0 \)

- Principal planes

\[ z_P = \frac{a_1 - d_0}{c_0} , \ z_P' = \frac{c_3 a_1 - c_3 d_0 + d_3 c_0}{a_1 c_0} \]
Linear Collineation

- Finite angles: \( \tan(u) \) must be taken:

  Magnification:

  \[
  m = \frac{\tan u'}{\tan u}
  \]

  Focal length:

  \[
  \frac{1}{f'} = \frac{\tan u' - \tan u}{h}
  \]

  Invariant:

  \[
  n y \tan u = n' y' \tan u'
  \]
Multi-Surface Systems

- Two lenses with distance d
  
  \[ F = F_1 + F_2 - \frac{d \cdot F_1 \cdot F_2}{n} \]

- Focal length
distance of inner focal points e
  
  \[ f = \frac{f_1 \cdot f_2}{f_1 + f_2 - d} = \frac{f_1 \cdot f_2}{e} \]

- Sequence of thin lenses close together
  
  \[ F = \sum_k F_k \]

- Sequence of surfaces with relative ray heights \( h_j \), paraxial
  
  \[ F = \sum_k \frac{h_k}{h_1} \cdot (n'_k n_k) \cdot \frac{1}{r_k} \]

- Magnification
  
  \[ m = \frac{s'_1}{s_1} \cdot \frac{s'_2}{s_2} \cdots \frac{s'_k}{s_k} \cdot \frac{n_1}{n'_k} \]
Two-Lens System

- Focal length
e: tube length

- Image location

\[ f' = \frac{f'_1 \cdot f'_2}{f'_1 + f'_2 - d} = \frac{f'_1 \cdot f'_2}{e} \]

\[ s'_2 = \frac{(f'_1 - d) \cdot f'_2}{f'_1 + f'_2 - d} = \frac{(f'_1 - d) \cdot f'}{f'_1} \]
- Ideal lens
  - one principal plane

- Aplanatic lens
  - principal surfaces are spheres
  - the marginal ray heights in the vortex plane are different for larger angles
  - inconsistencies in the layout drawings
Matrix Formulation of Paraxial Optics

- Linear relation of ray transport
- Simple case: free space propagation
- Advantages of matrix calculus:
  1. simple calculation of component combinations
  2. Automatic correct signs of properties
  3. Easy to implement
- General case: paraxial segment with matrix ABCD-matrix:

\[
\begin{bmatrix}
    x' \\
    u'
\end{bmatrix} = \begin{bmatrix}
    A & B \\
    C & D
\end{bmatrix} \begin{bmatrix}
    x \\
    u
\end{bmatrix} = M \begin{bmatrix}
    x \\
    u
\end{bmatrix}
\]
Matrix Formulation of Paraxial Optics

- Linear transfer of spatial coordinate \( x \) and angle \( u \)

\[
x' = Ax + Bu \\
u' = Cx + Du
\]

- Matrix representation

\[
\begin{pmatrix} x' \\ u' \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} x \\ u \end{pmatrix} = M \cdot \begin{pmatrix} x \\ u \end{pmatrix}
\]

- Lateral magnification for \( u=0 \)

\[
A = \frac{x'}{x} = m
\]

- Angle magnification of conjugated planes

\[
D = \frac{u'}{u} = \Gamma
\]

- Refractive power for \( u=0 \)

\[
C = \frac{u'}{x}
\]

- Composition of systems

\[
M = M_k \cdot M_{k-1} \cdots M_2 \cdot M_1
\]

- Determinant, only 3 variables

\[
\det M = AD - BC = \frac{n}{n'}
\]
• Ray: straight line between two intersection points
• System: sequence of spherical surfaces
• Data: - radii, curvature $c = 1/r$
  - vertex distances
  - refractive indices
  - transverse diameter
• Surfaces of 2nd order:
  Calculation of intersection points analytically possible: fast computation
Raytrace errors

- Vignetting/truncation of ray at finite sized diameter: can or can not considered (optional)
- No physical intersection point of ray with surface
- Total internal reflection
- Negative edge thickness of lenses
- Negative thickness without mirror-reflection
- Diffraction at boundaries
Imaging on axis: circular / rotational symmetry
Only spherical aberration and chromatical aberrations

Finite field size, object point off-axis:

- chief ray as reference
- skew ray bundles:
  coma and distortion
- Vignetting, cone of ray bundle
  not circular symmetric
- to distinguish:
  tangential and sagittal plane
Sag of a Surface

- Sag $z$ at height $y$ for a spherical surface:

$$z = r - \sqrt{r^2 - y^2}$$

- Paraxial approximation: quadratic term

$$z_p \approx \frac{y^2}{2r}$$
- Pupil sampling in 3D for spot diagram:
  all rays from one object point through all pupil points in 2D
- Light cone completely filled with rays
Pupil sampling for calculation of tranverse aberrations: all rays from one object point to all pupil points on x- and y-axis

- Two planes with 1-dimensional ray fans

- No complete information: no skew rays
Entrance and Exit Pupil

- Upper marginal ray
- Chief ray
- Lower coma ray
- Upper coma ray
- Lower marginal ray
- On axis point of image
- Field point of image
- Entrance pupil
- Exit pupil
- Outer field point of object
- Object point on axis
There are 4 types of windows in Zemax:
1. Editors for data input:
   - lens data, extra data, multiconfiguration, tolerances
2. Output windows for graphical representation of results
   - Here mostly setting-windowss are supported to optimize the layout
3. Text windows for output in ASCII numerical numbers (can be exported)
4. Dialog boxes for data input, error reports and more

There are several files associates with Zemax
1. Data files (.ZMX)
2. Session files (.SES) for system settings (can be de-activated)
3. Glass catalogs, lens catalogs, coating catalogs, BRDF catalogs, macros, images, POP data, refractive index files,...

There are in general two working modes of Zemax
1. Sequential raytrace (or partial non-sequencial)
2. Non-sequential
Coordinate systems and sign of quantities

- Coordinate systems
  - 2D sections: y-z shown

- Sign of lengths, radii, angles:
  - \( s \): negative: to the left, positive: to the right
  - \( R \): negative: C to the left, positive: C to the right
  - \( \phi \): angle positive: counterclockwise

Reference:
- y / meridional section
- tangential plane
- x / sagittal plane
- z / optical axis
System model

- Single step:
  - surface and transition
  - parameters: radius, diameter, thickness, refractive index, aspherical constants, conic parameter, decenter, tilt,...

- Complete system:
  - sequence of surfaces
  - object has index 0
  - image has index N
  - tN does not exist

- Ray path has fixed sequence
  0-1-2-...-(N-1)-N
- Graphical control of system and ray path
- Principal options in Zemax:
  1. 2D section for circular symmetry
  2. 3D general drawing
- Several options in settings
- Zooming with mouse
Multi Configuration

- Multi configuration editor
- Establishment of different system paths or configurations
- Toggle between configurations with CNTR A
- Examples:
  1. Zoom systems, lenses moved
  2. Scan systems, mirror rotated
  3. Switchable optics, components considered / not taken into account
  4. Interferometer, test and reference arm
  5. Camera with different object distances
  6. Microscope tube system for several objective lenses
  7. ...
- In the multi configuration editor, the parameters / differences must be defined
- Many output options and the optimization can take all configurations into account
- Special option: show all configuration in the 3D layout drawing simultaneously
  1. shifted, for comparison
  2. with same reference, overlayed
Multi Configuration

- Demonstrational example: Twyman-Green interferometer