Metrology and Sensing

Lecture 13: Metrology of aspheres and freeforms

2019-01-22

Herbert Gross
<table>
<thead>
<tr>
<th>No</th>
<th>Date</th>
<th>Subject</th>
<th>Detailed Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.10</td>
<td>Introduction</td>
<td>Introduction, optical measurements, shape measurements, errors, definition of the meter, sampling theorem</td>
</tr>
<tr>
<td>2</td>
<td>17.10</td>
<td>Wave optics</td>
<td>Basics, polarization, wave aberrations, PSF, OTF</td>
</tr>
<tr>
<td>3</td>
<td>30.10</td>
<td>Sensors</td>
<td>Introduction, basic properties, CCDs, filtering, noise</td>
</tr>
<tr>
<td>4</td>
<td>09.11</td>
<td>Fringe projection</td>
<td>Moire principle, illumination coding, fringe projection, deflectometry</td>
</tr>
<tr>
<td>5</td>
<td>13.11</td>
<td>Interferometry I</td>
<td>Introduction, interference, types of interferometers, miscellaneous</td>
</tr>
<tr>
<td>6</td>
<td>20.11</td>
<td>Interferometry II</td>
<td>Examples, interferogram interpretation, fringe evaluation methods</td>
</tr>
<tr>
<td>7</td>
<td>27.11</td>
<td>Wavefront sensors</td>
<td>Hartmann-Shack WFS, Hartmann method, miscellaneous methods</td>
</tr>
<tr>
<td>8</td>
<td>28.11</td>
<td>Geometrical methods</td>
<td>Tactile measurement, photogrammetry, triangulation, time of flight, Scheimpflug setup</td>
</tr>
<tr>
<td>9</td>
<td>11.12</td>
<td>Speckle methods</td>
<td>Spatial and temporal coherence, speckle, properties, speckle metrology</td>
</tr>
<tr>
<td>10</td>
<td>18.12</td>
<td>Holography</td>
<td>Introduction, holographic interferometry, applications, miscellaneous</td>
</tr>
<tr>
<td>11</td>
<td>08.01</td>
<td>Measurement of basic system properties</td>
<td>Basic properties, knife edge, slit scan, MTF measurement</td>
</tr>
<tr>
<td>12</td>
<td>15.01</td>
<td>Phase retrieval</td>
<td>Introduction, algorithms, practical aspects, accuracy</td>
</tr>
<tr>
<td>13</td>
<td>22.01</td>
<td>Metrology of aspheres and freeforms</td>
<td>Aspheres, null lens tests, CGH method, freeforms, metrology of freeforms</td>
</tr>
<tr>
<td>14</td>
<td>29.01</td>
<td>OCT</td>
<td>Principle of OCT, tissue optics, Fourier domain OCT, miscellaneous</td>
</tr>
<tr>
<td>15</td>
<td>05.02</td>
<td>Confocal sensors</td>
<td>Principle, resolution and PSF, microscopy, chromatical confocal method</td>
</tr>
</tbody>
</table>
Content

- Aspheres
- Null lens tests
- CGH method
- Freeforms
- Metrology of freeforms
Optical Components

- Asphere
- Cylindrical lens
- Freeform lens
- Axicon
- Prisms
Manufacturing of Freeform Surfaces

- **Sphere**: Fixed radius, rotational symmetry.
  - Parameters: Radius, Roughness.

- **Asphere**: Variable radius, rotational symmetry.
  - Parameters: Radius, Deviation from Radius $\Delta z(y)$, Roughness.

- **Aspherical Segment**: Variable radius, virtual symmetry.
  - Parameters: Radius, Deviation from Radius $\Delta z(y)$, Center, Roughness.

- **Freeform Surface**: Loss of any symmetry.
  - Parameters: Deviation from Surface Description, Roughness, Power Spectrum.

Ref: G. Günther
Manufacturing of Aspheres / Freeforms

- Grinding / polishing
- Molding (low TG glasses or plastics)
- Diamond turning

Ref: C. Menke
Asphere Manufacturing

- Principle of kinematics

- Radial spatial profile and curvature of the mold

Freeform Manufacturing

- Tooling machine
- Fast server tool

Ref: B. Satzer
Freeform Manufacturing

- Fast server tool:
  - z-movement by the tool
  - usually smaller stroke
    - IOF: \( \Delta z = 6 \text{ mm} \)
    - Schneider new: \( \Delta z = 25 \text{ mm} \)
  - closed loop control

- Slow server tool:
  - z-movement by the sample
  - open loop control
  - better roughness
  - larger stroke

- Precision: comparable
Form of Material Removal

- Traditional material removal: surface / area contact

- Diamond turning of freeforms: pointlike contact special deviation types with local errors

Ref: R. Börret
Aspherical Surface Types

- Conic section
  Special case spherical

- Cone

- Toroidal surface with radii $R_x$ and $R_y$ in the two section planes

- Generalized onic section without circular symmetry

- Roof surface

\[
z = \frac{c(x^2 + y^2)}{1 + \sqrt{1 - (1 + \kappa)c^2(x^2 + y^2)}} \]

\[
z = \frac{\sqrt{x^2 + y^2}}{\theta} \]

\[
z = R_y - \sqrt{(R_y - R_x + \sqrt{R_x^2 - x^2})^2 - y^2} \]

\[
z = \frac{c_x x^2 + c_y y^2}{1 + \sqrt{1 - (1 + \kappa_x)c_x^2 x^2 - (1 + \kappa_y)c_y^2 y^2}} \]

\[
z = |y| \cdot \tan \theta \]
Conic Sections

- Explicite surface equation, resolved to z
  Parameters: curvature $c = 1 / R$
  conic parameter $\kappa$
- Influence of $\kappa$ on the surface shape

$$z = \frac{c(x^2 + y^2)}{1 + \sqrt{1 - (1 + \kappa)c^2(x^2 + y^2)}}$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Surface shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa = -1$</td>
<td>paraboloid</td>
</tr>
<tr>
<td>$\kappa &lt; -1$</td>
<td>hyperboloid</td>
</tr>
<tr>
<td>$\kappa = 0$</td>
<td>sphere</td>
</tr>
<tr>
<td>$\kappa &gt; 0$</td>
<td>oblate ellipsoid (disc)</td>
</tr>
<tr>
<td>$0 &gt; \kappa &gt; -1$</td>
<td>prolate ellipsoid (cigar)</td>
</tr>
</tbody>
</table>

- Relations with axis lengths $a, b$ of conic sections

$$\kappa = \left(\frac{a}{b}\right)^2 - 1$$
$$c = \frac{b}{a^2}$$
$$b = \frac{1}{c(1 + \kappa)}$$
$$a = \frac{1}{|c\sqrt{1 + \kappa}|}$$
Simple Asphere – Parabolic Mirror

- Equation
  \[ z = \frac{y^2}{2R_s} \]

- Radius of curvature in vertex: \( R_s \)
- Perfect imaging on axis for object at infinity
- Strong coma aberration for finite field angles

Applications:
  1. Astronomical telescopes
  2. Collector in illumination systems
Simple Asphere – Elliptical Mirror

- Equation
- Radius of curvature \( r \) in vertex, curvature \( c \)
- Eccentricity \( \kappa \)
- Two different shapes: oblate / prolate
- Perfect imaging on axis for finite object and image location
- Different magnifications depending on used part of the mirror
- Applications:
  - Illumination systems

\[
z = \frac{c y^2}{1 + \sqrt{1 - (1 + \kappa) y^2 c^2}}
\]
- Perfect stigmatic imaging on axis: Hyperoloid rear surface

\[
\left( z + \frac{s}{n+1} \right)^2 - \frac{r^2}{\left( \frac{s}{n+1} \right)^2 - s^2 \cdot \left( \frac{n-1}{n+1} \right)} = 1
\]

- Strong decrease of performance for finite field size: dominant coma
- Alternative: ellipsoidal surface on front surface and concentric rear surface
Impact of Asphere

- Asphere far from pupil:
  - ray bundles of field points separated
  - field dependent correction
  - also impact on distortion

- Asphere near pupil:
  - all ray bundles equally affected
  - problem field angles: coma
Aspherical Single Lens

- Correction on axis and field point
- Field correction: two aspheres
Reducing the Number of Lenses with Aspheres

- Example photographic zoom lens
- Equivalent performance
- 9 lenses reduced to 6 lenses
- Overall length reduced

Photographic lens $f = 53 \text{ mm}$, $F\# = 6.5$

a) all spherical, 9 lenses

b) 3 aspheres, 6 lenses, shorter, better performance

Ref: H. Zügge
Lithographic Projection: Improvement by Aspheres

- Considerable reduction of length and diameter by aspherical surfaces
- Performance equivalent
- 2 lenses removable

a) NA = 0.8 spherical

b) NA = 0.8, 8 aspherical surfaces

Ref: W. Ulrich
- Reference: deviation from sphere
- Deviation $\Delta z$ along axis
- Better conditions: normal deviation $\Delta r_s$

![Diagram showing aspheres and geometry](Image)
- Improvement by higher orders
- Generation of high gradients
Aspheres: Correction of Higher Order

- Correction at discrete sampling
- Large deviations between sampling points
- Larger oscillations for higher orders
- Better description: slope, defines ray bending

\[ y' = c \frac{dA}{dy} \]

Corrected points with \( y' = 0 \)

Residual spherical transverse aberrations

Paraxial range

Points with maximal angle error

Perfect correcting surface

Corrected points residual angle deviation

Real asphere with oscillations
Basic form of a conic section superimposed by a Taylor expansion of $z$

$$z(h) = \frac{\rho h^2}{1 + \sqrt{1 - (1 + c)\rho^2 h^2}} + \sum_{m=0}^{M} a_m h^{2m+4}$$

$h$ ... Radial distance to optical axis

$$h = \sqrt{x^2 + y^2}$$

$\rho$ ... Curvature

c ... Conic constant

$a_m$ ... Apherical coefficients

Ref: K. Uhlendorf
Forbes Aspheres

- New representation of aspherical expansions according to Forbes (2007)
  \[ z(r) = \frac{c \cdot r^2}{1 + \sqrt{1 - (1 + \kappa) \cdot c^2 r^2}} + \sum_{k=2}^{k_{\text{max}}} a_k \cdot Q_k(r^2) \]

- Special polynomials \( Q_k(r^2) \):
  1. Contributions are orthogonal slope
  2. tolerancing is easily measurable
  3. optimization has better performance
  4. usually fewer coefficients are necessary
  5. use of normalized radial coordinate makes coefficients independent on diameter

- Two different versions possible:
  a) strong aspheres: deviation defined along \( z \)
  b) mild aspheres: deviation defined perpendicular to the surface
# Forbes Aspheres

<table>
<thead>
<tr>
<th>Strong asphere $Q_{\text{con}}$</th>
<th>Mild asphere $Q_{\text{bfs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>sag along z-axis</td>
<td>difference to best fit sphere</td>
</tr>
<tr>
<td>slope orthogonal</td>
<td>sag along local surface normal</td>
</tr>
<tr>
<td>true polynom</td>
<td>not slope orthogonal</td>
</tr>
<tr>
<td>type Q 1 in Zemax</td>
<td>not a polynomial</td>
</tr>
<tr>
<td>type Q 0 in Zemax</td>
<td>type Q 0 in Zemax</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
  z(r) &= \frac{c \cdot \bar{r}^2}{1 + \sqrt{1-(1+\kappa) \cdot c^2/\bar{r}^2}} + \bar{r}^4 \sum_{k=2}^{k_{\text{max}}} a_k \cdot Q_k (\bar{r}^2) \\
  z(r) &= \frac{c \bar{r}^2}{1 + \sqrt{1-c^2 \bar{r}^2}} + \frac{\bar{r}^2 (1-\bar{r}^2)}{\sqrt{1-c^2 \bar{r}^2}} \sum_{m=0}^{M} a_m B_m (\bar{r}^2)
\end{align*}
\]

direct tolerancing of coefficients

no direct relation of coefficients to slope
- Special correcting free shaped aspheres:
  - Inversion of incoming wave front
- Application: final correction of lithographic systems

- Conventional lens
- Lens with correcting surface
Curvature of Aspheres

- Asphere:
  The location of the center of curvature moves with the radial surface position
- Conventional reflex light measurement in autocollimation is not possible
Autocollimation Principle

- Spherical test surface:
  - incoming and outgoing wavefront spherical
  - concentric waves around center of curvature: autocollimation

- Aspherical test surface
Asphere Testing

- Creating a spherical wave for autocollimation

Ref: F. Hoeller
Compensating Null Systems

- Null compensation: improved accuracy by subtracting the main effect
- Null optic: refractive or CGH
- Different schemes for null compensation

Ref: B. Dörband
Test of Aspheres with Null Lenses

- K-system (null lens) generates aspherical replica of the wavefront for autokollimation
- Small residual perturbations of the autocollimation are resolved by the interferometer
- Alignment of the K-lens is critical due to large spherical contributions
Test of Aspheres with Null Lenses

- System configurations for compensating null lenses
  - a) test surface convex
  - b) test surface convex, asphere steeper outside
  - c) test surface concave, asphere less steep outside
c) concave test surface
no intermediate focus
asphere steep outside

d) concave test surface
with intermediate focus
asphere less steep outside

e) concave test surface
with intermediate focus
and field lens for diameter
adaptation
Test of Aspheres with CGH

- Measuring of an asphere with (cheap) spherical reference mirror
- Formation of the desired wavefront in front of the asphere by computer generated hologram
- Measurement in transmission and reflection possible
- Critical alignment of CGH
Asphere Test with CGH

without CGH:

→ test-beam from/to interferometer

→ to much interference fringes
→ analysis impossible

with CGH:

→ flat wave-front
→ simple analysis

Ref: F. Burmeister
Asphere Testing

Ref: F. Hoeller
CGH Null Test

1. CGH

2. Interferogram without CGH (asphere)

3. Interferogram with CGH

Ref: R. Kowarschik
CGH Null Test

1. CGH in reflection
2. CGH in transmission

Ref: R. Kowarschik
CGH Metrology - Example

9” CGH for primary mirror of the GAIA-satellite telescope

9” CGH for secondary mirror of the METi-satellite telescope

Critical Parameters:
• size up to 230mm x 230mm
• positioning accuracy
• data preparation!
• homogeneity of etching depth and shape of grooves
→ wave-front accuracy
  < 3nm (rms) demonstrated

Ref: U. Zeitner
Test of Aspheres

- In interferometer gradients are measured
- Absolute error differences are of no meaning
- Residual gradient differences are essential for the performance of a null system
- Example:
  system 1 (red) is more beneficial, because the gradients are smaller
Freeform Systems: Motivation and Definition

- General purpose:
  - freeform surfaces are useful for compact systems with small size
  - due to high performance requirements in imaging systems and limited technological accuracy most of the applications are in illumination systems
  - mirror systems are developed first in astronomical systems with complicated symmetry-free geometry to avoid central obscuration

- Definition:
  - surfaces without symmetry
  - reduced definition: plane symmetric or double plane symmetric surfaces are freeforms
  - special case: off-axis subaperture of circular symmetric aspheres
  - segmented surfaces included?
Spectacle Freeform Lenses

Degree of individualization

Complexity of the surface

Sphere
Asphere
Toric
Atoric
Freeform
Customized Freeform

Ref: W. Ulrich
Simultaneous correction of:
1. far, upper zone
2. near, lower zone
Continuous transition with reduced horizontal field of view, zone of progression
Approach in 1980: 800x800 patches, cubic spline description, optimization with $10^7$ parameters
Relaxed requirements on accuracy
Reflective Freeform Systems

- Telescopes
- Spectrometer
- Lithographic projection systems
Lithographic Lens

- Projection lenses in micro-Lithography today uses freeform surfaces:
  1. at 13.5 nm only mirrors are possible
  2. at 193 nm the mirrors are helpful in correcting the field flatness
- Typical impact of spatial frequency ranges on PSF
  - Low frequencies: loss of resolution classical Zernike range
  - High frequencies: Loss of contrast statistical
  - Large angle scattering
  - Mif spatial frequencies: complicated, often structured fals light distributions

![Diagram showing impact of spatial frequencies on PSF](image)
Diamond turning or milling creates regular ripple in nearly any case:
- reason: point-like tooling and tool vs workpiece oscillations
- in case of final polishing effect is strongly reduced

Depending on the ratio of tool size and surface diameter this structure cannot be described by figure representations.
Metrology of Freeform Surfaces

- Tactil / profilometer
- Confocal microscopy
- Optical coherence tomography
- Hartmann sensor
- Hartmann-Shack sensor
- Deflectometry
- Fringe projection
- Interferometer with stitching
- Interferometer with CGH for Null compensation
- Tilted Wave Interferometer
Measurement Approaches for Freeforms

Volume

- 1000 mm³
- 100 mm³
- 10 mm³
- 1 mm³

Accuracy

- 10 µm
- 1 µm
- 0.1 µm
- 0.01 µm
- 0.001 µm

Methods:

- Laser scanner
- Fringe projection
- Tactile
- UA3P - 6
- Interferometer
- Hartmann
- White light, AFM

Ref.: J. Heise
## Properties

<table>
<thead>
<tr>
<th>Method</th>
<th>Benefit</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tactile coordinate measuring machine</td>
<td>universal</td>
<td>slow, damage, expensive</td>
</tr>
<tr>
<td>Special machines ISARA, UA3P</td>
<td>universal, accurate</td>
<td>tactile, slow expensive</td>
</tr>
<tr>
<td>Interferometer with CGH</td>
<td>fast, accurate</td>
<td>expensive, small dynamic range</td>
</tr>
<tr>
<td>Fringe projection</td>
<td>fast</td>
<td>not accurate, poor lateral resolution</td>
</tr>
<tr>
<td>Shack-Hartmann-Sensor</td>
<td>fast</td>
<td>small dynamic range</td>
</tr>
</tbody>
</table>

Ref.: J. Heise
Tactile Measurement

- Scanning method
  - Sapphire sphere probes shape
  - slow
  - only some traces are measured

- Universal coordinate measuring machine (CMM) as basic engine

- Contact can damage the surface
- Accuracy 0.2 μm in best case

Ref: H. Hage / R.Börret
Tilted Wave Interferometer

- Basic setup: Twyman-Green interferometer
- Several points sources: at least one is in autocollimation to a sample point
- Calibration complicated
- Unusual interferogramms by superposition

Ref: H. Hage
Tilted Wave Interferometer

- Interferometer with array of points sources (ITO / W. Osten, Mahr)
- At least one source points generates a subaperture nearly perpendicular
- Complicated data evaluation
- Measurement of an freeform in transmission
- Shaping a spherical wavefront by computer generated hologram
- Preshaping the wavefront for autocollimation
- Method can be used in transmission or reflection
- Without CGH: dynamic range too small
- Expensive method
- Calibration of CGH necessary
Low Accuracy Measurement: Hartmann Sensor

- Measurement of eyeglasses with low accuracy: Hartmann sensor (hole mask)
- Hartmann-Shack sensor also possible
- Low spatial resolution
- Measurement in transmission preferred
Contributions of Surface Shape

- Decomposition of surface shape:
  1. separation of circular symmetric part
  2. separation of spherical part

Ref: B. Dörband
Measurement by Subaperture Stitching

- Stitching of complete surface by subapertures: dynamic range increased
- Overlapping subapertures: minimizing stitching errors due to movement
- Large computational effort

Ref: B. Dörband
shape deviation after grinding: PV 26.2 µm

shape deviation after correction and polishing: PV 2.5 µm

Micro roughness 40x (0.15x0.15 mm²)

Micro roughness 2.5x (2.5x2.5 mm²)

Ref: G. Günther
Positioning and Orientation of Freeforms

- Fixation of a surface by spheres
- Optical positioning of spheres by CGH with stitching subapertures in catseye setup
- Higher accuracy in comparison to tactile measurement