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- Collimated incident light
- Calibrated collimator with focal length $f_c$ and test chart with size $y$
- Selection of sharp image plane
- Analysis of image size

$$f' = -f'_c \cdot \frac{y'}{y}$$
Setup with distance object-image $L > 4f$
- Known location of the principal plane $P$ of the system
distance $d_P$ between principal planes
- Selection of two system locations with sharp image
- Relative axial shift $D$ between the two setups

\[ f = \frac{L - d_H}{4} - \frac{D^2}{4(L - d_H)} \]
- Setup with fiber and plane mirror for autocollimation
- Change of distance between test lens and fiber
- Analysis of the recoupled power into the fiber (confocal) gives the focal point
Criteria for best focus:

1. Paraxial centre of curvature for the paraxial spherical wave of an on axis object point.
2. Maximum of the Strehl ratio
3. Smallest rms-value of the wave aberration
4. Highest contrast of the modulation of an object feature of given spatial frequency
5. Highest value of the slope of an edge
6. Highest value of the entropy of the detected digital image

Requirements for focus detection procedure

1. Steep curve dependency to get high accuracy
2. Robust definition to deliver a large dynamic range
3. Suppression of side lobe effects to guarantee an unambiguous solution
4. High frequency pre-filtering to be noise insensitive
Determination of Best Focus

- Blur of defocussed plane

- Minimum of image entropy

\[ E = - \sum_j w_j \cdot \log_2 w_j \]

- Maximum of image contrast
Measurement by image analysis:

1. Maximum gradient of edges
   \[ g = |\nabla I(x, y)| = \sqrt{\left(\frac{\partial I}{\partial x}\right)^2 + \left(\frac{\partial I}{\partial y}\right)^2} \]

2. Power of gradients
   \[ G = \iint |\nabla I(x, y)|^2 \, dx \, dy \]

3. Laplacian
   \[ L = \iint |\nabla^2 I(x, y)|^2 \, dx \, dy \]
Measurement of Pupil Size

- Setup with collimating auxiliary lens

\[ \tan u = \frac{D}{2f} \]

- Determination with measuring microscope (dynameter)

\[ \text{light source} \quad \text{collimator} \quad \text{test system} \quad \text{exit pupil} \quad \text{movable dynameter lens} \]
- Setup with Ronchi grating
- Measurement of the lateral shift of higher diffraction orders at distance $z$

- High-NA in microscopy: $\text{NA}>1$
- Measurement of total internal reflection of fluorescence light
- Measurement of reflexes at lens vertex points
- Analysis of confocal signal in autocollimation
- Avoiding spherical aberration induced errors by ring illumination
- Measurement of tilt errors (plane or spherical surface) in autocollimation
- Projection of the cross
- Observation of lateral shift in Fourier plane \( x = f \cdot 2\varphi \)
- Projection of test marker
- Autocollimation of sharp image, focal point coincides with center of curvature of surface with radius $r$
- Rotation of test system: tilt of surface induces a lateral shift of the image
- Problems with inner surfaces

\[ v = \beta \cdot v_M = 2 \cdot \beta \cdot r \cdot \kappa \]
Reasons for reduced system transmission:
1. Absorption in the bulk material of the components
2. Scattering in the bulk materials by inclusions or finite scattering parameters
3. Absorption in the coatings of the surfaces
4. Partial reflection or transmission at the coatings at transmissive or reflective surfaces
5. Blocking of light via mechanical or diaphragm parts of the system due to vignetting
6. Scattering of light by local surface imperfections or non-perfect polished surfaces
7. Deflection of light by diffraction of the light at edges
8. Deflection of light in unwanted higher orders of diffractive elements

Usually strong dependency on:
1. field position
2. wavelength of light
3. used pupil location
4. polarization

Critical:
1. absolute values for test lens
2. influence of auxiliary components
3. change of vignetting and incidence angles
Measurement of transmission:

- **Reasons for measurement errors:**
  1. Absorption in the component materials
  2. Absorption in the coatings
  3. Finite reflectivity of the coatings
  4. Vignetting of the aperture bundle for oblique chief rays
  5. Natural vignetting according for oblique chief rays and projection of tilted planes
  6. False light from surrounding light sources, which reach the image plane
  7. Scattering of light at components of the system mechanical design
  8. False light due to ghost images or narcissus in infrared systems

\[
T = \frac{P_{in}}{P_{out}}
\]
• Measurement of unwanted light: 2 different approaches:

1. object area black, surrounded by bright source
detection of irradiance in image region

2. intensive isolated point light source in the object plane at different locations
detection of artificial distributions in the image area: glare spread function
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 \( \mu \text{m} \) in best case

Ref: H. Hage / R. Börret
Tactile Measurement

- Influence of the taste sphere: filtering of higher spatial frequencies due to finite size
- Gradient of skew touching geometry can be calibrated and corrected
- Periods of same size as the sphere: error in amplitude
- High frequencies: not detected
Measurement by Fringe Projection

- Projection of a light sheet onto a deformed surface
- Corresponds to one fringe in more complicated pattern projection
Example Fringe projection

- Monochromatic illuminated technical surface
3D Shape Measurement for Biometry

- Colored biometric fringe projection
- Projection of a 2D triangular pattern
Shape Measurement by Fringe Projection

- Shape measurement of a surface
- Projection of a fringe pattern onto the surface
- Observation of the fringe deformation by a camera
  A shift corresponds to a change in depth
- Non-trivial image processing
Data evaluation

- Fringe period

\[ d_x = \frac{d}{\cos \theta_1} \]

- Lateral shift

- Corresponding depth value \( z \)

\[ u = z \cdot (\cos \theta_1 + \cos \theta_2) \]

\[ f(x) = \frac{u}{d_x} = \frac{z \cdot (\cos \theta_1 + \cos \theta_2)}{d / \cos \theta_1} = \frac{z}{d} \cdot \frac{\sin(\theta_1 + \theta_2)}{\cos \theta_2} \]
- Measurement of the refractive index of a liquid
- Thin film of test liquid between prisms, adjustment of total internal reflection
- Special setup with direct sight prisms, no color fringes
Two Beam Interference

- Two beam interference of two waves:
  - propagation in the same direction
  - same polarization
  - phase difference smaller than axial length of coherence

- Coherent superposition of waves

\[ I = |E_1 + E_2|^2 \]

\[ = I_1 + I_2 + 2 \sqrt{I_1 \cdot I_2} \cdot \cos \Delta \varphi_{12} \]

- Difference of phase / path difference

\[ \Delta s = \frac{\lambda}{2\pi} \cdot \Delta \varphi_{12} \]

\[ N = \frac{\Delta \varphi_{12}}{2\pi} = \frac{\Delta s}{\lambda} \]

- Number of fringes
  location of same phase

- Contrast

\[ K = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{2 \sqrt{I_1 \cdot I_2}}{I_1 + I_2} \]
Interferometry

- Basic idea:
  - separation of a wave into two beams (test and reference arm)
  - every beam surpasses different paths
  - superposition and interference of both beams
  - analysis of the pattern

- Different setups for:
  - the beam splitting
  - the superposition
  - the referencing

- Different path lengths

\[ \Delta = n_1 t_1 - n_2 t_2 = N \cdot t_w \]

\[ t_w = \frac{\lambda}{2n} \]

- Measurement of plates:
  - Haidinger fringes of equal inclination
  - Newton fringes of equal thickness

Ref: W. Osten
Autocollimation Principle

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

- Aspherical test surface
Classification of Interferometers

- **Division of amplitude:**
  - Michelson interferometer
  - Mach-Zehnder interferometer
  - Sagnac interferometer
  - Nomarski interferometer
  - Talbot interferometer
  - Point diffraction interferometer

- **Division of wavefront:**
  - Young interferometer
  - Rayleigh interferometer

- **Division of source:**
  - Lloyds mirror
  - Fresnel biprism

Ref: R. Kowarschik
Real Interferometers

Ref: R. Kowarschik
Interferometer

- Ligo interferometer
- Michelson type
- Caltech, arm lengths 4 km
- Measurement of gravitational waves
- Nobel price 2017

Ref: S. Balmer
Interferometers

- Accuracy of interferometers

Resolution of a digital interferometer

Resolution = 0.029 nm = 1/3 diameter of an atom

corresponds to a height resolution of Germany with < 200µm

Ref: F. Hoeller
Testing with Fizeau Interferometer

- Long common path, quite insensitive setup
- Autocollimating Fizeau surface quite near to test surface, short cavity length
- Imaging of test surface on detector
- Straylight stop to block unwanted light
- Curved test surface: auxiliary objective lens (aplanatic, double path)
- Highest accuracy
Testing with Twyman-Green Interferometer

- Short common path, sensible setup
- Two different operation modes for reflection or transmission
- Always factor of 2 between detected wave and component under test

1. mode:
lens tested in transmission
auxiliary mirror for auto-collimation

2. mode:
surface tested in reflection
auxiliary lens to generate convergent beam
- Separation of wavefront: self reference
- Interferograms are looking completely different
- Aperture reduced due to shear
- Splitting and shift of wavefront:
  - by thin plate
  - by grating
Test by Newton Fringes

- Reference surface and test surface with nearly the same radii
- Interference in the air gap
- Reference flat or curved possible
- Corresponds to Fizeau setup with contact
- Broad application in simple optical shop test
- Radii of fringes

\[ r_m = \sqrt{mR\lambda} \]

Ref: W. Osten
Interferograms of Primary Aberrations

Spherical aberration $1\lambda$

Astigmatism $1\lambda$

Coma $1\lambda$

Defocussing in $\lambda$

-1  -0.5  0  +0.5  +1
Critical definition of the interferogram boundary and the Zernike normalization radius in reality
Interferograms

- Examples
Temporal Coherence

- Radiation of a single atom:
  Finite time $\Delta t$, wave train of finite length,
  No periodic function, representation as Fourier integral
  with spectral amplitude $A(\nu)$

- Example rectangular spectral distribution

- Finite time of duration: spectral broadening $\Delta \nu$,
  schematic drawing of spectral width
- Corresponding axial coherence time

\[
\tau_c = \frac{1}{\Delta \nu}
\]

- Axial coherence length

\[
l_c = c \cdot \tau_c
\]

\[
E(t) = \int A(\nu) \cdot e^{2\pi i \nu t} \, d\nu
\]

\[
A(\nu) = \frac{\sin(\pi \cdot \nu \cdot \Delta t)}{\pi \cdot \nu \cdot \Delta t}
\]

$\Delta \nu = 1 / \Delta t$
Lateral and Axial Resolution

- Intensity distributions
- Aberration-free Airy pattern: lateral resolution
  \[ D_{\text{Airy}} = \frac{1.22 \cdot \lambda}{\text{NA}} \]

axial resolution
  \[ R_E = \frac{n \cdot \lambda}{\text{NA}^2} \]

Ref: U. Kubitschek
OCT Setup

- Basic principle of OCT
- Michelson interferometer
- Time domain signal
Optical Coherence Tomography

- Example: sample with two reflecting surfaces
- 1. Spatial domain
- 2. Complete signal
- 3. Filtered signal high-frequency content removed

Ref: M. Kaschke
Example of OCT Imaging

Example:
Fundus of the human eye
Dimensions of OCT imaging:
- a) only depth (A-scan), one-dimensional
- b) depth and one lateral coordinate (B-scan), two-dimensional
- c) all three coordinates, volume imaging

Ref: M. Kaschke
White Light Interferometry

- Examples

Ref: R. Kowarschik
Knife Edge Method

- Moving a knife edge perpendicular through the beam cross section
- Relationship between power transmission and intensity: Abel transform for circular symmetry

\[ P(x) = 2 \int_{x}^{\infty} \int_{\xi}^{\infty} \frac{I(r) r \, dr}{\sqrt{r^2 - \xi^2}} \, d\xi \]

- Example: geometrical spot with spherical aberration
- Measurement of an edge image
- Evaluating the derivative: Line spread function
- Fourier transform: optical transfer function

\[ I_{LSF}(x') = \frac{d I_{ESF}(x')}{d x'} \]

\[ H_{OTF}(s) = \hat{F}[I_{LSF}(x')] \]
- Lenslet array divides the wavefront into subapertures
- Every lenslet generates a single spot in the focal plane
- The averaged local tilt produces a transverse offset of the spot center
- Integration of the derivative matrix delivers the wave front $W(x,y)$
- Typical setup for component testing

- Lenslet array
- Aberrations produce a distorted spot pattern
- Calibration of the setup for intrinsic residual errors
- Problem: correspondence of the spots to the subapertures
Problem in practice: definition of the boundary
- Wave front determines local direction of propagation
- Propagation over distance $z$ : change of transverse intensity distribution
- Intensity propagation contains phase information
- Principle of phase retrieval for metrology of optical systems
- Measurement of intensity caustic z-stack
- Reconstruction of the phase in the exit pupil
Example Phase Retrieval

- Evaluation of real data psf-stack
Time is Over
Many mysterious things and new notations

Ref: T. Kaiser
Feedback

nothing clear?

to complicated?

to much stuff?

Ref: D. Shafer
Thank you for your attending the lecture